Samuel Sheldon

TRANSACTIONS

OF THE

AMERICAN INSTITUTE

OF

ELECTRICAL ENGINEERS,

JANUARY TO MAY, 1907.

VOL. XXVI, PART I.

PUBLISHED BY THE
AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS,
33 WEST THIRTY-NINTH STREET,
NEW YORK, N. Y., U. S. A.
1908

Press of McIlroy & Emmet, 22 Thames Street, New York.

OFFICERS AND BOARD OF DIRECTORS.

1906-1907.

PRESIDENT.
SAMUEL SHELDON.
Term expires 1907.

JUNIOR PAST-PRESIDENTS.

JOHN W. LIEB, JR. SCHUYLER S. WHEELER.

VICE-PRESIDENTS.

Term expires 1907.	Term expires 1908.
CHARLES A. TERRY.	A. H. ARMSTRONG.
TOWNSEND WOLCOTT.	FRANK G. BAUM.
GANO DUNN.	H. H. HUMPHREY.

MANAGERS.

Term expires 1907.	Term expires 1908.	Term expires 1909.
C. O. MAILLOUX.	CUMMINGS C. CHESNEY.	A. M. SCHOEN.
HENRY G. STOTT.	BANCROFT GHERARDI.	PAUL SPENCER.
JAMES G. WHITE.	CALVERT TOWNLEY.	JOHN J. CARTY.
LOUIS A. FERGUSON.	CHARLES L. EDGAR.	PAUL M. LINCOLN.

TREASURER.
Term expires 1907.
GEORGE A. HAMILTON,
463 West St., New York, N. Y.

SECRETARY.
Term expires 1907.
RALPH W. POPE,
33 West Thirty-ninth St., New York, N. Y.

PAST-PRESIDENTS.

NORVIN GREEN, 1884-5-6.
FRANKLIN L. POPE, 1886-7.
T. COMMERFORD MARTIN, 1887-8.
EDWARD WESTON, 1888-9.
ELIHU THOMSON, 1889-90.
WILLIAM A. ANTHONY, 1890-91.
ALEX. GRAHAM BELL, 1891-2.
FRANK J. SPRAGUE, 1892-3.
EDWIN J. HOUSTON, 1893-4-5.
LOUIS DUNCAN, 1895-6-7.
FRANCIS B. CROCKER, 1897-8.
ARTHUR E. KENNELLY, 1898-1900.
CARL HERING, 1900-1901.
CHARLES P. STEINMETZ, 1901-2.
CHARLES F. SCOTT, 1902-3.
BION J. ARNOLD, 1903-4.
JOHN W. LIEB, JR., 1904-5.
SCHUYLER S. WHEELER, 1905-6.

STANDING COMMITTEES AND LOCAL SECRETARIES.

1906-1907.

Executive Committee.

SAMUEL SHELDON, Chairman,

JOHN J. CARTY.
GEORGE A. HAMILTON.
RALPH W. POPE.
HENRY G. STOTT.
CHARLES A. TERRY.
CALVERT TOWNLEY.

Library Committee.

WM. J. JENKS, Chairman.
EDWARD CALDWELL.
CHARLES F. CHANDLER.
CHARLES A. TERRY.
F. N. WATERMAN.

Board of Examiners.

WM. MAVER, JR., Chairman.
H. FLEETWOOD ALBRIGHT.
FRANK W. ROLLER.
LEWIS B. STILLWELL.
TOWNSEND WOLCOTT.

Editing Committee.

THOS. J. JOHNSTON, Chairman.
GANO DUNN.
CECIL P. POOLE.

Committee on Papers.

HENRY G. STOTT, Chairman.
BERNHARD A. BEHREND.
HENRY A. LARDNER.
PAUL M. LINCOLN.
E. WILBUR RICE, JR.

Committee on Finance.

JOHN J. CARTY, Chairman.
GANO DUNN.
JAMES G. WHITE.

Local Honorary Secretaries.

JAMES S. FITZMAURICE, 210 George St., Sydney, N. S. W.
H. F. PARSHALL, Salisbury House, London Wall E. C., London.
ROBERT B. OWENS, McGill University, Montreal, P. Q.
WM. B. HALE. Arco de San Augustin 8, City of Mexico.
CLARE F. BEAMES, [for Porto Rico and West Indies], San Juan, P. R.
W. G. T. GOODMAN, Adelaide, South Australia.

Local Secretaries.

ADOLPH SHANE, Iowa State College, Ames, Iowa.
C. J. WHIPPLE, University of Michigan, Ann Arbor, Mich.
W. R. COLLIER, Atlanta, Ga.
CHAS. G. EDWARDS, Baltimore, Md.
M. T. SALDANA, Lehigh University, Bethlehem, Pa.
C. H. PORTER, Mass. Inst. Technology, Boston, Mass.
A. C. STREAMER, University of Colorado, Boulder, Colo.
C. E. FREEMAN, Armour Inst. of Technology, Chicago, Ill.
H. R. KING, Chicago, Ill.
LAURENT LOWENBERG, Cincinnati, O.
H. D. CARPENTER, University of Missouri, Columbia, Mo.
F. E. BEUTLER, Ohio State University, Columbus, O.
H. L. COOK, Columbus, O.
G. C. BAKER, University of Arkansas, Fayetteville, Ark.
H. H. NORRIS, Cornell University, Ithaca, N. Y.
J. W. ESTERLINE, Purdue University, Lafayette, Ind.
J. W. SHUSTER, University of Wisconsin, Madison, Wis.
S. R. INCH, University of Montana, Missoula, Mont.
H. F. SANVILLE, Philadelphia, Pa.
H. D. JAMES, Pittsburg, Pa.
S. H. BLAKE, Pittsfield, Mass.
W. E. BRYAN, Washington University, St. Louis, Mo.
A. S. LANGSDORF, St. Louis, Mo.
BARRY DIBBLE, St. Paul, Minn.
A. H. BABCOCK, San Francisco, Cal.
E. E. F. CREIGHTON, Schenectady, N. Y.
W. S. WHEELER, Seattle, Wash.
H. L. FREDERICK, Pennsylvania State College, State College, Pa.
A. M. WYGANT, Syracuse University, Syracuse, N. Y.
GEO. E. KIRK, Toledo, O.
L. W. PRATT, Toronto, Ont.
M. K. AKERS, University of Illinois, Urbana, Ill.
PHILANDER BETTS, Washington, D. C.
A. T. CHILDS, Worcester Poly. Inst., Worcester, Mass.

CONTENTS.

MEETING AT NEW YORK, MARCH 22, 1907.

MEETING AT CHICAGO, MARCH 26, 1907.

MEETING AT NEW YORK, MARCH 29, 1907.

MEETING AT NEW YORK, APRIL 15, 1907.

MEETING AT SCHENECTADY, APRIL 25, 1907.

A paper presented at the meeting of the Boston Branch of American Institute of Electrical Engineers, Boston, Mass., January 9, 1907.

GAS-ENGINE REGULATION FOR DIRECT-CONNECTED UNITS

BY CHARLES E. LUCKE

The speed of an engine may be expressed in revolutions per minute, or in terms of the linear velocity of the crank-pin in feet per minute. Revolutions per minute is rather more indefinite than crank-pin velocity in feet per minute, because feet per minute is accepted as not simply a measurement for a minute of time, whereas revolutions per minute more frequently is. Revolutions per minute may mean half the actual number of revolutions completed in two minutes or twice the number of revolutions completed in one-half minute, or it may mean the momentary rate of completing a revolution without any implied time. As there is a possibility of a lack of agreement on the implication in the term revolutions per minute, I should prefer to define the engine-speed in terms of crank-pin velocity in feet per minute, which can be expressed momentarily for any period of time, and does not imply any particular time. This velocity so expressed is the integral of the accelerating forces with respect to time, and in fact may be so defined according to the laws of mechanics.

The problem of regulation is really a problem of force balancing, and there are always two forces or two resultant forces in question: one a driving tangential force on the crank pin, the other a resisting tangential force at the same place. When these two forces are equal the acceleration is zero, and its integral, the engine-speed, is constant. If these forces are unequal there is a real acceleration, due to their difference, either positive or negative, and the engine-speed changes. The problem of regulation resolves itself into a demand for a balancing of forces at the crank pin after the desired speed is once attained. The exact solution of this problem is impossible and always will be, regardless of the type of engine or the conditions of operation. While it is impossible ever to keep the acceleration zero, and the actual engine-speed constant and of predetermined velocity, it is by no means impossible to keep the mean of these driving and resisting forces equal for certain periods of time, and the mean resultant speed any constant value desired. The prime variable in the problem is the resisting force, generally expressed in terms of load; but as load does not accurately describe actual resisting force, regulation cannot be directly studied from load alone and load must be resolved back to force. Practically all of the work that has been done in the solution of this problem of regulation in practice has concerned itself, either directly or indirectly, with the problem of securing a mean of equality or an equality of mean forces for some time-period, and a speed limitation by introducing heavy rotors.

This sort of study is decidedly useful but it does not give as clearly the nature of the problem or the available means of its solution as does the other point of view, which calls for a comparison of actual momentary forces and not mean forces, and further may lead to misinterpretation of results obtained. The problem of regulating steam engines has been discussed for many, many years; the problem of regulating gas engines for comparatively few years. By regulating I do not mean merely the preventing of undue and dangerous speeds, but the problem of securing uniform crank-pin velocities. There really existed no such problem calling for solution by mechanical engineers until electrical engineering developed a demand for a dynamo driven at a constant crank-pin velocity. The demand for this close regulation, therefore, is recent, but more recent still is the development of the large commercial gas engine. The methods and means for accomplishing regulation of steam engines have been very fully discussed, although the problem is by no means solved. There are many papers written on the subject, and a few of these will be examined. In general, however, they present limited data and only a part solution of the problem. An analysis of the problem of regulating steam engines will show it to consist of a few elemental problems, each equally important, some interdependent and some dependent. Some of these elementary problems are precisely the same for the steam engine as for the gas engine, and it is desirable that those interested in solving the gas-engine problem should have a clear understanding of what has been accomplished in the regulation of the steam engine. It will be found that a good many of the steam-engine problems have been fairly well solved, and this experience can be applied directly to the gas engine; but there are certain characteristics of the gas engine which must be separately treated and which differentiate its regulation problem from that of the steam engine.

Among the numerous papers on regulation and engine governing, all the early ones are concerned with governors. Until about 1898, when parallel operation of alternators became an important problem, it is surprising what a large amount of the literature reveals the idea that engine regulation is a problem of governor design. While up to that time this may have been more or less justified in view of the kind of regulation necessary, it is no longer the case; governor design, important as it is in limiting mean speeds and keeping mean speeds at high and low loads close together, is to-day only one factor in solving problems of regulation calling for uniform crank-pin velocities. Following two or three years' strenuous experience in regulation of steam engines for driving alternators in parallel, there appeared a remarkable series of papers before the American Society of Mechanical Engineers and the American Institute of Electrical Engineers setting forth the problem and giving some of the experience gained.

It is rather a noteworthy fact and coincidence that during the same period the gas engine as a competitor of the steam engine for general power purposes came into rapid development. At first economy was sought, and found; then life and low maintenance, which to-day is still a problem, together with gas-engine regulation for electrical work and the design for special service of special gas engines.

An examination of the early papers on governors will show that the design of masses developing centrifugal and so-called inertia forces for controlling valve-gears is fairly well understood. Barring the unknown elements of windage, friction, and valve-gear resistance, the problem is one of simple mechanics. The papers on steam-engine regulation show considerably more concerning the problem. Some of the important ones are worth a review, but first a few elementary principles will clarify the situation.

Every engine has some form of valve-gear. This valve-gear is intended to distribute steam in steam engines, to measure air and gas in gas engines, mix them, distribute the mixture, ignite it, and then more or less expel the products. This valve-gear, in engines intended for speed regulation, is adjustable either wholly or in part. The adjustable part is adjusted to enable the engine to do an amount of work commensurate with the resistance or load. A certain number of strokes is necessary for a complete cycle of operations. When the work done by the engine in this complete cycle equals the resisting work or the load, the engine will always have at the end of each cycle the same speed as at the beginning, however it may vary during the execution of the cycle.

A change in the position of the valve-gear will change the amount of work the engine is capable of doing by a change either in the steam distribution or in the handling of explosive mixtures. If the engine is to be commercial, the first requisite is that the amount of work the engine is capable of doing must be dependent upon and determined by the position of the adjustable part of the valve-gear, and that for any given position of the valve-gear, regardless of all previous positions, the engine should be capable of doing the same amount of work every time the gear reaches this position. The amount of work done by the engine is proportional to the area of its indicator card, so that the first requisite for an engine capable of close regulation is that for any given position of the valve-gear there must always be produced the same area of indicator card, and for any other position a different indicator card, different in area, and possibly, although not essentially, different in form. To fix the position of the adjustable valve-gear there is but one principle employed, and that is to leave it to the control of the centrifugal force acting through the governor. The centrifugal governor contains elements which have fixed positions for every speed. These elements are connected with the valve-gear so that it will have a fixed position for every different speed. With this combination, therefore, of a governor and valve-gear having a fixed position for every speed and an engine-control valve, igniters, etc., giving a fixed amount of work and a fixed indicator card for every position, there will result a mechanism in which the amount of work done per cycle by the engine will depend upon the speed. It is always the same at any given speed and cannot be changed without first changing the speed.

Different designs of governors containing different distributions of the masses, different fixed speeds, and arrangements of parts differ only in their ability to move the valve-gear a certain distance against a certain resistance in a certain time with a given speed-change. It is a problem of simple mechanics with a few unknown elements to design a governor that will, with any given change in speed, 1%, 2% or x% above or below the mean or average for the cycle, move any valve gear, however strongly it may resist, through any distance it may be necessary to move it, and as quickly as may be necessary. It may be assumed as entirely feasible, and not by any means difficult, to design a governor that will accomplish any valve adjustment in as short a time and with as small a speed as may be desired. There must be, however, a speed-change before the governor gear can move, and if the engine is capable of doing a constant amount of work per cycle for every governor position the amount of work per cycle it can do will depend upon the governor positions or speed. The mean speed for the cycle will be constant when the work of the cycle done is equal to the resistance work; therefore, for an absolutely steady load, in which the resistance per cycle is equal to the effort of the cycle, the mean speed will be constant and the governor stand still holding the valve-gear still.

To be strictly correct, the above statement should be modified because centrifugal governor position does not depend upon the mean speed for the cycle but upon the actual momentary speed, together with the inertia, friction, etc., of its parts and attached gear. If the work done per cycle is exactly equal to the resistance work for the cycle, then the mean speed will be constant, but the actual speed during the cycle may vary very much. Consequently, the valve-gear may change position during the cycle, which may or may not have, but probably will have, some effect upon the work to be done. To stand perfectly still all the time, the governor must be subject to a constant speed. This can be obtained only with a persistent equality between the driving force and the resisting force, irrespective of the work per cycle. Should the forces change throughout the cycle, the governor position will change, cylinder distribution change, and there would be a continual changing of work done, alternately increasing and decreasing. This is all due to the fact that the crank-pin forces throughout the cycle do not maintain equality and the valve-gear and work done per cycle depend, not on mean speed, but on actual speed in every instance, which is a consequence of the equality or inequality of the two crank-pin forces. With a centrifugal governor, therefore, even if the engine were capable of giving the same area of cards for every governor position, there cannot be a constancy of speed with a variation of resultant crank-pin force throughout the cycle. The governor may be damped; that is to say, it may be made less sensitive to speed changes either by dash-pots or other devices, in which case it becomes, not a simple centrifugal governor, whose position depends upon actual momentary speed, but a modified centrifugal governor whose position depends upon a sustained speed or mean sustained for some definite length of time. For such a governor to be perfect in its modifications it should have a position consequent on the mean speed for the cycle and not upon the actual momentary speed at any instant. If it had a position depending upon the mean speed for the cycle, then the valve-gear would stand still when the work done was equal to the load for the cycle, regardless also how the actual speed may have changed. The actual speed in such a case will change throughout the cycle, but the mean will be constant for the entire cycle and a predetermined speed reached at the end of every cycle with no undue hunting of the valve-gear from an over-sensitive governor in combination with a widely varying difference between widely varying crank-pin forces. If there were an actual equality between the driving force throughout the cycle such damping of the governor would be harmful instead of beneficial.

Since the valve-gear position in any case depends upon the governor position, and this upon the speed, it is certain that the valve-gear will not have the same position for high and low speeds or at the same time when little work is being done the speed cannot be the same as when much work is being done, the amount of work in each case being dependent upon the position of the valve-gear. In an engine producing the same indicator card for any position of the governor gear, which is controlled by a centrifugal governor, the no-load speed must be higher than the full-load speed, though each mean cycle speed may be constant if the load is constant.

If the actual load varies from time to time throughout the cycle of the engine, giving the mean load a constant value for the cycle, the effect will be the same as that obtained with a constant actual resistance and a more widely varying actual effort, so that to prevent an untimely change in the valve-gear position due to a momentarily changing governor position, as a result of this crank-pin force discrepancy, the centrifugal governor will have to be a modified centrifugal governor of the type that aims to maintain a fixed governor position for the mean speed of the cycle rather than for the actual speed. The modification of a governor to secure this aim, as was mentioned above, of the dash-pot order, involving some resistance to its motion, or it may be a long belt that will take up any flapping and stretching momentary changes, driving a governor having considerable inertia—in any case the actual speed-change due to discrepancy between the forces driving and resisting may be reduced by fly-wheel inertia. This is really all that a fly-wheel does in an engine. It plays no part whatever in the adjustment of the equality between the work and the load, but reduces the actual speed changes due to disturbing differences between the driving and resisting forces. No matter how big the fly-wheel, these speed-changes will exist and last for just the same periods of time as the difference between the driving and resisting forces. Pure inertia governors have not a steady position dependent upon the speed; they are dependent on the rate of speed-change for their motion, and are useful only in connection with centrifugal governors, to bring about a quick change in valve-gear.

It has been said that the design of these governors to accomplish the desired motion of the valve-gear any instant of time, regardless of resistance, is a simple method. It is, if all the elements are known. Books on mechanics enable us to equate resisting and driving moments in which the forces and loads, centrifugal forces, valve-gear inertia, pin and bearing friction, and possibly steam or gas friction, and windage. It is possible to find all of the existing windage. In some recent tests in the laboratories at Columbia University, I have been able to show that the motion of the governor is in some cases not more than one-half that found by neglecting friction and windage in the governor itself. The other elements unknown are valve-gear inertia and mechanical friction, but it should be possible to evaluate these by simple test, although very little data on the subject are in existence. Even with all these elements known, it may be extremely likely that cases will rise calling for very large governors due to a desire for prompt action against considerable resistance on the part of the valve-gear, having a considerable motion between full-load and no-load positions. To avoid making these very large governors, the indirect system of governing has been developed in which the governor controls no more than a pilot valve, which in turn distributes fluid pressure to pistons controlling the gear proper. These pistons, with their pilot valves under governor control, involve another complication in arrangement, which, however, is for the sole purpose of avoiding too large sizes in the governor, but which plays no part in the regulation proper except moving the valve-gear as a simple governor might move it. In all these devices the position of the piston should coincide with the position of the governor, or, to put it otherwise, with rapidly varying actual forces and constancy of mean work, the piston-position should be constant and related to the mean speed for the cycle, while in this case the governor position may actually vary as it will.

With a constant load, the valve-gear attached to the governor may be at rest or in oscillatory motion, depending upon whether there is a difference between the actual forces, driving and resisting; whether the governor and valve gear move as a result of actual speed or a sustained or mean speed for the cycle. The discussion so far applies equally well to the steam engines and gas engines, and so far as the governor itself is concerned with its connection to the valve-gear, direct or indirect, simple centrifugal or modified centrifugal, with or without inertia elements there will continue to be no difference between the steam engine and the gas engine. So much of the regulation, therefore, that depends upon governor and fly-wheel design itself is absolutely the same for steam and gas engines, with possibly one exception, that of a simple governor taking on momentarily new positions, due to actual speed change as a result of momentary force-difference, which might appear that for the gas engine or the steam engine these force differences shown by the turning effort diagram may be more inconsistent for one than the other; as a matter of fact they are not except in special cases. It is after the valve-gear has moved under the influence of the governor, either from a sustained speed-change or momentary speed-change, direct or indirect, that the real difference between the steam engine and the gas engine is found. There is a slight difference that will be met with in the constancy of the indicator card for a fixed gear position. All the steam valve-gears, will give absolutely constant cards for fixed governor positions, while only the best gas engine can do this. The cycle of operations in a gas-engine cylinder or steam-engine cylinder occurs in a certain order and the control gear never affects all the phases of the cycle. If an adjustment is made after the susceptible phase has passed, no results will appear until all other phases have been completed. The indicator card of the steam engine can be affected positively during steam admission only, but there are cases in which the compression line will be correspondingly affected. If the governor should move during the admission period the admission may be immediately affected, and a change of effort immediately follow within the lapse of part of one stroke. With a single cylinder, single-acting steam engine, after cut-off, the governor can have no effect. Expansion must be completed, exhaust, and compression, so that if the governor moves the valve to the new position with cut-off, something over a stroke and approaching two strokes may elapse before a change in effort can occur. For this reason no single-cylinder, single-acting steam engine is employed for close regulation. By using a double-acting or two-cylinder engine one stroke can be cut out of this period which must elapse, or approximately one. By using more than one double-acting cylinder it becomes possible still further to reduce the cylic time, which must elapse between a change of valve-gear and new effort. The common type of large power-station engine is two cylinder, compound and often twin, giving four double-acting cylinders at some undetermined crank-angle, so that only a fraction of one stroke will have to elapse after a movement of the valve-gear before a change of effort, usually quite a small fraction.

The four-cycle gas engine may be regulated by the hit-and-miss governor, which is out of the question for close regulation since there is absolutely no attempt to graduate the effort. Next, there are throttling governors, which vary the amount of mixture by throttling the suction. There are others which admit a full charge during suction and expel part of it at compression by holding the valve open. Still another class, including oil-engines like the Diesel and Hornsby, admit fuel at or near the end of compression, and govern by varying either by the time of the injection or its length, generally the latter. Two-cycle gas engines of the Korting type may govern by acting on the suction of the gas pump with a throttle or delayed closure by any of the devices used on four-cycle engines, or it may govern by bleeding the charge in the gas chamber between the pump and motor cylinder. In both two- and four-cyle engines there may be an adjustment of the igniter. For reducing the time that will elapse between the valve movement and the beginning of a new effort the action should take place as late as possible in the cycle, which will give the effect as early as possible in point of time. For this reason a delayed opening on suction will be better than suction-throttling by a fraction of a stroke, and correspondingly the igniter action will be as prompt as affecting the admission as the steam engine. Equally prompt would be a fuel injection into compressed air at or near the end. No gas engine uses this. Unfortunately, however, for any igniter action, even a slight change will affect the economy and the range, is practically in only one direction. If the igniter is set right for economy, governor action can take place only to make it late and not to make it earlier with the proper effect. Making it late will reduce the effort and so will making it early, whereas an increase in effort is necessary in using this arrangement for regulating. In order to have a proper range for regulation by the ignition, the ignition should be normally set between properly early and very late, which gives poor economy. In any case where ignition is not used, as the beginning of a new effort, it may be assumed to take place on the beginning of combustion or the expansion stroke; the entire compression more or less must elapse between the valve gear at the charge and this beginning of combustion, a little less than a complete compression for delayed closure of the suction valve and a little more for the throttling action. In general it seems impossible to reduce the cycle of time to less than one stroke.

With this cyclic time it is useless to attempt to govern closely any engine with less than two double-acting, four-cycle cylinders, or one double-acting, two-cycle cylinder. It is useless to put a very sensitive governor or one of the highly refined inertia type on an engine that has been proved to be not worthy of it in the above mentioned respects.

A number of valuable papers on some of the phases of this regulation problem that are common to steam engines have appeared and a few of them will be examined.

Keilholtz: *A. I. E. E., October* 1901. In this paper a method for calculating the turning-force diagram is given, and the time, speed, and consequent angular variation from uniform rotary motion are calculated and experimental determinations reported. The paper is elaborate and involves a number of assumptions to simplify the work, but shows within the limits of experimental error and under conditions assumed it is possible to calculate true speed and to measure it so that the two results agree within the limits of experimental error. It is important to note, however, that the paper is confined to the case of constant resistance, equal to the mean effort, and the results depend for their value on the validity of these assumptions. Nothing whatever is determined concerning the effect of a fluctuating periodic load having the same constant mean, nor of the effects of load changes, nor the different speeds for different loads, nor the adjustment of effort and resistance by a true centrifugal governor, (whose position depends upon actual momentary speed), nor of a similar effect with the governor adjusted so that its position is determined for the mean speed for the cycle.

Slichter. Slichter notes a variation of speed: first, due to a change of load in which the average speed changes; secondly, irregularity throughout any given revolution or cycle while the mean speed is constant. He states that the adjustment of the mean is altogether a function of the governor and then drops the subject without pointing out the fact that no governor can accomplish this with a difference between driving and resisting efforts, if it is of the type whose position depends upon actual momentary speeds. The rest of Slichter's paper is taken up with the fly-wheel effects in reducing angular displacement from the mean or constant velocity positions with crank-pin force differences. The work is directed mainly towards alternators working in parallel, and the first problem for the solution is the determination of the crank-pin or pole displacements from true mean position, which will limit the cross-current to 10% of full load. In the course of his work he assumes the effort curve to be sinusoidal, which permits the development of a formula for a fly-wheel weight to limit the displacement. An example is worked out to illustrate the formula. Slichter however, aside from the errors introduced by taking the effort curve to be sinusoidal, makes the further assumption that the mean resistance is constant and equal to the mean effort. In other words, constant-load conditions only are discussed. He does however, make one important point, that when the alternators by any accident or fault of design get out of phase even slightly the actual resistance will be undulatory, although the mean may be constant.

Berg. Berg's paper is almost entirely electrical, and is concerned with the electrical conditions for parallel operation of alternators. The main feature with respect to regulation brought out in this paper is the pulsation of actual resistance with the constant mean when the alternators are slightly out of step, which is due to unequal momentary speeds of different machines in parallel, and which may be exaggerated by steam-effort impulses. It is not clearly pointed out that the real cause of exaggeration of these speed conditions is the fact that an alternator, taking positions due to momentary speeds, may be admitting steam in a pulsating way throughout a cycle, due to governor jumps when differences beween the actual effort wave and pulsating resistance becomes greater as the crests of the two waves may become opposed. The remedy observed is the use of a governor registering mean velocity for the cycle, and holding the valve-gear to the proper position for that mean. The means suggested by Berg is a dash-pot which is one of the ways of attempting to secure a mean velocity governor.

Steinmetz: *A. I. E. E., March* 1902. Steinmetz's paper is concerned with the problem of regulation with parallel alternator operation, and he notes three conditions to be examined: first a permanent change in speed due to a change in load. He points out here that there will be a different speed for every different load, the load, of course, being in any case a constant. This is an essential characteristic, as noted before, of centrifugal governors and their effects on the mechanism. Secondly, a temporary change in speed due to a change in load. In this connection he points out that on a change of load it is impossible for a governor to adjust the effort to the new resistance without the lapse of a considerable time. This causes a corresponding excess or deficiency of speed before the adjustment is accomplished. Thirdly, the periodic change of speed during "each revolution," which, of course, would be better read in "each cycle" as in some engines the cycle is not accomplished in one revolution. Steinmetz shows in this paper how important for the proper distribution of load between two alternators is this feature of having a different speed for every different constant load, and that a permanent drop in speed with increase in load is desirable. The absolute impossibility of a constant turning-effort diagram is shown, but the desirability and possibility of reducing variation of the turning-effort diagram by cylinder combination and crank-angles is pointed out, as well as the effect of reducing speed-changes for a given variation of effort by the fly-wheel. The periodic variation in speed, due to actual variation between effort and resistance, is assigned by Steinmetz as the cause of the hunting of alternators and synchronous apparatus, and he says that the effects are aggravated by the use of heavy fly-wheels. Steinmetz notes two kinds of hunting between alternators: forced surging, and cumulative or resonating surging. Forced surging is that due to momentary crank-pin-force differences, and cumulative surging is that due to certain electrical characteristics of the circuit, or may be assigned to the mechanical construction of the engine, especially the governor if the governor has a tendency to jump, which is explained as a tendency to take on a position due to momentary velocities.

Emmet. Emmet's paper is entirely concerned with parallel operation of alternators driven by steam engines and the effect of governor damping on the reduction of cross-current or surging. The paper gives examples of engines operating in Philadelphia and Boston. In Philadelphia it was found that the governor was in constant motion even with constant mean load, and that the indicator cards were consequently continually varying under the same constant load, as might be expected. The governor, when blocked, held the valve-gear in a constant position, and in this way absolutely constant cards were obtained. This shows that there was no fault in the governor and valve-gear as such, but rather that the load, although apparently constant in its mean value, was a pulsating one and the governor and valve-gear took momentary positions due to momentary speeds, due in turn to momentary force differences at the crank-pin. The fact that the surging was worse at times than at others is simply an indication of that fact noted above that while the mean load was constant and governor jumping could result with variation of effort, the pulsating load gave a wave of force, the crests of which sometimes coincide with and sometimes oppose the crests of the effort wave, giving, therefore, at times, a greater force-difference and at other times a less force-difference than with constant resistance. The trouble was cured by dash-pots on the governor, which had the effect of preventing the governor taking positions due to momentary velocities, and making it rather tend to assume a position due to mean velocity for the cycle. It was found in Boston that while similar surging existed and became less by the use of dash-pots, it could not be cured even when the dash-pot was strongly resisting the governor motion, as it permitted the mean speed to vary considerably. In this case, therefore, it appears that dash-pots may fail to accomplish the result of making the governor take a position due to the mean speed of the cycle, but, on the contrary, may actually resist any motion on the governor so that it becomes no longer a governor. This led to what has been called the "time-relay dash-pot," which is really no more than an improved form of modified centrifugal governor to make it more nearly fixed in position for the mean speed for the cycle without resisting an adjustment to a new mean. It is also interesting to note that Emmet reports a light fly-wheel better than a heavy one for successful parallel operation.

Rice discussing Emmet. Rice points out that a method of adjusting the fly-wheel weight by the allowable generator wheel displacements and the turning-force curve for the engine for constant load, but does not consider a variable load curve either periodically or irregularly variable.

Also on governors he states that they must have certain characteristics: they must be adjustable for speed-position to allow voltage adjustment and load distribution between machines; they must be adjustable with damping; they must have power enough to control speed in spite of damping; they must be switchboard controlled.

There is no discussion whatever in connection with this governor question by Mr. Rice of the period that must elapse between the governor movement and resultant effort change, nor of the limitations imposed by the cycle of operations on this period.

Seymour discussing Emmet. Seymour refers to the misapprehension of the specific nature of the requirements for parallel operation under which salesmen for engines and generators, as well as purchasers of the apparatus, may be laboring. He states that close regulation is generally interpreted to mean small differences between mean speed at no load and at full load, and points out that a small difference between these mean speeds is not a requirement of alternator parallel operation, and in fact it is better for load distribution between alternators that this difference be large comparatively. He next considers fly-wheel weights and says that a fly-wheel heavy enough for a uniform effort, when there is a discrepancy between driving and resisting forces, will increase the trouble from generator surging, referred to as "cumulative" by Steinmetz. The importance of noting the period of governor jumps, and the period of the varying resisting forces coinciding with the variable effort-crests, when the alternators are slightly displaced, is given some attention. The impossibility of correcting faults by governors alone is also pointed out when undulatory resisting-crests oppose undulatory effort-crests. Seymour does not state it quite this way, but this is in effect what I understand he means. He then gives some experimental data on the regulation of engines built by his firm.

Scott discussing Emmet. Scott first draws a parallel between parallel operation and two engines driving generators by gear wheels on the same shaft. Scott also notes the importance of the periodicity of governor jumps synchronizing with the periodicity of the maximum difference between driving and resisting forces, shown by the effort and resisting force; but as in the case with Seymour he does not state the situation quite this way. The point he makes is the special importance of noting the periodic nature of the electrical load in certain cases even when the output is constant, and gives examples of an alternator, which worked satisfactorily on a lamp load but would not at all with a synchronous converter in the circuit.

Mershon discussing Emmet. By curves between speed and load, when load is constant, Mershon shows the importance of having a considerable difference between full load and no load for proper distribution of load between the machines, and shows by variation of these curves why the distribution may be more stable at one load than at another.

Steinmetz discussing Emmet. Steinmetz points out that a heavy fly-wheel is bad only because by reason of its great inertia it permits the governor to overrun resisting synchronizing after once displaced.

Behrend discussing Emmet. Behrend refers to two alternators abroad, driven from the same engine shaft, which would not run in parallel at all. This is a striking example of the periodic nature of an electrical load and shows the importance of realizing that electrical circuit characteristics are matters of as great importance in parallel operation as engine characteristics, and that a failure to operate satisfactorily in parallel cannot always be traced to the engine regulation.

Slichter: *A. S. M. E.*, 1902. Among other matters taken up similar to those in his other paper in the Institute he lays particular stress on the computation of displacement of the alternator by inconstant turning effort and shows that the cross-currents and magnetic pull on the rotating system depend upon the amount of displacement. The difficulty is greatest with the greatest number of poles. He refers to a paper by Longwell before the Engine Builders' Association on the "Synchronization Torque of Generators" due to the displacement from the mean position where the torque is proportional to the displacement. The displacement is greatest also at the time when the disturbing effort is greatest, so that the two effects of synchronous torque and displacing effort torque are additive, and being additive are cumulative, helping to put the generators out of step. Some examples are given involving turning effort curves and computations of displacement.

Longwell discussing Slichter. Longwell first refers to a paper by Rosenberg, engineer for Korting Bros., gas engine manufacturers in Germany, in the *Electro Zeitschrift*, 1902, in which the cumulative effect of the magnetic pull and the disturbing irregular turning forces are shown to be impossible of prediction, and dependent upon the type of engine among other things. Mr. Longwell concludes that no mathematical treatment of this subject is adequate. This is true because the effect is partly mechanical and partly electrical and not all of the variables, either electrical or mechanical, are known.

Astrom, A. S. M. E., 1901. "Fly Wheels and Angular Variations." First there is given a complete calculation of turning effort and the effects on turning effort of the mechanical forces, due to reciprocation parts, rotary parts, gravity elements, and the connecting rods which partly rotate and partly reciprocate. This concludes with a number of turning-efforts diagrams and variable-load curves for pumps and compressors, enabling the crank-pin force difference curves to be plotted. The coefficient of fluctuation of speed for different classes of machinery are given in fractions of the mean, but it is pointed out that as machines of the same class with the same coefficient of speed fluctuation do not work equally well, it is evident that a small coefficient does not assure satisfactory speed regulation. The consequent displacement from the mean position is then developed as a substitute for the coefficient mentioned in fixing a unit regulation, and is shown to be the result of double integration of the force curve. Some turning-effort curves are given for steam engines at full load and light load, and the effects of different crank-angles on the uniformity of effort together with the reduction in fly-wheel weight for equal regularity of motion computed. Astrom makes only one reference to load changes and makes no attempt whatever to get results in speed changes.

Abbot discussing Astrom. Abbot gives a complete calculation for a steam engine, in which the coefficient is as small as one-three-thousandth and the displacement 2.5 electrical degrees when calculated by the usual method of turning-effort diagram with mean effort equal to mean resistance and resistance constant. No reference whatever is made to variations in resistance.

Paper by Dr. Franke, on the coefficient of irregularity. L' Eclarage Electric. In this paper there is a discussion concerning the coefficient of irregularity or speed steadiness for alternating-current and direct-current machines, and it is stated that this unit is a very satisfactory one for judging a direct current machine, as it represents very nearly the variation in voltage and the flickering of the lamps. 1/200 is considered to be good, and as low as 1/80 satisfactory, while 1/65 is considered impossibly bad. It is pointed out that with a single-cylinder, four-cycle gas engine 1/80 and 1/100 should easily be obtained without abnormal fly-wheels and these machines can, therefore, be depended upon for satisfactory voltage regulation. No reference, whatever, is made to what will happen on the change of load; this is based on the usual method of calculation for constant load and mean effort. With respect to alternators: it is pointed out that if the coefficient is too small the result will probably be worse than if it is not small enough. He considers 1/200 quite satisfactory. It is pointed out that cross-currents tend to accelerate the lagging machine and retard the leading, and the accelerating force or magnetic pull depends not at all upon actual speed but on the displacement of the poles, and that heavy fly-wheels resist in bringing into its proper place a pole once displaced, although it would seem ~~at first to be~~ sufficient guarantee against displacement initially. Light fly-wheels are recommended as better than heavy ones, but there is no means given for judging their weights except the old rule of computation of constant resistance with variable turning effort.

Summarizing the variations of conditions entering into the regulation problem under the headings of load, effort, governor, fly-wheel, and valve-gears, we have the following:

Kind of load.

1. Load may be constant and equal to the mean effort.

2. It may be constant and greater than or less than the mean effort.

3. Load may be undulatory, having a mean equal to the mean effort.

4. Load may be undulatory with a mean equal to the mean of an undulating effort.

5. Load may be constant at a maximum.

6. Load may be constant at zero.

7. Load may suddenly change from one constant value to another constant value, up or down.

8. Load may suddenly change from an undulatory with a constant mean to another undulatory with a constant mean.

9. Load may suddenly change from an undulatory with a constant mean to a constant.

10. Load may change from any value to an undulatory with a constant mean.

11. Load may change from an undulatory with a constant mean to another undulatory with a constant mean.

12. Load may change from any irregular value to any other irregular value with no particular relation between.

13. The time at which the load changes may occur at the most favorable point of the cycle for a change of effort.

14. The time at which the load changes may occur at the most unfavorable point of the cycle for a change of effort.

15. The time at which the load changes may occur at the same point between most favorable and unfavorable point of the cycle.

Kind of effort.

1. The effort may be absolutely constant for full load and a maximum.

2. Effort may be absolutely constant at zero.

3. Effort may be constant at any value between maximum and zero

4. Effort may be regularly undulatory with a constant mean for each cycle.

5. Effort may be irregularly undulatory with a constant mean for each cycle.

6. Effort may be irregular with a constant mean for two cycles.

7. Effort may be irregular with a constant mean for no full number of cycles.

8. Effort may be that for a steam engine, single cylinder, with low or high inertia.

9. Effort may be that for a double-acting, single-cylinder steam engine with a low or high inertia.

10. Effort may be that for any number of cylinders of the double acting, simple, triple, compound, etc., with a low or

high inertia of any number of cranks spaced in any particular way.

11. Effort may be that for a single-cylinder, four-cycle gas engine, single acting, low or high inertia.

12. Effort may be that for a single-cylinder, single-acting, two-cycle engine, low or high inertia.

13. Effort may be that for a single-cylinder, double-acting, four-cycle gas engine, low or high inertia.

14. Effort may be that for a single-cylinder, double-acting, two-cycle gas engine, low or high inertia.

15. Effort may be that for a two- or four-cycle engine, single or double acting, with any number of cylinders, low or high inertia, with any number of cranks grouped at any particular angle.

16. The fly-wheel may be light or heavy with large or small mean diameter.

Governors:

1. The governor may be a simple centrifugal governor, taking a position corresponding to the momentary actual speed.

2. The governor may be a modified centrifugal governor, taking a position not due to the momentary actual speed.

3. Governor may be of a modified, centrifugal type, taking a position due to the mean speed for the cycle.

4. The governor may or may not have inertia elements to affect the promptness of the motion of the valve-gear independent of actual speed, but depending on momentary acceleration, positive or negative.

5. The governor may be large or small with ability to move the valve-gear through large or small distance in short or long periods of time, against large or small valve resistances.

6. All the simple, centrifugal types or modified centrifugal types with or without inertia effects.

Valve-gears.

1. Valve-gears may affect the cycle so as to change the effort immediately.

2. Valve-gears may be so designed as to affect the cycle only with the lapse of some part of the cycle or some part of more than one cycle.

3. Valve-gears may be heavy or light with or without gravity resistance in one direction, with or without gravity assistance in the other direction, with or without inertia resisting its motion with high or low frictional resistance through change of position.

To study adequately all the conditions appearing in this summary, including the unusually large number of variables under the five groups, more or less dependent, is a very tedious matter, but nevertheless worth while. I think, however, from the review of the papers given, it seems pretty clear what is the function and limitations of governors or fly-wheels. From the large number of turning-effort diagrams, steam and gas engines, the nature of this effort-curve and its change with load, cylinder combinations, grouping of crank-angles, different inertias and reciprocating parts, have become fairly well known. To those not familiar with such turning-effort diagrams of gas engines, reference may be had to Guldner, Haeder, Lucke, and numerous papers. A comparison of the gas engine, turning-effort diagram with that of the steam engine will show that it is possible to secure as regular an effort curve for the gas engine as for the steam engine; regular with respect to the number of fluctuations above or below the mean, and with respect to the value of the coefficient of fluctuation. That is to say, that the turning-effort diagrams for the gas and steam engine are equally good as computed under the constant load condition, and this is the only basis on which they have been computed. What happens when the load changes and before the governor has had time to balance the effort with resistance, will be different for the two classes of engine and different again for individual examples of each class.

The things that have not received much attention, or anywhere near adequate attention are:

A. The electrical effects in producing variables actual resistance at the crank-pin for constant bus-bar loads.

B. Cyclic interference between governor control and effort effect.

C. The speed-change due to load-change due to a period of unbalance exaggerated by cyclic interference and pulsating effects, which cannot be overcome by any refinement of governor construction and which are just as likely to require light as much as heavy fly-wheels on the engine, but which probably can be met in the gas engine by a change in valve-gear control functions or a change in cycle.

Just what can be accomplished along these lines can only be determined by plotting force diagrams representing driving and resisting forces for each moment of the cycle, and in connection with each force-diagram a consequent velocity-diagram obtained by the integration of the force or accelerating diagrams. The force used in this integration will be the algebraic sum of the driving and resisting forces of each moment, and if both are varying they may be additive or subtractive.

To illustrate this method of treatment the following sketches are presented, not as a solution but solely to illustrate the method of procedure. Fig. 1 shows the force-diagram and velocity-diagram for a steam turbine with a constant-resistance load. This diagram shows a full-load and light-load force and speed curve and indicates that the light-load speed is higher than the full-load speed and instead of being exactly constant are nearly so with constant mean. The effort curve

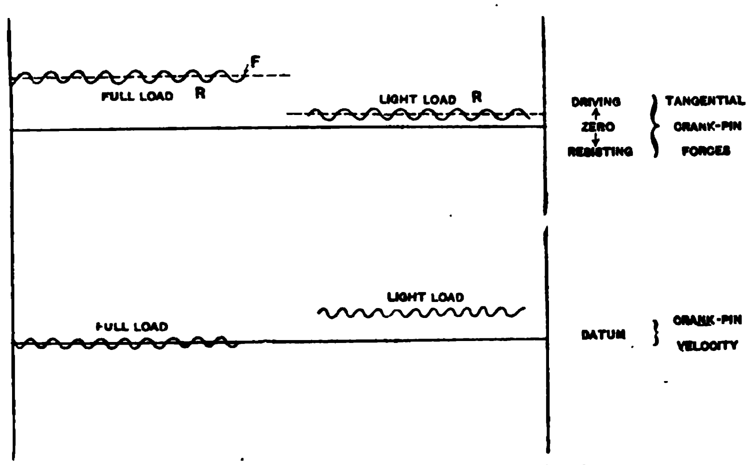


Fig. 1—Steam turbine resistance constant, effort pulsating constant mean

on the turbine slightly rises and falls fairly regularly for a constant resistance, which is shown by the dotted line.

Fig. 2 shows a variable resistance of a wave-form nature and a similar waving effort, both with constant mean. The velocity-diagram for these conditions will involve greater waves than before or greater fluctuations above and below the mean, because the effort and resistance become additive at crests and hollows, even though the mean value of each is constant.

Fig. 3 shows force and velocity diagrams for a constant full load change to a constant light load with a corresponding jump in velocity during the period of governor action.

Such curves as these indicate clearly the fly-wheel effect, and show that it merely limits the maximum velocity during the period of unbalance and has no effect on the period of unbalance or the period of acceleration. These curves also show that the maximum velocity is attained after an acceleration when that acceleration has again decreased to the mean value. They will also show how the governor must override in its efforts to reduce a too high velocity to the required new mean value. If such curves are shown for steam and gas engine with their available effort-diagrams in place of these nearly constant turbine effort-diagrams, I think it will be easy to see how clearly the problem of regulation can be studied and also the effects of variable actual load at the crank-pin when they do or do not synchronize with the effort wave.

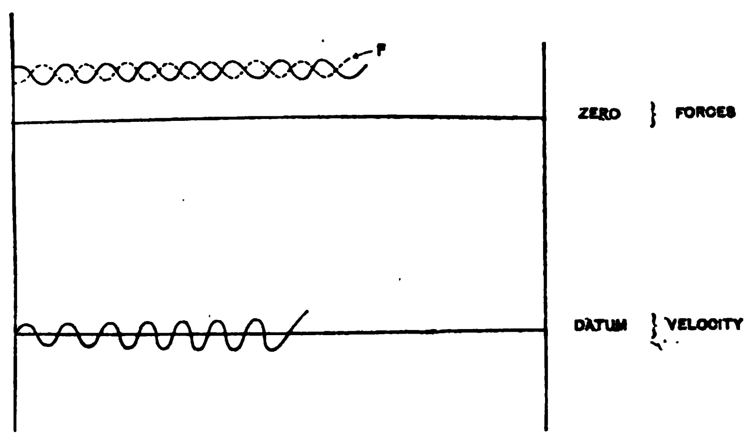


FIG. 2—Steam turbine resistance wave form constant mean, effort wave form constant mean, crests against hollows

There is no use in attempting to regulate a gas engine that will not meet the first requirement of absolutely invariable indicator card with the valve-gear blocked in position. This is the first difference between the problem of regulating the gas engine and the steam engine, and must be checked. Only the best gas engines will give such invariable cards. The next step is to run the governor with all valve-gear connected but with the engine at rest, the governor being driven from an external source to determine valve-gear positions at different speeds of the governor. This requires very accurate speed-measuring apparatus. The next experimental check is to measure the mean effective pressure obtainable at all different positions of the valve-gear, it being blocked during measurements and the engine held to about the proper speed with suitable resistance and the governor cut out. From this the speed horsepower curve should be plotted and there must be not too small a difference between mean speed at constant full load and the same at constant no load. The result should be checked by operating the engine with everything connected and a variable load. Every precaution should be taken to insure the governor operating valve from sticking either by tar or dust collection. The next important difference between the steam engine and gas engine regulation will come in as the result of cyclic interference in each. This requires calculation and experimental check to obtain proper data on the necessary sensitivness and type

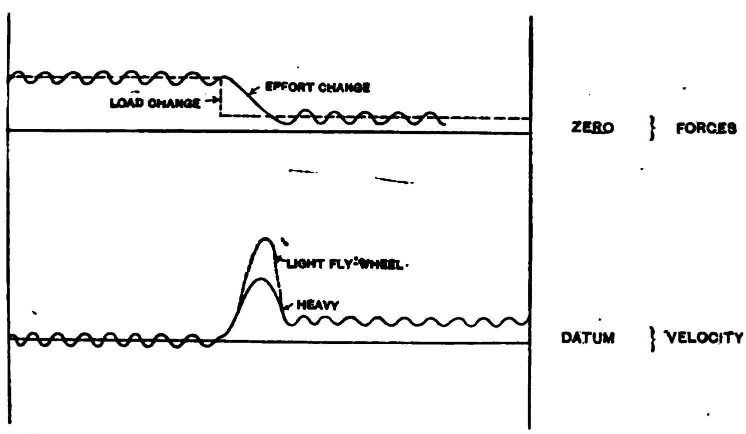


FIG. 3—Steam turbine load change, constant full to constant light

of governor fly-wheel effect, which should neither be too much nor too little in the light of the operation requirements.

Failures to obtain proper regulation of gas engines from any of the causes mentioned, but chiefly from cyclic interference have been overcome or rather avoided by the introduction of flexible couplings, consisting of leather link, spring, friction slip joints, centrifugal devices, all of which are intended to allow the driven rotor to move at a uniform speed, even though that of the driving engine should fluctuate. These devices have never been used on large units and are by no means solutions.

Large gas engines are operated fairly satisfactory with twenty-five cycle alternators and the cyclic interference, while it is always noticable is not prohibitively bad. With 60-cycle work this is not the case, and gas-engine-driven, 60-cycle alternators must be so far pronounced unsatisfactory, though some are doing well. Considering the nature of the problem; its newness, its difficulty, and the more insistent demands of the public for economy of fuel, and ruggedness of construction than for close regulation up to the present time, I think that the gas engine has done extremely well. The wonder is, then, not that the gas engine cannot regulate as well as the steam engine, but that it regulates as well as it does. In the light of all this I feel that the gas engine has only just started on its career of usefulness.

In conclusion I believe that an intelligent examination of the nature of the problem of gas-engine regulation and the study of numerous diagrams, force and velocity, of the kind here presented, will result in the elimination of many of the present handicaps of the gas-engine cycle and make possible regulation as good as that of the steam engine.

A paper presented at a meeting of the Baltimore Branch of the American Institute of Electrical Engineers, January 11, 1907, in the Physical Laboratory of the Johns Hopkins University.

UNDERGROUND TRANSMISSION AND DISTRIBUTION OF ELECTRICAL ENERGY.

BY CHARLES E. PHELPS.

The faults in underground cables naturally classify themselves as follows:

1. Defects in the cable itself.
2. Injury received during installation.
3. Faulty workmanship.
4. Mechanical injury.
5. Electrolytic action.
6. Certain external injuries, the cause of which may not be conclusively established.

And to these six may be added the injuries which occur to cables not strictly underground, but which are above the surface of the ground on poles, etc., making connection with aerial conductors. This latter is uniformly the result of imperfect covering protection, or results from contact with the cable sheath of aerial wires; they can hardly be classed with the faults of underground cables.

Referring to the other six classes of faults, the first three; viz.

1. Defects in the cable itself.
2. Injury received during installation,
3. Faulty workmanship;

should be sufficiently provided against in the contract for the cable and in the character of conduit construction, that they may be developed on the breakdown test which is invariably applied to a completed cable before putting it into continuous service. This test usually requires that at least double the ordinary working voltage shall be applied to the insulation of the cable; that is, between conductors and ground, for various periods of time depending upon the judgment of the purchaser and acquiescence of the contractor. The test should never be pushed to a point where the insulation is liable to be pin-holed by the strain of the test voltage, and experience has generally pointed to the continuance of the test voltage for from one to two minutes' duration, instead of thirty or more minutes which have often been specified. Under this test the defect should be developed and the obligation should, by contract, be imposed upon the contractor to make it good. If it should have been caused by any defect in the conduit construction the cable contractor would, of course, be blameless. The other faults:

4. Mechanical injury,
5. Electrolytic action,
6. Damage to cable above ground.

All these are of purely external cause.

In order to illustrate this feature more prominently, below is given a tabulated record of cable faults in this city for the seven years ending December 31, 1906, together with the lengths of cable in use in each year. This tabulation includes all classes of cables:

13,000 =	volt	alternating-current,	three-conductor	cable.		
6600 =	"	"	"	"	"	"
2300 =	"	"	"	"	"	"
1000 =	"	"	"	two-	"	"
500 =	"	street railway feeders,				
250 =	"	three-wire distribution,				

Telephone cables from 5 to 400 pairs,
Telegraph " " 20 to 200 wire,

and various smaller cables used for burglar and fire alarm and other signalling purposes, including the police and fire alarm wires of the city. In fact the table includes injuries to all those classes of wires which are found to be necessary in the activities of any large and growing city. Summarized by classes of faults and by years, the table is as follows:

It should be noted in connection with the table above given that damage under head of gas explosions was not the immediate result of the explosion, but was caused by the falling of debris and burning gas. No cable has been directly injured from any gas explosion under observation. Also, that the damage under "Flood Water—Jones' Falls" was due to the carrying away of cables on temporary suspension under a bridge crossing Jones' Falls, by heavy timbers carried down by flood water.

Class	Nature of Damage	1900	1901	1902	1903	1904	1905	1906	Total
1	Defective cable...	—	1	—	—	—	2	—	3
2-3	Damage during installation.......	—	—	—	3	7	4	10	24
4	Damage by picks, bars, etc.......	—	2	6	6	13	27	4	58
4	Flood water, Jones Falls...........	—	—	—	1	—	1	—	2
4	Gas explosions....	1	—	—	—	1	—	—	2
4	Rats.............	—	—	—	—	—	—	5	5
4	By workmen in manholes.......	—	—	—	2	3	4	4	13
5	Electrolytic action	1	—	2	15	5	4	4	31
6	Cables above ground.........	—	1	1	—	—	—	—	2
7	Unknown........	—	—	—	—	—	7	1	8
	Totals.......	2	4	9	27	29	49	28	148
Feet of cable in operation at end of each year...............		106,779	236,266	470,154	708,152	853,948	1,246,443	1,535,294	
Fault per 1000 ft. of cable..............		0.018	0.017	0.019	0.038	0.034	0.039	0.018	

Summary of Cable Faults

Class	Nature	Number of faults	Per cent. of whole
1.	Defective cable....................................	3	2
2.	Damaged in installation.............................	24	16
3.	Mechanical injury..................................	80	55
4.	Electrolytic action.................................	31	20
5.	Cables above ground................................	2	1.5
6.	Unknown causes.....................................	8	5.5
		148	100

The percentage in importance of each class of fault to the whole number is:

1. Defective cables.................... 2 per cent.
2. Damaged in installation. ....16 "
3. Mechanical injury..................55 "
4. Electrolytic action..................20 "
5. Cables above ground................ 1.5 "
6. Unknown........................... 5.5 "

This is for the whole period of seven years; the record of the year 1906, just past, during which time there were over 1,500,000 ft. of cable in operation, is as follows:

1. Defective cables............................none
2. Damaged in installation...................... 10
3. Mechanical injury.......................... 13
4. Electrolytic action.......................... 4
5. Cables above ground......................none
6. Unknown................................ 1

a total of 28 or $\frac{18}{1000}$ per 1000 ft. of cable in operation.

In considering the tabulations of cable faults, these data must be understood to show actual existing and not sporadic conditions; that not only do they cover a considerable period of time but they cover also a time during which progress in this particular branch of the art was undergoing great changes. A part of the time may even be taken as experimental In addition to this, the data for the years 1904 and 1905, shown in these tables, will suffer in its application to a normal situation by reason of the apparently high percentage of faults developed on account of mechanical injury.

Out of a total of 80 faults by mechanical injury for seven years, exectly one-half, or 40 of them, occurred during the years 1904 and 1905, although in 1906 there were but four, while the amount of cable in use was much greater.

This disproportion is easily explained by pointing out that during 1904 and 1905 all street improvements consequent upon the fire of February 1904 were carried out. Street lines and grades were changed, necessitating a similar change in conduits and of cables within them. A great many men were employed upon all sorts of work and naturally the underground system has to stand its share of damage.

In studying the list of cable faults you will see that, barring the sole element of human frailty, all the faults may be to a large extent anticipated, and in a large measure avoided. By analyzing these failures, you will find some definite reason for each of them to which a remedy can be applied. I do not intend to convey the impression that a cable system can be developed which will never be fault-proof, because the conditions under which it is operated are not those of a parlor game; but one has to deal with men and materials that are by no means perfect.

I can perhaps illustrate the conclusion which I desire to convey to you. Suppose, say 20 important companies on this continent engaged in the same character of electrical business were to keep accurate records of the performance of their underground equipment under actual operation, with clear explanation of the conditions surrounding and the effect of each cable fault; and suppose that all these 20 separate sets of data were available to each one of the companies concerned so that each would have, in addition to its own data, those concerning the cable performance of 19 other companies. Suppose now you had these data in hand, what would be the result? You would eagerly search out those of the companies which showed few faults where you were subjected to many of the same kind, and you would get in touch with them and learn in what particular they had succeeded where you had failed. In the same way you would be called upon to explain your successful methods to certain others who had failed where you had succeeded. This is a process which seems so easy, so simple, and so inexpensive when the great benefits that would accrue are considered, that it seems surprising it is not an almost universal custom. I cannot refrain from backing up this statement by saying that this spirit of coöperation and coördination is one of the important elements which has maintained the preeminence of the Bell Telephone Company in its particular field of operation, judging solely by results from the point of view of an outside but interested observer.

Before closing this paper I ask your consideration to a brief review of this particular subject which may really be termed the crux of the whole situation. Taking the cable faults in the order they appear on the chart, the first three:

1. Defect in cable itself,
2. Damage during installation,
3. Faulty workmanship,

should be covered by the contract for purchase and installation of cable, and they should be " smoked out " by the installation test before described. Owing to the fact that the factory test of cable before shipment is much more severe than the installation test, and that the factory test is made on the cable while submerged in water, it is more than probable that any fault developed in the body of the cable itself will be caused either during shipment or during installation.

It will generally be impossible to determine on light and power cables, which was the real cause, for the effect of the breakdown is to destroy the evidence entirely; the affected part of the cable will vanish to parts unknown.

Faults due to installation are in general due to four causes;

1. Defective conduit structure,
2. Reckless or improper methods of pulling cable into ducts,
3. Rough handling or too sharp bends in manholes,
4. Badly made joints.

I think it sufficient simply to enumerate these causes to indicate the prevention or remedy.

Faulty workmanship may occur either during installation or later, due to additional taps or connections being made to an existing cable. Here the remedy, aside from the employment of only skilled and careful workmen, is to provide a manhole suitable for the conditions under which this work is to be done. There should be plenty of elbow-room, and cleanliness is one of the best friends to the underground cable. Even in a city without sewers, the expense of consistent drainage of manholes by expensive methods is justified.

Mechanical injury may come from without through the agency of the energetic man with the pick who generally never works so hard as when he is hacking away at something he has no business to hack; or it may come by reason of improper use of the manhole by workmen; or from such an unusual source as the despised rat, which has been dignified by what I hope are five obituary notices in our exhibited list, under the year 1906.

I hardly feel able to point out any remedies against this prolific cause of cable trouble that have not already perhaps occurred to you, but there is one which comes from within and which often and unnecessarily results in trouble and is easily avoided. This, as is usually the case with internal cable troubles, concerns the manholes. I have myself recently seen inside the manholes of an important underground system where the cables therein were so run through the manholes that it is impossible for a workman to get to the floor of the holes without using these cables as a step ladder. This was the case, not in a single manhole, but in many of them. Apparently the manholes were built simply because every other underground system had them, and they exhibited utter disregard of their permanent use by the cable equipment for which they were built.

A paper presented at the 213th meeting of the American Institute of Electrical Engineers, New York, January 25, 1907.

ON THE SUBSTITUTION OF THE ELECTRIC MOTOR FOR THE STEAM LOCOMOTIVE.

BY LEWIS B. STILLWELL AND HENRY ST. CLAIR PUTNAM.

The purpose of this paper is fourfold: 1, to record certain facts relative to heavy electric traction which have been established by experience; 2, to present calculations of relative costs of steam and electric traction in railway service based upon these facts; 3, to point out the transcendent importance of standardizing electric railway traction equipment as rapidly as may be consistent with progress; and 4, to raise the question whether a frequency of 25 cycles per second or 15 cycles per second should be adopted in railway operation by alternating-current motors.

Few subjects which are to-day engaging the attention of the engineering world are comparable either in scientific interest or in practical importance to the substitution of the electric motor for the steam locomotive engine. Three-phase and single-phase alternating-current railway motors are now developed to a point where they fairly challenge the steam locomotive, even in long-haul freight service, in which class of work the direct-current motor hitherto has found itself unable to compete with success. The direct-current motor has demonstrated impressively, and upon a large scale, its superiority to the steam locomotive, not only in operating single cars and short trains on lines of moderate length, but also in frequent and heavy passenger service in which the length of train is limited only by the length of station platform, while the motive power equipment far exceeds in power developed the limits hitherto established in steam passenger service.

On the Valtellina line and through the Simplon tunnel 70-ton electric locomotives with three-phase motor equipment, capable of developing a draw-bar pull of 28,000 lb., have displaced the steam locomotive, with results showing both marked improvement in service and substantial economy in operating costs. In the New York Subway, eight-car trains weighing 320 tons are in operation, equipped with motors developing during acceleration a tractive effort equivalent to a draw-bar pull of 55,000 lb.

The heaviest passenger locomotive used on the Erie system in 1905, weighs, exclusive of tender, 206,000 lb., of which 55.8%, or 115,000 lb., is effective on drivers. Assuming the adhesion to be 20%, such a locomotive exerts a draw-bar pull of 23,000 lb. The motors of the eight-car electric train of the New York Subway, therefore, exert a tractive effort equivalent to more than twice the draw-bar pull of this locomotive.

Managers and engineers of railways using steam are considering the possibilities of electricity. Naturally, the problem usually presents itself in reference to particular cases in which special conditions emphasize the advantages of electric traction; but a point has been reached in the development of electric railway equipment where it is evident that no absolute and permanent limits beyond which the motor may not go can be fixed; and it is not unreasonable to consider the possibilities of the electric motor not only in passenger service but also in freight service, not only in the operation of railway terminals, but also for the operation of railway divisions and even for trunk lines.

At the present time, what is needed is not prophecy but facts, and particularly facts demonstrated by experience. A study of the relative advantages of steam and electric traction should rest as firmly as possible upon results attained in practical operation. Facts thus established and available to date are insufficient to justify conclusions which in detail may not have to be modified, but it is believed that they are adequate to permit comparative studies leading to deductions, which, as a whole, may be relied upon.

The answer to the question: " Will it pay to electrify? " involves consideration of both relative earnings and relative cost of operation; therefore, before discussing the comparative expenses involved, it is pertinent to refer briefly, even at the risk of repeating what has been said in papers hitherto presented by others, to the more important factors which ocoperate in securing for electric traction an increase in earning power.

Passenger Service Factors Contributing to Increased Earning Power.

The more important considerations which affect gross earnings are:

1. Frequency of service.
2. Speed.
3. General comfort of passengers.
4. Safety.
5. Reliability of service.
6. Increased capacity of line.
7. Frequency of stops.
8. Convenient establishment of feeder lines.

1. *Frequency of Service.* The motor-driven, interurban car operating upon scores of lines in competition with steam railway service has convincingly demonstrated its ability, not only to attract business from competing steam lines but also to create new business. In almost every case where such competition has been encountered by the steam railway, a large part, if not practically all of its local passenger traffic has been 'ost. In comparing results attained by the competing systems in such cases, it is impossible, of course, to state in terms of precision how far frequency of service is responsible for the remarkable results observed, since to these results a number of other causes also contribute. But without attempting to differentiate between these various factors, it is sufficient here to say that of the several causes contributing to the marked success of lines using electricity, the operation of train units or of single cars upon close headway is recognized to be especially attractive.

The advantages resulting from frequency of service become relatively less as the length of run is increased. It is recognized, however, that the operation of trains under close headway generally increases traffic, even where the haul is of considerable length, as shown by the experience of the Philadelphia & Reading Railroad in operating its fast trains upon one-hour headway between New York and Philadelphia.

2. *Speed:* The possibilities of operating by electricity at speeds exceeding the maximum which can be obtained safely in steam operation, owing to the elimination of unbalanced reciprocating

parts of the locomotive, is well-known. It was strikingly illustrated in the Berlin-Zossen trials by the attainment of a speed exceeding 130 miles an hour. These tests demonstrated the ability of electric equipment to operate at a sustained speed more than twice as great as that of our fastest express trains on runs of any considerable length, and exceeding by about 50% the maximum which can be attained even for a short distance by the steam locomotive with a reasonable degree of safety.

Even at speeds at which steam locomotives may be operated without great danger of leaving the track, as a result of the effect of unbalanced reciprocating parts, electric engines are far better able to maintain speed while drawing heavy trains. At speeds of 80 or 90 miles an hour, for example, it is extremely difficult to operate with satisfactory results two steam locomotives at the head of the train; while multiple-unit control places any necessary number of locomotive units absolutely and instantly responsive to the will and touch of a single operator. At high speeds, also, the economy of the steam locomotive falls off rapidly while that of its competitor remains practically constant.

The increase in average speed resulting from the relatively high acceleration obtainable in the use of multiple-unit electric equipment in service where stations are very close together; *e.g.*, elevated and subway lines in cities, and in suburban service in the vicinity of large cities, has been discussed frequently from the theoretical standpoint and is well understood.

3. *General Comfort of Passengers:* The great advantages of electric traction in respect to comfort of passengers are well-known. Cleanliness and improved ventilation made possible by the elimination of smoke and cinders; lighting practically without heat and at low cost by a system which makes it easy to place lights in any desired location, and heating apparatus effectively and conveniently controlled, are factors of very great importance in building up passenger business under conditions of competition. In operating through tunnels, ventilated with difficulty, the electric motor, in eliminating smoke and the gases of combustion, possesses an advantage which is frequently controlling.

4. *Safety:* So much has been said and printed in the daily press regarding the alleged dangers of electric traction, that it is well to place on record here a statement of the considera-

tions which inevitably lead to the conclusion that electric traction, if the equipment be properly designed and installed, is essentially and materially safer, so far as the traveling public is concerned, than steam traction. The more important of these considerations are:

a. The fact that in case of a rear-end collision, which is perhaps the most frequent form of accident experienced in the operation of our railway systems, the energy which propels the electric train can be shut off generally with great promptness. On the other hand, the steam locomotive carrying in its fire-box from 1500 to 2000 lb. of coal heated to incandescence, almost invariably sets fire to any broken cars, or other combustible material with which it comes in contact. Where the electric supply to trains is obtained at low potential from a third rail, the risk of short circuit, which may result in fire if the cars be not fireproof, is greater than it is in the case of overhead construction, even when the voltage employed in the latter case is very high. In fact, in the latter case it may be said that risk from the physiological effects of the current or from fire resulting from short circuit, is practically eliminated, except perhaps in tunnels of very limited clearance.

b. The elimination of the boiler carrying steam at high pressure, also means the removal of an element of risk which in many railroad accidents has destroyed life.

c. The absence of smoke in tunnels, and consequent ability to see signals clearly at all times, constitutes an advantage of the utmost importance for electric operation.

d. Cars drawn by steam locomotives must be heated either by steam from the locomotives, or by some form of stove carried on the individual cars. In the former case, steam from broken steam pipes becomes a serious source of danger in case of accident; in the latter the hot coals from the stove, even in the improved modern types which have greatly reduced the risk formerly encountered, are a source of danger. The substitution of the electric heater affords opportunity not only for ideal control of temperature of the cars but almost absolutely eliminates risk of fire.

e. The elimination of the gas tank and the oil lamp used for lighting in steam traction, and the substitution of electric lighting, also implies a material gain in safety.

f. The danger of derailment in the case of the electric locomotive is far less than in case of the steam locomotive, by reation of the elimination of unbalanced reciprocating parts which tend to lift the steam locomotive from the tracks. The hammer-blow also, in the case of the steam locomotive, is responsible not infrequently in cold weather for broken rails, as a direct result of which many serious accidents have occurred.

g. The electrification of railways where high-speed passenger traffic is involved, affords opportunity for improved methods of protecting trains by signal systems, automatic or other.

h. The ability to cut off power at will from a given section and therefore from trains operating upon that section under certain conditions, which arise not infrequently in railway service, may be availed of to prevent accidents. In steam railway service, when an operator at a tower having allowed a train to pass learns too late that another train is approaching in the opposite direction, he is powerless to avert the impending collision. Where the motive power of these trains, however, is transmitted by electricity, the power supplied to the section might be cut off and probably in time to prevent the catastrophe.

As against the considerations above referred to, all of which tend to make electric operation safer than operation by steam locomotive, the addition to the permanent way equipment of an electric conductor conveying power to trains imposes in the former case a material risk not involved in the latter. If the power be supplied through a third rail, a guard should be used whenever possible to prevent accidental contact with the rail by employes or by others walking upon or crossing the track. Several effective forms of guard are available, of which at least one has been in service upon a convincing scale for five years.

5. *Reliability of Train Service:* Interesting evidence in respect to the relative reliability of steam locomotives, and of electric motors carried upon cars and controlled by the multiple-unit system of train-control, is derived from the official records of the transportation department of the Manhattan Division of the Interborough Rapid Transit system of New York. Upon the elevated lines, steam locomotives were used from the inauguration of the first constituent line of the ultimate system in 1872 until 1902, during which year and a part of the following year, electric equipment was gradually substituted. The locomotives were operated under exceptionally favorable conditions, were not overloaded, were of simple construction, and admirably maintained. The electric equipment that succeeded them is operating trains which average

5.3 cars as against 3.8 cars in the days of steam operation. The average speed is materially higher. The tractive effort during acceleration of a six-car train is 30,000 lb. as against a maximum draw-bar pull of approximately 7,000 lb. exerted by the steam locomotive.

Accurate record is kept of the duration of every delay in the operation of the trains. The results for the months November 1900 to March 1901, when steam was used, and the corresponding months of the years 1905-6 under conditions of electric operation, illustrate in a striking manner the marked gain in reliability of service which has resulted from the adoption of electricity. For the five months of steam operation the aggregate car-mileage was 18,527,773 miles, and the aggregate delay 8258 train minutes. The car-mileage per train-minute delay was 2243.

For the corresponding period of electric operation, 5 years later, the car-mileage was 25,482,081, the aggregate train-minutes' delay 5970 and the car-mileage per train-minute delay was 4268.

It will be noted that the months involved in the above comparison are those in which the difficulties of operation, owing to weather conditions and number of passengers transported are at a maximum. Snow and sleet are among the greatest difficulties to be overcome in the operation of a third-rail system, when, as in the case of the Manhattan, the third rail cannot be effectively protected by reason of limitations in space avail able on the stucture. In view of these difficulties and of the increase in density of traffic, the results obtained are remarkable

6. *Increased Capacity of Line.* Electric traction as compared with steam traction enables us to develop much greater sustained tractive efforts with given weight on drivers, by reason of more uniform rotative effort. Even where electric locomotives are used, it also eliminates dead weight by abolishing the tender and facilitating construction under which practically the entire weight of the locomotive is carried upon the drivers. Where the locomotive is dispensed with, and the motors mounted directly upon trucks of cars constituting the train, the best results are obtained, the proportion of weight upon wheels driven by motive power being greater than is otherwise practicable. This increase in weight available for adhesion, in conjunction with the characteristics of the electric motor, makes it possible to attain in electric service rates of accelera-

tion altogether impracticable in steam service; consequently trains in passenger service where short headway is desirable can follow each other at shorter intervals than is feasible where steam motive power equipment is employed.

In the operation of freight trains, if it should ever become practicable to distribute electric locomotives throughout the length of the train and operate them by multiple-unit control, trains of length far beyond present limits could be operated. At present, the length of a freight train is limited by the strength of the draft-gear, and steam locomotives cannot advantageously be distributed at intervals throughout a very long train, as no means is available for controlling their effort simultaneously and satisfactorily.

Obviously, a system permitting distribution of the motive power at convenient intervals throughout the train, and simultaneously controlled by the hand of a single engineman, presents possibilities of increasing track capacity which under conditions now existing on many through lines should be of great value.

7. *Frequency of Stops:* The interurban electric line competing with the steam railroad for traffic between two cities possesses great advantage in the collection and distribution of passengers, from the ability of its cars to stop at any street intersection or other convenient point, instead of receiving and discharging passengers at a single railway station in each town. These frequent stops, however, operate to reduce speed materially, and but for the ability of the electric equipment to accelerate rapidly the limitation would be very serious. As speed between terminals is increased, the tendency to reduce the number of stops made to take on or let off passengers is noticeable in the development of many interurban lines.

8. *Convenient Establishment of Feeder Lines:* Frequency of stops for convenient collection and distribution of passengers, and high speed between terminals, being considerations which are essentially opposed, the advantages of a four-track system permitting operation of local or collecting train units on two tracks, and express trains on the other two tracks, are obvious. The great expense of such a system, however, can be borne only where traffic is very heavy.

A natural development which during the last five years has been very rapid, is found in the use of comparatively short electric trolley lines in connection with steam express service for long-distance runs. This method of utilizing the advantages of local electric lines by the companies operating trunk line systems is eminently wise, and in general should be highly advantageous to the properties concerned while increasing materially the facilities offered to the public. It may be pointed out, however, that were the trunk line systems to utilize electricity for through traffic, the extension and systematic improvement of local feeders would be facilitated for a number of reasons, notably:

1. The fact that power developed in large amount, as for the operation of heavy through traffic, is produced at low cost per unit, and would be available at all points along the line for the operation of cars on local feeder lines.

2. The convenient possibility of attaching cars or short trains arriving on local lines to through trains at points of junction. The multiple-unit system of car equipment lends itself admirably to this method of operation.

ILLUSTRATIONS OF PASSENGER BUSINESS DEVELOPED BY INTERURBAN ELECTRIC LINES.

In a very comprehensive paper presented by Mr. J. G. White before the International Engineering Congress at St. Louis in 1904, the following striking illustrations of the advantages of frequent service are given:

"*Cleveland-Oberlin Line.* These cities are 34 miles apart. The competitors for passenger traffic between these cities and intermediate points are the Lake Shore & Michigan Southern Railroad (steam) and the Cleveland, Elyria & Western (electric). In 1895 the total number of passengers carried by the steam railway between these cities and intermediate points was 203,014. This total decreased gradually after the competing electric line was opened to a minimum in 1899 of 71,755, from which it gradually recovered in 1902 to 91,761, but during this same year the electric road carried a total of about 3,000,000.

"*Cleveland-Painesville Line.* These cities are 39 miles apart. The competitors for passenger traffic are the Lake Shore (steam) and the Cleveland-Painesville & Eastern Railway (electric). In 1895 the steam road carried between the terminals and intermediate points 199,292 passengers, but in 1902 it carried only 28,708 passengers, while the electric system carried 1,537,754 passengers.

"*Cleveland-Lorain Line.* These cities are 26 miles apart.

Competitors are the New York, Chicago & St. Louis Railroad (steam) and the Lake Shore (electric). In 1895 the steam road carried 42,526 passengers but in 1902 it carried only 9,795 passengers, the electric road in the same year carrying 3,896,902 passengers."

The Lackawanna & Wyoming Valley Railway Company, operating a double track system between the cities of Scranton and Wilkes-Barre, Pa., carried, during the four months ending October 1906, 1,396,833 passengers. This railway, 18 miles in length, competes with two double-track steam railways having excellent terminals in both cities, and with a third double-track steam railway having an equally good terminal in Scranton, but a less favorably located terminal at the Wilkes-Barre end of the line. The electric railway charges 30 cents for the ride between the two cities and sells round-trip tickets for 50 cents. Except at certain hours, it operates its service upon 10 minutes' headway. At least one of the steam railways, in the endeavor to retain its passenger business, has reduced its rate to 40 cents for the round trip. It has also increased the frequency of its train service. We have been unable to ascertain the number of passengers carried by the competing steam lines during the four months above referred to, but the earning power of frequent electric service is strikingly demonstrated by the fact that this railroad, operating in competition with three double-track steam railways of practically identical length and substantially equal terminal facilities, should be doing a business which represents an income of $5.00 per capita per annum of tributary population, including that of the terminal cities.

Electrification of Transportation Systems in Manhattan and the Bronx—Effect upon Traffic

A study of the transportation statistics of New York City, particularly during the last decade, is not only of great local interest, but is instructive as illustrating the effect of improvement in transit facilities upon gross receipts.

The data graphically summarized in Figs. 1, 2, and 3 have been compiled from official records; those subsequent to June 30, 1883, being obtained from the reports of the State Surveyor and of the Railroad Commission of the State of New York. The effects of improved service are clearly evident from an inspection of these figures.

In Fig. 1, the line marked "All lines" indicates for each year ending June 30, the aggregate paid fares collected by all surface, elevated, and subway lines in the Boroughs of Manhattan and Bronx. It will be noticed that the aggregate paid fares for the year ending June 30, 1894, and also for the following year, were slightly less than for the year ending June 30, 1893, this reduction doubtless being due to the hard times which then

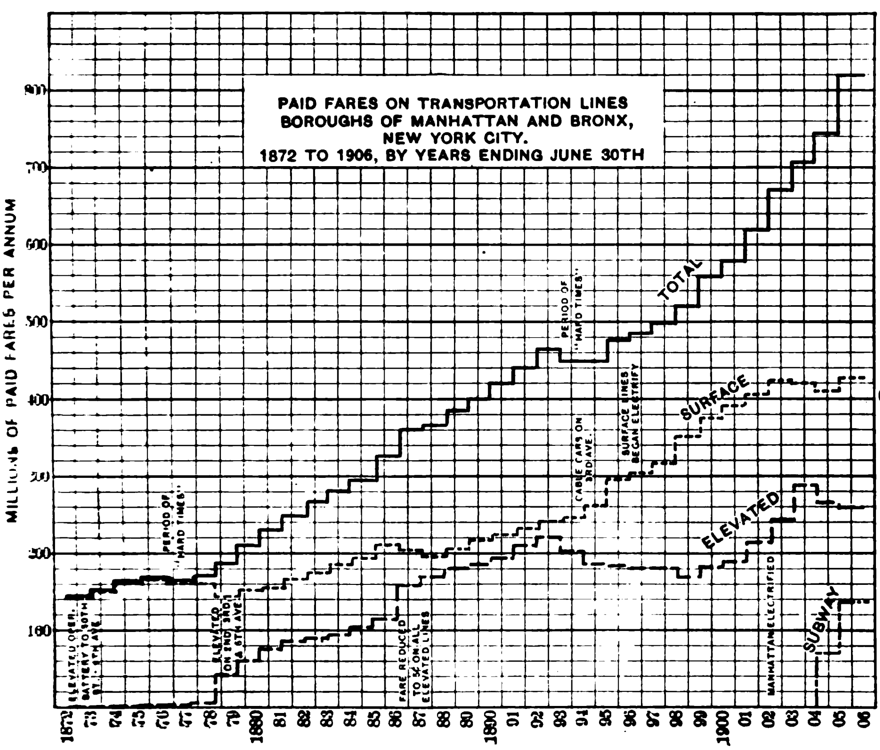


FIG. 1.

prevailed. With this exception, the aggregate of paid fares for all lines shows in each year an increase over the preceding year. Comparing the Manhattan System for the year 1893 with the same system for the year 1899, a decrease of 21% in paid fares is shown. During the same period the paid fares of surface lines, which meanwhile in large degree had adopted electric operation, increased by 43%. That the decrease in business on the elevated lines was not due to any decrease in the service, is shown by Fig. 2, from which it will be seen that the car mileage operated increased steadily during this period. The unavoidable inference is that the diversion of traffic to the surface lines was a direct result of the improved service offered by the latter.

During the year ending June 30, 1901, the last fiscal year of steam operation on the elevated lines, the Manhattan system

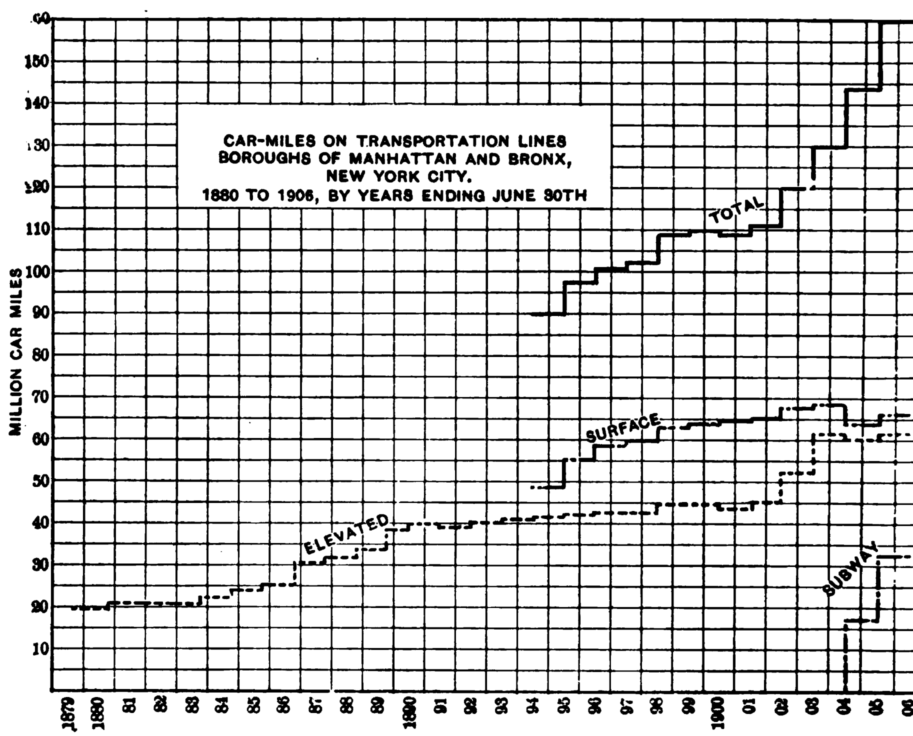


FIG. 2.

collected 190,045,741 fares. The surface lines collected 388,108,794 fares. During the year ending June 30, 1904, the Manhattan System, now operated by electricity, collected 286,634,195 fares, an increase of 50%, while the surface lines collected 419,423,092, an increase of about 8%. In the following year, 1904, the subway began operation, and both elevated and surface lines recorded a decrease in fares collected.

In Fig. 4 are plotted curves showing the population of, *a*, Greater New York and, *b*, the Boroughs of Manhattan and the Bronx. The points which fix these curves from 1860 to 1900

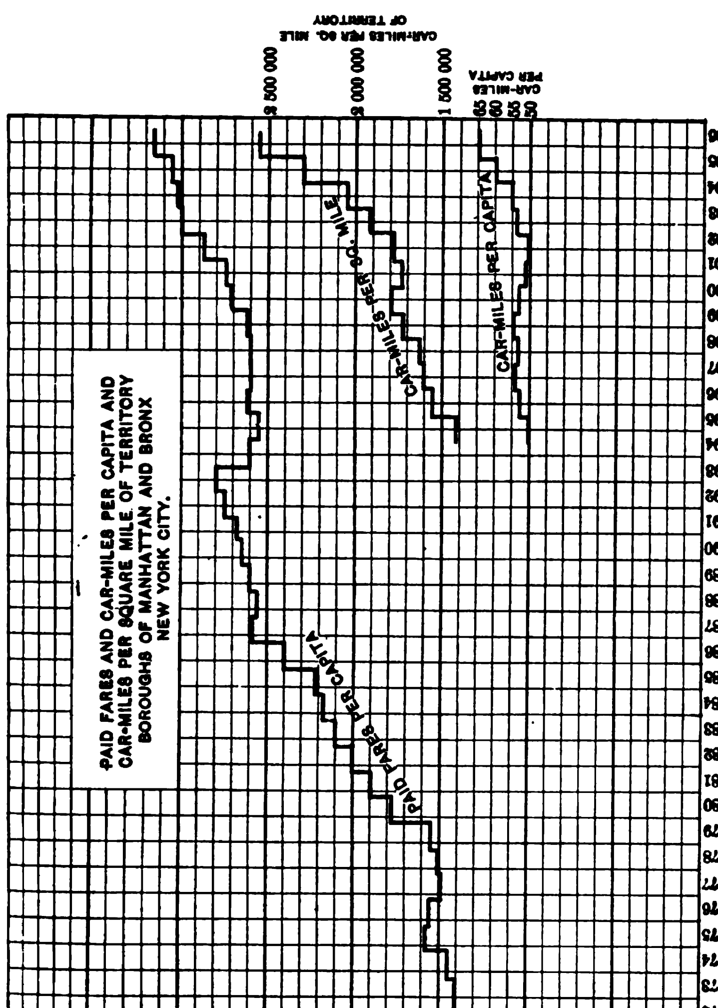


FIG. 3.

inclusive, are from the United States Census Reports. For the years 1910 and 1920 the estimated population is based upon the average rate of change in the per cent. increase per

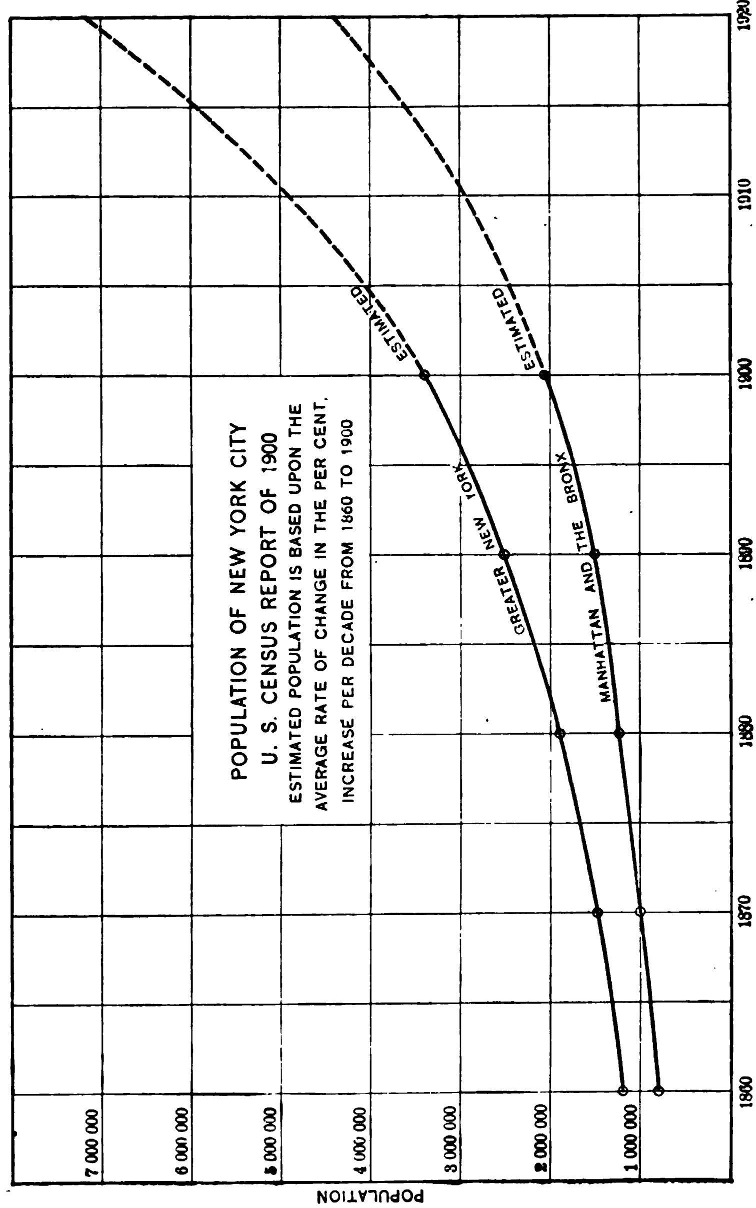

POPULATION OF NEW YORK CITY
U. S. CENSUS REPORT OF 1900
ESTIMATED POPULATION IS BASED UPON THE
AVERAGE RATE OF CHANGE IN THE PER CENT.
INCREASE PER DECADE FROM 1860 TO 1900
ESTIMATED
ESTIMATED
GREATER NEW YORK
MANHATTAN AND THE BRONX
7 000 000
6 000 000
5 000 000
4 000 000
3 000 000
2 000 000
1 000 000
POPULATION
1860
1870
1880
1890
1900
1910
1920

FIG. 4.

decade from 1860 to 1900. Up to 1905, the population as indicated in these curves is undoubtedly not far from the fact; for 1910 and 1920 the probable populations indicated are interesting, although the curves take no account of the effect of improved transit facilities between Manhattan and Long Island, and between Manhattan and New Jersey.

Notwithstanding the very rapid increase in population of the Boroughs of Manhattan and Bronx from 1890 to 1905, the paid fares collected by the several transportation systems have increased still more rapidly, as shown in the curve of paid fares per capita in Fig. 3.

In the same figure are shown the increase in car-miles per capita per annum, and in car-miles per annum per square mile of territory served.

While it is not directly pertinent to this discussion, we would here call attention to a fact of great importance to those responsible for the development of the systems of transportation in the City of New York; viz., the fact that while for the year ending June 30, 1906, the subway carried 137,919,632 passengers, the aggregate carried by the elevated and surface lines was but 23,684,957 less than the aggregate carried by these lines during the year ending June 30, 1904, the last fiscal year before the subway began operation. In other words, comparing the year 1906 with 1904, the aggregate paid fares on elevated, surface, and subway lines, increased by 114,234,675, which is about three-fourths the ultimate capacity of the present subway. It is evident from inspection of these curves, that the existing systems are destined to be still further and greatly overcrowded before additional subways can be completed.

It is of course impracticable in studying the results of improved service in the electrification of elevated, surface, and subway lines in New York, to attempt to differentiate the causes which have contributed to the increased traffic. While that increase has been due undoubtedly in large part to the improved service offered, it is also obvious that the number of passengers carried would have increased very materially by the growth of population, even had no improvement in the old conditions of service been effected. But it cannot be too strongly emphasized, that while from one point of view improved transit facilities are a result of increased population, from another and equally tenable point of view, increased population is a result of improved transit facilities.

Comparative Costs of Operation.

As the standard with which to compare our estimates of cost of electric operation, we have adopted the grand average results obtained in operation by steam locomotives upon the existing railways of the United States, as set forth in the report of Statistics of Railways for 1904 compiled by the Interstate Commerce Commission, and proof-sheets of the report of the Commission for the year 1905. We shall follow the classification of operating expenses adopted by the commission, and generally used by the railroad companies in their annual reports. The estimated costs of electric operation being approximately determined as compared with the grand averages obtaining in steam railroad practice in this country, the work of determining, for any given case, the relative advantages and disadvantages of steam and electric operation will perhaps be facilitated. We compare, of course, the itemized operating expenses in the case of operation by electricity with corresponding expenses under existing conditions of steam motive power equipment. In estimating operating expenses of electric equipment, we have based conclusions upon results obtained in practice so far as we possess the necessary data.

The substitution of electric for steam equipment involves a large investment in power plant, and in electric conductors and apparatus for conveying power from the power plant to the moving trains, The distributing system for alternating-current equipment, which is the only class of equipment deserving serious consideration in connection with the general problem which we are discussing, comprises an addition to permanent way equipment in the form of overhead construction and electrical conductors conveying power from the power house to the trolley or conductor which is carried above the track. At the present time, the limit of potential generally adopted in this country in constructing alternating-current dynamos is 11,000 volts. Where this voltage is generated, and the distance from the power house to the section of railroad to be electrified does not exceed 25 or 30 miles, step-up and step-down transformers are unnecessary. For greater distances, higher potentials are used upon the feeder circuits between power house and trolley, transformers for increasing the generated potential being installed in the power house, and transformers for lowering the potential to that selected for the trolley; *e.g.*, 11,000 volts, being located in suitable transformer houses at intervals of from 30 to 50 miles, depending chiefly upon density of traffic.

For the trolley, a potential of 11,000 volts is suitable and can be adequately insulated. The mechanical support for the trolley comprises, preferably steel poles with brackets or light steel bridges spanning the track.

The cost of the power plant and distributing system are properly chargeable to capital account.

Our estimates are based upon the assumption that single-phase alternating-current equipment is used; that the trolley potential is 11,000 volts; that each power-house supplies railway line to a distance of 150 miles in each direction, the feeder potential employed being 60,000 volts; that the overhead construction is first class in every respect, steel bridges and steel poles set in concrete being used exclusively for the support of both trolley conductors and feeders.*

As regards equipment of the rolling stock, it is the general practice of our railways to charge against operating expenses all new equipment purchased to replace that which has been worn out in service. In the adoption of electricity, it would seem that this method might be followed in general by our more important railway systems, the substitution of electric equipment beginning naturally upon those parts of the system where the resulting advantages are maximum. In other words, worn-out locomotives, etc., on such a system might be replaced by electric equipment and the cost of the equipment charged against operation, just as the cost of new steam locomotives otherwise required would be charged against operation. For example, the Erie Railroad system, on June 30, 1906, had 1333 locomotives in service. Taking no account of increases necessitated by growth of the company's business, not less than 60 new locomotives should be added to this equipment each year to take the place of those worn out in service. The cost of these new locomotives under steam operation would be charged against "Repairs and renewals of locomotives," and it would seem that their value expended for electric equipment to replace them might be similarly charged. In addition to the purchase of new locomotives to replace those worn out in service, our railroads are compelled from year to year, by the

*In assuming the use of the single-phase system we are not condemning other systems. The three-phase system has not received from American engineers in general, that degree of consideration which its possibilities and demonstrated advantages justify. Its use, at least on mountain-grade divisions, can be supported by very strong arguments.

growth of their business, to purchase additional locomotives and other rolling equipment. While these are usually charged against capital account in one form or another, it may be pointed out that any method of financing their cost which may be adopted is equally applicable to electric locomotives.

In cases where the initial substitution of electricity is on a large scale, as compared with the total rolling stock equipment of the railroad making the change, it is probable that a part if not all of the cost of electric rolling stock equipment will generally be charged to capital account.

We proceed to compare the cost of electric operation with the cost of operation by steam locomotives, using as our standard of comparison the grand average results in steam operation in the United States for the years 1901–1905, inclusive. These average results are set forth in the following tables compiled from the reports of the Interstate Commerce Commission and printed on the three following pages. Many of the items included in this tabulation vary between wide limits in the practice of different railroads.

Maintenance of Way and Structures

Under the general heading, "Maintenance of Way and Structures," item No. 1, "Repairs of Roadway," if changed at all should show some reduction under conditions of electric operation, but obviously no material change is to be expected. We assume therefore that this item, amounting to 10.818% of total operating expenses, will remain unchanged.

The items, "Renewals of rails," "Renewals of ties," and "Repairs and renewals of bridges and culverts," may be conveniently grouped. In the aggregate, these on the average steam operated railroad amount to 6.33% of the total cost of operation. If the electric locomotive be substituted for the steam locomotive, it is safe to predict that this group of items of expense will be reduced; but it is practically impossible to state with accuracy what the reduction will amount to. In general, it is obvious that the substitution of electric locomotives developing equal draw-bar pull, with axle-loads reduced at least 25% as compared with steam locomotives, and with wheel-bases not exceeding those of steam locomotives, should favorably affect these items. From the best study which we have been able to make of the detailed factors comprised under these three items of the classification, it would seem that under

TABLE I

Item	Amount 1905	Per cent. 1905	1904	1903	1902	1901	Average Five Years	Estimated Cost of operation by Electricity
Maintenance of Way and Structures......	274,415,279	19.784	19.519	21.185	22.255	22.272	21.003	22.354
1. Repairs of roadway	144,161,701	10.393	10.348	11.093	11.331	10.294	10.818	10.818
2. Renewals of rails..	18,259,022	1.316	1.298	1.386	1.521	1.676	1.439	
3. Renewals of ties...	36,856,864	2.657	2.519	2.487	2.838	3.140	2.728	5.00
4. Repairs and renewals of bridges and culverts..........	32,166,990	2.319	2.228	2.461	2.593	2.730	2.466	
5. Repairs and renewals of fences, road-crossings, signs and cattle-guards.....	6,179,686	0.446	0.437	0.527	0.625	0.598	0.527	0.527
6. Repairs and renewals of buildings and fixtures..........	29,320,204	2.114	2.147	2.590	2.562	2.417	2.366	1.300
7. Repairs and renewals of docks and wharves..........	2,883,274	0.208	0.209	0.235	0.220	0.283	0.231	0.231
8. Repairs and renewals of telegraph...	2,374,932	0.171	0.179	0.165	0.173	0.158	0.169	0.169
9. Stationery and printing..........	383,158	0.028	0.029	0.032	0.031	0.029	0.030	0.030
10. Other expenses....	1,829,448	0.132	0.125	0.209	0.361	0.317	0.229	0.229
Repairs and renewals of track bonding.............								0.800
Repairs and renewals of overhead construction......								3.250
Maintenance of Equipment.............	288,012,604	20.765	19.967	19.133	19.127	18.629	19.524	12.287
11. Superintendence ..	7,831,965	0.565	0.567	0.559	0.601	0.599	0.578	0.578
12. Repairs and renewals of locomotives.	114,968,428	8.290	7.904	7.408	7.246	6.695	7.509	2.253
13. Repairs and renewals of passenger cars............	27,342,120	1.971	1.951	2.044	2.157	2.277	2.080	2.080
14. Repairs and renewals of freight cars.	113,723,239	8.199	7.777	7.442	7.432	7.436	7.657	6.000
15. Repairs and renewals of work cars.....	3,360,390	0.242	0.231	0.242	0.245	0.233	0.238	0.238
16. Repairs and renewals of marine equipment............	2,650,543	0.191	0.154	0.177	0.215	0.234	0.194	0.194
17. Repairs and renewals of shop machinery and tools.....	9,186,101	0.663	0.704	0.696	0.643	0.605	0.662	0.500
18. Stationery and printing..........	595,571	0.043	0.042	0.046	0.044	0.043	0.044	0.044
19. Other expenses....	8,334,240	0.601	0.637	0.519	0.544	0.507	0.562	0.400

NOTE.—It is customary with some railroads using electric equipment to include under the general heading "Maintenance of Equipment," the maintenance of the power plant and electric transmission systems. Both of these, however, are more conveniently treated by including them in the cost of electric power delivered to the overhead trolley system or third rail.

TABLE I.—*Continued.*

Item	Amount 1905	Per cent. 1905	1904	1903	1902	1901	Average Five Years	Estimated Cost of operation by Electricity
Conducting Transportation	769,613,017	55.486	56.670	55.893	54.671	54.979	55.540	43.603
20. Superintendence	25,007,322	1.803	1.779	1.742	1.711	1.726	1.752	1.752
21. Engine- and round-house men	130,437,844	9.404	9.550	9.562	9.401	9.340	9.451	4.710
22. Fuel for locomotives	156,429,245	11.278	12.128	11.675	10.776	10.602	11.292	5.702
23. Water supply for locomotives	9,147,590	0.660	0.659	0.614	0.623	0.612	0.634	0.000
24. Oil, tallow, and waste for locomotives	5,442,970	0.392	0.397	0.389	0.366	0.361	0.381	0.250
25. Other supplies for locomotives	3,295,384	0.238	0.248	0.232	0.218	0.206	0.228	0.228
26. Train service	90,654,520	6.536	6.735	6.677	6.737	7.011	6.739	6.739
27. Train supplies and expenses	21,963,086	1.583	1.581	1.552	1.500	1.471	1.537	1.000
28 Switchmen, flagmen and watchmen	60,141,422	4.336	4.386	4.313	3.984	3.848	4.173	4.173
29. Telegraph expenses	24,823,266	1.790	1.788	1.754	1.784	1.785	1.780	2.000
30. Station service	89,304,658	6.438	6.605	6.664	6.832	6.947	6.697	6.697
31. Station supplies	8,961,573	0.646	0.686	0.667	0.676	0.672	0.669	0.669
32. Switching charges, balance	4,201,050	0.303	0.280	0.244	0.272	0.319	0.284	0.284
33 Car per diem and mileage, balance	18,835,325	1.358	1.358	1.400	1.480	1.618	1.423	1.423
34. Hire of equipment, balance	3,040,641	0.219	0.195	0.214	0.180	0.161	0.194	0.194
35. Loss and damage	19,782,692	1.426	1.279	1.094	0.990	0.819	1.112	0.750
36. Injuries to persons	16,034,727	1.156	1.196	1.120	1.048	0.911	1.086	1.000
37. Clearing wrecks	3,594,658	0.259	0.275	0.284	0.221	0.189	0.246	0.200
38. Operating marine equipment	9,903,479	0.714	0.696	0.745	0.721	0.862	0.748	0.748
39. Advertising	5,959,380	0.430	0.418	0.428	0.429	0.428	0.427	0.427
40. Outside agencies	19,688,261	1.419	1.411	1.449	1.579	1.615	1.495	1.495
41. Commissions	233,987	0.017	0.022	0.044	0.077	0.089	0.050	0.050
42. Stock yards and elevators	786,850	0.057	0.060	0.057	0.069	0.075	0.064	0.064
43. Rents of tracks, yards and terminals	23,947,881	1.727	1.563	1.544	1.519	1.724	1.615	1.615
44. Rents of building and other property	4,814,407	0.347	0.382	0.411	0.440	0.440	0.404	0.404
45. Stationery and printing	8,772,789	0.632	0.640	0.642	0.622	0.638	0.634	0.634
46. Other expenses	4,408,010	0.318	0.353	0.376	0.416	0.510	0.395	0.395

TABLE I.—*Continued.*

Item	Amount 1905	Per cent. 1905	1904	1903	1902	1901	Average Five Years	Estimated Cost of operation by Electricity
General Expenses.....	55,022,127	3.965	3.844	3.789	3.947	4.120	3.933	3.933
47. Salaries of general officers...........	11,676,616	0.842	0.841	0.823	0.925	0.984	0.883	0.883
48. Salaries of clerks and attendants...	18,582,142	1.340	1.313	1.254	1.244	1.262	1.283	1.283
49. General office expenses and supplies.............	3,459,470	0.249	0.230	0.234	0.249	0.257	0.244	0.244
50. Insurance.........	6,885,932	0.496	0.471	0.432	0.412	0.384	0.439	0.439
51. Law expenses.....	7,096,275	0.512	0.513	0.541	0.558	0.549	0.549	0.549
52. Stationery and printing (general expenses)........	2,439,781	0.176	0.170	0.175	0.168	0.161	0.170	0.170
53. Other expenses....	4,861,911	0.350	0.306	0.3330	0.391	0.447	0.365	0.365
Recapitulation of Expenses...........								
54. Maintenance of way and structures	274,415,279	19.784	19.519	21.185	22.255	22.272	21.003	22.354
55. Maintenance of equipment........	288,012,604	20.765	19.967	19.133	19.127	18.629	19.524	12.287
56. Conducting transportation.........	769,613,017	55.486	56.670	55.893	54.671	54.979	55.540	43.603
57. General expenses..	55,002,127	3.965	3.844	3.789	3.947	4.120	3.933	3.933
Grand Total......	1,387,043,0	27100.	100.	100.	100.	100.	100.	82.177

electric operation they should be reduced about one-fourth; in other words, they should approximate 5% of the total operating expenses. It is not to be imagined, of course, that railroads adopting electric traction would limit themselves to equal draw-bar pull and not increase loads. They would, naturally, take advantage of the possibility of increasing draw-bar pull so far as strength of draft-gear may permit, thereby effecting gains far outweighing the decrease in operating expenses represented by saving in maintenance of roadway, rails, and ties, which would result from a decrease in the weight of locomotives. This argument is valid, not only with reference to high-speed passenger traffic, in which the hammer-blow of the engine is emphasized, but also in connection with freight traffic, where in recent years there is a marked tendency to employ trains of great length and locomotives of extreme weight.

The cost of track-maintenance is increased by reason of the electric bonding of the rails. This bonding, including the cost of special bonds necessary where an automatic track signal system is used, will cost about $500 per mile under average conditions. Its cost of inspection and maintenance should not exceed $50 per mile of single track per annum.

The annual cost of " Renewals of rails," " Renewals of ties," and " Repairs and Renewals of bridges and culverts," averages in the United States $400 per mile of track, which as above stated, is 6.633% of average operating expenses, under steam operation, and for equal trains, as we have estimated, 5% for electric operation. The effect of the cost of track-bonding, therefore, would increase the items under consideration by about one-eighth, which is equivalent to an increase of 0.8% in operating expenses. To avoid possible confusion, we include the cost of " Repairs and renewals of track bonding " as a separate item in the column " Estimated Cost of Operation by Electricity."

Under the general conditions which will govern where electricity is substituted for steam in railway operation, there can be no doubt that the substitution will result in a material reduction in the cost of maintenance of rails, ties, bridges, and culverts. In this substitution electric locomotives will be used for freight traffic, while for passenger traffic locomotives will be eliminated ultimately and multiple-unit car equipments employed. For the immediate future, however, locomotives will be employed not only for freight traffic but also in some cases for passenger traffic, for the practical reasons which have impelled the Pennsylvania, the New York Central, and the New York, New Haven & Hartford systems in electrifying their New York terminals to adopt electric locomotives for handling their through trains.

The hammer-blow upon rails, is largely and in some cases wholly avoided by the adoption of electricity; *e.g.*, the entire electric equipment of the heavy locomotives used in the Baltimore tunnel is spring-borne; this is true also of the 70-ton Ganz locomotives recently placed in operation upon the Valtellina, and of the single-phase locomotives ordered by the New York, New Haven & Hartford Railroad. In the case of the locomotives recently constructed for the New York Central Railroad the motor armature is carried by the axle. The armature and axle weigh 7460 lb.; obviously the hammer-blow, even in this case, is not to be compared with the tremendous blow due to unbalanced reciprocating parts, the inertia of which in steam locomotives at high speeds is sufficient actually to lift the wheels from the track.

The hammer-blow is less serious at the speeds at which freight trains usually travel; but even if we ignore entirely the effect of the unbalanced parts in this case, the electric locomotive still possesses the important advantage that its ratio of tractive effort to weight is much higher than that of the steam locomotive.

The most striking feature in American railway operation in recent years is the increase in length of train and weight of locomotive, under pressure of business which has increased at a ratio much exceeding the ratio of increase in track mileage. Despite the efforts of our railway engineers and managers, the roadbed has not kept pace with this advance; and while the weight of rail has been increased materially, the factors of safety as regards weight upon ties and bridges, and particularly as regards the security of rails against displacement due to side-thrust on curves, are by no means what they should be, and yet apparently have reached their limit. Lieut.-Col. Yorke, Chief Inspector for the British Board of Trade, in his report of the results of his observations in the United States in 1903, called particular attention to this fact, and expressed the opinion that American railway practice is tending towards British practice in respect to the distribution of weight on ties secured by inserting chairs between the rails and the ties.

In view of the fact that our railways have been spending large sums of money to increase the stability of the roadbed, to strengthen bridges and culverts, and to maintain rails in position upon the ties, the advantage which the electric locomotive possesses in its higher ratio of tractive effort to weight is important, even in freight traffic at low speed. The necessity of utilizing track capacity to the utmost, and the economies resulting from the operation of long trains, have resulted in gradually increasing the length and weight of freight trains until it would appear that the limit has been reached, unless further improvement in draft-gear, track, and roadbed, and further increase in weight of locomotives, be found possible. It is evident, however, that if electric locomotives operated by the multiple-unit system could be used and located at suitable distances throughout the train, the possible length of a freight train would not be limited by its practicable motive power equipment.

Operation of electric locomotives thus located presupposes upon all roads the addition of control-wiring and couplers to freight cars. The report of the Interstate Commerce Commission for 1904 shows that of a grand total of 1,845,304 locomotives and cars operated by our railways, 1,823,030 are equipped with automatic couplers and 1,554,772 are fitted with train brakes. At the present time, the cost of train-line and couplers would approximate $75 a car, but a reasonable cost for the apparatus required, if furnished in large quantities, would not exceed $50 per car.

As regards the making up of trains, it is now necessary to couple the air-line between cars, and the additional labor of connecting the control-couplers would not be serious.

While the cost of equipping freight cars, and of additional labor involved in connecting trains, is very small as compared with the immense advantages which in many cases would result from the ability to distribute locomotives at suitable intervals in a freight train, and control them simultaneously and perfectly by the hand of the engineman at the head of the train, the probability of adoption of multiple-unit operation for freight trains appears remote, since there is apparently no sufficient reason why a railroad company not adopting electricity should equip its cars for electric operation over the lines of another company which may adopt the newer motive power. Whether it be possible for a company desiring to avail itself fully of the advantages of electric traction for freight, as well as for passenger traffic, to bring to bear upon other lines interchanging freight with it, pressure sufficient to induce those lines to spend $50 per freight car for electric equipment is a question outside the scope of our present consideration.

Reverting to Table I, item 5, "Repairs and renewals of fences, road-crossings, signs and cattle-guards," will not be changed by the adoption of electricity.

Item 6, "Repairs and renewals of buildings and fixtures," includes repairs and renewals of engine houses and shops, also water tanks and coal-handling apparatus. Under electric operation, it is evident that this item would be materially reduced. This subject will be further discussed when we come to consider item 12, "Repairs and renewals of locomotives." It is conservative to say that for the operation of a given train-mileage, under the average conditions of railway service in this country, the number of electric locomotives required should not exceed one half the number of steam locomotives now used. The reduction in the number of locomotives implies, of course, a reduction in the cost of repairs and renewals of engine house and shops, and taking this into account, in connection with the elimination of water tanks and coal-handling apparatus, distributed along the line, it is our opinion that this item will be reduced from 2.366% to about 1.3% of the total annual operating expenses.

Item 7, " Repairs and renewals of docks and wharves " obviously will not be affected.

Item 8, " Repairs and renewals of telegraph." It is probable that this item will be somewhat increased in general where electric operation is adopted. The effect upon the operating expenses, however, is so slight as to be practically negligible in our consideration of the general problems of comparative expenses of steam and electric service.

Item 9, " Stationery and printing " will not be changed.

Item 10, " Other expenses " we may assume will not be affected.

Under the general heading " Maintenance of Way and Structures," the classified statement of operating expenses of a railroad electrically equipped includes the following items in addition to the foregoing:

a. " Repairs and renewals of track bonding."

This has been referred to in our discussion of items 2, 3, and 4, and it is included in our tabulated statement as a separate item amounting to 0.8% of operating expenses.

b. " Repairs and renewals of overhead or third-rail construction."

From detailed calculations of the cost of high class overhead construction, where two tracks are to be equipped the cost of overhead construction is approximately $10,300 per mile. This includes trolley conductors equivalent to No. 4/0 wire B. & S. gauge, insulated for 11,000 volts alternating, and supported by steel cables, carried by substantial steel bridges set in concrete, and spanning the tracks. For single-track work using steel poles and brackets and catenery support, the cost closely approximates $4800 a mile.

Of the total line mileage of the United States in 1905, amounting to 216,974 miles, approximately 0.4 are in double track, including yards and sidings for single-track lines, and 0.6 are single-track.

The grand average cost of overhead steel construction of the type considered, therefore, closely approximates $5000 per mile of track. In this case, our estimate of the annual cost of "Repairs and renewals of overhead construction" cannot rest directly upon actual experience, since practically no overhead construction of this character is in use under the conditions of railway service. We may, however, base conclusions which should be reasonably correct upon consideration of first-class overhead trolley construction such as is used by our best interurban lines. Some light is also thrown upon the subject by extensive experience in the operation of high potential transmission circuits, and the experience of the Valtellina line is particularly instructive.

Light steel bridges, set in concrete, subject to the comparatively slight strains involved in supporting the light conductors required, should last almost indefinitely if kept properly painted. The absence of smoke and gasses from locomotives favors their long life. The cost of these steel bridges and poles is a large part of the overhead construction.

The wear of the trolley wire will depend upon density of traffic, but its original cost is only $700 a mile, and judging from the experience of ordinary trolley lines and the results obtained on the Valtellina its life should be long.

The steel catenary cables supporting the conductor being well galvanized should last many years without renewals.

Breakage of insulators, such as are now available, will not constitute a large item of expense.

As regards life of steel structures, it is instructive to note the fact that much of the structure of the Manhattan Elevated lines still in use is more than 30 years of age, and is apparently unimpaired notwithstanding the heavy and frequent traffic which it has carried and still carries.

It is probable that engineering opinion in regard to the amount which should be allowed for "Repairs and renewals of overhead construction" under consideration will not be unanimous, but taking into account all of the factors which appear to affect the problem, it is our judgment that the amount required should not exceed $150 per mile of track per annum. This is equivalent to $210 per mile of line per annum, the average ratio of track-mileage to line-mileage being 1.4 to 1.

The increase in operating expenses due to this item is about 3.25% the average operating expenses per line-mile in the United States for the year 1905 being $6451.00.

It is of course, possible to erect a much cheaper form of construction if wood poles be used. Though the first cost of such construction is low, it involves repairs and renewals constituting a much larger percentage of its cost than in the case of the steel bridge and pole construction set in concrete. The annual effect upon operating expenses with this type of construction as an average figure may be expected to approximate 2.5%.

"MAINTENANCE OF EQUIPMENT."

Item 11. "Cost of superintendence" will not be changed.

Item 12. "Repairs and renewals of locomotives" amounts to 7.509% of the average operating expenses of our steam railroads. This item, as we find in the classification of operating expenses prescribed by the interstate Commerce Commission, "does not include the expense of cleaning boiler tubes and packing cylinders, nor ordinary regular inspection, this being charged to the item "Engine and Roundhouse Men." It does include "all expenditures for account of repairs and renewals and rebuilding of locomotives, tenders, snow-plows (when attached to locomotives), furniture and loose and movable tools and supplies used in connection therewith. It also includes the cost of locomotives, tenders and appurtenances thereunto belonging, built or purchased to make good the original number charged to construction or equipment."

As regards "Repairs and renewals of electric locomotives," actual experience to date is not sufficient to justify us in fixing a figure for this item which can be regarded as established. There is, however, evidence sufficient to justify an estimate which in the average case should be approximately correct.

Before considering data based upon experience, it is pertinent to remark that a moment's consideration of the constituent details of mechanism, their relative complexity, and their respective functions, leads directly to the conclusion that the repairs and renewals of an electric locomotive should be very small as compared with the same item of expense in the operation of a steam locomotive. If we imagine for a moment that electric locomotives had been in use for many years while steam locomotives had but recently come forward as competitors, and that the engineering world of to-day being familiar for years with the essential simplicity of the electric motor as applied to traction purposes, were now called upon to judge the comparative merits of the essentially complicated aggregation of mechanism which we call a steam locomotive, the verdict, as regards the relative cost of repairs and renewals to be expected, is obvious but the argument *a priori* cannot be conceded, and we proceed to consider such evidence based upon comparative results in actual service as we have been able to secure.

1. INTERBOROUGH RAPID TRANSIT CO., MANHATTAN DIVISION.

In the operation of the Manhattan Railway under steam and electric traction, respectively, data for interesting comparisons are afforded; although owing to the fact that in this case multiple-unit electric equipment, applied to two-thirds of the cars constituting the trains, has been substituted for the steam locomotive, the comparison is less favorable to electric operation so far as this item of expense is concerned than it would be were electric locomotives used. The reason is found in the relatively great complication of multiple-unit equipment as compared with locomotive equipment; as a result of this the number of parts in this case is multiplied in the approximate proportion of three to one, and the cost of repairs and renewals is therefore radically increased beyond what it would be were electric locomotives employed.

For the year ending June 30, 1901, the car-mileage operated by the Manhattan Railway was 43,860,158. The cost of repairs of locomotives was $173,609, or 0.39 cents per car-mile.

For the year ending June 30, 1906, the car-mileage operated by the Manhattan Railway was 61,723,112. The cost of repairs of the electric equipment, including lamps, lamp wiring, and heaters, was $171,927, or 0.28 cents per car-mile.

Had electric locomotives been used instead of the multiple-unit system, the number of parts constituting the electric equipment, as stated, would have been about one-third that now in use. These parts would have been larger and more expensive than the corresponding individual parts constituting the multiple-unit equipment, but the cost of repairs of the aggregate electrical equipment (which is largely labor of inspection) probably would not exceed 60% of the present cost. The results are further influenced unfavorably to electric traction as regards this comparison by the fact that the speed, and consequently the power consumption per car, have been radically increased, and by the fact that the repairs and renewals of lamps, heaters, and wiring are included.

A careful consideration of the detailed factors involved has led us to the conclusion that had electric locomotives been substituted for steam locomotives, and had the weight and speed of trains not been increased, the cost of repairs of electric equipment would have approximated 0.2 cents per locomotive mile. We estimate also that the cost of repairs to these small locomotives exclusive of their electric equipment operating under the existing conditions would not have exceeded 0.2 cents per locomotive-mile, and that the total cost would have approximated one-fourth of the cost of the corresponding item under steam traction. This figure of course is available only as a ratio in our consideration of the general railway problem.

The very low cost which was actually obtained in the case of steam locomotives on the Manhattan; viz., 1.57 cents per locomotive mile, is explained by the extremely simple construction of the engines, the fact that they were not overloaded, were operated on an elevated structure, and were admirably maintained. It is also to be noted that the amount expended for repairs was minimized in view of the contemplated adoption of electricity.*

In applying to the general railroad problem evidence afforded by Manhattan experience, it must be noted that the elevation of the tracks places the motors beyond the reach of the dust or cinders which the rush of a train at certain seasons raises from the average railway track. On the other hand, the fact that the average run between stations on the elevated system is only about 2000 ft. exposes both motor and control to the action of brake-shoe dust which is liberated in quantities many times as great as would be the case in average railway service, and this brake-shoe dust is far more injurious to both motors and control than is dust from disintegrated ballast or cinders.

In designing electric equipment for general railway service, it is advisable and not difficult to protect the motors effectively against the admission of dust of all kinds, particularly in cases where locomotives rather than multiple-unit equipment is adopted. This would be accomplished naturally by thoroughly enclosing the motor, and ventilating it by forced draft so directed as to prevent admission of dust.

*In this connection it is interesting to note that the cost of maintenance of locomotive and average train under steam operation for the year ending June 30, 1901, was 4.2c. per train-mile while the cost in the case of an equivalent electric train, as shown by records for corresponding months for the year ending June 30, 1906, was 2.1c. per train-mile.

2. Interborough Rapid Transit Company, Subway Division

For the year ending June 30, 1906, the car-mileage operated by the New York Subway was 31,931,073. The cost of repairs and renewals of electric equipment of rolling stock was 0.38 cents per car-mile. Estimating the probable cost of repairs and renewals of electric equipment, were electric locomotives in use instead of the multiple-unit car equipment, the approximate cost in this case works out at 0.7 cents per train-mile. A locomotive doing the same work as the electric equipment of the average train in the subway (about five cars) must be capable of exerting a draw-bar pull of 30,000 lb., which with 20% adhesion calls for 75 net tons on drivers. This is about double the weight on drivers of the average steam passenger locomotive, and the figure 0.7 cents per train-mile, obtained in actual service under conditions very severe in respect to maintenance of electric equipment, by reason of the presence of great quantities of brake-shoe dust, is to be compared with the cost of maintenance of steam locomotives exclusive of running-gear, frame, cab, and those other parts common to both electric and steam equipment.

3. Wilkes-Barre & Hazleton R.R.

Operation for the year 1905:

Equipment comprises motor cars weighing 43 tons without passengers, and equipped with four 125-h.p. motors and multiple-unit control.

Effective draw-bar pull (20% adhesion) = 17,000 lb.

Speed of operation in local service = 30 miles per hour.

Total length of run = 27 miles.

Average number of stops = 6.

Car-mileage operated in 1905 = 262,947.

Cost of repairs and renewals of electric motors = $1,021.70 = 0.39 cents per car-mile.

This road operates in a mountainous country, ranging in elevation from about 500 ft. to 1700 ft. above sea-level. About one-third of the length of the road is on a grade of 3%.

4. Lackawanna & Wyoming Valley Railroad.

Operation for a period of four months ending October 31, 1906:

Equipment: *a*, 16 passenger cars, 77,500 lb. each; *b*, 14 passenger cars, 64,500 lb. each; *c*, 4 freight and express motor cars, 61,300 lb. each; *d*, 1 electric locomotive, 94,600 lb.

Car-mileage operated = 527,554.

Repairs and renewals of electric equipment = \$4,450.43 = 0.84 cents per car-mile.

5. Niagara, Buffalo & Lockport Railroad.

Operation for a period of six months ending Nov. 30, 1906:

Equipment: passenger cars weighing about 60,000 lb., driven by four direct-current motors.

Average speed outside of Buffalo city limits, 20 miles an hour. Approximate number of stops one way trip: 30 on Buffalo & Niagara Falls division, and 6 on Buffalo & Lockport division.

Length of run outside of Buffalo, approximately 20 miles.

Car-mileage operated, 1,309,682.

Repairs and renewals of electric equipment, 0.79 cents per car-mile.

6. Rete Adriatica-Valtellina Line.

Perhaps the best instance of electric operation directly comparable with cost of steam operation is afforded by the records of the actual results realized on the Valtellina line where both freight and passenger traffic are operated over a line 66 miles in length, traversing a very rugged country and in the winter exposed to severe climatic conditions. The equipment for the year ending July 1, 1904, comprised 10 motor cars and five 70-ton locomotives. The service performed amounted to 61,934,569 ton-kilometers. The average annual mileage of motor cars and locomotives amounted to 54,351 kilometers, while the steam locomotives superseded by electric equipment never exceeded an average of 29,000 kilometers.

The total cost of electrical and mechanical repairs to locomotives and motor cars, for the year ending July 1904, works out at 1.4 cents per locomotive or motor car-mile. During the last six months of 1906, the repairs to locomotives cost 1.8 cent per locomotive-mile. The rolling stock used on this line is excellent in design and construction and is particularly well adapted to operate in railway service at low cost of maintenance, by reason of the fact that three-phase motors and water rheostats are employed instead of commutating motors and switch-control. The equipment has not been operating long enough to have reached the point where renewals, as distinguished from repairs, have become necessary.

Summarizing the foregoing we have the following:

	Tractive effort 20% adhesion	Repairs of electric equipment of equivalent electric locomotive. Estimated
Manhattan Railway..........	22,000 lb	0.5¢
Subway train...............	33,000 "	0.7¢
Wilkes-Barre & Hazleton R.R.	17,000 "	0.38¢ (actual)
Lackawanna & Wyoming Valley R.R.................	14,000 "	0.84¢
Niagara, Buffalo & Lockport R.R.....................	12,000 "	0.79¢
Rete Adriatica-Valtellina line Locomotives, complete cost of maintenance...........		1.8¢ (actual)

It may be conceded freely in respect to the foregoing data that they are neither sufficiently comprehensive in scope nor extended in respect to duration of service to justify definite and final conclusions. It must be noted also on the one hand that the cost of maintenance may be expected to decrease by reason of further improvement in the construction of apparatus of comparatively new types, and on the other hand that the costs given are for inspection and repairs rather than renewals, since the time has not arrived when any of this equipment has been thrown aside and replaced by new equipment charged to this item of operating expenses as is usual with steam railways.

The reports of the Interstate Commerce Commission do not show what proportion of the item, " Repairs and renewals of locomotives " is chargeable to renewals, but from inspection of detailed reports of our most important railway systems it seems fair to assume that in the case of the average railway from 4% to 5% of the total cost of repairs and renewals of locomotives represents the cost of renewals.

Taking into account all of the various considerations which must affect the conclusions in the general case, so far as we have been able to gather them, we are of the opinion that for equal draw-bar pull, the repairs and renewals of electric equipment of locomotives, assuming good design and construction according to present standards of the art, should not exceed 1 cent per locomotive-mile, and will probably approximate 0.9 cent per locomotive-mile.

Taking the higher figure, it is evident that the substitution of electric equipment for all parts of a steam locomotive other than frame, wheels, axles, cab, and other parts which are common both to electric and steam locomotive construction, a very great saving is effected. We have been unable to fix with satisfactory exactness a figure representing the average cost of repairs and renewals of these parts, but it would seem liberal to allow 1.5 cents per locomotive-mile, this being equivalent to an allowance of something over $400 per annum per locomotive. Taking this figure and adding the estimated costs of repairs and renewals of electric equipment, we have 2.5 cents per locomotive-mile as the estimated total cost of repairs and renewals of electric locomotives, performing the average work now done by steam locomotives.

In 1904 the aggregate revenue train-mileage operated was about 1,050,000,000. To cover locomotive mileage in switching, operating work-trains, and pushers we assume 1,300,000 locomotive-miles. In 1904 the aggregate repairs and renewals of locomotives was $105,633,752, the average cost per locomotive-mile, therefore, being 8.1 cents. A reduction to 2.5 cents, therefore, is equivalent to a saving of 70% in the cost of this item, or 5.256% of operating expenses, reducing this item to 2.253% of total operating expenses under electric operation.

In the foregoing consideration of the item repairs and renewals of locomotives, we have assumed equal locomotive mileage per day in steam and electric service. The item of expense under consideration will be proportional approximately to the mileage, and therefore we have made the comparison upon this basis.

The relative number of locomotives required for a given service is, however, a question of much importance and may here be appropriately referred to.

According to the report of the Interstate Commerce Commission for 1904, the aggregate train-mileage operated in the United States as above stated was 1,050,000,000. The locomotives in service numbered 46,743. The effective train-mileage, not including work-trains, pushers, or shifting mileage, was 58 miles per locomotive per day. We have been unable to ascertain from the report of the Commission what percentage should be added to this figure to cover accurately the locomotive mileage of work-trains and shifting and to take account of double headers and pushers, but inspection of the report of a number of our leading railways indicates that the effective train mileage averages from 70% to 75% of the locomotive mileage. It follows, therefore, that the daily run of the average locomotive in the United States is approximately 80 miles. Naturally there is a wide variation in the performance of locomotives on various lines; *e.g.*, passenger mileage as shown by reports of some of our leading railways varies from 90 miles to nearly 200 miles a day and individual cases are reported of locomotives making as much as 300 miles a day.

The average freight locomotive is actually on the road not more than 6 hours in each 24-hour period, and the same figure is approximately correct for the average passenger locomotive. In the case of electric locomotives there is no reason, so far as the mechanism is concerned, why it cannot be kept in practically continuous service. Ordinary inspection and maintenance require very little time, and if the equipment be well designed and constructed repairs of magnitude will be necessary only at intervals very infrequent as compared with steam practice.

The fact that the average daily run of the average locomotive is approximately 80 miles, is due in large measure to causes which would still exist were electric locomotives substituted. The time spent by freight locomotives in yards and terminals making up trains or awaiting opportunity to take their place in the processions of trains which in these days are demonstrating the insufficiency of track equipment for the business of the country, is a large factor. Perhaps this would not be greatly modified were electric locomotives employed. But other considerations which operate to reduce average mileage are the facts that the steam locomotive spends a large part of its life in the repair shop, and a still larger part in firing up and preparing for its work and in withdrawing fires, having boiler tubes cleaned, etc., after its daily run. Nothing short of years of actual experience can establish definitely the ratio of electric to steam locomotives required in average service, but it seems reasonable to assume that this ratio will not exceed 2 to 3 and will probably approximate 1 to 2. It will be noted that the foregoing estimate of cost of repairs and renewals is independent of any assumption as to the relative number of locomotives required since it is reckoned on locomotive mileage.

Item 13. "Repairs and renewals of passenger cars." In cases where electric locomotives are substituted for steam locomotives, there should be some reduction in this item. Painting should be considerably reduced by reason of the elimination of smoke. The life of the upholstery and interior decoration of the car will be increased.

Item 14. " Repairs and renewals of freight cars." This item will be favorably and very materially affected if it should ever prove practicable to operate heavy freight trains by locomotives located at intervals throughout the trains and controlled by the multiple-unit system. As has been pointed out, however, this will become practicable only when a large proportion of the freight cars in use are supplied with electric train line equipment. The bare possibility of this at present may seem fanciful, but those who realize the extent to which the wear and tear of freight cars results from the terrific strains to which the draft-gear is subjected under present operating conditions, especially on mountain grades, and who understand also the increase in track capacity and decrease in cost of train crews which would result from the adoption of a system which makes it possible, if necessary, to double the length and weight of the longest and heaviest freight trains now in use, will be ready to give this possibility serious consideration. The mere substitution of electricity for steam without altering the present make-up of trains, so far as location of the locomotive is concerned, makes it possible to operate two or more locomotive units at the head of the train, and to utilize their power to the utmost by multiple-unit control operated by a single operator on the leading engine.

Assuming that the methods of train operation remain the same, the adoption of electricity will still effect a reduction in the cost of Item 14, and for two reasons, viz;

1. The practical elimination of damage by fire which now frequently is superimposed upon damage caused by collision or derailment.

2. Reduction of wear and tear of wheels and brake equipment in descending long grades, by reason of the opportunity afforded to brake the trains by causing the motors to operate as generators. On lines where grades are heavy and of considerable length, the saving thus effected will be large. Generally speaking, the energy developed by the motors working as generators will be returned to the overhead circuit and utilized in coöperation with energy from the power house to furnish power to trains on the same division which may be ascending the grade.

No statistical data are available upon which to base an estimate of the probable reduction in this item to be expected from this cause. On comparatively level lines it will not be important, but on mountain-grade divisions it should operate to prevent a very large proportion not only of wear and tear directly due to grade but also of the destructive freight wrecks which are now so frequent. In the way of an estimate, nothing more definite than a guess based upon consideration of probabilities, and the views of various operating officials, can be advanced; but in the opinion of the writers the general substitution of electricity for steam operation in freight service should reduce this item from 7.657% to something like 6% of operating expenses.

Item 15. " Repairs and renewals of work cars," will not be changed materially.

Item 16. " Repairs and renewals of marine equipment," obviously will not be changed.

Item 17. " Repairs and renewals of shop machinery and tools," will be reduced under electric operation since the repairs to locomotives will be decreased radically as shown, and since the tool equipment required for the electrical machinery is materially less expensive and varied.

It would seem reasonable to expect that this item would be reduced from 0.662% to about 0.5% of total operating expenses. Of course a large proportion of the shop machinery and tools are for car repairs.

Item 18. " Stationery and printing," will not be changed.

Item 19. " Other expenses." The classification of operating expenses includes under this item " all expenditures for account of electric light, torches and lamps used in machinery department, shops, roundhouses and offices and the oil and material for the same; the proportion of labor and material for the proper operation and repair of electric lights used in connection with other departments; wages of engineers and firemen and the cost of fuel and water in operation of stationary engines or boilers for supplying power and heat to shops, buildings and roundhouses."

Other factors comprised are comparatively small and it is evident that the ability to use electricity for light and power purposes in shops, roundhouses and offices produced at a works cost of 0.6 cents and delivered to the point of consumption at a figure which on the average will approximate 0.75 cents will effect a material reduction in this item. We estimate that it will be reduced to about 0.4 cents.

CONDUCTING TRANSPORTATION.

Item 20. " Superintendence," will not be changed.

Item 21. " Engine and roundhouse men," includes in addition to the engine crew, round-house men whose work, of course, is chiefly in connection with the cleaning and maintenance of the engines. This item averages for the railroads of the United States 9.451% of the operating expenses, of which 91%, or about 8.6% of the operating expenses are for engine men and for firemen. Of this 8.6% approximately 5.5% is for engine men and 3.1% for firemen.

In considering the substitution of the electric locomotive for the steam locomotive it is obvious that the change eliminates the work which the fireman is employed to perform. The point is frequently made, however, that to reduce the engine crew to one man means an increase in the risk incurred in train operation and this point obviously is of such importance as to require careful consideration.

If we compare conditions which now exist upon such systems as the Manhattan Elevated with the conditions which existed before electricity was adopted, it seems reasonably clear that with a competent motorman operating a controller which instantly cuts off power and applies the brakes in case the hand of the motorman is removed from the handle of the controller, the safety of trains and passengers is assured in higher degree than it was under the old conditions. The usual argument against the elimination of the fireman is of course, found in the allegation that in case of the sudden death or serious illness of the engineman the fireman can take his place and bring the train to a stop or operate it to the next station. The controller which automatically cuts off power and applies the brakes cannot operate the train to the next station, but it can stop it much more promptly than the fireman possibly can, even when he is so located upon the engine as to be in sight of the engineman.

But a very large proportion of our steam locomotives are now designed in such a way that the engineman is not in sight of the fireman, and the mechanism of the steam locomotive which he controls has no automatic device for shutting off power and applying the brakes in case he suddenly dies at his post. In such an emergency on trunk-line railways there would be some advantage in tne presence of the fireman, owing to the fact that if competent he could operate the train to the next station. This point might be met by having the train conductor or brakeman or flagman qualified to operate the electric train to its destination in case of accident to the motorman. The degree of skill required, so far as actual manipulation of the mechanism is concerned, would be far less than in the case of the fireman who in emergency might be entrusted with the responsibility of operating the steam train.

It would seem, therefore, that there can be no question of the reasonableness and safety of entrusting the operation of an electric locomotive to one man, provided the control system is equipped with effective appliances arranged to cut off the power and apply the brakes in case the motorman's hand leaves the hand of the controller.

As regards the wages of the engineman, the Manhattan Railway decided to pay its motormen the same wages which it had paid its enginemen. This decision was based largely upon consideration of the fact that familiarity with the road and experience in operating trains under the extremely close headway prevailing upon this system were of such importance that any risk which might be incurred by substituting new men must be avoided. The great majority of electrically equipped railways operating under conditions similar to the Manhattan, however, pay their motormen wages comparable to the wages of the men who operate street cars rather than to the wages of locomotive enginemen.

The work required of the motorman operating an electric train is far less onerous and is performed under conditions much less severe than is the case with the locomotive engine-driver, nor is the motorman in order effectively to perform his duties required to serve years of apprenticeship during which he must become familiar with the complicated mechanism under his control and competent to make upon the road any ordinary emergency repairs. The work required being relatively easy, the apprenticeship comparatively short, and the mechanical knowledge necessary greatly reduced, it is reasonable and proper that the compensation of the motorman, under average conditions, should be less than that of the engineman.

Apart from the attitude to be expected upon the part of employees, and aside from any question of sentiment, however, the management of a railway contemplating the substitution of electricity for steam would not be justified in lowering the standard so far as character and judgment are concerned, which are requisite for the motorman equally with the engineman. It must be remembered also that familiarity with the road and with signals, etc., are as important in his case as in that of his predecessor.

It is impossible of course to fix with definiteness a figure representing the wages of the motorman in railway service as compared with that of the engineman whom he may succeed, but it seems reasonable to assume that under average conditions the services of thoroughly competent motormen can be obtained at a figure which will represent a reduction of 1% in operating expenses, making this item 4.5% instead of 5.5%.

The expense for round-housemen, which under steam operation is about 0.85%, will be greatly reduced both by reason of the reduction in the number of locomotives required for a given service and also by reason of the demonstrated less cost of maintenance per locomotive unit. It is entirely liberal to allow for this item one fourth of its cost in steam operation, the saving here effected being equal to 0.64% of the average operating expenses of steam railroads in the United States.

The estimated cost of the item under consideration, therefore, is 4.71% of total operating expenses.

Item 22, " Fuel for locomotives." One of the marked economies resulting from the substitution of the electric motor for the steam locomotive in railway operation is in the reduction of the fuel account. The cost of fuel upon the average steam railway in the United States for the five years 1901 to 1905 inclusive constituted 11.292% of total operating expenses. The aggregate cost in 1905 was $156,429,245.

The following figures show comparative fuel consumption upon the Manhattan Railway during the year ending June 30, 1901, when steam locomotives were employed and during the year ending June 30, 1904, when electricity was used. During the period first mentioned one pound of coal produced 2.23 ton-miles, if the weight of the locomotive be included, and 1.5 ton-miles, if the weight of the cars only be considered.

During the latter period (electric traction) one pound of coal burned at the power house produced 3.85 ton-miles, excluding weight of locomotives; therefore, the ratio of ton-mileage per pound of coal in favor of electric operation was 2.57 to 1. Including weight of locomotive it was 1.72 to 1.

The average speed under electric operation was approximately 2 miles an hour greater than that attained by steam, and if correction be made for this difference the ratio of ton-mileage per pound of coal excluding weight of locomotives is approximately 3 to 1, and including locomotives 2 to 1 in favor of electric traction. It should be noted also that in this case the coal burned at the power house was of lower grade, and therefore less expensive than that used by the locomotives, and it is reasonable to expect that in general electric traction will mean utilization of cheaper fuel.

We would point out that the argument from Manhattan experience cannot be met by the statement that the Manhattan is not an average railroad. Were the steam and electric apparatus now operating the Manhattan lines applied to the operation of a division of a trunk-line railway, the one part of the system which would be affected in respect to efficiency is the high potential transmission lines, and the effect of their greater length in general would be to increase the relative fuel consumption of the electric system by not more than 5%. For trains drawn by locomotives the fuel account (coal only) under electric operation would still be approximately one-half of the cost of the fuel for steam operation, and for passenger service using multiple-unit equipment it would be less than 40% of the fuel used in equivalent steam service, even if we assume that the system of alternating transmission and conversion to direct current by synchronous converters be employed.

The advantage in favor of electric operation is even more marked if we assume that alternating-current equipment is to be used, as in general would be the case in the electrification of trunk lines or long divisions. In a particular case which we have worked out with great care, the trolley and track rail losses average 3.9%, the load factor being 0.33. This is the result obtained in using the single-phase system for the equipment of a division approximately 40 miles in length, the potential being 11,000 volts. The grand average of traffic in the United States does not exceed seven trains per day passing a given point in each direction, and the trolley and track rail energy losses for this traffic would be less than 2%.

Assuming that such a trolley voltage is used in connection with a feeder potential of say 40,000 to 60,000 volts, the allowable loss in these feeders at maximum load certainly will not exceed 10% and the energy efficiency of step-up transformers, transmission feeders, and step-down transformers will be 92%. Combining this figure with the energy efficiency of trolley and track, as above stated, the resultant efficiency from bus-bars of power house to the train will be 90%.

The works-cost of a kilowatt-hour at the bus-bars of the Manhattan plant is less than 0.6 cent when coal costs $3.00 per ton, this coal having a calorific value of 14,000 B.t.u. per lb. This cost includes fuel, water, labor, maintenance, miscellaneous supplies, and in short everything except capital charges. It is not abnormally low, the cost of both coal and labor being relatively high as compared with the grand average cost of equivalent coal and labor throughout the United States. Where fuel is less expensive, as in the middle West, large modern plants, using steam turbines, are producing the average kilowatt-hour at a price not exceeding 0.5 cent exclusive of capital charges, and in at least one case at a works-cost approximating 0.4 cent.

As will be shown hereinafter, were all the railroads of the United States to be operated by electricity, the average plant required, assuming power to be transmitted 150 miles, would approximate 4,000 kw. if the plants supplied but a single line 300 miles in length. The great bulk of the total power supplied however, would be derived from large plants in which the cost of producing the unit of energy, considering average costs of fuel and labor, should be less than 0.6 cent. While the small plants would exceed this figure we believe that as a grand average 0.6 cent is ample to cover the case. In this connection, it may be remarked that water powers and other sources of cheap power supply would tend to keep down the average cost of power under the assumed condition of electrification of the entire railroad system of the country.

In the case of the single-phase, 25-cycle motor, assuming the average length of run for freight trains to be 15 miles and for passenger trains 20 miles, we have calculated that of the energy delivered to the locomotive approximately 86% will be effective for traction in the case of the passenger locomotive, which is gearless, and about 84% in the case of the freight locomotive, which uses single-reduction gear. Combining the two, it is safe to say that of the energy supplied at the bus-bars in the power house not less than 75% will be effective for traction in the average locomotive equipped with this apparatus.*

The cost of a kilowatt-hour effective for traction therefore

*For the motor curves upon which these figures are based, we are indebted to the courtesy of the Westinghouse Electric & Mfg. Co.

is 0.8 cent and the cost of a horse-power hour effective for traction about 0.6 cent of which 0.35 cent is for fuel when coal of 14,000 B.t.u. per lb., costs $3.00 per ton of 2240 lb., and 0.25 cent is for other power-house supplies, power-house labor, and maintenance of power-house equipment.

As we have stated, the railroads of the United States in 1905 used coal costing $156,429,245. For the purpose of estimating the cost of equivalent electric power the following data are necessary, of which those marked by an * are furnished by the report of the Interstate Commerce Commission while the others involve certain assumptions:

Passenger Service

*Passenger train-miles.
Passenger car-miles.
*Passenger-miles.
Average weight of passenger trains:
  a. Weight of locomotives.
  b. Weight of cars.
  c. Weight per passenger.
Average speed of passenger trains.
Average length of run.
*Mail and express train-mileage.
Average weight of mail and express trains.
Non-revenue ton-mileage.

Freight Service

*Freight train-mileage.
*Freight car-mileage.
*Revenue freight ton-miles.
Average weight of freight trains:
  a. Weight of locomotive.
  b. Weight of cars.
Average speed of freight trains.
Average length of run.
Non-revenue ton-mileage, work-trains, switching, etc.

Referring to the several items in the foregoing lists not directly derived from the report of the Interstate Commerce Commission the assumptions made are as follows:

Passenger Service

Passenger Car-Miles: These we have calculated from the stated train mileage and the assumption that the average number of cars per train is 5.5.

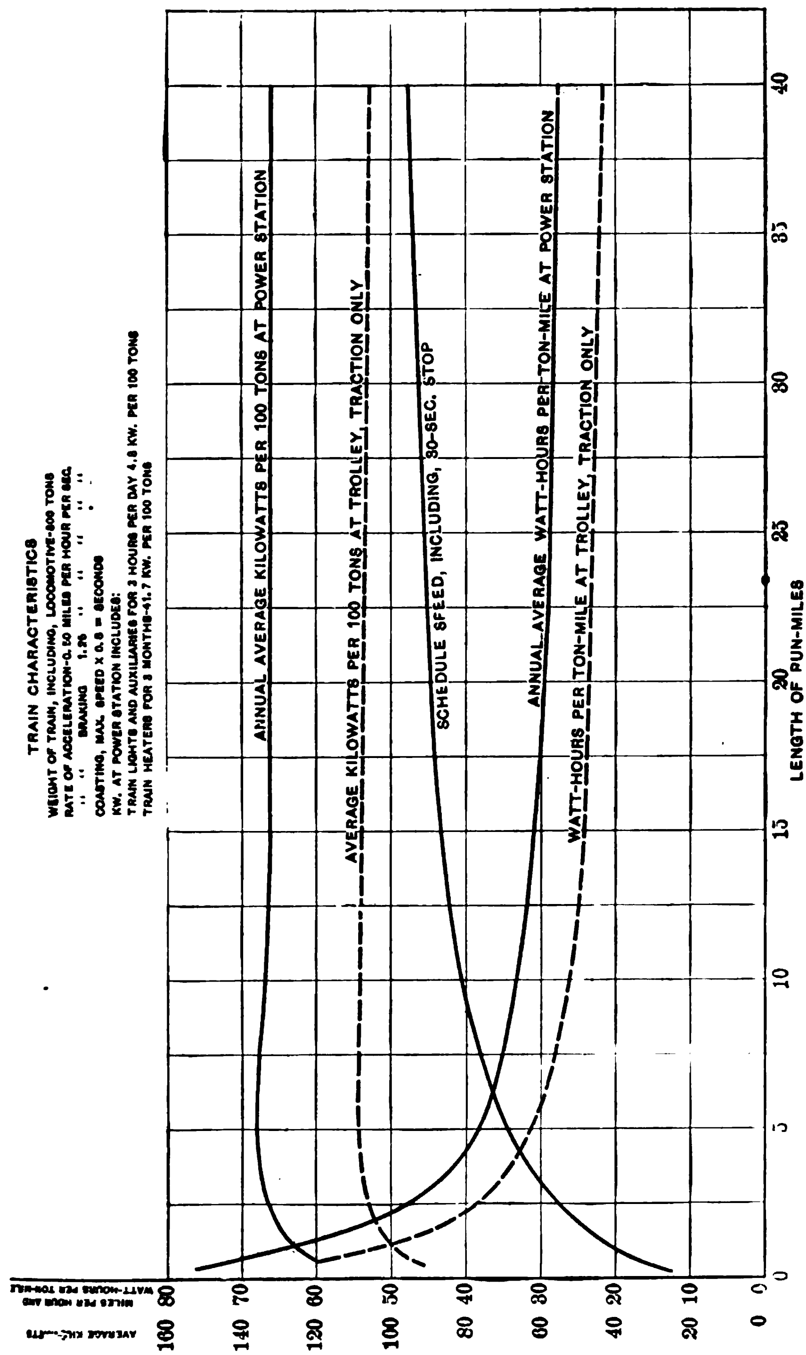

TRAIN CHARACTERISTICS
WEIGHT OF TRAIN, INCLUDING, LOCOMOTIVE-800 TONS
RATE OF ACCELERATION-0.50 MILES PER HOUR PER SEC.
" " BRAKING 1.25 " " " " "
COASTING, MAX. SPEED X 0.8 = SECONDS
KW. AT POWER STATION INCLUDES:
TRAIN LIGHTS AND AUXILIARIES FOR 3 HOURS PER DAY 4.8 KW. PER 100 TONS
TRAIN HEATERS FOR 8 MONTHS-41.7 KW. PER 100 TONS
ANNUAL AVERAGE KILOWATTS PER 100 TONS AT POWER STATION
AVERAGE KILOWATTS PER 100 TONS AT TROLLEY, TRACTION ONLY
SCHEDULE SPEED, INCLUDING, 30-SEC. STOP
ANNUAL AVERAGE WATT-HOURS PER TON-MILE AT POWER STATION
WATT-HOURS PER TON-MILE AT TROLLEY, TRACTION ONLY
LENGTH OF RUN-MILES
MILES PER HOUR AND WATT-HOURS PER TON-MILE
AVERAGE KILOWATTS
0 5 10 15 20 25 30 35 40
0 10 20 30 40 50 60 70 80
0 20 40 60 80 100 120 140 160

FIG. 5.

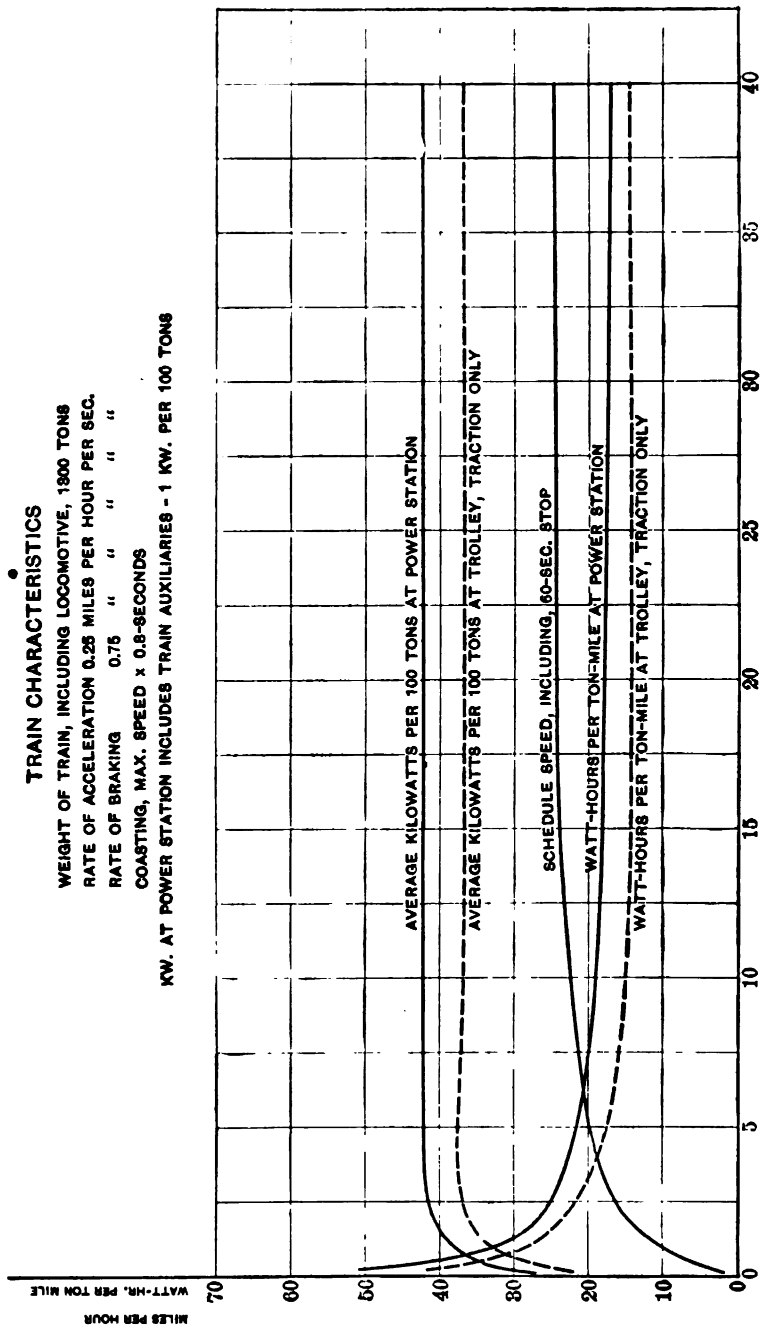

TRAIN CHARACTERISTICS
WEIGHT OF TRAIN, INCLUDING LOCOMOTIVE, 1800 TONS
RATE OF ACCELERATION 0.25 MILES PER HOUR PER SEC.
RATE OF BRAKING 0.75 " " " " "
COASTING, MAX. SPEED x 0.8-SECONDS
KW. AT POWER STATION INCLUDES TRAIN AUXILIARIES - 1 KW. PER 100 TONS
AVERAGE KILOWATTS PER 100 TONS AT POWER STATION
AVERAGE KILOWATTS PER 100 TONS AT TROLLEY, TRACTION ONLY
SCHEDULE SPEED, INCLUDING 60-SEC. STOP
WATT-HOURS PER TON-MILE AT POWER STATION
WATT-HOURS PER TON-MILE AT TROLLEY, TRACTION ONLY
WATT-HR. PER TON MILE
MILES PER HOUR
AVERAGE KILOWATTS
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
LENGTH OF RUN-MILES

FIG. 6.

Average Weight of Passenger Trains: We assume,

a, Weight of the average locomotive exclusive of tender equals 60 tons—the weight on drivers is 38 tons—this is the weight of the average passenger locomotive used by the Erie system;

b, Average weight of ordinary passenger coaches without live load equals 30 tons. This weight is somewhat in excess of the average weight of cars used by a number of railroads using rolling stock undoubtedly representative of the average in use throughout the country. To this we have added 10% in estimating train weight to cover additional weight of Pullman cars.

c, Average number of cars in trains. We assume five and a half cars per train which is approximately correct for a number of the more important railroads and is probably slightly above rather than below the grand average.

d, Weight per passenger. We have assumed an average weight of 140 lb.

Average Speed of Passenger Trains: Referring to Fig. 5, the curve expressing the variation in the amount of energy required for traction as dependent upon average length of run between stations, shows that the increase resulting from a decrease in length of run from 20 miles to 10 miles is but 10%. If the average length of run be further decreased to 5 miles, the increase of energy for traction as compared with that required for a 10-mile run is approximately 18%.

Including energy required for heating and lighting the cars, it is not far from accurate to assume 33 watt-hours output at power-house per ton-mile in average passenger service.

Average Length of Run: We have assumed, as stated, 33 watt-hours at power house per ton-mile including light and heat. This corresponds to an average run of 10 miles.

Average Weight of Mail and Express Trains: We have assumed average weight of mail and express trains to be the same as that of the average passenger train, viz., 180 tons without locomotive or live load.

Non-Revenue Ton-Mileage: This is assumed at 10% to cover "double-headers," switching and additional power consumption due to grades and curves. The assumption is slightly less favorable to electric traction than the facts would probably warrant.

FREIGHT SERVICE.

Average Weight of Freight Trains: As regards freight service, in estimating the average weight of trains we have assumed the following:

a, Weight of locomotives equals 68 tons on drivers. This is the actual average of the freight locomotives of the Erie system exclusive of tender.

b, Weight of cars equals 15 tons. This figure closely approximates the average weight of all freight cars belonging to the Erie Railroad Company.

Average Speed of Freight Trains: Our curves (Fig. 6) are based upon a gear ratio which produces on straight and level track a maximum speed of 25 miles an hour.

Determination of the error involved by any mistake in our assumption of the average speed in freight service is facilitated by Fig. 8, which shows, for example, the following relations:

Maximum Speed.	Average speed, including 60 seconds stop, miles per hour.	Average watt-hours per ton-mile at power station.
20	19	17
25	23	18
30	27	19

Average Length of Run: We have assumed that for all freight service the average length of run is 15 miles. The actual average length of run may vary considerably from the distance assumed without causing material error in our calculation as shown in Fig. 6.

Non-Revenue Ton-Mileage: We have added 15% to the tota revenue earning ton-mileage to cover switching and pusher service and increased power consumption due to grades and curves.

Basing our calculations upon the foregoing statistical facts and the assumptions noted, we estimate that for the operation of the entire freight and passenger service of the United States as existing in 1905, the aggregate energy required at bus-bars of power houses would approximate 13,200,000,000 kilowatt-hours per annum.

At 0.6 cent per kilowatt-hour the total cost of energy for traction, for the operation of all auxiliaries, and for the supply of light and heat to passenger trains would closely approximate $79,000,000 per annum. This figure represents a saving of about

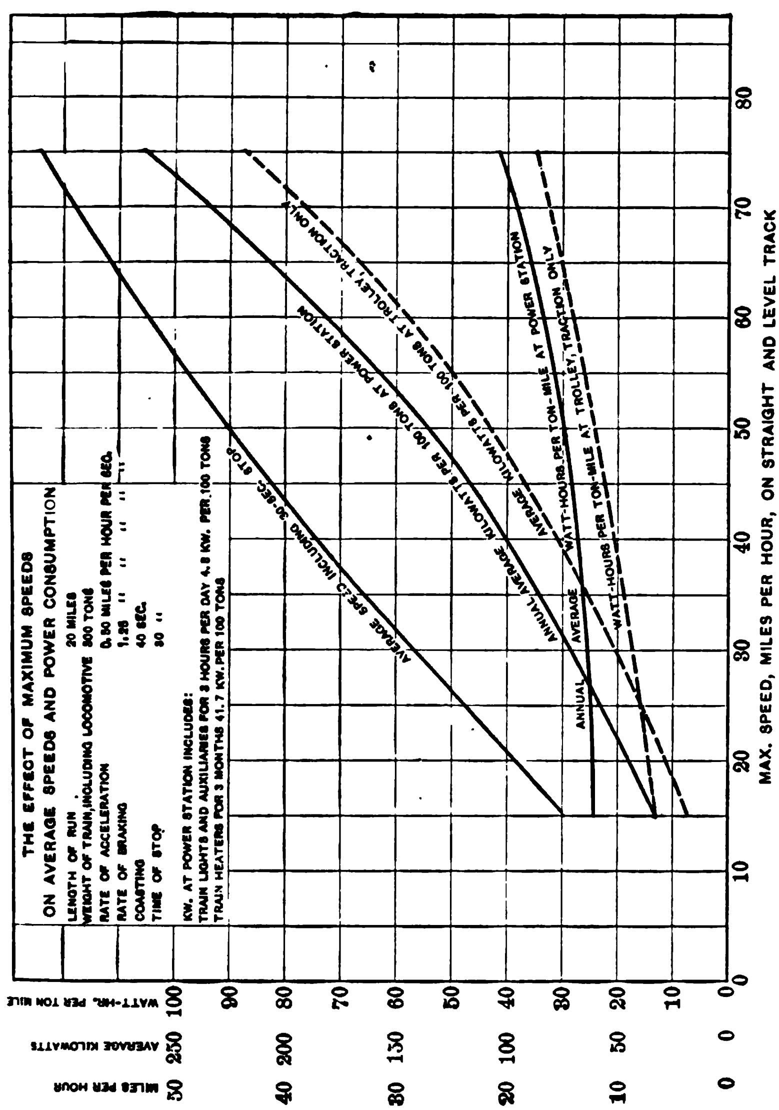

THE EFFECT OF MAXIMUM SPEEDS
ON AVERAGE SPEEDS AND POWER CONSUMPTION
LENGTH OF RUN 20 MILES
WEIGHT OF TRAIN, INCLUDING LOCOMOTIVE 300 TONS
RATE OF ACCELERATION 0.80 MILES PER HOUR PER SEC.
RATE OF BRAKING 1.25 " " " " "
COASTING 40 SEC.
TIME OF STOP 30 "
KW. AT POWER STATION INCLUDES:
TRAIN LIGHTS AND AUXILIARIES FOR 3 HOURS PER DAY 4.8 KW. PER 100 TONS
TRAIN HEATERS FOR 3 MONTHS 41.7 KW. PER 100 TONS
AVERAGE SPEED INCLUDING 30-SEC. STOP
ANNUAL AVERAGE KILOWATTS PER 100 TONS AT POWER STATION
AVERAGE KILOWATTS PER 100 TONS AT TROLLEY, TRACTION ONLY
ANNUAL AVERAGE WATT-HOURS PER TON-MILE AT POWER STATION
WATT-HOURS PER TON-MILE AT TROLLEY, TRACTION ONLY
MAX. SPEED, MILES PER HOUR, ON STRAIGHT AND LEVEL TRACK
WATT-HR. PER TON MILE
AVERAGE KILOWATTS
MILES PER HOUR

FIG. 7.

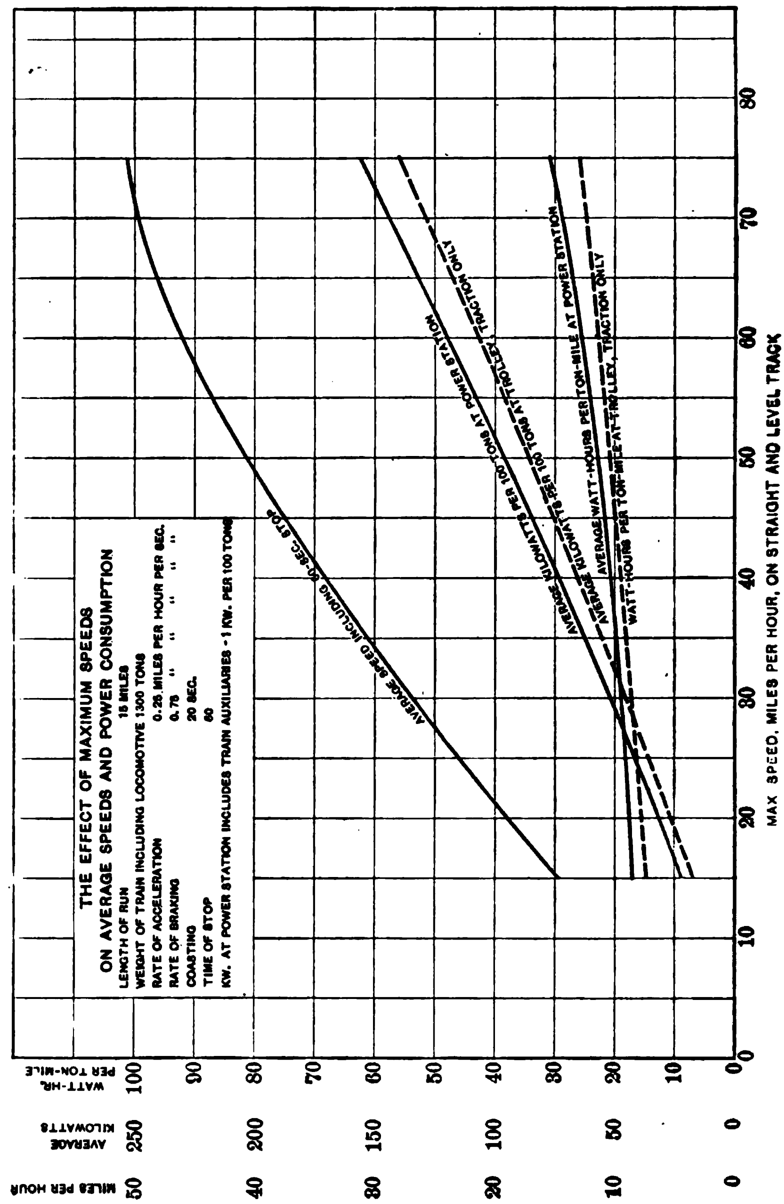

THE EFFECT OF MAXIMUM SPEEDS
ON AVERAGE SPEEDS AND POWER CONSUMPTION
LENGTH OF RUN 15 MILES
WEIGHT OF TRAIN INCLUDING LOCOMOTIVE 1300 TONS
RATE OF ACCELERATION 0.25 MILES PER HOUR PER SEC.
RATE OF BRAKING 0.75 " " " " "
COASTING 20 SEC.
TIME OF STOP 60
KW. AT POWER STATION INCLUDES TRAIN AUXILIARIES - 1 KW. PER 100 TONS
AVERAGE SPEED INCLUDING 60-SEC. STOPS
AVERAGE KILOWATTS PER 100 TONS AT POWER STATION
AVERAGE KILOWATTS PER 100 TONS AT TROLLEY, TRACTION ONLY
AVERAGE WATT-HOURS PER TON-MILE AT POWER STATION
WATT-HOURS PER TON-MILE AT TROLLEY, TRACTION ONLY
WATT-HR. PER TON-MILE
AVERAGE KILOWATTS
MILES PER HOUR
MAX SPEED, MILES PER HOUR, ON STRAIGHT AND LEVEL TRACK
0
10
20
30
40
50
60
70
80
90
100
150
200
250

FIG. 8.

$77,500,000 as compared with the coal used by steam locomotives in the year 1905.

Referring to the table, the average cost of this item for 5 years, viz., 11.292%, would be reduced by electric traction to 5.702%.

Item 23. "Water supply for locomotives." This item is eliminated if electricity be substituted for steam.

Item 24. "Oil, tallow, and waste for locomotives." This item should be considerably reduced. We assume that it will be reduced to 0.25%.

Item 25. "Other supplies for locomotives." We make no change in this item.

Item 26. "Train service." This item is not changed.

Item 27. "Train supplies and expenses." This item among many others includes the following which will be changed by the substitution of electric motive power, viz.: "Heating, lighting, cleaning and lubricating cars, including the cost of supplying and pumping gas into cars."

In discussing Item 22, we have included in the estimate of electric power required energy sufficient to light all cars three hours out of every twenty-four. We have also included energy sufficient to heat all passenger trains by electricity an average of three months per annum. Both of these are important items. The cost of cleaning the cars should also be reduced by the elimination of smoke and cinders from the locomotives. All things considered we believe it is fair to assume that under electric operation this item will approximate one per cent. of operating expenses.

Item 28. "Switchmen, flagmen, and watchmen" will not be changed.

Item 29. "Telegraph expenses." In general it is not to be expected that the large amounts of power required for train operation can be transmitted electrically under conditions which make it necessary to parallel telegraph lines by power circuits without more or less interference with the telegraph and telephone service. Certain technical questions in regard to methods of preventing interference remain to be worked out. The erection of overhead circuits carrying power supply will involve generally more or less shifting of the location of the telegraph lines. This item of expense is taken care of in our estimate by inclusion the in cost of overhead construction, and is treated as a capital account.

Telegraph circuits being rearranged with reference to the power circuits, or equipped with one or another of the devices which have been suggested as preventives of difficulties resulting from inductive effects of the power circuits, it might be assumed, perhaps with safety, that Item 29 would not be changed, but we are inclined to the opinion that there will be a slight increase in the cost of this item even under the best plans heretofore proposed, and we therefore increase it in our estimate to 0.2%.

Item 30. " Station service." Examination of the factors constituting this large item indicates no material change.

Item 31. " Station supplies." This item includes among many others the following, viz., " All expenditures for account of heating and lighting depots, waiting rooms, freight and passenger offices and other station buildings; fuel and supplies for engines operating freight carriers on docks, wharves and piers to convey freight between boats and cars; supplies used for stations and yards, signal lights, street lights, switch lights, semaphore lamps, etc., also bills of municipalities for lighting highway crossings."

The ability to employ conveniently for the lighting of important passenger stations and yards, electricity delivered at the point of consumption at a cost which, exclusive of capital charges upon power plant, closely approximates 0.6 cent per kilowatt-hour, to substitute electric motors for engines now used to operate freight carriers on docks, wharves, and piers, and to avail conveniently of electric hoists and telpher systems, are important advantages incident to the adoption of electricity. For lighting and incidental power service of this kind, equivalent to that with which railroads are now apparently satisfied, the change would undoubtedly mean reduction in cost. We will let it stand as it is, however, and would point out the fact that without increasing the cost of this item, a great improvement in facilities for handling freight at docks and wharves and for lighting passenger stations and yards will result from the substitution of electric power.

Items 32, 33, and 34. viz, " Switching charges, balance," " Car per diem and mileage, balance," and " Hire of equipment, balance," will not be changed.

Item 35. " Loss and damage," Under this item the important factors which will be affected by the substitution of electricity for steam are the following: viz., " Charges for loss, damage, delays or destruction of freight, parcels, express matter, baggage and other property entrusted for transportation (including live stock received for shipment) and all expenses directly incident thereto. * * * Charges for damages to or destruction of crops, buildings, lands, fencing, vehicles, or any property other than that entrusted for transportation, whether occasioned by fire, collision, overflow, or otherwise; also services and expenses of employees or others while engaged as witnesses in the case of suits."

For reasons which have been referred to in our discussion of the subject " Safety," it is clear that there should be a material reduction in the charges for loss due to destruction of freight, etc.

Another saving will result from the practical elimination by reason of damage of fire, which now not infrequently is caused by sparks from locomotives.

These savings will be offset to some extent by damage due to telegraph, telephone, or other wires coming in contact with the power circuits of the railway, unless reasonable care be exercised in preventing such accidental contact by the adoption of proper precautions when the electric equipment is installed.

In our estimate we have reduced item 35 to 0.75%.

Item 36. Injuries to persons." " This account includes all charges on account of employes or other persons killed or injured except lawyers' fees and court expenses."

For reasons referred to under the heading " Safety " some reduction in the number of passengers and employes killed and injured in railway accidents may be expected to result from the use of electricity. The risk of fire following collision being materially reduced, we should anticipate a relatively greater reduction in the number of passengers and employees killed in accidents caused by collision or derailment than in the number injured and a reduction in the average severity of non-fatal injuries may also be expected. On the other hand, a certain number of deaths and injuries will result directly from the use of electric power in large amount, by accidental contact with charged conductors. These accidents, however, should not be frequent if care is taken in the installation and proper maintenance of the electric equipment.

In the year 1904, of 10,046 fatal casualties reported by the Interstate Commerce Commission " 3,632 were sustained by employes, 441 by passengers and 5,973 by other persons. Of this last number 5,105 were reported as trespassing, from which it may be presumed that the railways are in no sense legally responsible for the deaths in question; suicides are included in this class."

" The number of injuries sustained by employees during the year was 67,000. The number of injuries sustained by passengers was 11,111 and the number of injuries sustained by persons other than passengers and employees was 7,977."

As regards the expenses included under item 36, we have no data indicating how these are divided other than the fact that the railroads apparently were put to little if any expense on account of about 80% of those persons other than passengers and employees who were killed and injured. While it is probable that a large part of the expenditures was on account of passengers killed and injured, and while any reduction in fatal and serious accidents to passengers therefore would materially affect this item, we have thought it best in the absence of satisfactory data to leave it practically as it stands, our estimate being 1%.

Item 37. " Clearing wrecks." In our opinion this item will be reduced under electric operation for reasons which have been sufficiently indicated in what we have said in regard to item 35. It would seem that 0.2% is a fair estimate of its probable amount.

The following items will not be changed:

Item 38, " Operating Marine Equipment."

Item 39, " Advertising."

Item 40, " Outside agencies."

Item 41, " Commissions."

Item 42, " Stock yards and elevator."

Item 43, " Rents of tracks, yards and terminals."

Item 44, " Rents of buildings and other property."

Item 45, " Stationery and printing."

Item 46, " Other expenses."

General Expenses

As regards the several items included under the heading " General expenses," the adoption of electricity will cause no material change.

Summary and Conclusions.

Our approximate estimate of the expenses chargeable to operation if electricity were in use to-day for the operation of all the railways in the United States, as discussed in the foregoing pages, is recorded in detail, item for item, in the last column of the tabulated data in Table I; these data with the exception of this column of estimates being the official records of the reports of the Interstate Commerce Commission. When considered in detail, the estimates are naturally subject to criticism more or less destructive, as in respect to many items we have not found opportunities to secure and investigate the great mass of detailed data showing in segregated form the scores of factors which are included in the aggregates appearing as single items in the summarized table of operating expenses; but while recognizing fully the imperfections and incompleteness of the attempted comparative analysis, we believe that the conclusions reached are correct within a reasonable degree of approximation.

According to our estimate, if all the railways of the United States were to-day operated by electricity using the single-phase alternating-current system at the potential adopted for the equipment of the New Haven Railroad, the energy required for operation being developed by power plants such as are to-day in extensive use and transmitted at potentials well within limits established in practical service, and if the rolling stock equipment consisted of locomotives and multiple-unit trains fitted with motors and control apparatus no better than the best which now exist, the aggregate cost of operation which in 1905 amounted in round numbers to $1,400,000,000, would be reduced by about $250,000,000.

To accomplish this result, power plants delivering about 13,200,000,000 kilowatt-hours per annum would be required. Assuming the radius of transmission from power houses to be 150 miles, the load-factor in railway service should be not less than 0.75, and taking this figure it appears that power plants capable of delivering a maximum output of about 2,800,000 kilowatts will be sufficient to operate the entire railway service of the United States as existing in the year 1905. The average output required is about 10 kilowatts per mile of line and 7 kilowatts per mile of track.

In 1905 the average gross earnings of our railroads per mile of line were $9,598, and the average operating expenses $6,409. The foregoing calculations lead to the conclusion that high-class electric equipment now available would reduce this average cost to $5,265. The difference is $1,144 per mile of line, against which apparent saving must be charged the annual interest and depreciation of the power plant, the addition to permanent way equipment, comprising overhead construction and track bonding, the transmission circuits, and the sub-stations with their equipment. Assuming 5% interest on cash cost of these items and allowing 5% for a sinking fund to cover depreciation of power house with its equipment and 2½% for a sinking fund to cover depreciation of the overhead construction and distributing system, the aggregate of fixed charges works out at $837 per mile of line. The saving in operating expenses, therefore, is more than sufficient to take care of the increase of fixed charges. In other words, it appears that the entire railroad system of the United States could be operated to-day at less cost by the electric motor than by the steam locomotive. That the railroads in general if so equipped would realize a large increase in earning power will be admitted by all who have given the subject intelligent attention.

In charging against electric operation 5% upon cost of power plant and 2.5% upon overhead construction, transmission circuits, substations, and track bonding, we have departed from methods usually adopted in financing American railway properties. If no depreciation be charged against the increased capital account represented by the items named, the apparent saving will be materially increased.

While our estimates have led us to the conclusion that, under average existing conditions of railway operation in the United States, improved financial results would be attained by the substitution of the electric motor for the steam locomotive, the immediate and general adoption of the new motive power by our railroad companies is neither possible or desirable. It requires no argument to demonstrate the wisdom of making haste with deliberation in a matter involving interests of such magnitude as those which are tied up with the transportation systems of the United States. Recognizing the magnitude of these interests and having in mind the fact that the art of electric traction as applied upon a large scale to heavy train units is yet young, the point which we desire here to emphasize is the necessity of conservative and carefully considered action upon the part of all members of this Institute who may be called upon to advise in respect to the electrification of railways now operated by steam.

Referring to the following tabulated results, in which we have applied the estimated reductions in operating expenses under electric traction, amounting to 18% of the present average operating expenses to the ten geographical groups into which the railroad systems of the United States are divided by the Interstate Commerce Commission, the relatively great advantages of applying electric traction to systems operating heavy traffic showing large gross earnings per mile of line are evident at a glance.

TABLE II.

COMPARISON PER MILE OF LINE—BY GROUPS STEAM AND ELECTRIC OPERATION.

(216,974 Miles Represented.) (Dollars per mile of line per year.)

Group No.	General Location	Miles of Line Represented	Gross Earnings	(Steam) Operating Expenses	(Electric) Operating Expenses	Difference Steam and Electric Operation	5% interest on Electrical Equipment Excluding Rolling Stock.
I	New England	8,094	$14,511	$10,493	$8,604	$1,889	$647
II	New York, Pa., et al.	23,281	20,752	13,671	11,210	2,461	790
III	Ohio, Ind., Mich.	25208	12,483	9,198	7,542	1,656	640
IV	Virginias, N. and S. Carolina	12,542	7,359	4,590	3,764	826	484
V	Kentucky, Fla., Louis, et al.	24,563	6,867	4,899	4,017	882	475
VI	Ills., Wis., Dakotas, Ia., et al.	48,672	8,021	5,169	4,239	930	525
VII	Mont., Neb., and Wyoming	11,546	7,737	4,092	3,355	737	461
VIII	Colo., Ark., Missouri, et al.	30,456	6,362	4,308	3,533	775	461
IX	Texas and New Mexico	14,875	5,588	4,108	3,369	739	445
X	Pacific States	17,737	8,439	4,880	4,002	878	464
	United States, Total	216,974	9,598	6,409	5,255	1,154	516

The Standardization of Electric Railway Traction Equipment

Electricity, entering the field hitherto occupied exclusively by the steam locomotive, encounters conditions which greatly emphasize the necessity of prompt standardization of engineering practice. The management of our railways, beginning by electrifying terminals, tunnels, and mountain-grade divisions, will inevitably be led to extend these zones of electrification until they include divisions of very considerable length, and even trunk-line systems. To call attention to the transcendent importance of standarizing the location of such additions to permanent way equipment as the overhead trolley conductor and the third rail, is to demonstrate its necessity.

Electrical engineers now generally recognize the great value of established standards of frequency and potential in plants installed for lighting and power purposes. In recent years, the Institute, through its Standardization Committee has done splendid work for the manufacturer of electrical apparatus, as well as for the investor, by using its influence to promote the adoption of standards. Not many years ago, however, manufacturing companies, and consulting engineers, were in many cases prone to put forward or specify apparatus without reference to its ability to operate effectively in conjunction with other central station equipment, even when the latter was in actual operation in the immediate vicinity of the new plant. Fortunately, this tendency was less marked in the United States than it was, for example, in Great Britain. What will happen from a failure to adopt standards of practice at an early stage in the development of an industrial art of this nature, is well illustrated by the problem now presented in London, where the engineering advisers of the London County Council are engaged in studying the problem—how to supply electricity in bulk to 62 central-station plants producing electricity in bewildering variety of frequency and potential.

In the railway field, obviously, general principles are the same as in lighting; but wise foresight is more necessary and failure to exercise such foresight at this date less excusable. Moreover, the advocates of electric traction, unlike those who introduced the electric light into commercial service, are called upon to deal with a great body of trained engineers and experienced managers who are engaged in operating and extending systems of transportation which challenge admiration and respect. The rolling stock equipment of our railways, as a whole, is justly an object of national pride. The engineers and managers directing and controlling these properties are probably the equals of any body of men in the world as regards intelligence and experience. Obviously, it is of the utmost importance that they who accept the responsibility involved in the substitution of electricity for steam in the operation of certain parts of our great railways, should avoid fancies or fads and should in every way coöperate in the great work of evolving promptly standards of electric railway practice which shall withstand the test of time. The comparatively small beginnings of to-day will in all probability extend with a rapidity which we cannot now realize, and the confusion and loss which will inevitably result in the near future, if a variety of electric equipment be grafted at different points upon the existing railroad systems now operating by steam, may be imagined. The trouble and expense caused some years ago by the existence of several gauges of railway track in America were as nothing compared with what may result from a failure to establish promptly standards of practice in the field of electric railway traction.

Where to-day are the "16,000 alternation" system of lighting, the "15,000 alternation" system of lighting, the "constant-current alternating-current arc light system," the "40-cycle system" and the "monocyclic system?" Where ten years from to-day will be the 1200-volt, or the 1500-volt, direct-current systems which have been suggested as substitutes for high-potential alternating-current systems in heavy electric traction?

While emphasizing the great importance of the early establishment of standards in the field of heavy electric traction, it must be recognized clearly that further inventions are liable at any time to modify views based upon present knowledge. The work of standardizing, therefore, should proceed with caution; but surely if present knowledge, not only of existing apparatus but of the lines along which applicable improvements must take place, is not sufficient to justify conservative application of the principle of standards, it is not sufficient to justify the investment of the very large sums which are now being expended for electric equipment.

Engineers constituting the membership of this Institute owe it to themselves, as well as to their clients, to use every effort without prejudice and without fad, to prevent waste by opposing the introduction of apparatus which, from its limitations, cannot solve the general problem of railway electrification; and it is to be hoped that they will use their united influence to fix proper standards as rapidly as this establishment may be consistent with progress.

Fortunately, knowledge of the possibilities and limitations of electric apparatus to-day is a very different thing from what it was in the early days of electric lighting. At the present time we have available theory so complete that electric science is less exact only than the science of astronomy and in applying this science in constructive work agreement between results carefully predetermined by calculation and those realized in practice is far closer than in any other comparable branch of engineering. There can be no doubt that it is possible to-day, in passing upon such a question, for example, as that of best frequency for railway operation to make a choice which shall withstand the test of time.

The necessity of proper standardization is obvious. Specifically, it would seem feasible and eminently wise to agree upon standards of practice in respect to the following:

a. Location of third rail.

b. Location of overhead conductor used with single-phase alternating-current system.

c. Frequency of alternating-current traction systems.

It is equally desirable, but probably less easy, to agree upon a standard system of multiple-unit control for train operation.

The Question of Frequency.

While appreciating throughly and desiring to emphasize the importance of establishing and maintaining standards, it is also of the greatest importance that standards should be wisely chosen. The choice should be made, if possible, with full knowledge of the essential factors involved, and correct perspective view of their relative importance. It is with the feeling that so far as the frequency 25 cycles per second may be said to have become established, considerations obvious at first glance, but not properly controlling, may have influenced the choice unduly that we desire to present for discussion, the very important question whether 25 cycles per second or a lower frequency; *e.g.*, 15 cycles per second, is best adapted and should be established as a standard in the equipment of railways by electricity.

Final decision of such a question should be left neither to manufacturing companies, the management of which may be unduly influenced by commercial considerations, affecting their own immediate prosperity or convenience, nor should it be left to the individual consulting engineer. It is precisely the kind of question which the Institute should pass upon by the adoption of a recommendation carefully considered by its Standardization Committee. The manufacturing companies, which are largely and very influentially represented in the body of the Institute, will doubtless be willing to coöperate in the collection and study of the facts requisite to the formation of a well-grounded report.

While the adoption of a standard by the Institute has the force only of a recommendation, the American Railway Association perhaps might deem it wise to indorse the choice of the Institute. Such action on the part of these two bodies would go far definitely to establish the standard.

Comparing the relative advantages of 25-cycles and 15-cycles in railway service the salient advantages of the former are the following:

1. It is to-day in extensive use in plants developing and distributing energy for lighting and power purposes, and through sub-stations equipped with converters for the operation of many interurban lines. It has been adopted on a very large scale by such companies as the Interborough Rapid Transit Company of New York for the operation of its subway, surface, and elevated lines, by the Pennsylvania & Long Island Railway Companies for the electrification of New York terminal service and operation over a considerable part of Long Island, and by the New York Central for the electrification of its terminal service It is also the frequency developed by all of the great power plants at Niagara Falls, and from this source of power it is possible for all railway lines within a radius of 150 miles, or an even greater distance, to procure an ample supply of very cheap power.

It has been adopted by the New York, New Haven & Hartford Railway Company, the pioneer among American railroads in the adoption of the alternating-current motor in heavy railway traction, and by the Grand Trunk Railway for the electrification of the Sarnia Tunnel. Alternating current at 25-cycles is also utilized without the interposition of converters by the motor equipment on a dozen or more interurban trolley lines.

2. Our great manufacturing companies have drawings, patterns, and dies which enable them to manufacture conveniently and promptly practically all power-house and sub-station equipment required for 25-cycle apparatus. The weight of this consideration, however, is somewhat lessened by the fact that the march of progress—just now greatly accelerated by the general adoption of steam turbines—will undoubtedly cause a large proportion of existing drawings and patterns to be superseded probably in the very near future and certainly within the next five years.

3. The 25-cycle system is preferable to the lower frequency in the design of turbo-generators, since it affords wider range within which to select speed for units of various outputs. For very large units a frequency of 15-cycles, for example, requires either a 2-pole generator operating at 900 rev. per min., a 4-pole generator operating at 450 rev. per min., or a 6-pole generator operating at 300 rev. per min. Reduction in the number of revolutions per minute implies increase in diameter of the revolving element of generator and turbine, and in machines of large output the diameter of the revolving element in turbines of certain types may become too large for shipment in view of the limitations imposed by tunnels.

4. A frequency of 25 cycles permits convenient and effective lighting of yards and shops by incandescent lamps. It is also more favorable than a lower frequency as regards operation of induction motors for shop purposes.

Should our railways in general be equipped for electric operation, it is to be expected that in many cases they would undertake to supply electricity for light and power purposes beyond their own requirements, and the higher frequency possesses important advantages with reference to such commercial service.

For lighting and general power purposes in cases where service for lighting purposes that shall be thoroughly satisfactory in respect to voltage, regulation and continuity is requisite, commercial supply at 25 cycles would be preferable. Through the interposition of motor-generator sets or converters in combination with storage batteries in such cases either frequency is applicable.

5. The higher frequency possesses some advantage in respect to the ratio of tractive effort to weight upon drivers. The best information available to date appears to indicate that the difference between 25 cycles and 15 cycles in respect to

this consideration probably approximates 10%. Further data from actual test are desirable, and must be obtained before it is possible to estimate closely the weight of advantage possessed by the higher frequency.

6. The higher frequency is preferable for induction motors in railway service requiring a considerable range of speed adjustment. The force of this consideration depends upon the probability of using induction motors for traction purposes, and applies not only to the excellent three-phase motors, such as are in very successful use upon the Valtellina line, but also to the single-phase induction motor which, perhaps, is not beyond the range of probability. It is probable that in any general electrification of our railway system, induction motors will play a part by no means unimportant.

Without attempting detailed discussion, it is evident from the foregoing brief statement of the more important considerations in favor of 25 cycles that extremely weighty reasons must exist if the adoption of a lower frequency, *e.g.*, 15 cycles, is justified.

While our object in raising this question of frequency is to present it for discussion with a view to securing additional data and, if possible, a careful consideration of this very important question by the Institute through its Standardization Committee, or a special committee, and while we desire to avoid anticipating the verdict resulting from such an investigation, it is proper to state here that consideration of the facts now available leads us to conclude that notwithstanding the number and force of the arguments in favor of 25 cycles, a frequency of 15 cycles is preferable and should be adopted for heavy electric traction. The fundamental and, as it would appear, controlling reason which leads to this conclusion is the fact that within given dimensions a materially more powerful, efficient, and generally effective single-phase motor can be constructed for 15-cycle operation than is possible if 25 cycles be selected.

Final decision of the question whether the advantages of the 15-cycle motor as compared with the 25-cycle motor in respect to dimensions, weight, efficiency, power-factor, and commutation are such as outweigh the many and important considerations which favor the higher frequency, requires more complete data than we have been able to secure up to the present time. That the difference is material, however, is established not only by general theoretical consideration of the effect of a reduction in frequency upon the design and performance of single-phase commutating motors, but also by the following facts:

1. In the case of multiple-unit equipment of passenger cars where locomotives are dispensed with and motors carried upon the car trucks, it is very important that the dimensions of motors be reduced to a minimum. Cars weighing, say, 35 tons without equipment and operating on straight and level track at speeds of from 60 to 70 miles an hour, require but two motors, except as it may become necessary to employ four motors by reason of lack of sufficient clearance at cross-overs. The difference between a two-motor equipment and a four-motor equipment in such a case approximates $2,500.00 per car, besides which the four-motor equipment adds materially to weight, practically doubles complication, and, for both of these reasons, increases cost of operation. The difference between the dimensions of a 15-cycle and a 25-cycle motor may easily be the controlling consideration compelling the adoption of the four-motor equipment.

2. In the application of single-phase commutating motors to locomotives in general railway service, the minimizing of motor dimensions is perhaps still more important, although in this instance the limitations imposed by the space available are less obvious.

High-speed passenger locomotives at least should be gearless. For any assumed limits of weight per axle and length of wheel-base, that frequency is preferable which permits the construction of a motor which will exert the greater pull at the draw-bar, provided efficiency, commutation, and power-factors are substantially equal.

Those who are engaged directly in the design of single-phase motors are probably in position to contribute to the discussion of this paper data which will throw much light upon the subject; but it would seem probable that within given limits of dimensions, 15-cycle motors would materially surpass 25-cycle equipment in this respect. We are inclined to this opinion notwithstanding the probable advantage of 25-cycle equipment as regards the ratio of effective draw-bar pull to weight upon drivers.

3. There can be no question of the superiority of the 15-cycle motor in respect to the very important features, commutation, efficiency, and power-factor. Efficiency is obviously and directly important. Power-factor affects the efficiency of the

entire system from the motor to, and including, the generator. Commutation, in view of the large and expensive commutators and the brush complication of this type of motor, is of great importance.

In order that the question raised may be looked at in proper perspective the following estimates based upon foregoing calculations will be useful:

For the equipment of the entire railway system of the United States as now existing an aggregate power-house output capable of supplying continuously 2,100,000 kilowatts would be required. Of the electric apparatus installed in the power-houses, a change in frequency affects the generators, transformers, and a large proportion of the measuring and indicating instruments. It also affects the cost of the engine or turbine employed to drive the generator. At 25 cycles, the apparatus affected by frequency should cost approximately $30 per kilowatt. At 15 cycles it would cost on the average perhaps $33 per kilowatt. Cost of sub-station transformers would be increased approximately one-third, and, in round numbers, the total cost of turbines and electrical power house and sub-station apparatus would be increased from $70,000,000 to $80,000,000.

If it be assumed that one electric locomotive will do the work of two steam locomotives, about 24,000 electric locomotives would be required to take care of the present railway business of the country. Assuming the cost of the average electric locomotive to be $25,000 the aggregate cost of locomotives required would be $600,000,000. Allowing for the increased cost of the 15-cycle transformers, it would seem that the difference in cost of the average locomotive should be not less than $1,000 in favor of the lower frequency, or for 24,000 locomotives $24,000,000. This is more than twice the estimated difference in cost of power-house and sub-station equipment.

It seems entirely safe to say, therefore, that the aggregate first cost of electric equipment and of steam turbine will be decreased by a change from 25 cycles to 15 cycles. The operating cost will obviously be decreased very materially. At least three-fourths of the above estimated cost of electric locomotives, say $450,-000,000 represents cost of electric equipment. It will be seen, therefore, that of the apparatus which our electrical manufacuring companies may be called upon to furnish, more than 85% is rolling stock. Obviously, any argument in favor of 25-cycle equipment which may rest upon existence of drawings and patterns and convenience in manufacturing should have comparatively little weight.

The use of 15 cycles instead of 25 cycles also secures considerable advantage in respect to the overhead trolley conductor and track return. With a given limit of voltage-drop, this advantage may be utilized by reducing size and, consequently, cost of the overhead copper and the copper used to reinforce the track return.

Under the plans which we have assumed as a basis of our calculations, the amount of copper required for feeder circuits, trolleys, and reinforced track-return, estimated at 20 cents per pound would cost approximately $750,000,000 were the entire railway system of the country as existing in 1905 to be equipped for electric operation.*

We desire to acknowledge with appreciation, assistance kindly rendered in the collection of data for this paper by Mr. J. M. Graham, vice-president of the Erie Railroad Company; Mr. Theo. N. Ely, chief of motive power of the Pennsylvania Railroad Company; Mr. George Gould, president of the Missouri Pacific and other railway systems; Mr. E. Z. Jeffrey, president of the Denver & Rio Grande Railroad Co.; Mr. E. P. Bryan, vice-president and Mr. Frank Hedley, general manager, of the Interborough Rapid Transit Company; Mr. G. Leve, of the Railway Electric Power Company; Mr. Alvan Markle, president of the Wilkes-Barre & Hazleton Railway Company; Mr. George C. Smith, vice-president of the Security Investment Company; Mr. H.J. Pierce, president of the International Railway Company: Messrs. Conwell, Shepard and McLaren, of the Westinghouse Electric & Manufacturing Company; and Messrs. Potter and Mahony, of the General Electric Company.

*In all our estimates we have included 0000 copper conductor in the return circuit, this being bonded to the rails at intervals for the purpose of preventing dangerous potential on track in case of a broken bond.

APPENDIX

Power-House Output and Load-Factor

The report of the Interstate Commerce Commission gives the total revenue traffic for the entire United States for the year ending June 30, 1905, as 1,038,441, 430 train-miles, of which 459,827,029 is passenger-train mileage, 546,424,405 freight-train mileage, and the unclassified balance, 32,189,996, we have assumed to be mail- and express-train mileage. Including the mail and express trains with the passenger-train service, there is an average of 6.2 passenger and 6.9 freight trains per mile of line per day, or approximately 7 trains each way per day.

Using average weights of equipments, as stated in our paper, and average hauls of goods and passengers, and making allowances for switching, etc., the traffic amounts to 3,000,000 ton-miles per mile of line per annum, of which 600,000 ton-miles are in passenger service and 2,400,000 ton-miles in freight service. In electric operation these figures will be reduced by the weight of engine tenders and a part of the weights on pony trucks.

To supply electric power for the operation of the steam roads, we have assumed that power houses would be located at average intervals of 300 miles. This requires a transmission of 150 miles and for this purpose we have employed in our calculations 60,000 volts. As stated in our paper, both the distance of transmission and the voltage employed are within current practice in plants now in commercial operation in this country, under conditions and for purposes identical with those contemplated in our paper.

In our calculations we have assumed that passenger trains are geared for a maximum speed of 50 miles per hour and freight trains 25 miles per hour, on a tangent and level track. We have assumed that the average run of passenger trains is 10 miles and freight trains 15 miles between stops. With the gear ratios used this gives an average speed of 40.5 and 23 miles per hour, respectively. At these speeds the average load on each power station supplying 300 miles of line is 1.98 passenger trains and 3.84 freight trains, an average of 5.82 trains of both kinds. With equal intervals between passenger and freight trains, respectively, the average load on the power house is 2100 kw., the load-factor is 0.97 and the maximum momentary peak is estimated to be 3000 kw. This method of operation is shown in Fig. 9.

The schedule speeds above mentioned include momentary stops only. As trains are now operated, the average passenger train, owing to stops and delays of various kinds, does not average more than 30 miles an hour, and through and local freight trains probably do not average more than 12 miles an hour. In Fig. 10 we have illustrated the result at the power house if trains are operated at these modified average speeds. The average load

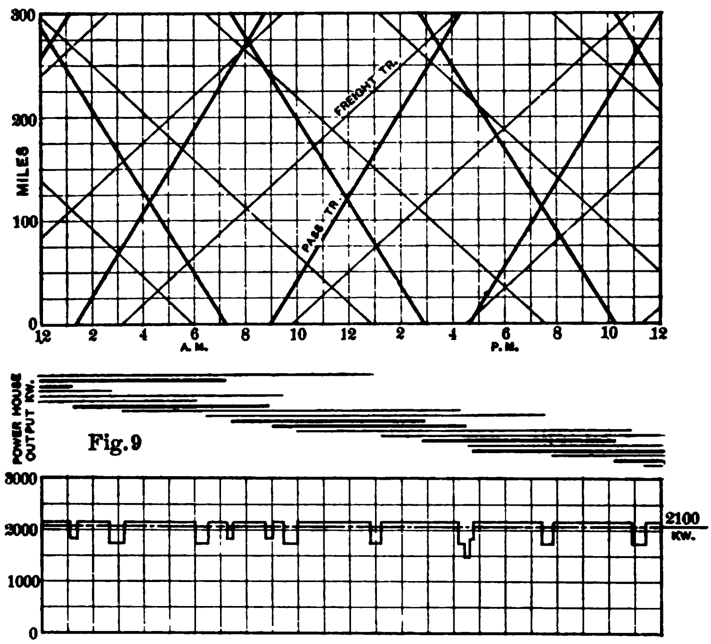


FIG. 9.—POWER-HOUSE LOAD, MAXIMUM AVERAGE SPEEDS.
Passenger trains, 226 tons, 40·5 miles per hr. 273 kw.
Freight trains, 937 tons, 23.0 miles per hr. 351 kw.
Transmission efficiency 90%. Average trains on section, 5.8.
Average power-house load 2100 kw. Load-factor 0.968.
Estimated momentary peak 2970 kw., 85% efficiency.

remains practically the same as before, while the load-factor is reduced to 0.82 and the estimated maximum momentary peak is increased to 4700 kw.

Our estimate of the total power-house capacity for all the railroads of the United States is 2,100,000 kw., which is approximately 3,000 kw. for each 300-mile section. This is nearly 50% in excess of the average load. The generators proposed for this power-house equipment have a momentary overload output of

100% and can carry an overload of 50% for several hours. It is evident, therefore, that the average power plant provided, after deducting 20% for reserve, is ample to take care of ordinary variations in traffic.

It is manifestly impossible for railroads to operate their passenger and freight trains on equal headway. Some roads as a matter of convenience despatch freight trains in "fleets", and

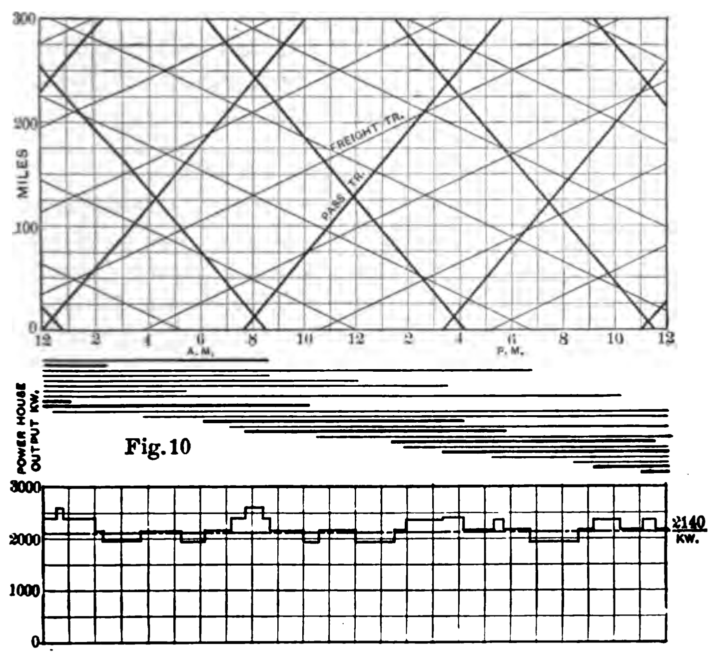


FIG. 10.—POWER-HOUSE LOAD, MINIMUM AVERAGE SPEEDS.
Passenger trains, 226 tons, 30 miles per hr. 210 kw.
Freight trains, 937 tons, 12 miles per hr. 187 kw.
Transmission efficiency, 90 %. Average trains on section 10.0.
Average power-house load 2140 kw. Load-factor 0.823.
Estimated momentary peak 4720 kw. 85% efficiency.

cattle and some produce trains must arrive at their destinations at fixed times of the day. This method of operation is desirable and practicable in steam operation and obviously is objectionable in electric operation, as power-house capacity must be provided for the maximum number of trains on the division. On the other hand, on those roads where traffic is most congested, the track facilities can best be utilized by equal spacing of trains. When this question becomes important, therefore, the natural tendency is towards an approximately equal distribution. As the generators include in our estimates have a continuous overload capacity of 25%, 50% for several hours, and 100% momentarily, and as we have provided an excess of nearly 50% over average demands, the power-house capacity provided appears ample for any reasonable variation in the method of operating trains. In this connection, we wish to call attention to the fact that under average conditions freight trains require 25 hours to traverse the length of line supplied from a single power house; hence if trains are despatched in " fleets " a second fleet will begin to draw upon the power house as the first fleet passes off the power-house load remaining practically constant.

Resistance Due to Grades

In many cases we have found so far as power house-requirements are concerned that the additional resistance, due to grades and curves, can be practically neglected in the electric operation of trains. Unlike the steam locomotive, the electric motor, under certain conditions, operates at higher efficiency on grades and curves than when running free on a straight and level track. This is due to the fact that the motor and gear ratio are properly selected to obtain the highest average efficiency in operation. The effect of this selection throws the load in continuous operation on level track below the point of maximum efficiency. In ascending a grade the speed is reduced, and within reasonable limits this reduction implies an increase in motor efficiency. Again, the reduction in speed, due to grade, results in a reduction in rolling friction and train resistance. These gains are not offset in descending grades unless, in addition to gravity, power be used to attain a speed exceeding the maximum limit which we have assumed, namely, 50 miles an hour in passenger service and 25 miles an hour in freight service. Theoretically, as long as the grade does not introduce a resistance in excess of that of the train-friction independent of the grade, the energy expended in lifting the train will be recovered in overcoming train-friction in going down grade. If the ascending and descending speeds are equal the energy consumption will be the same per ton-mile as on a straight and level track of the same length. If the ascending speed is reduced, as it is in the case of the series motor, the total watt-hour consumption will also be reduced. In Fig. 11 and Fig. 12 we have plotted the effect of grades upon power consumption in both passenger and freight service. In order to keep this discussion distinct from the question of motor and transmission efficiencies, we have assumed a motor efficiency of 85% in all cases and 90% transmission efficiency. All power calculations are carried back to the power house, and that portion of the recuperated energy which cannot be utilized by the train auxiliaries has been returned to the power house at 90% efficiency. Extra electric locomotives are added as needed. With the train weights employed, it will be noted from an inspec-

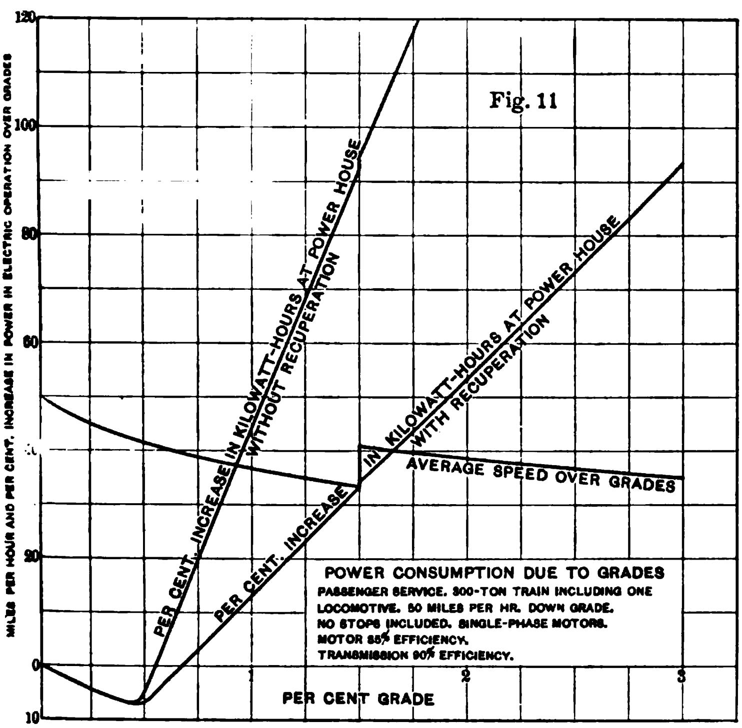


FIG. 11.

tion of these curves that the power consumption over grades is less than it is over straight and level track in passenger service for all grades less than 0.55%, and in freight service less than 0.35%. Comparatively few lines are absolutely level, but on the other hand the aggregate mileage on grades exceeding 0.5% is relatively small. It is believed, therefore, that the general result as to power consumption will be very close to that required over straight and level track. Nevertheless, as stated in our paper, we have added to our calculations of energy required 10% in the case of passenger service, and 15% in case of freight service, to cover contingencies, including switching, "double headers" and the additional resistance due to grades and curves.

In some recent calculations in which we went into the subject

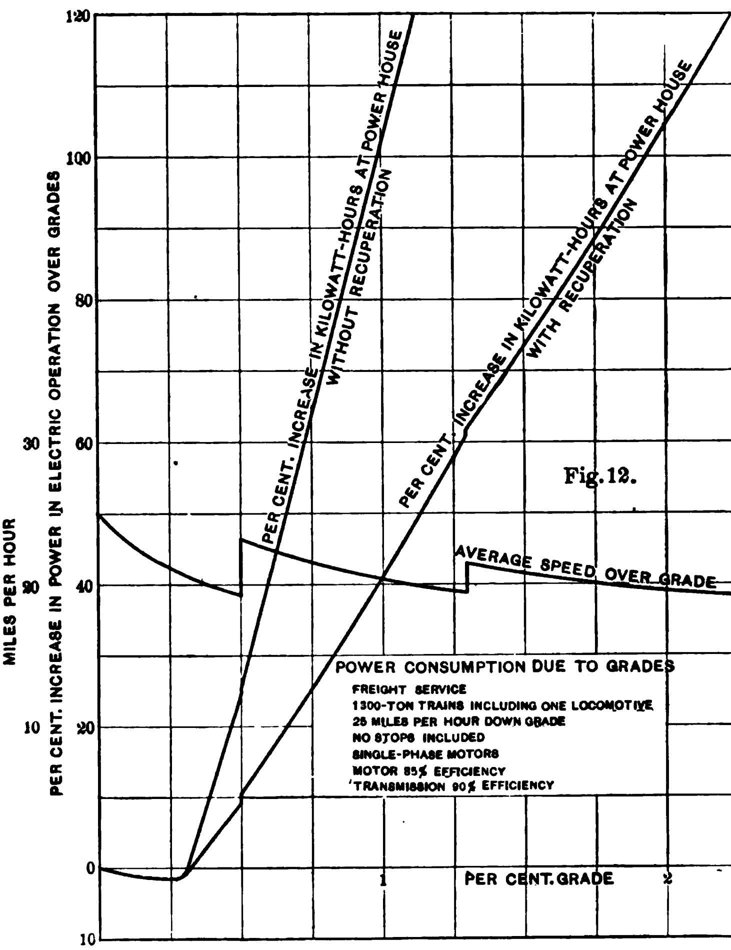


FIG. 12.

in great detail the foregoing conclusions were corroborated. In one case in express service the detailed calculations of runs over the road showed a consumption of power of 53 watt-hours per ton-mile, while 52.8 watt-hours per ton-mile was obtained by using an average run on a straight and level track. In the local service over the same line the figures were 84.2 watt-hours in the detailed calculations and 86 watt-hours for an average run on a straight and level track. These results were obtained from calculations relative to the electrification of the suburban portion of a steam railroad over 30 miles in length; a large percentage of its tracks being on grades and curves. There were maximum grades of 1.47%, 1.55%, and 2.32% and curves of 6° 22′ and 8° 30′. Numerous other calculations and road tests have verified these results.

Recuperation.

In making our calculations as to power consumption, we have made no deduction for the electrical return of power to the line. In the case of the higher grades this becomes a matter of importance, as shown by Fig. 11 and Fig. 12. Where the force of gravity due to grade exceeds the amount that can be utilized mechanically in overcoming train-friction, recuperation reduces the increase in power consumption due to the grade by approximately 60% over a grade of 1.5%, so that even in freight service over mountain grades the power required will not exceed that consumed on a level track by more than from 40% to 60%. With recuperation, the power consumption or what is its equivalent, the coal consumption, is not doubled until we reach grades of over 3% in passenger service and 2% in freight service. These grades are considerably in excess of any used on our trunk-line railroads. The ability to recuperate energy is important on lines that have heavy grades. In addition to the saving in power, the saving in wear and tear from mechanical breaking is of as great, and perhaps even greater, importance. The energy represented by the difference between the curves shown on Fig. 11 and Fig. 12 representing the power required at the power house with and without recuperation, increased by the energy losses absorbed by the motor and transmission lines, must be absorbed by the brake-shoes and wheels when mechanical braking is used.

DISCUSSION ON "ON THE SUBSTITUTION OF THE ELECTRIC MOTOR FOR THE STEAM LOCOMOTIVE," AT NEW YORK, JANUARY 25, 1907.

Frank J. Sprague: This paper has evidently been prepared with a good deal of care, but in certain essentials I am absolutely at variance with some of the conclusions which have been expressed. There is so much to be said, and the time is so limited, that it would be discourteous to the authors and an injustice to myself to attempt to enter into detailed comment, so I shall content myself for the present with only a few remarks.

Briefly, the authors have given an interesting resume of statistical information based almost entirely upon direct-current operation in this country, with some report of results from operation on the three-phase system abroad under conditions differing largely from those characterizing American railroads. They have generalized the features of operation of the steam railroads of the United States, and on that generalization have formulated certain conclusions favorable to the adoption of electricity. All these should receive careful attention and analysis. In addition, they plead for standardization of electric apparatus and equipment, and, if I understand correctly, for a standard of operation based upon the use of single-phase alternating-current motors operated at 11,000 volts and 15 cycles from an overhead trolley.

Their attitude, as expressed in their paper, is emphasized by these two statements:

The distributing system for altenating-current equipment, which is the only class of equipment deserving serious consideration in connection with the general problem which we are discussing, comprises an addition to permanent way equipment in the form of overhead construction, and electric conductors conveying power from the power house to the trolley or conductor which is carried above the track.

The advantage in favor of electric operation is of course more marked if we assume that alternating-current equipment is to be used, as in general would be the case in the electrification of trunk lines or long divisions.

These are certainly positive affirmations, and if sound would perhaps warrant that spirit of enthusiastic and inquiring prophecy in which the sound basic principles which have made electric traction successful are coupled with various unscientific and quickly discarded proposals, and lightly brushed aside with the query:

Where, ten years from to-day, will be the 1200-volt or 1500-volt direct-current systems which have been suggested as substitutes for high-potential altenating-current systems in heavy electric traction?

I think I see my initials under these specific voltages; and it is right here that I beg to differ from the conclusions expressed by the authors, and venture to correct them. The higher-potential direct-current systems will still be here, just as we have the lower voltages of the past 19 years, no matter what other developments may take place.

I have been guilty, gentlemen, of some " fads and fancies " while a member of this Institute for a time covering the entire practical development of the electric railway, in which I have played some material part; they have been translated into facts. I have ventured a few prophecies; they are now a part of history.

Operation at 1200 to 1500 volts by direct current has not been advanced by me as a " substitute " for high-pressure alternating currents for heavy electric traction, or as the only means available for this purpose; it has been advocated as one practical development along existing lines which under many conditions, and with the present development of the 25-cycle alternating-current motor, offered some possibilities of railroad operation denied to the latter.

I prefer to define my own position rather than to have it determined for me by others. I do not profess to know what the ultimate developments in this art are going to be, nor will I enter into any rivalry in predicting that a specific type of equipment must be universally adopted, for I feel sure that the selection of a system by any road must be largely individual, and determined by its own necessities.

There will be opportunities for alternating-current equipment, and there are many hopeful alternating-current possibilities, but surely these are not the only practicable methods worthy of serious consideration by such trunk-line divisions as may reasonably consider the possibilities of electric operation to-day.

As useful as a mass of statistics may be, I do not think it necessary, to come to specific conclusions in the matter of electric railway equipment, to generalize all the railroads of the United States. There are a lot of them in the hands of receivers, and some of the others ought to be. They could not be taken out of their hands if they were electrified, and could not raise the money to be electrified if they wanted to. I prefer to deal with the living, immediate questions. There will in the near future be three great trunk-line railroads terminating in New York City, to say nothing of those terminating in Jersey City and elsewhere, on which the question of electric operation is assuming special importance. One of them is proceeding along certain lines, another by somewhat different methods. There has been considerable discussion as to the wisdom of both. I have been guilty of some of the development on one, and I am not ashamed of it. I have somewhat frankly criticized some matters connected with the other, and I have no apologies to offer on that account. But leaving these two roads out of consideration, do we need to look further for a typical trunk-line division than to the third road, the Pennsylvania, from here to Philadelphia? An engine run, and none more typical. I am going to venture, not a prophecy, but a statement. If that line were called upon to be electrified to-day—and it can very properly and seriously consider it—it would not, in my present judgment, be best done by a single-phase overhead trolley alternating-current equipment, whether 25 cycles, 15 cycles, or 1 cycle. There would be a variable half cycle, and it would be the length of time between controller operations. And on many other lines which can properly consider electrification, the higher voltage direct-current system, according to any present development, will give better results than the alternating-current overhead system.

These conclusions are based in part upon a four months' study and analysis of one of the most difficult railroad problems in this country. Had I not been closely occupied in trying to complete that particular investigation, I should be in a better position more fully to discuss the paper of the evening. I hope, however, in the comparatively near future to present to this Institute, of which I have had the honor to be a President, a few comparative statements on the subject of direct-current and alternating-current operation, and I will reserve until that time most of what I have to say.

B. G. Lamme: As the time is limited, I shall confine myself to the question of frequency alone. It may be of interest to consider the changes in frequency from the earliest time to the present, and see what Mr. Stillwell has had to do with such changes. Back in the early times of alternating-current, work, 133 cycles per second was the common frequency. About 1889 or 1890, Mr. Stillwell, in going over the problem, saw that the larger work which was coming called for a lower frequency, and he was one of the strongest advocates in adopting 60 cycles as against 133. A few years later, in connection with the Niagara Falls first large generating station, the question of a still lower frequency came in, and Mr. Stillwell practically made the decision in favor of 25 cycles. At that time it was considered that the development of street railway work, and the use of synchronous converters in such work, was such that it was more economical to use the lower frequency. He now comes forward with 15 cycles for heavy railway work on the basis that the field is going to be large enough to call for a new and more suitable frequency.

It seems to me also, considering the total amount involved in the electrification of the railroads of this country, about $1,500,000,000, that the problem is big enough to call for a frequency which is best suited for the work. The question is whether that should be 25 cycles or something lower. Over four years ago I presented a paper before this Institute, in which I described the Washington, Baltimore and Annapolis single-phase railway, and the frequency given was 16⅔ cycles, a ratio of 2 to 3 to the standard frequency of 25. There were certain reasons for adopting that particular frequency, although 10 per cent. higher or lower would not have been of very great importance as far as the operation of the apparatus was concerned. It was found at the time that there was considerable opposition to the use of lower frequency, principally because most of the projects presented involved existing power plants, or it was necessary to tie the new plant to existing power plants. The projects were also relatively small. Because of commerical conditions, we were practically forced to begin at 25 cycles. However, I still advocated the use of lower frequency when it came to heavier work, as will be found in my discussion of single-phase railway apparatus at the Institute meeting at St. Louis Exposition in September 1904. At that time I said that I considered the heavy railway electrification of sufficient importance to warrant the use of a low frequency which is most suitable for such work, independently of any frequencies already in use. I still hold to that opinion.

The strongest reason which can be given for the lower frequency is the greater output that can be got from a given motor. For instance, with a first-class motor, built for 25 cycles, the operation may be above question, the machine may be considered perfect in every way; but take that same machine and operate it on 15 cycles, and the induction can be raised from 25 to 40 per cent., which means that 25 to 40 per cent. higher voltage can be applied with the same motor-speed, and 25 to 40 per cent. greater output is obtained from the same motor, or 25 to 40 per cent. greater tractive effort can be developed. That in itself is a controlling feature in the question. We have verified it by actual test. For instance, we have taken a 100-h.p. 25-cycle motor, and obtained from it 125 h.p. at 15 cycles. This motor has good efficiency, good power-factor, and good commutation on both frequencies, at the above ratings. It is therefore not a question whether the 25-cycle motor will work, for it will work successfully, but it is a question how much more can be got out of it by going to the lower frequency. It may be questioned that if 15 cycles is better than 25 cycles, why is not a still lower frequency recommended? The answer is that at 15 cycles the machine is practically saturated, which fixes the output. At still lower frequency there would be a gain in efficiency and power-factor, but not much in output; and there would be loss in other things, such as the speed of turbo-generators and weight of transformers. So there is some point at which a compromise can be made; and it is my opinion, and has been for a long time, that this compromise is considerably below 25 cycles and should be about 15 cycles.

The increased output to be got from a motor at the lower frequency is of advantage principally in getting a smaller number of motors under a locomotive or car, which directly decreases the cost; or, on a locomotive, keeping the same number of motors, there is obtained a bigger output for a given weight of locomotive. But there are some cases where not much is gained by the use of lower frequency; for instance, where it is necessary to operate alternating current-direct current requiring four motors in order to obtain series-parallel control. In most cases we do not get the full gain from the use of 15 cycles for we can not reduce the number of motors. That is one of the conditions met in the New Haven railway equipment, for the direct-current operation on the New York end requires the use of four motors. There are many cases where the power is purchased in which it is necessary to use the higher frequency. Of course, the results are obtained at a somewhat lesser capacity or at increased cost.

There is one point Mr. Stillwell has not touched on, and that is the fact that the single-phase series motor can be made to operate on both 15 and 25 cycles; for instance, a 25-cycle motor will operate beautifully at 15 cycles and at practically the same speed, because the speed has nothing to do with the frequency. A 15-cycle motor, if well designed, will operate on 25 cycles fairly well, at its nominal capacity; at a slightly reduced capacity it will operate very well, so that if a locomotive should be equipped with transformers suitable for operating at 15 cycles, for instance, it could operate on both 25 or 15 cycles. By taking a 25-cycle equipment, nominally designed for 25 cycles, and putting a 15-cycle transformer on it, the equipment is adapted for operation on both 25 and 15 cycles. That is important in connection with the fact that 25 cycles will have to be used in a certain number of cases, but in other cases where the generating conditions can be made suitable, 15 cycles will work to better advantage.

Mr. Stillwell speaks of some of the advantages of the higher frequency, one of which is the better ratio of tractive effort to weight on drivers. We have been making tests at East Pittsburg on some electrical locomotives, at both 15 and 25 cycles, and it is very difficult to determine any difference in the ratio of tractive effort to the weight on the drivers. In some cases the tests are possibly in favor of 15 cycles, in others in favor of 25 cycles; and the difference is probably no more than would be found in making two consecutive tests at any one frequency. If the motors are spring-connected, or have some flexibility between the armature and the driver, which is true in most cases, especially where they are geared, the difference in the tendency to slip practically disappears.

In discussing this question of 15 cycles, we are asked—where is it in use? I will call attention to the fact that quite a number of European companies have adopted 15 cycles for railway work. The Valtellina, plant put in by the Ganz Company, with three-phase motors, uses 15 cycles; and I feel safe in saying that a great deal of the success and good operation of that plant is due to the choice of this frequency. I think they could have made the apparatus a success with 25 cycles, but it would have required much heavier equipment, and with poorer efficiency and power-factor, especially at low speeds. The manufacturers recognized that 15 cycles gave better conditions with the polyphase motors, and adopted it regardless of the fact that that was not a standard frequency in Europe. That system is being extended on the Italian roads.

The Oerlikon Company, of Switzerland, has gone into the single-phase work extensively, with 15 cycles as a standard. The Siemens-Schuckert Company, of Germany, is also manufacturing series railway motors for 15 cycles. The Allgemeine Company, of Berlin, is the principal company which is adhering to 25 cycles, and that is largely due to their type of motor. They have a so-called "series repulsion" motor, in which the characteristics of the motor apparently show to better advantage if the frequency is not too low. It is not directly due to the high frequency that they get better results, but to the fact that the motor should preferably run below the nominal synchronous speed, and this condition is obtained to better advantage by keeping up the frequency.

Bion J. Arnold: On the morning of December 18, 1903, when I arrived in New York from Pittsburg, where I had been examining Mr. Lamme's new single-phase motor and complimenting him on its work. I received a telegram saying that the single-phase locomotive which I had been developing for three years past, and which was at that time ready to make its trial run, had been destroyed by fire. While experimental runs had been made some months before with a rather crude machine, I had everything arranged to make the trial run on the first day of January, 1904, with a new electropneumatic motor which I had developed, and by means of which I expected to demonstrate a single-phase railway in operation. I did not then discover, nor have I yet discovered, the cause of the fire, but it burned up the machine. I felt that unless the machine were rebuilt and an attempt made to operate it, I might be misunderstood by those not familiar with the circumstances. I therefore rebuilt the machine and operated it on August 3, 1904, in time to antedate my competitor in this country by some days. That experiment cost me about $50,000, but thanks to good fortune it cost no other man a dollar.

I believe that by this experiment I was instrumental in advancing the state of the art to such an extent that to-day two or three of our large railroads are being equipped with the single-phase system, invented by others, to be sure, but I believe forwarded by my efforts of some four or five years ago. If my efforts have done that, and I have been instrumental in advancing the art, I am glad I spent the money, as I could not have spent it in any better cause.

I shall not attempt to go into a detailed analysis of the various systems which are involved in the paper, because I think each system has its able champions. It makes no great difference to me personally which system wins, so long as we get a system of electric railroading in this country that will operate the trains for less than it now costs to operate them by steam. I had that idea in mind in starting out on the single-phase experiment, because in 1898 I was engaged in building the Chicago and Milwaukee electric railway, which I believe is considered the pioneer synchronous converter sub-station railroad in the country, possibly in the world; at any rate, the first to be driven by a steam station. I took much risk in that undertaking, risking my personal reputation and my financial resources, in order to demonstrate the success of that enterprise. It was a success, and as you know most of the suburban roads have since been built on those lines.

I make no claim for the invention of many of the devices which entered into the systems. They were invented by some of the gentlemen here present, and by others, and some had just begun to come into commercial use; namely, the synchronous converter, which made the system possible; but I took the risk of putting into practice such a system, took the engineering and financial responsibilities, of making it go. It went. When engaged in that work I felt that that system was not the complete solution of the electric railway problem, because the introduction of the synchronous converter sub-station necessitated men in the sub-stations, and necessitated more investment than I thought the railroad systems of the country could stand, if they were to be attracted to electrical operation. That started me on the single-phase idea, and as many of you will recollect, we had various discussions on the subject, and it was stated by some of those here present who are now advocating the system, that it could not be done. I maintained it could be done, and had to be done, and it cost me much to find that out. It has been done since by at least two companies in this country, and two or three abroad, and seems to be coming quite rapidly into practice for steam railroad work.

I do not agree entirely with the authors in regard to standardizing this apparatus, as this would shut out the utilization of the talent of the members of this Institute and other societies in this country, and other countries, and the prospect of developing something that may prove better than anything we have now. I am willing to concede, if we are going to use alternating-current railway systems, that we should adopt a standard frequency. So far as my investigation has gone, in conjunction with Mr. Stillwell as a member of the electric traction commission of the Erie railroad, my leaning is toward the 15-cycle frequency. Although I do not want definitely to stand on that conclusion now, I think it is the frequency we will come to on account of the fact that to get the requisite amount of capacity between the wheels of a railroad-car truck, the gauge being limited, it is necessary to get as much power in the space as possible. This can be done by adopting 15-cycle motors, as these motors are more powerful than 25-cycle motors of equal size. It makes the total weight of the locomotive or car practically the same as at 25 cycles, as it increases the size of the transformer. Even then we do not get as much power on the wheels with the alternating-current motor as with the direct-current motor.

I personally believe that some form of high-potential overhead conductor is going to be the final solution of the railroad electrification problem. I believe in the third-rail, where it is applicable, but I do not believe there are many places where it is applicable; in other words, I think that legislation in this country will prohibit the use of the third-rail in exposed places. There are certain types of third-rail which have recently been adopted, which I believe are safer than previous third-rails; I refer to the rail that was devised by Messrs. Wilgus and Sprague and used in the New York Central installation—but I do not think that the use of the third-rail in yards, and under the feet of men, and in other exposed places, will be accepted as the final solution of the problem. In the analysis of the Grand Trunk problem, which I have in charge so far as the engineering decisions are concerned, I chose the alternating-current system, overhead conductor, for tunnel work principally, for the reason that in the large yards at each end of the tunnel, where much switching is done, it seemed essential that the conductor be kept from under the feet of the men. The decision to use the single-phase motor was made some five months prior to the decision by the officials of the New Haven Company to adopt the alternating-current system on their road. The officials of the Grand Trunk did not publish their decision, as certain matters had to go abroad for approval by the English officials before the matter could be publicly announced. but there are men in this room who know that the decision was made at that time.

W. B. Potter: I heartily endorse the recommendation of the authors of this paper as to the desirability of making an effort toward standardizing the essential principles which are involved in the determination of electric railroad problems. To this general proposition may well be added the plea for a uniformity of dimension for such parts of the equipment or general system as might reasonably be made interchangeable.

Considering the matter of standardization in its broader aspect, there does not appear to be any one general system of electrification, in the present state of the art, which engineers would be willing or ought to accept as the standard. For the ordinary city or interurban trolley lines, 600 volts direct current is to-day recognized as a standard. For other classes of work, particularly over long-distance lines with relatively infrequent headway, both the single-phase alternating and the high-voltage direct-current systems possess advantages. The fundamental reasons, however, which have lead to the consideration of a higher voltage trolley may also apply to limit the application of the high-voltage trolley under conditions which can be more economically met by 600-volt apparatus. However much we may desire to limit the number of standard systems we must still recognize that the element of cost, considered broadly, is often the determining factor to be reckoned with. A railroad company could hardly be expected to consider favorably any particular system simply because of general reasons, if the installation of this system involved any considerable additional expenditure on their part.

The matter under discussion this evening, however, relates more particularly to the consideration of the single-phase alternating system than a discussion of the general subject. Of all the apparatus used in the electrification of a railroad, the motor is in particular that part of the equipment which is limited in dimension by the height of the car-body, the clearance over the rails, the width between wheels, and the wheel-base of the trucks. By reason of these limitations, and considering further the proportion of cost which the motors bear to the general expense of electrification, any condition which diminishes the capacity of a motor of given size may very well become subordinate to the motors themselves.

The output of a single-phase motor, particularly its tractive power in the larger sizes, may be limited by the permissible commutation, and as commutation is improved with reduced frequency the suggestion of 15 cycles instead of 25 cycles is worthy of serious consideration. The field of application for the single-phase motor, particularly in the larger sizes which are required for locomotives and heavy railroad operation, will unquestionably be greater if the motors are operated at a lower frequency than 25 cycles.

Compared with a direct-current motor, a 25-cycle motor of corresponding service capacity would weigh approximately 25% more; while at 15 cycles, the single-phase motor would weigh probably not more than 10% in excess of the direct-current motor. The efficiency and power-factor of the single-phase motor on either 25 or 15 cycles would be approximately the same. While the motors and the reactance of line and track are benefited by a lower frequency, there is the increased cost of the generators and transformers to be taken into account.

Messrs. Stillwell and Lamme have both spoken of the effect of a lower frequency upon the maximum available tractive effort. You will appreciate that owing to the characteristics of an alternating current, the average tractive effort of the single-phase motor is approximately 50% of the maximum at the top of the current wave, and with a motor rigidly mounted the wheels would begin to slip at about one half the tractive effort which would be given by a direct-current motor under the same conditions of track and weight on drivers. With the motor mounted on springs in the usual manner, there is introduced some degree of flexibility, and the impulse due to the top of the wave is absorbed by the springs so that the average torque is considerably higher than the theoretical 50%. Under similar conditions of track, with equal weight on drivers and the same method of mounting, tests have been made which indicate that in comparison with the same motor on direct current, the maximum available tractive effort at 25 cycles is from 80% to 90%, and on 15 cycles from 70% to 80%. The maximum available tractive effort is not generally important except in locomotive operation where the maximum draw-bar pull is in a sense the measure of the locomotive's value for starting a train, and during acceleration. On motor cars there is usually an excess of weight on the drivers over that required for acceleration, so that the maximum tractive effort is a matter of less importance.

It is, incidentally, an interesting fact that after the wheels have commenced slipping the direct-current motor shows a much greater reduction in tractive effort than the single-phase motor. The torque being maintained uniformly with a direct-current motor, the wheels rotate rapidly, reducing the coefficient of friction with the rail to something like 20% or 30% of the maximum adhesion. With the alternating-current motor, both on 25 and 15 cycles, although the initial slip is at a lower maximum, the draw-bar pull is only reduced to 80% or 90% of the maximum adhesion. This appears to be due to the fluctuating character of the torque, which at its minimum allows the wheel to secure a slight grip on the rail after the wheel begins to slip. When the wheel is slipping its rotation is not uniform but fluctuates, corresponding with the frequency. While of interest, this higher tractive effort, after the wheels commence to slip, is of little practical value.

Mr. Sprague has referred to higher voltage direct-current motors. With respect to motors suitable for operation on higher voltage direct current and also on 600 volts, I would mention the marked improvement in the motor that has been obtained by the addition of a commutating pole. As an illustration, a motor having commutating poles and designed for operation on 600 volts, can be run at full load on 1000 volts so far as commutation is concerned, and further, such a motor, when the current is momentarily interrupted or there is a momentary rise in voltage, will not flash over, as sometimes happens with motors not having commutating poles. A commutating-pole motor designed for 1200 volts and operated at that potential would be superior to the ordinary 600-volt motor, both with respect to commutation and liability to flash over. I feel that the addition of the commutating pole to the direct-current railway motor, in its effect on commutation, is comparable to the improvement made by the substitution of the carbon brush in place of the copper brush. The carbon brush reduced the sparking and flashing to a permissible degree, and the commutating pole by neutralizing the cause has finally eliminated defective commutation.

A word with regard to the much maligned third-rail. I feel that there is much to be said in its favor. We have not as yet had an equal opportunity to pass judgment on the heavy overhead construction, and I would suggest that we await developments before expressing our opinion too positively with regard to either system of conductors. Both the third-rail and the overhead conductor have a proper field in heavy railroad application; they should be so regarded, and neither of them condemned in the light of our present knowledge.

W. S. Murray: During the year and a half that I have been associated with the New Haven road I have been able to make some rather interesting experiments with steam locomotives, of the freight and passenger types. I thought they might be of interest, particularly in view of Mr. Stillwell's reference to Item 12 of the paper, which relates to "Repairs and Renewals of Locomotives." I understand that this item, for the Valtellina line, represents a figure of 1.8 cents per locomotive-mile. That is a figure I have been very anxious, indeed, to obtain. I have here some accurate figures on the cost of steam locomotive repairs extending over a period of exactly one year, in which ten freight and ten passenger engines were involved. I think you will all be surprised to note what these figures are. I have divided the cost of repairs into two parts; one on the basis of maintenance, the other for purely mechanical or shop repairs, each including labor and material. I have included in the maintenance the following heads: Cost of oil and waste, flues cleaned, ash-pan and grates cleaned, engines wiped, engines turned, engines fired, boilers washed, and the cost of sand. Of course, some of these figures will be matched in electric operation, but to gėt the actual figure I have included them all.

The record is as follows:

For passenger locomotives: maintenance $0.0172; shop repairs $0.0388; total repairs per locomotive-mile $0.056.

For freight locomotives: maintenance $0.0142; shop repairs $0.0668; total repairs per locomotive-mile $0.081. I believe that these figures give a definite idea of the saving to be effected by the electric method of train propulsion.

I think the most interesting feature of the paper is in regard to the matter of standardization. I hardly think the Interstate Commerce Commission reports are a fair basis to be a determining factor in the establishment of a standard frequency. The Interstate Commerce Commission report includes all the transcontinental lines, and there is no doubt that those lines which have been unassailed yet by electricity could be electrified a great deal cheaper with low-frequency than with high-frequency apparatus, but I do not think that this fact should influence us. I think it is a misleading factor. We must not forget that the electrification of steam railways we are going to consider for the present are to be intimately connected with 25-cycle plants now in operation. It is possible that all of us may see a transcontinental road electrified, but I do not think that that ought to influence us in the determination of a standard frequency.

What " may be " should not decide this question but " what is." I think we should remember the fixed charges associated with 25-cycle plants that have not been taken into account in this report, and that the new frequency universally applied would make it necessary to re-equip all these plants operated upon what may now be termed a standard frequency; namely, 25 cycles.

I believe that for power transmission purposes we will all agree that 25 cycles has nearly occupied the position of a standard frequency. Now then, the fixed charges of the properties operated upon a 25-cycle frequency can later be taken care of by a properly provided depreciation figure or sinking-fund, and at the expiration of the depreciation periods we can avail ourselves of the greater data to decide which should be the standard frequency. The gradual interchange of the two frequencies can then be effected without hindrance to operation.

I have not time here to go into the details of this change, but I am sure all of us are agreed that this can be done. I am in favor of having more data and in letting the future consideration of the new data, in connection with the old, decide the proper standard frequency

O. S. Lyford Jr.: This paper is a prophecy. It is interesting to note that the fulfilment of the prophecy has already begun One of the oldest railroads in the country has proved itself the most progressive and has during this present week put into commercial service an electric traction system which embodies most of the features which the authors have assumed as probable characteristics of the standard of the future. Two other roads referred to in the paper have made a start in the direction proposed, but the Erie was the first to arrive. On January 22 the Erie Railroad ran its first electric train into Rochester.

The essential features of the Erie equipment are as follows:

Single-phase railway motors.

Multiple-unit control.

Pantagraph trolley.

Trolley wire supported with steel catenary construction at a height of 22 feet, except under bridges.

Trolley voltage. 11,000.

One sub-station feeding 34 miles of track.

Power received from a power station 90 miles away over a 60,000-volt transmission line.

The conditions are in many ways almost identical with the assumptions made by the authors.

I may say that the operation of the entire equipment was perfect and fully demonstrated the sufficiency and general practicability of the system. On the return trip the Vice-president's private car was hauled as a trailer, resulting in a total weight of train 22 per cent. heavier than that for which the motors were designed. This was on icy, slippery rails.

The impression given by the overhead catenary construction is that it is the adequate thing for heavy railroading. An

11,000-volt trolley wire so supported is a safe proposition. The 11,000-volt wires on the car are so short and so well guarded that they are not a source of increased danger, and all the other wires, housed in the usual way, and operated at only one-half the usual voltage, are unusually safe.

The system in this case is necessarily operated at 25 cycles, as the power comes from one of the Niagara Falls plants which are all built for 25 cycles. The advantage of the lower frequency is apparent, however, Trucks of unusual size are entirely filled with 100-h.p. motors. At 15 cycles, motors of 150 h.p. capacity could be used on the same trucks.

Referring to that part of the paper which relates to comparative costs of operation, more emphasis should be placed on the tabular matter and the deductions made therefrom. The one question is: can steam railroads be operated more economically by electricity? The three items which I presume will be most questioned are Items 12, " Repairs and Renewals of Locomotives;" Item 21, " Engine and Roundhouse Men;" and Item 22, " Fuel for Locomotives," or, in the case of the electric work, the cost of power delivered to the locomotive. I do not propose to discuss these different items in detail, but I would like to point out the fact that they might even be doubled, and still the electrical operation would not cost more than steam. Those of us who have had occasion to study different specific problems have found that the adoption of electric traction, particularly if a high-voltage trolley is used, will not mean an operating cost greater than the cost of steam, and in many cases the saving is considerable. In other words, specific cases which have been investigated, as well as this study of the problem as a whole, show that electric traction is commercially practicable for such lines as can provide for the initial investment. Furthermore, the advantages to be gained by electric traction, due to increased facility of operation and increased loads which can be carried, have not been capitalized in this paper.

The trunk lines of the country are confronted with the problem of more capacity, as has recently been strongly emphasized by Mr. J. J. Hill. There is no doubt but that more traffic can be handled with electric than with steam locomotives, and, at equal cost per locomotive-mile electric traction can be adopted to great advantage by the railroads of this country. On such an occasion as this we should place emphasis on this one important fact and not get into too much discussion of details.

C. L. de Muralt: Mr. Stillwell and Mr. Putnam have covered the questions of comparative energy consumption and comparative operating costs so ably and so fully that there is not much room left for discussion on these points. But on the subject of comparative speed and power characteristics of the various types of locomotives I believe I am in a position to add a few figures which may be of some interest to you. I have had occasion to make an investigation into the hauling capacities of certain locomotives when operating under heavy load conditions. The diagrams compiled during this investigation showed so strikingly the superiority of the electric locomotives over their steam competitors, and, incidentally, also the great superiority of the three-phase aternating-current locomotives over any other type of electric locomotive, that I thought it worth while to elaborate the results somewhat to present them for your consideration.

To make the comparison as broad as possible I have taken what I thought to be the most representative locomotives of their respective classes: the latest direct-current locomotives of the New York Central and Hudson River Railroad, the single-phase alternating-current locomotive of the New York, New Haven and Hartford Railroad, and a European three-phase alternating-current locomotive of the type used by the Italian State Railways. And with these I have compared a Pacific, an Atlantic, and a Consolidation type steam locomotive of recent American Locomotive Company's design—all the steam locomotives being chosen with reference to possessing the greatest possible power; that is, the greatest feasible heating surface, consistent with their weight on drivers.

Detailed descriptions of the mechanical and electrical features of the New York Central direct-current locomotive have appeared in the technical press[1]. So I will simply repeat here some characteristic figures required for the comparison:

Total weight, 95 tons.
Weight on drivers, 68 tons.
Nominal rated horse power, 2200.
Maximum horse power, 3000.
Maximum tractive effort at starting, 34,000 lb.
Three main running speeds:
a. Four motors in series.
b. Two groups in parallel, each of two motors in series.
c. Four motors in parallel.
Normal operating pressure of motors, 600 volts.

On the New York, New Haven and Hartford single-phase alternating-current locomotive, complete data were published last year[2], and I merely extract the following figures:

Total weight, 85 tons.
Weight on drivers, 85 tons.
Nominal rated horse power, 1000.
Horse power in continuous running, 800.
Maximum tractive effort at starting, 42,500 lb.
Speed controlled by voltage variation, motors permanently connected two in series, two in parallel, numerous speed steps.
Normal operating pressure of motors, 235 volts.

1. *Street Railway Journal*, November 19, 1904.
2. *Street Railway Journal*, April 14, 1906.

The three-phase alternating-current locomotive has four driving axles and three motors suspended between them, and the locomotive possesses the following characteristics:

Total weight, 95 tons.
Weight on drivers, 95 tons.
Nominal rated horse power, 2250.
Maximum horse power, about six times nominal full load rating.
Maximum tractive effort at starting, 47,500 lb.
Three main running speeds:
a. Three motors in cascade connection.
b. Two motors in cascade connection.
c. Two motors in parallel.
Normal operating pressure of motors, 3000 volts.

A locomotive of exactly the same type, but slightly lighter, has the following typical dimensions:

Total weight, 85 tons.
Weight on drivers, 85 tons.
Nominal rated horse power, 2000.

I refer to the heavier locomotive as type A, and the lighter one as type B.

Descriptions of the three steam locomotives will be found in the American Locomotive Company's publication. The principal features of the Pacific type locomotive (No. 1212, of the Southern Railway) are as follows:

Total weight including tender,	175	tons.
Total weight of engine alone,	109	"
Weight on drivers,	67	"
Cylinder diameter,	22	inches.
Stroke of piston,	28	"
Diameter of drivers,	72.5	"
Total heating surface,	3895	sq. ft.
Maximum sustained horse power,	1640	
Maximum tractive effort at starting,	33,500	lb.

The Atlantic type of locomotive (No. 3000, of the New York Central and Hudson River Railroad) has the following characteristics:

Total weight including tender,	161	tons.
Total weight engine alone,	100	"
Weight on drivers,	55	"
Cylinder diameters,	15½ and 25	in.
Stroke of piston,	26	"
Diameter of drivers,	79	"
Total heating surface,	3445	sq. ft.
Maximum sustained horse power,	1360	
Maximum tractive effort at starting,	27,500	lb.

And, the Consolidation type locomotive (No. 221, of the Delaware and Hudson Railway) may be briefly described as follows:

Total weight including tender,	164	tons.
Total weight engine alone,	96.5	"
Weight on drivers,	85	"
Cylinder diameter,	21	in.
Stroke of piston,	30	"
Diameter of drivers,	57	"
Total heating surface,	3408	sq. ft.
Maximum sustained horse power,	1020	
Maximum tractive effort at starting,	42 500	lb.

All of these locomotives have a maximum speed of about 70 miles per hour except the Consolidation, the maximum speed of which is about 40 to 45 miles per hour.

The running characteristics, expressed in the shape of tractive effort, speed curves, of all of these locomotives are indicated in Fig. 1.

All of these curves start at a point corresponding to the maximum tractive effort which is obtainable by the full use of the adhesive weight of the locomotive, just below the point where the wheels begin to slip. This maximum tractive effort, dependent only on the adhesive weight, can for each locomotive be counted upon up to a certain well determined speed. Beyond that point, clearly shown in the curves,. the maximum tractive effort is independent of the adhesive weight and dependent on the maximum power which the locomotive can develop. And it is from this point that the various locomotives show marked differences in behavior.

The horse power which a steam locomotive can develop is determined by the amount of water which the boiler can evaporate and the economy of the cylinders. If W represents the pounds of water evaporated into steam per hour at the given pressure, and N the water rate of the cylinders in pounds of steam per indicated horse power hour, then the maximum indicated or cylinder horse power in this part of the curve is $\frac{W}{N}$. Tests conducted under the auspices of the Pennsylvania Railroad at the Louisiana Purchase Exposition in 1904, showed that the evaporation per square foot of heating surface per hour for different types of locomotives varied between 8 and 16 pounds, also that the steam consumption of the cylinders averages 23.7 to 29 pounds per indicated horse power-hour. The largest Consolidation locomotive built, with 100 tons on drivers, has about 4000 square feet of heating surface; the largest Pacific locomotive, with 67 tons on drivers, about 3900 square feet; and the largest Atlantic, with 57.5 tons on drivers, about 3600 square feet. The average evaporation and the average economy under service, not test, conditions, is approximately 12 pounds per square foot of heating surface per hour, and 27 pounds per indicated horse power-hour, respectively. For one horse power developed in the cylinders there must thus be 2.25 square feet of heating surface in the boiler, or:

Cylinder horse power = 0.43 × heating surface in square feet and:

$$\text{Tractive effort} = \frac{375 \times \text{cylinder horse power}}{\text{speed in miles per hour,}} - \text{frictional}$$

tractive effort =

$$\frac{161 \times \text{heating surface in square feet}}{\text{speed in miles per hour}} - \text{frictional tractive effort.}$$

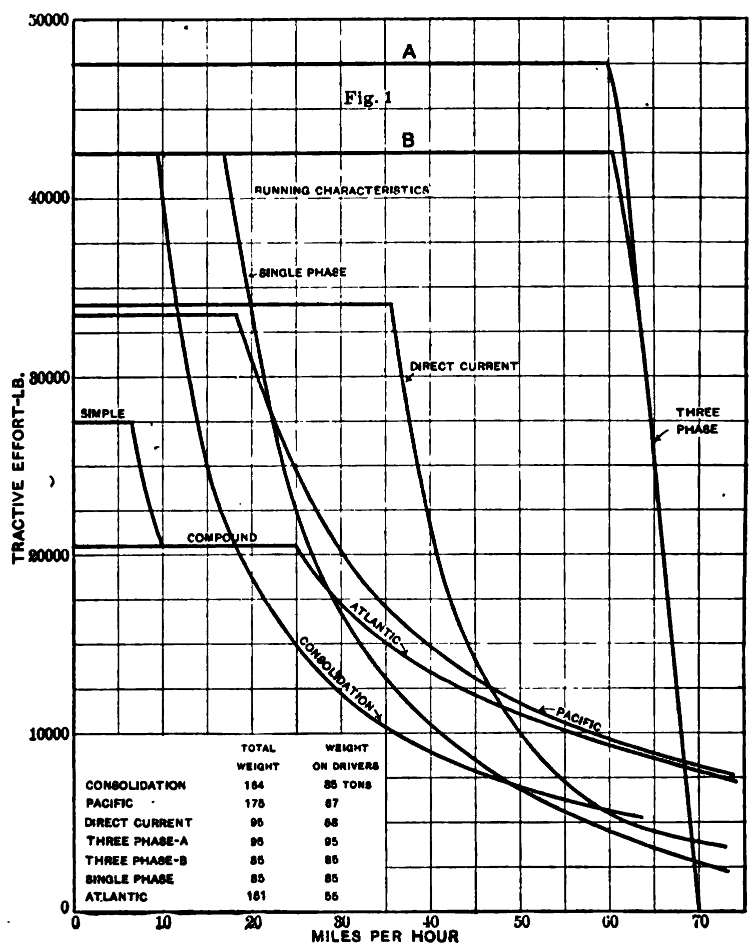


FIG. 1.

The machine efficiency varies in different types, over the range of speeds, from about 74% to 93%. The mean effective pressure corresponding to frictional loss is very nearly constant for all speeds and cut-offs, and averages 3.8 pounds per square inch. The maximum tractive effort, therefore, is given by the relation:

$$\text{Tractive effort} = \frac{161 \times \text{heating surface in sq. ft.}}{\text{speed in miles per hour,}} - \frac{3.8\, d^2\, L}{D}$$

where d is diameter of cylinder in inches, L the length of stroke in feet, and D the diameter of driver in feet. This formula, developed by Professor Goss,[1] for simple engines, has been found to corroborate actual tests with exceedingly good accuracy. The majority of the curve sheets in the Pennsylvania tests referred to, show the calculated and test curves in practical coincidence. The curve of the Atlantic type, four-cylinder balanced compound locomotives, No. 3000 of the New York Central and Hudson River Railroad, was plotted from an actual test made at St. Louis.

The curve obtained from the above equation represents the normal continuous output of the steam locomotive. This continuous output is practically the maximum output, since the overload capacity of the steam locomotive is limited to perhaps 25% for periods not exceeding 5 minutes, on account of the impossibility of forcing the boiler above its normal capacity for extended periods.

Electric locomotives, on the contrary, can sustain overloads of considerably greater magnitude for much longer periods of time, without any difficulty.

The curves of the direct-current and the single-phase alternating-current locomotives are very similar in character to the curves of the steam locomotives. These electric locomotives have motors, with so-called series characteristics, that slow down in speed with any increase in load. The direct-current and the single-phase electric locomotives, in common with the steam locomotive, will therefore reduce their speed when they are called upon to haul an increase in load, either in the shape of a heavier train or when running up-grade.

This feature is clearly shown by the curves in Fig. 1, and it is quite interesting to note that the curves of the steam and electric locomotives cross each other. In other words, the tractive effort of the direct-current and single-phase alternating current locomotives, which is better than that of the steam locomotive at low speeds, actually drops off considerably faster with increasing speed, until it is much worse than that of the steam locomotive at high speeds. In fact, if we consider carefully, the curve of the steam locomotive is the result of practically constant power output, while with the direct-current and single-phase alternating-current locomotive the power output as such diminishes together with the tractive effort.

But the greater advantage of the electric locomotive lies in the fact that it can utilize its weight very much better than can the steam locomotive; and if the actual values of tractive effort taken from the curves are compared with the weights of the

[1] New England Railroad Club, December, 1901.

corresponding locomotives it will be found that the direct-current and the single-phase alternating-current locomotives are capable at low speeds of exerting a very much greater tractive effort proportional to their weight than can the steam locomotives, and even at high speeds their proportional performance is better than that of the steam locomotive.

An additional, and perhaps even more important advantage of these electric locomotives over their steam competitors, lies in the fact that the electric locomotive can readily respond to almost any kind of overload demand. As a matter of fact, a prolonged grade for instance, may seriously decrease the usefulness of a given steam locomotive, due to the impossibility of forcing the latter's boiler for any considerable length of time above rated capacity ,while the electric locomotive will slow down, of course, but will, with the assistance of the power house, carry great overloads for any reasonable length of time.

The three-phase alternating-current locomotive not only accomodates itself to such increased demands on its hauling power, but it does so without any great drop in speed, and automatically adjusts its power to the demand. If at 1500 horse power normal output the motors of a given three-phase locomotive have a 2% slip, then at five times the normal tractive effort the slip will be approximately 10%, and the speed will drop from 68.5 to 63.0 miles per hour. Three-phase induction motors of this size (750 horse power) can be built with a maximum torque of 6 to 7 times full load-torque with very good electric qualities. And, notwithstanding the objection sometimes urged that the design must be very liberal for such service, it remains a fact that the three-phase motor can do what the others cannot do, and its intrinsic lighter weight per horse power, its higher efficiency, its more economical distributed winding, and the absence of the commutator, keep down the cost of the three-phase locomotive within the limits governed by competition.

It goes without saying that this constant-speed variable-power characteristic of the three-phase locomotive need not necessarily be made use of in cases where a decrease in speed is no serious objection, while it may perhaps be desired to keep the power within limits. In such cases the three-phase locomotive can just as well be run at lower speeds for the heavier draw-bar pulls. But it may be well to point out here that the power required; for instance, for a 300-ton train running at about 70 miles per hour on a grade of 0.335%, is the same as that required to accelerate the same train on the level with an initial acceleration of 0.56 miles per hour per second. Inasmuch as the system will be designed for the maximum power demands caused by the heaviest trains accelerating, no additional investment in copper or machinery will be required by this constant-speed, variable-power characteristic of the three-phase locomotive.

Instead of saying that the three-phase locomotive is capable of maintaining practically constant speed under any load, while direct-current and single-phase locomotives will drop in speed with increasing load, the thesis may be reversed and the equally true statement be made that the three-phase locomotive is able to develop a certain given tractive effort from zero clear up to practically maximum speed, while the tractive effort of the direct-current and the single-phase locomotives will fall off seriously with increasing speeds, and at maximum speed is only a fraction of what it was at low speed. The curve of the direct-current locomotive shows, for instance, a drop from more than 3000 horse power at 36 miles per hour to only 960 horse power at 60 miles per hour, and the curve of the single-phase locomotive a drop from about 1540 horse power at 23 miles per hour to only 670 horse power at 60 miles per hour. And this is not a question of liberal design, but an inherent unalterable characteristic of all locomotives using series motors.

These features are brought out very clearly by the curves of Fig. 1, but a few hypothetical examples may go to show just exactly how these characteristics affect the actual hauling of trains.

Let us take a locomotive capable of hauling a 150-ton train, and run it over a given stretch in, say 16 minutes, by the use of a maximum running speed of about 65 miles per hour. Now increase the train-weight to 300 tons. The three-phase locomotive will haul the heavier train over the given stretch as before, in 16 minutes, but the direct-current locomotive or the single-phase alternating-current locomotive will have to drop in speed, and will now take 18 minutes to cover the same distance. A loss of over 10% in time, which loss increases with increasing load.

Or take a line of track with one or more grades. Hauling trains of the same weight, the direct-current locomotive and the single-phase locomotive will, compared with the three-phase locomotive, lose a certain amount of time at each grade, and their total running time will, with the same maximum speed, be necessarily considerably poorer than that of the three-phase locomotive.

Or, take the actual curves of Fig. 1 and send the locomotives over a level line at an average running speed of 60 miles per hour, which corresponds to a schedule speed of about 50 miles per hour with stops about 15 miles apart. We then find the maximum tractive effort for each locomotive, and the maximum trailing load which each can haul (assuming a train resistance of 17 pounds per ton) to be as follows:

	Maximum tractive effort	Weight of locomotive and tender	Trailing train weight
Single phase .	4250 pounds	85 tons	165 tons
Direct current	6000 "	95 "	258 "
Atlantic......	9250 "	161 "	382 "
Pacific.......	9750 "	175 "	398 "
Three-phase	**9375** "	**95** "	**457** "

If we investigate the maximum grade which each locomotive can take with a given train at a given speed we shall find the same order of things. It seems, therefore, entirely fair to draw the broad conclusion that for its weight the three-phase locomotive is by far the most powerful hauling engine extant.

To complete the comparison I have plotted a few curves Figs. 2, 3, and 4) showing the relative accelerations which can be obtained from the various locomotives above referred to and I have endeavored to bring together for this purpose locomotives directly comparable, as much as possible, with reference to their weight characteristics. In Fig. 2, I compare the Pacific type steam locomotive (109 tons, 67 tons on drivers) with the direct-current locomotive (95 tons, 68 tons on drivers) and the

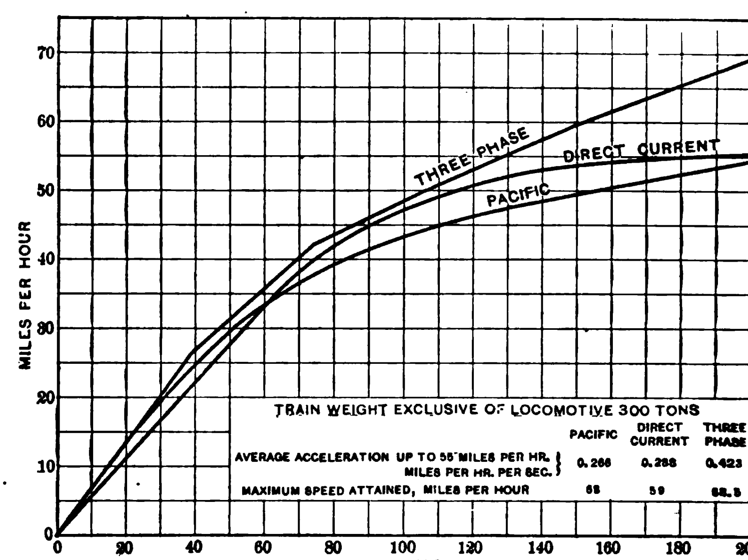


Fig. 2.

heavier of the two three-phase locomotives (95 tons, all on drivers). On Fig. 3 the Atlantic type (100 tons, 55 tons on drivers), a most powerful engine for its weight, is compared with the single-phase locomotive (85 tons, all on drivers) and the lighter three-phase locomotive (85 tons, all on drivers). And on Fig. 4 the Consolidation (96.5 tons, 85 tons on drivers) is compared with the lighter three-phase locomotive (85 tons, all on drivers). These weights are sufficiently close together to permit a fair comparison, but I may point out that to eliminate even these small differences in weight, I have assumed that the electric locomotives would use only such portion of their adhesive weight as corresponds to the adhesive weight of the steam locomotive compared with it.

This being strictly a comparison of acceleration characteristics, the period of acceleration was assumed to extend to a speed of 55 miles per hour only, so as not to be unfair to those locomotives having a very low rate of acceleration at high speeds.

In Fig. 2 a six-car train, weighing 300 tons exclusive of locomotive, was assumed. The steam locomotive uses its full adhesive weight up to 18.4 miles per hour, accelerating at 0.653 miles per hour per second. From then on the tractive effort drops according to the curve in Fig. 1, and the rate of acceleration correspondingly. A speed of 55 miles per hour is reached after about 200 seconds. The direct-current locomotive

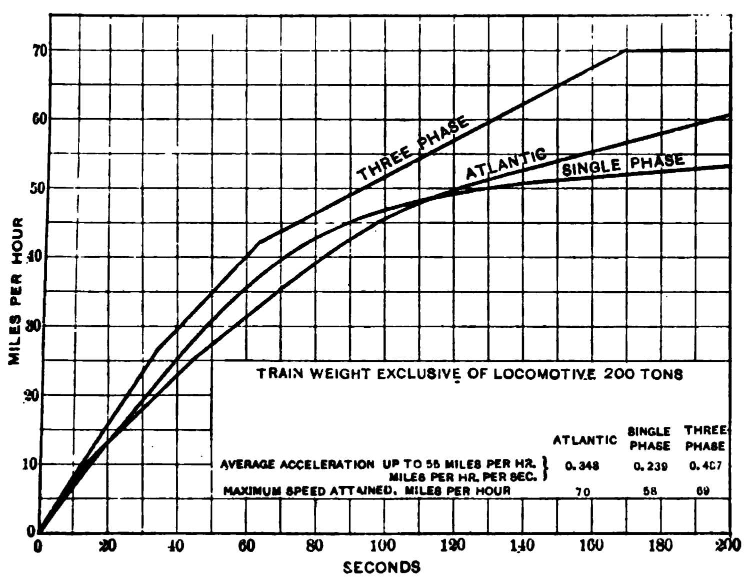


FIG. 3.

accelerates with 875 amperes per motor constant input, 2100 kilowatts maximum, up to 38 miles per hour, from which point on it accelerates on the motor curve at a constantly decreasing rate, until 55 miles per hour is reached, after about 180 seconds. The three-phase locomotive accelerates with a constant input of 2450 kilovolt-amperes, 2200 kilowatts maximum, with three different rates of acceleration corresponding to the three motor connections, reaching 55 miles per hour after about 130 seconds. The energy consumption for the direct-current locomotive and the three-phase locomotive is the same and equal to about 300,000 kilowatt-seconds.

In Fig. 3 where the train-weight is assumed to be 200 tons exclusive of locomotive, the steam locomotive again starts with the use of full adhesive weight, and although having at first a low rate of acceleration, it uses its great capacity at higher speeds to full advantage, and reaches 55 miles per hour after about 160 seconds. The single-phase locomotive and the three-phase locomotive start with the same initial input of 2,000 kilovolt-amperes, which, however, gives the three-phase locomotive a better initial tractive effort on account of its better power-factor and efficiency. After 33 miles per hour, the single-phase locomotive accelerates on the motor curve at a constantly diminishing rate of acceleration while the three-phase locomotive utilizes the same initial input up to full speed. A speed of 55 miles per hour is reached by the single-phase locomotive after about 220 seconds, and by the three-phase locomotive after about 115 seconds.

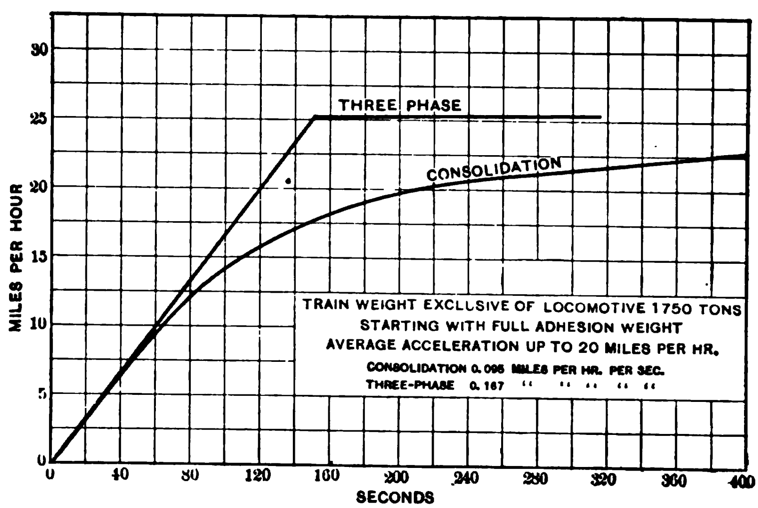


Fig. 4.

In Fig. 4 both the steam locomotive and the three-phase locomotive start with full adhesive weight and accelerate a 1750-ton freight train up to 20 miles per hour at the rate of 0.095 and 0.167 miles per hour per second, respectively, reaching 20 miles per hour after about 200 seconds and about 120 seconds, respectively. By reducing the input for the electric locomotive the acceleration period would be lengthened, but the performance would still excel that of the steam locomotive.

The three-phase locomotive seems, therefore, to be ahead of its competitors also in accelerating qualities, which is quite natural because it is the only one which can utilize a constant input up to full running speed. The three-phase locomotive is mathematically sure of reaching full speed after a certain predetermined time. Locomotives with series characteristics will approach full speed so slowly, that they very frequently do not reach it at all unless the distance between stops is very great.

Conclusion

The constantly increasing business on trunk and suburban lines will have as an inevitable result—track congestion. On certain railroads trains are now so heavy, and run at such high speeds, as to tax the capacity of the most powerful steam locomotives to the limit, and the headway between trains is as small as permissible. Here, then, electrification becomes an absolute necessity if the traffic capacity of the lines is to be increased without the tremendous expense of adding new tracks. We have seen that electric locomotives are in themselves more powerful than steam locomotives of even weight; but it is furthermore possible to couple two or more electric locomotives together by multiple-control connections, and to operate them for all practical purposes as one locomotive by one man. Thus an unlimited amount of power can be concentrated in one unit and traffic can be handled both in increased train weights, not limited by considerations of gradients, and also at higher speeds than are at present employed. That the three-phase alternating-current locomotive is by far the most suitable engine for this purpose I believe to have demonstrated above.

A. H. Armstrong: We have listened to the advocates of the 600-volt and the 1200-volt direct-current systems and the various alternating-current motor systems, and have learned that each of these types of motors possesses qualifications that permit the construction of an electric locomotive much superior to the present steam locomotive. It strikes me that each speaker uses his own individual method of saying the same thing—that we have in the electric locomotive a piece of apparatus which can accomplish results not possible with the present steam locomotive. We have outgrown the days of a machine having an indicated output under 2,000 horse power, a maintenance charge of eight to ten cents per locomotive-mile under the best conditions of level-track operation, and double this amount when the conditions are adverse; and we have at our disposal a locomotive that gave a maintenance charge of less than one and one-half cents per locomotive-mile during an endurance test of 50,000 miles, a concentrated output of 2200 horse power nominal, and fifty per cent. increase for unlimited periods by using forced ventilation. I believe that with the assets we have in the electric locomotive, the day has come when we can approach large railroad problems with supreme confidence of winning out over steam competition. It is not a case of the type of apparatus to be used, nor is it a question of frequency, as each case must be considered by itself in order to make the best individual showing for the local conditions involved. Ten years from now we will still be disputing over the question of frequency, alternating-current or direct-current operation, types of motors, and control to be used, etc. Looking back on the history of the steam locomotive, the same lack of agreement is apparent, and even to-day there is no standard type of steam locomotive receiving the universal approval of engineers and operators.

It is not necessary at the present time to standardize electric locomotives or systems of electrical distribution, as we have not yet demonstrated the best type of motor and the apparatus best suited to take care of the needs of both heavy and light electric railroading. No standardizing can be attempted without full experimental and operating data, showing without question that a particular type of apparatus is the survival of the fittest. I regret that no such full operating data are in existence to-day; in fact, no locomotive of the single-phase alternating-current or 1200 volts direct-current type is yet operating in commercial service.

The electric motor provides opportunity for doing something that cannot be accomplished by steam, and this is the reason why it has superseded steam power in the past and will continue to replace the steam locomotive in the future. It is not a question of petty economies effected; it is the broader question of increased facilities, increased gross receipts, and increased opportunities for earning money by means of the electric motor that makes it a successful revival of the steam locomotive. This point has been illustrated in the past by the entire elimination of the steam locomotive in urban and short-haul suburban work. It is being demonstrated in the big terminal electrifications now going on in and around New York. The managers of our large western roads are seriously considering the substitution of electricity for steam, based solely upon the fact that their roads are in need of a type of locomotive which can surpass the best performance of the steam locomotive as constructed to-day, or as foreseen in the future. A steam locomotive having a capacity of 500 tons trailing on a two per cent. grade is going to be a thing of the past as soon as full appreciation is paid to the fact that it can be replaced by an electric locomotive capable of hauling increased tonnage at double the speed. In face of such facts it is a matter of detail consideration to discuss the question of frequency and types of motive power when there are not sufficient operating data and experience at our disposal to enable one type of motor and one system of distribution to stand above all others as possessing qualifications demanding its universal adoption, and, hence, its standardization.

N. W. Storer: It seems to me that the whole question of the electrification of steam railroads comes down to one of dollars and cents, and the system that can be operated and installed for the least money will be the one to be adopted. As may be seen, there are many different ideas on the same question. Many engineers are working on designs of electric locomotives to meet the many requirements which are constantly being requested of manufacturing companies. I have worked over them for some time past, and every time a new proposition comes in, the matter of frequency, or alternating-current or direct-current operation must be decided. It is a question whether the problem can be solved by the simple direct-current system, which our friend, the father of electricity, loves so well, or whether we must go to something higher and nobler up with our voltage and up in the air with our trolley. Our experience is that the decision is generally in favor of locomotive of the single-phase type. I have considered the direct-current locomotive, and the three-phase locomotive, prayerfully and carefully, but, it does not seem to me that either one of these is the type of locomotive which will meet the requirements of the railways of this country. The direct-current locomotive as it has been designed certainly will not do it. In speed characteristics, the single-phase locomotive pleases me much better than the three-phase.

The single-phase locomotive seems to offer the greatest possibilities. With it, we can not only operate up to what might be called the normal speed of a locomotive, but far beyond that. High speeds become simply a question of applying higher voltages from the transformer to the terminals of the motor. The same locomotive can be operated just as well at 10, 15, 20, or 25 per cent. above what might be called its normal voltage as the direct-current locomotive can be operated at it normal voltage. The question of commutation in the single-phase motor is not so much one of voltage as one of induction in the field, one of current which the motor is carrying or, in other words, of the tractive effort which it is exerting.

Every time a single-phase motor is designed for heavy work, the question of frequency arises, and it always works out much better for 15 cycles, for this reason: at least 30 per cent. greater output can be got from motors at 15 cycles than from motors of the same size operated at 25 cycles. That means that at the limit there must be 30 per cent. more motors if the motor is to operate on 25 cycles than would be needed on 15 cycles. That not only increases the cost of motors very much, but increases the cost of all mechanical parts, the motor-trucks must be heavier than trail-trucks—the entire equipment must necessarily be heavier.

The question of efficiency alone is bound to influence the matter very largely. The 15-cycle motor approaches closely the efficiency reached by the direct-current motor, and there is so little difference that it can hardly be detected. In power-factor it comes very close to the direct-current motor. It is above 90 per cent. throughout the entire range of loads in most sizes—it is practically unity.

The saving in cost of locomotives which might be effected by using 15 cycles instead of 25 cycles is mentioned in the paper, and I am bound to say that the difference which is shown is entirely inadequate to cover what in our opinion it would be. I should say that the difference would be at least $5,000, rather than $1,000. That makes a difference which seems to me to be overwhelmingly in favor of the 15 cycles; it is due largely to the number of motors.

In regard to the lighting of the cars, I believe that satisfactory lighting can be obtained with 15 cycles, by using a low-voltage lamp having a heavy filament. A lamp designed 15 volts, to operate on a 15-cycle circuit, will give just as good light and as perfect illumination as the ordinary incandescent lamp on a 25-cyle circuit. It will be entirely satisfactory for the lighting of cars. The many other questions which come up in connection with railway installations will of course influence the choice of frequency very largely, but as I said in the beginning, it is simply a matter of dollars and cents that will determine whether 15 cycles or 25 cycles is going to be adopted for railway work.

William McClellan: Having passed through the experience of equipping some cars with single-phase motors and proper multiple-unit control for 11,000 volts, I believe firmly that the solution of the railroad problem is going to be by means of the 11,000-volt system. Perhaps not exactly 11,000 volts, but a high-voltage overhead trolley with a single-phase motor. In spite of the fact that a heavier motor is needed for the power developed; in spite of the fact that the sub-station is separated into pieces carried on the motor-cars making a large amount of ton-miles in the course of a year—as a whole the system provides a better solution for trunk-line electrification than any other in sight at the present time. This is particularly true if engineers can be brought to think that 15 cycles is better than 25. I, for one, after a very careful examination of every argument, feel sure that nothing stands in the way of the standardizing of this frequency.

Although the steam railroads have not standardized as to details, they have standardized so that they can make necessary interchange of equipment. Electrical engineers must do such necessary standardizing at once. Unless this standardizing is done at once there might result one kind of trolley on this road running locomotives of one type, and another type on that road; this condition might not prove serious with electric locomotives, but if cars cannot be exchanged freely it will be impossible to electrify the railroads of the country, particularly on the grand scale suggested in this paper. So, therefore, I certainly agree that it would be advisable and possible to standardize immediately certain features of railroad practice, the height of trolley, the location of the third-rail, and the voltage and frequency at the trolley and third-rail.

In spite of the fact that the two great manufacturing companies in this country have different systems of control, I see no reason why the train-line jumper should not be standardized as to position and number of wires. That would solve a great many problems in itself, particularly if the jumper could also connect a heating and lighting bus-bar at a standard voltage, making thereby one jumper between the cars to be handled in addition to the air-brake connections. The largest jumper I know of has twelve conductors for the train line, and it is probable that this number is a maximum. Any particular system could use as many of these conductors as desirable. Such an arrangement would permit easy interchange of Pullmans, express cars, mail cars, fast-freight cars, etc., which might have to be used as trailers in multiple-unit trains of different systems.

The above features include all necessary standardization. This, I believe, is the only standardization that is possible or ought to be allowed at present, because anything else would stifle proper advance in the art.

The firm with which I am associated has always found it difficult to derive useful data from published information on costs of locomotive operation. Therefore, another scheme was adopted. It was to take several railroad divisions having different kinds of traffic, a division with large passenger traffic, another having large freight traffic, and another having a good mixed traffic, and if possible get costs on these. In this way we hoped to arrive at some general figures which could be relied upon. I am free to say that while we did have some success and did arrive at some results, on the whole they were unsatisfactory. It was difficult to obtain any reliable costs for coal, wood, and water stations; but the results given in the paper for maintenance of way and structures are as nearly correct as can be stated.

When we came to Item 12, all figures were very unreliable. I believe the only useful method is the one Mr. Murray has adopted of watching very carefully certain locomotives in service. One scheme we tried was to assume that we could substract the cost of boiler repairs and leave only engine repairs, and by some process of assumption get a comparison between costs of electric locomotives and steam locomotives. We found a pretty good agreement that boiler repairs were one-sixth of the total repairs of the engine, but we could find no railroad people who would agree in the assumption that an electric locomotive would cost anything less for maintenance than the machine part of a steam locomotive. Assuming the figures are the same, the maintenance on the electric locomotive might then be considered five-sixths of the present cost of the steam locomotive.

I ask you to beware of any figures given on maintenance by European railways, for the reason that labor is cheap in Europe; and secondly, a great deal of care is given to operation, and costs are likely to be very low. Neither can the cost of running a locomotive 50,000 miles, where it has been in the hands of trained electrical engineers, be taken as a comparative figure for a locomotive running day in and day out, put in the roundhouse at intervals, given more or less attention, but most of the time in the hands of a road engineer who may or may not be able to take care of it.

Some very interesting results were obtained in connection with Item 21. In the first place, I am confident that a "deadman controller" is as reliable as a second engineman, and makes his presence wholly unnecessary. In the second place, a very complete study by a prominent steam railroad man at several different roundhouses at which forty to sixty locomotives were handled per day showed a total cost per engine handled of $1.18. This included all operations from the time the engineman dropped his engine until he took it again. It was found that 54 per cent. of this was peculiar to steam, and could be omitted with electric locomotives. How much, however, would have to be added as peculiar to electric locomotives could not be satisfactorily estimated.

Forsaking figures, there are broad lines on which we may approach any railroad electrification problem and hope to solve it. These are:

1. The flexibility of motor equipment permitting multiple-unit operation for passenger and freight service in a variety of ways.

2. The possible increase in road-miles per locomotive on account of decreased time in roundhouse, etc. An average steam locomotive, making perhaps 3,000 miles per month in freight service, is about 45% of its time on the road, 30% in the roundhouse, and 25% in the yard awaiting orders, etc.

3. The possibility of generating power cheaply by locating the power plants close to coal mines, which will avoid hauling of the coal, and also by making use of large number of small water powers which, if properly developed, amount to a great asset for the railroad; water powers which would be of little use to an individual, but might be of great use to the railroad because its load is distributed over a large territory.

W. I. Slichter: I have been particularly interested in that part of the paper relating to the choice of frequency for single-phase railway work. I have studied the subject for some time and believe there is no question but that a lower frequency is very desirable for the single-phase motor.

There seems to be a unanimous opinion that the output of the motor may be increased some 30 or 35 per cent. by a decrease in frequency from 25 to 15 cycles. In many cases this will make it possible to build in the limited space available on the trucks of a car, a motor of sufficient power to perform the service required, whereas at 25 cycles it would be impossible to obtain sufficient power. But as Mr. Stillwell has pointed out, we must consider how much this change will cost. The other parts of the system, except the transmission line, are more expensive at the lower frequency.

The generator itself may be increased in cost anywhere from 15 to 50%, depending on the size and design. This is due to the fact that a speed corresponding to 15 cycles will be difficult to obtain in turbines, while for slow-speed engine-driven units there will be no great difficulties.

Transformers are increased in cost about 20% by the change, while the distributing system will be decreased about 10% in cost.

Considering, first, an interurban road in which the amount of motive power is small compared with that considered for a large steam road as discussed by Messrs. Stillwell and Putnam, the relative costs of the various parts of an installation are fairly represented as follows:

	25 cycles	15 cycles
Generating station........	34.4%	38 %
Sub-stations..............	1.8%	2.1%
Low-tension construction..	14.8%	14.8%
Low-tension copper........	12. %	11. %
High-tension line..........	5.4%	5.4%
Bonding.................	7. %	7. %
Equipments and cars......	24.6%	23. %
	100 %	101.3%

For this interurban road then a 15-cycle installation would be more expensive.

But turning to a road which approximates steam railroad conditions, the cost of the equipment forms a much larger proportion of the total cost, while the increase in the cost of the power station is not so great on account of the larger size of the units. This transfers the balance to the other side and the figures are similar to those given in the paper. This shows that as we approach heavy railroad work the greater will be the need for the lower frequency.

It has not been pointed out, however, that although the rated (one hour) output of the motor is increased some 35 per cent. by the change in frequency, this is only the output during acceleration, whereas the continuous output rating of the motor is not changed accordingly. For passenger service with long runs and a small percentage of acceleration, not as much is to be gained by the use of the lower frequency.

J. B. Whitehead: As I have listened to the discussion, a certain aspect of the question has suggested itself, and I venture to bring it forward. In considering an electrically propelled vehicle, I take it we may consider that vehicle best which possesses two characteristics to the greatest degree, other things being equal; and these characteristics are the degree to which the vehicle is self-contained and the greatest power that can be got into the space given to the motors. In speaking of the degree to which an electrically propelled vehicle is self-contained, I wish to draw attention to the fact that we may consider an electric locomotive or car more self-contained so far as it requires less attention from the outside. That is to say, the greater the distance between sub-stations and the less complicated the apparatus at the sub-stations, the better. In these respects the alternating-current has the advantages of the direct-current. If the advocates of the direct-current system, could bring forward apparatus that would operate and transmit at the same voltages that the alternating-current system does, a great deal of this discussion would not have taken place. From the standpoint of self-containment, I think that we must look for something from the direct-current side before we yield the position taken by the advocates of the alternating-current system.

It has been very interesting to hear the comments on the other aspect, the greater power which can be got into the space available for motors by reducing the frequency. If 15 cycles is the point at which the advantage of an increase of power within this space stops, being offset by the greater weight and greater cost of transformers, and the difficulties in the generating apparatus, then that is the frequency that will finally be adopted.

The problem is to do the right thing in the right way; and if we can stretch out more and more the distances between the points where the motor needs help from outside by using the alternating-current system, then the alternating-current system will prevail. The footnote suggests a danger from the rising potential of a broken bond, in the case of high-potential operation. I ask if there is any instance on record where there have been unpleasant results attendant upon a broken bond?

L. B. Stillwell: First, I shall reply to Mr. Whitehead's question. We have assumed in our estimate a No. 4/0 conductor in the track circuit in order to aviod the possibility of a dangerous potential on the track in case of broken bonds. My attention has never been called to any case in which danger has occurred from this cause, but it appears to me a theoretical possibility and we desire to make our estimates eminently fair to the steam side of this proposition.

I have been greatly gratified by the discussion on this paper. and I hope that members of the Institute who have additional concrete facts bearing upon the important question of frequency will contribute these facts by letter.

It is evident that the great majority of engineers present would admit that the question of frequency is settled decisively by the testimony we have had in favor of 15 cycles. The testimony of Mr. Lamme, the inventor of the single-phase motor; of Mr. Storer; of Mr. Slichter, and other men who have been active in their development and practical application, to my mind is conclusive as regards the performance of the motor, and they have testified that the difference in favor of 15 cycles, as measured at the draw-bar, is approximately one-third. When this fact is taken into consideration, in view of the general perspective of the problem, which we have endeavored to establish by considering the electrification of our railroads as a whole, it seems to me there is only one conclusion to draw.

In our estimates we calculated that the expenditure for electrical equipment of rolling stock, if the 25-cycle system were used, would approximate $450,000,000. Mr. Storer has stated that the difference in favor of 15 cycles would be at least $5,000 per locomotive, but his figure for the entire locomotive is considerably higher than that which we have assumed in our estimates, and therefore we may scale this $5,000 down to about $4,000. Applying this to 24,000 locomotives, the difference in favor of 15 cycles is $96,000,000, which is ten times the difference in cost of the power-house equipment which is adversely affected by a reduction of frequency.

I believe that to-day we are able wisely to standardize frequency as well as the position of the overload trolley. These things certainly should be agreed upon. The steam roads have standardized everything essential to the interchange of their rolling stock. We must follow that precedent or we shall get involved in all sorts of trouble.

Mr. Sprague is in favor of the direct-current system. He has done so much in the development and application of electric apparatus for traction purposes, first by the direct-current motor and more recently by the multiple-unit system of control, that I should be very sorry to see him make a serious mistake, and I hope that before he nails his flag to the 1500-volt direct-current masthead he will take into account all the evidence presented to-night.

Frank J. Sprague (by letter): Commenting briefly on some statements made by various speakers, which in one breath describe the perfection of results attained by 25-cycle motors and yet complain of their lack of capacity, I am reminded of a sign which I often see in the Subway cars: "We could not improve the powder, so we improved the box."

My criticism of the 25-cycle motor, which has been so well exploited, has not been because of the potential at which a trolley line must be operated. The relations of potential to size of conductor are really of such common knowledge in the primer classes of electrical engineering that it is hardly worth while to discuss that particular feature. Obviously, if alternating currents are to be used then just as high potentials as the physical facts will permit should be adopted, and there is nothing revolutionary in the use of 11,000 instead of 3,000 volts.

Capacity is the keynote of an equipment, and capacity is not measured alone by that of conductors, but ultimately also by motor equipments; and the entire testimony of this evening bears out my criticism, that the 25-cycle motor as constructed to-day does not under like conditions approach the capacity of the direct-current motor. It is proposed to increase this capacity of lowering the frequency. This, also, in itself is not a novel proposition, for it has been discussed for a number of years. It involves a good many questions, some of them going back to the central station. It may be advisable in the end to adopt for alternating-current operation this periodicity, and I ventured months ago to predict that the largest 25-cycle railroad enterprise now carried on would adopt a lower frequency.

In view of the fact that reduction of frequency, which brings a motor more nearly to direct-current conditions, is now acknowledged and advocated as an essential, I find some difficulty in reconciling myself to that subtle reasoning which holds that because a motor is to be run on a part of its route from direct-current supply it is better that it should be designed for the higher frequency.

While in entire sympathy with every practical development, I care not by what means or along what lines, I have opposed, and will continue to oppose any basis of camparison which assumes as worthy of the fullest credence any and every claim made for single-phase alternating motors, while denying either the possibility, practicability, or importance of the utmost development along direct-current lines, whether used for overhead or third-rail construction.

During the last 19 years I have advocated many radical developments on the floor of this Institute, with what results the gentlemen present are familiar. Now, rightly or wrongly, my name is particularly identified with efforts toward higher voltage direct-current operation, even with the third-rail. I willingly accept the sponsorship of that development, and in answer to Mr. Arnold venture to assert that, so far as public sentiment or restrictions are concerned, while it is quite possible that the continued introduction of an exposed top-contact third-rail will be condemned, as it ought to be, it is quite as likely that high-voltage overhead lines, often in close proximity to highway bridges and crossings, and in possibly dangerous proximity to the general public at city terminals, will come under the ban as that a well protected under-contact third-rail will do so.

Further, I will take direct issue with Mr. McClellan, and venture to prophesy that third-rail installations will still proceed with a good deal of regularity.

I am quite sure that many of the critics of the direct-current development are not as familiar as they might be with what has been done in this line within the last year or two, especially in commutating-pole construction and gearless motors. The former, one of my early babies, and now a vital feature in single-phase alternating-current motors, has been reduced to practice with direct-current motors with such success that I fully confirm Mr. Potter's statement as to its efficiency. To my personal knowledge, four-pole motors of this type, varying from 40 to

240 h.p., normal hour capacity, will operate, so far as commutation is concerned, at excess voltages of 75 or 100% with entire freedom from all commutator disturbance. This improvement alone is one of the most remarkable in electric motor construction in recent years; and directly dependent upon it is the possibility of a return to my earlier methods of varying speed and torque of a motor by varying the field-magnet strength, a principle now in common use in variable-speed shunt motors, and which is equally applicable to series machines. This addition of a shunt to the series field has an important bearing upon the comparisons made by Mr. Muralt. The series motor is no longer a machine with a fixed curve, but one with a very wide range of speed and torque control.

In connection with the other important developments, it would be unjust to omit mention of that modest engineer, Mr. Batchelder, who, Columbus-like, by one bold stroke created a departure in gearless machines, individual to direct current work, which is of the utmost importance, and which has received its very practical proof and demonstration, much to the surprise of many critics in this Institute, in the locomotives recently built for the New York Central Railroad.

As most of you are aware, these are gearless machines in which the previously accepted axiomatic principle of fixity of relation between field and armature was abandoned, the latter being mounted directly on the axle, and the fields being carried upon, and as an integral part of, the locomotive frame, supported by its springs and hence moving freely, irrespective of the armature. Not only gears, but armature and axle-bearings are all dispensed with, and the acme of simplicity in motor construction reached. If desired, the armatures of course can also be springborne.

It may interest those who have somewhat cynically questioned 1200-volt direct-current operation, to know that the General Electric, the Westinghouse, and the Electro-Dynamic companies have all either taken, or bid for contracts requiring the use of motors at this potential.

On the matter of standardization, perhaps I can add a few words. To a certain extent some things take care of themselves. The height of a trolley wire is dictated by the necessity of a clear height above a man on a freight car, and is about 22 ft. There can, of course, be considerable variation from this without in any way interfering with actual operation. The location of the third-rail, with center 28.25 in. from the gauge line, and with a working surface from 2.75 in. to 3 in. above the rail, has been practically accepted, as per suggestion sent out a long time ago by Vice-president Wilgus of the New York Central Railroad as chairman of that road's electric commission.

I suppose I ought to feel flattered to see the universal testimony to the benefits of multiple-unit operation; but some of the speakers outdo the parent in love for his child, and have committed themselves to recommendations of an extreme character. Here, too, there is little to be said in the matter of standardization. I settled that nine years ago when I created a train line composed of sections carried upon, and terminating in couplers on each car, and joined by reversible jumpers between the cars—all constructed, connected, and located so that cars could be connected up in any required order, number, or sequence, and indifferently as to end-relation; and the master-controllers connected therewith had like characteristics with reference to track movement. One of the essential features of this train line is the relative location of speed- and direction-controlling wires, the former unchanged in any connection, and the latter reversed in connection when cars are reversed. Would-be improvers departed from the essential five-wire system, abandoned automatic control, and introduced for a time additional individual wires for various rheostatic steps in the speed control, as on the elevated railway in this city; but the progress of events is carrying them all back to the original lines which I laid down. Practical experience, however, leads me to oppose the introduction into a train line of wires for trunk-line connections, heating, lighting, or brake-control.

I am not able to get up any enthusiasm about a proposition to equip the freight cars of the country with train lines. While the control of two distantly placed freight locomotives would at times be useful, it is not vital, nor are there the same reasons which make simultaneous control of motor cars in passenger trains essential.

Certainly no train operation would be conducted without competent men on locomotives which are distantly removed from each other. Moreover, in view of the universal interchange of freight cars, even if the majority of them were equipped with train lines the introduction of a single one without such an equipment would make useless the balance, and the switching necessary to avoid this would be objectionable. The possible advantages of such an equipment are vastly more than offset by the enormous cost.

Calvert Townley (by letter): The tabulation of distributed opertaing costs of steam roads, contrasted with the estimated costs which it is expected will obtain when steam roads shall have been electrified, is interesting, and the conclusions reached are in line with what electrical engineers very generally believe. I am not sanguine that this tabulation will be given material weight by the men whom it is most desirable to convince; namely, the steam railroad operating officials. Such men, as a class, attach, and properly I believe, much greater weight to statistics showing what has been accomplished than to any figures showing what it is expected will be accomplished, no matter how logical these latter figures may be, or with what care and satisfaction to the compiler they may have been prepared. It is also perhaps unfortunate that in the comparison of the operating costs, the authors of the paper should have omitted any figures on fixed charges. Naturally, such charges, resulting as they would from investments needed to electrify, will increase the total expenditures under electric operation, and will act to offset in varying degrees the estimated savings which Messrs. Stillwell and Putnam have taken. To the man who is unable to estimate what will be the investment required to electrify, this may unfortunately be interpreted to indicate a dread on the part of the electrical engineer that a complete comparison of all expenditures for both methods of traction should be made. There is, furthermore, a deeply rooted feeling that the depreciation in electrical equipment due to the replacement of one type by another, so-called amortization, is much higher than is the case with steam equipment, and there is only one way by which such conviction is likely to be removed; that is, by the actual demonstration in practice that the amount chargeable to amortization is small.

With the principle enunciated by Messrs. Stillwell and Putnam on standardization, I am thoroughly and heartily in sympathy; but in the words of an engineer with whom I discussed this matter, I believe we should only undertake standardization when we have something to standardize. Standards are artificial only to a limited degree, and no edict of the Institute, or of any other body, can successfully long maintain a so-called standard against something better, or when greater advantages can be obtained by departing from the avowed standard. I cannot but feel that the Institute would lay itself open to serious criticism if it should undertake, for example, to establish a standard frequency for electrically equipped steam railroads, when there is no single electrified steam road in this country operated by single-phase current. Particularly would this be true if they should adopt a standard different from every single-phase trolley road now in operation, or in process of being equipped in this country, and having as a basis for such adopted standard only the calculations and experiments of the engineers of the manufacturing companies, extending over but a short period of time. The best type of equipment for the electrification of steam roads will ultimately prevail; but it will prevail by practical demonstration as to its fitness, and in no other way. I should regard it as far better that a few railroads should spend some extra money in later changing the equipment which they may have adopted, rather than that some important development in the art should be hampered or prevented because of a decision made now on insufficient evidence. If the authors of this paper should now advise their clients to adopt something which later may be found to be one of the "discards from the deck," they would only have taken a chance which other engineers have taken before, are taking to-day, and must continue to take for some time to come.

With respect to the advantage of 15 cycles, or any other modification of a standard frequency that may be suggested, the burden of proof obviously lies with those advocating the change; to receive serious consideration, reasons for the change must be weighty and the evidence supporting them fairly conclusive. In the present instance, the arguments advanced in favor of 15 cycles are essentially two: first, the lower frequency permits a lighter and more compact motor; and secondly, the induction in the line and track are reduced. Of these two reasons, the first is advanced as the controlling one. Every other consideration is confessedly adverse. It is, therefore, pertinent to inquire, in fact we must know, to consider the subject intelligently, how much smaller, lighter, and cheaper the lower-frequency motor is to be. In undertaking to procure this information, however, we are at once confronted with embarrassment. There being no 15-cycle equipments in existence in this country it is not surprising that the Westinghouse engineers hesitate definitely to predict what will be their relative weight, cost, etc., when they shall have been constructed to meet the necessary widely varying specifications that will certainly be forthcoming as soon as the electrification of steam roads is fairly under way.

In considering the electrification of the N.Y.N.H.&H.R.R. Co., plans were submitted by the Westinghouse Elec. & Mfg. Company for both 15- and 25-cycle passenger locomotives. designed to perform identically the same service. Here, then, we have a definite statement of the relative characteristics of the two types applied to a concrete case, and carefully worked out. The figures include, moreover, not only a comparison of motors, where the 15-cycle is lighter, but also of the transformers, where the 15-cycle is heavier, and, further, of the other parts of the locomotive, which are affected variously and in different degrees. It was found that the 15-cycle machine had the advantage of 5.2% in weight, about 3% in cost, and was slightly better as to its efficiency and power-factor. I have been told that the specifications in this cases were not such as to permit full advantage to be taken of possible 15-cycle construction, but the specifications imposed absolutely no limitation in this direction that was not fixed by the operating conditions. I am further advised that there have been subsequent improvements in 15-cycle motor design that now warrant better claims for it, and that in consequence the present difference of weight of locomotives may perhaps be nearly 10%, or, in some cases, and under varying conditions favorable to 15 cycles, even more.

If the locomotive weight may be said to average 30% of the total train weight, the use of a locomotive weighing 5.2% more will add 1.56% to the total train-tonnage. Similarly, ten per cent. increase in locomotive weight will add 3% to the total train-tonnage. In freight service the ratio of locomotive weight to train weight being less, the increase in total tonnage due to additional locomotive weight would be correspondingly smaller. These additional weights, while undoubtedly undesirable, could hardly be considered controlling or as constituting a sufficient offset to the serious objections of a change in standards, even if such change were not coupled, as it is, with the attendant disadvantages to power station construction in lighting, and in the use of auxiliaries of all kinds.

The statement that there have been recent improvements in 15-cycle motor design is interesting as an indication that the last word in single-phase motor design has by no means been said; indeed, it would be a most remarkable condition of affairs and decidedly contrary to the history of every other electrical development were it otherwise, whether the motor be designed for 15 cycles or for any other frequency.

In the light of these facts, with our high-priced prosperity labor and a soaring material market, it is obviously dangerous even to attempt to state the difference which we may reasonably expect will obtain between the cost, for example, of motors of two different frequencies when the dust settles. On this account it appears to me impossible seriously to consider or to attach much weight to the comparative-cost figures presented by Messrs. Stillwell and Putnam for the possible future electrification of the entire railway sytems of the United States.

In this connection it may be proper to point out a future possibility that has not been touched upon, but which may prove to be an important factor in the frequency question. An engineer who has been familiar with trolley practice only, and who studies steam railroad electrification for the first time, may be pardoned if he is surprised as the comparatively small amount of power required by the steam, and he is likely to be further astounded, and perhaps appalled, at the high peaks and wide fluctuations in load. These conditions do not make for the economical generation of power, but on the contrary impose an abnormally heavy fixed charge to cover capital sufficient to handle peak loads, and an unduly large operating cost for the additional force necessary to operate a station to handle peak loads, the average output of which station is, however, but a small per cent. of its capacity. It is possible that Messrs. Stillwell and Putnam had this feature before them in suggesting the distribution of power 150 miles in each direction from centrally located power houses. However, I am not able to justify the general adoption of such a plan, either on the score of expense or of reliability, though there may sometime be found a particularly favorable case where power can be generated from steam and economically transmitted this distance. I am confident, however, that a much smaller initial investment will be required, and a considerably lower operating cost will obtain, if smaller stations are installed at much more frequent intervals. I believe that such a plan will be found more economical, even with the reduced load-factor thereby entailed. But the question of load-factor brings me to the future possibility above referred to, which is this: as soon as the railway manager discovers that in order to make cheap power he must make it in larger quantities than his road can use, and that his station must also have a good load-factor, he will utilize his good railroad credit in the direction of establishing larger power plants than he himself needs, and he will sell quantities of cheap power to neighboring industries, thereby affording them the advantage of such power at lower rates than they could themselves produce it, and securing for himself, not only cheap power for his own use, but a profit on the sale of the surplus.

Twenty-five cycles is a standard and a satisfactory frequency for induction motors in industrial establishments and for synchronous converters where direct-current trolley systems are in operation. Fifteen cycles is likewise applicable to such service but is concededly not so good, and it is not at present a standard. Should it become so, the cost of transformers for use with it will be materially greater than the cost of transformers for 25 cycles—perhaps somewhat in the neighborhood of 40% more, and the frequency is not one that affords as great a flexibility in the speeds of the induction motors supplied by it.

In the light of the foregoing, the following seem to me clear:

1. That it would be wrong to undertake to establish a standard frequency for single-phase railway operation at the present time.

2. That even after it has been credited with all the estimated advantages claimed for it, a 15-cycle frequency has not yet made out a case entitling it to general preference.

Ralph D. Mershon (by letter): It seems to me that we should go slowly in the matter of adopting a standard frequency for traction work. The reasons for caution in this matter are pretty well set forth in the paper, but there is one of the considerations touched upon which will, I believe, before long have considerably more weight than at present. This consideration is that of the use of induction motors for traction purposes, especially motors whose speed characteristics may be varied by a change in the number of poles, In the case of such method of speed-control, a higher frequency than 15 cycles is desirable as giving greater flexibility in the range of speed. It seems to me it would be much better to wait until the lines of development of traction work are more clearly defined than at present before adopting as standard a frequency lower than 25 cycles.

H. M. Brinckerhoff (by letter): The wide field covered by this timely paper and the broad lines on which the authors have laid out their general argument deserves a much more careful analysis and discussion than was possible at the meeting at which it was presented. A brief written contribution, giving some additional data upon some points contained in the paper or referred to in the verbal discussion may therefore not be out of place.

The first of the four points enumerated by the authors; that is, "the record of certain facts relative to heavy electric traction which have been established by experience" brought out in the discussion various references to one of the items that might be further elaborated upon.

The record of the results obtained on the Manhattan Elevated. Subway, and various interurban railways are used as a basis of comparison upon which to estimate operating costs for steam railway electrification. One of the most frequent criticisms offered by steam railway men is that the period of operation of electric installations has been too short to show fully the cost of repairs and renewals, such as are found in similar items in long established steam railroad operation.

The earliest heavy electric railway system is the Metropolitan West Side Elevated Railway in Chicago, which was the first to operate commercially with the third-rail. Starting in April 1895, nearly twelve years ago, it operated with one motor car per train until 1905, then the multiple-unit control was adopted and a second motor car used on four and five car trains, instead of one as previously.

The total cost of operation per car-mile on this road, starting at about $0.075 in 1896-7-8, showed small fluctuations up to 1905, when it was $0.0931, the highest single year being $0.0971 and the average for the ten years $0.0836. Here then we have a system in its tenth year showing a cost per car-mile for all expenses, omitting taxes only, which compares with the steam locomotive operation of the South Side Elevated of Chicago of $0.106, the Lake Street Elevated of $0.1174 and the Manhattan Elevated of New York of $0.1198 per car mile. The increase noted for electric operation on the Metropolitan from 1895 to 1905 is partly accounted for by considerable increases in rates of wages and cost of fuel and general supplies.

As the writer was connected with this road from the start, and general manager for six years prior to 1906, he states on his personal knowledge that the tenth-year costs included renewals in all the items—ties, rails, frogs, and switches, repainting cars, renewals of armatures, commutators, gears, pinions, and all the various items that might be said to have a considerable first life. The fear very naturally entertained at first, that after a certain period the renewals would become excessive, has not been realized, even after a ten years' term of constant heavy service. The costs are greater the tenth year than the first or second, but are still 25% or 30% below corresponding costs of similar steam locomotive operation. At the same time the service has been immensely improved in speed, frequency, and general desirability.

While it is difficult to compare electric car-mile statistics with steam railway train-mile figures, the facts here noted certainly support the contention of Messrs. Stillwell and Putnam for operating costs at least 20% lower for electric than for steam operation under favorable average conditions.

In using the general average results in the carefully prepared tables of statistics presented by the authors, the danger of applying general averages to specific cases should be clearly pointed out. An average is simply the mean value of two or more amounts, and this average value may vary so greatly from some individual figure on the list from which it is derived as to make a specific application based upon it very misleading. General averages are valuable for general broad considerations, but specific cases must be analyzed and determined upon in their individual conditions.

In their estimates of the costs, the authors have assumed the universal use of single-phase alternating-current apparatus. In the discussion at the meeting it was contended that this assumption was too radical, since no single-phase installation of this character has begun actual service. On the other hand, some speakers criticised the idea and use of the third-rail system as out of date. All past experience shows that a radical innovation is not in itself necessarily bad, neither should an existing successfully operating system, whose limitations have been demonstrated under service conditions, be broadly condemned on these points alone. The present existing heavy electric traction systems are the result of development along a line radically differing from the previous lighter forms of street and other railway apparatus, but this has not prevented the enormous extension of the older lighter form in the field for which it is adapted.

As the writer happened to be engaged upon the design of the original third-rail installation for the Intramural Railway at the Columbian Exposition in Chicago during 1892-3, and joint patentee of the various devices then developed, he feels authorized in saying that no claim was then made that *the only true and correct solution of the electric railway problem* had been evolved. Certain conditions had to be met—a light elevated structure of limited dimensions and clearances, trains of four cars to carry dense passenger traffic, with stations close together, and demands for the highest possible speed and regularity of operation.

This problem was then absolutely new. That the system was evolved, the apparatus designed, installed, and put in operation in less than eight months, and fourteen four-car trains on a line about three miles long, carried successfully from 100,000 to 125,000 passengers in days of 14 to 15 consecutive hours, does not call for any apologies from those connected with this work.

The use of the third-rail itself was brought about by the necessity for collecting large amounts of electric current from a stationary conductor, by apparatus attached to moving cars. The decision to use a large cast-iron shoe sliding on a steel rail was met with many predictions of failure; the result is a matter of history.

The problem met in 1893 is presented to-day, changed only in magnitude. The solution then evolved accomplished its purpose so successfully that in the year 1906 the third-rail system of the U. S. hauled close upon 700,000,000 passengers, at a cost fully 20% below what it would have been with steam.

The writer does not wish to be understood as advocating the whole sale installation of the third-rail on all the steam railway systems of the United States. It has a field, however, of its own which it is occupying successfully. That it has been found to have objectionable features in certain cases is not surprising; on the contrary the variety of conditions which it has successfully met is rather remarkable.

When we discuss the broad problem of electrifying transcontinental railway systems, the added magnitude of the problem involves the further conditions of great distances and large and infrequent train units. The obvious course to pursue under such conditions is to raise the voltage on the working conductor, and that this involves overhead contact is very apparent.

In examining the many forms of alternating-current single- and three-phase lines in Europe last winter, the writer could not but help noting a number of details which are pertinent to this discussion. The use of the relatively high-voltage trolley is successfully accomplished and the insulation of the high-tension-side of the apparatus on the car is not seriously troublesome. It is also true that a system like the Valtellina Line in northern Italy performs all the functions of a steam railway system. Trains of through freight, local freight, express passenger trains, local passenger trains, excursion and specials are run, with interchange of cars and traffic, with the steam railway systems of the country.

There are some points upon which we must be on our guard, however, in making comparisons. Continental railway roadbeds are very superior, as a rule, to the average in America, nor have they the immense and complicated freight-yard layouts and intricate switching problems seen on our lines. The cars are much lower and very light compared with our freight, passenger, and Pullman cars. Wages are much lower and the demand of the public as to quality of service not so severe.

All these must be allowed for in using their cost figures. What they have accomplished in various lines is very instructive and interesting, and it is flattering to know that the incentive vigorously to develop single-phase railway equipments now being pushed by some of the largest firms in Europe came from reports of American effort in this line.

The authors' third point: "Importance of Standardizing Electrical Railway equipment as rapidly as may be consistent with progress" is certainly timely and well taken. Upon the assumption of ultimate universal electrification of the entire railway systems of the country, it is well to note that the interchangeability at present effective on the steam railways does not mean actual identity of apparatus, but sufficient similarity to insure coupling, hauling, heating, and renewal of parts such as journal brasses, etc., upon all lines.

As there is now a variety of types of locomotives on connecting systems and these are operated, generally speaking, on their own lines, so it should be possible to operate through passenger and freight business entirely by standardizing the few items mentioned, and yet retain the advantages of motive power apparatus of different types specially suited to meet certain local conditions.

The great flexibility thus far shown in the development of electric railway apparatus, such as the use of the third rail on private right-of-way and overhead trolley upon streets; and running alternating current on one part and direct current on other parts of a line with the same cars, are only indications of the possible interchangeability of systems of apparently hopelessly divergent characteristics. The two classes, freight and heavy Pullman or passenger cars, are, broadly speaking, the through equipment. On neither of these is it likely to be found desirable or economical to install individual motor equipment and multiple-unit control. The local and suburban trains, with multiple-unit control, will not leave the parent system. Interchangeability then of the *through equipment* does not prevent the selection locally of the most desirable motive power system, provided the present degree of standardization common in steam railway practice is adhered to.

During the present period of development and adjustment of electric traction to steam railroad conditions, the existence and advocacy of different types of apparatus brings to the problem a spirit of emulation and competition that is tending to greater perfection of detail and much more rapid progress than would be the case were all engineers working on a single type. The fact of honest difference of opinion by men striving to meet certain specific conditions successfully is not a sign of weakness as some doubters would have us believe, but a strong argument for the broad applicability of electric power.

A. H. Babcock (by letter): The salient points of the paper seem to me to be the statement that the alternating-current equipment is the only class of equipment deserving serious consideration in connection with the general problem of heavy traction. the question, " where ten years from to-day, will be the 1200-volt of 1500-volt direct-current system? " and the plea for standardization of 15-cycle apparatus.

It is to be regretted that at present there is not available any detailed information covering the actual operating data (such as follows) on the few single-phase roads now in operation. In one of the cases that has come under my personal notice, three passenger cars and two work cars are operated. The passenger cars are equipped with from 100 h.p. motors and weight equipped, but not loaded, 40 tons. The work cars have four h.p. motor equipments and weigh somewhat less. Power is purchased at three phase 60 cycles, is converted to single phase 25 cycles, is metered and paid for at the rate of $1\frac{1}{4}$ cents on the three-phase side of the converting set. Measured here, the following figures were obtained for one month's operation last fall.

Average tonnage per car operated	36.25
" watt-hours per ton-mile	153
" cost of energy per car-mile	6.92 cents.
" kilowatt-hours per passenger car-mile	6.12
" cost of energy per passenger car-mile	7.65 cents.

It should be noted that the foregoing figures are for power alone, without any fixed charges or other expense. With a total of five cars of all kinds under operation, eight men including the foreman, were needed and employed in the car house on motor-car repairs, with two more men available for emergencies.

Is this sort of thing "the only class of equipment deserving serious consideration in connection with the general problem which we are discussing?"

If this road had been equipped with 1200-volt direct current, under the same operating conditions and losses in transmission as are now made, the energy per ton-mile would have been 107 watt-hours as against the 153 actually recorded, and the monthly cost of energy would have been reduced in proportion.

It is safe to say that the 1200-volt or the 1500-volt direct-current system will be heard of in ten years, if the single-phase system is not developed far beyond the inefficient case cited above.

With reference to standardizing 15 cycles, it may be remembered that the first installation proposed called for $16\frac{2}{3}$ cycles. Afterward 25 cycles was made the standard in order to fit existing apparatus, and we were informed that the change in frequency made no difference. Now we are informed with equal positiveness that 15 cycles is to be the panacea, and this in spite of the fact that not one 15-cycle installation is in operation in this country. An engineer responsible for the expenditure of large sums of money may well hesitate about standardizing anything in a field where the very first development has yet to be made and proved.

It is not my intention to appear to condemn the entire single phase system on the showing of the one road the operating costs of which have been investigated by me; nor is the fact that 1200-volt direct-current motors have been specified by me for a large suburban service to be taken as a declaration in favor of high-voltage direct-current as a substitute for single-phase in all cases. The right is reserved to choose for every specific case the type of apparatus best adapted.

All engineers in a similar position must regret the absence of published accurate disinterested information on the operating costs of the few single-phase roads now in operation.

W. S. Murray (by letter): Upon the belief that the two departments in which the greatest economies to be derived in electric versus steam operated trains are fuel and locomotive repairs, it has been my effort during the past eighteen months to secure absolutely reliable data in these two departments of cost concerning the steam operated trains of the New York Division of the New York, New Haven, and Hartford Railroad Company.

FUEL.

Ton-miles are produced in several classes of service, viz:

1. Passenger express.
2. Passenger express-local.
3. Passenger local.
4. Freight.

TABLE 1.—EXPRESS PASSENGER SERVICE.

No. of Locomotive.	Mileage of locomotive in 18 days.	Pounds of coal burned in 18 days.	Average weight of train, including locomotive and passengers.	Total ton-miles of train, including locomotive, passengers, and switching for 18 days.	Total horse-power hours for 18 days of locomotive in revenue service based on average h.p. between Woodlawn and New Haven.	Pounds of coal per indicated h.p.-hour based on average indicated h.p. between Woodlawn and New Haven.	Total revenue ton-miles of train, including passengers and locomotive for 18 days.	Pounds coal per revenue ton-mile.	Pounds coal per indicated h.p.-hour by average ton-mile method.
832	2,782	301,384	573.5	1,556,730	73,100	4.12	1,545,000	0.195	4.40
841	2,336	215,830	480.7	1,123,050	53,150	4.06	1,123,000	0.192	4.34
Avg.	2,559	258,607	527.1	1,339,890	63,125	4.06	1,334,000	0.194	4.37

LOCAL EXPRESS PASSENGER SERVICE.

1262	3,160	295,038	303.0	914,330	63 900	4.62	894.000	0.330	4.54
1258	2,644	264,138	302.2	795,182	57,000	4.64	794,500	0.330	4.54
1272	3,482	353,396	351.5	1,147,520	80,000	4.42	1,114,000	0.317	4.36
1571	1,890	187,180	307.8	577,929	40,600	4.61	566,000	0.331	4.55
1574	1,938	216,583	306.4	593,838	42,500	5.10	593,000	0.366	5.04
Average	2,623	263,267	314.2	805,760	56,800	4.68	792,300	0.335	4.61

An interesting and valuable query is, what fraction of a pound of coal is consumed in producing a ton-mile in any one of the above services? Tables 1 and 2, following, show that it takes 0.169 lb. of coal, 0.194 lb. of coal, and 0.335 lb. of coal to produce a ton-mile in freight, express passenger, and express local passenger service, respectively.

It will be further noted that in the above tables there is given the pounds of coal required per indicated horse power hour for the passenger service. The ten heads under which the compilation of these tables were made show, in order that these data be absolutely reliable, the following conditions must be satisfied:

1. Exact mileages measured.
2. Exact weight of tonnage hauled.
3. Exact weight of coal burned.
4. Maximum continuous number of indicator diagrams taken to determine indicated horse power.
5. A sufficient number of days of continuous test to assure average results.

1. *Exact Mileages Measured.* The zone over which the test was conducted was the New York Division of the N. Y. N. H. & H. R.R. Co. and all trains runs had specified terminals within the zone, the mileages of whch are measured.

2. *Exact Weight of Tonnage Hauled.* The engines, twenty in number, and all cars included in the test were in the regular

TABLE 2.—FREIGHT SERVICE.

No. of Locomotive	Mileage of locomotive in 18 days	Pounds of coal burned in 18 days	Average weight of train, including locomotive	Total ton-miles of train, including locomotive, for 18 days	Pounds of coal per ton-mile
300..........	1,557	230,376	930	1,446,868	0.159
301..........	1,153	184,836	661	761,755	0.242
325..........	1,592	231,366	696	1,108,615	0.209
373..........	2,010	237,006	1,060	2,129,575	0.111
382..........	2,018	304,044	1,240	2,495,072	0.122
386..........	1,274	220,680	731	930,792	0.237
448..........	2,272	413,106	1,255	2,850,046	0.145
453..........	2,350	255,444	872	2,053,142	0.124
Average......	1,778	259,607	931	1,721,983	0.169

log of the mechanical superintendent and the superintendent of car service, with measured weights.

3. *Exact Weight of Coal Burned.* Each of the twenty engines coaled from an individual car, the weight of the coal therein being measured immediately before and after the test, the coal cars being placed at the regular coaling points of the locomotives.

4. *Maximum Continuous Number of Indicator Diagrams Taken to Determine Indicated Horse Power.* A continuous set of indicator diagrams were taken on a locomotive for both express and express local runs between Woodlawn and New Haven. A wind-shield was erected over the left cylinder of the locomotive, and the following scheme of indication adopted, viz:

a. One minute allowed for changing cards on steam indicator.

b. Six diagrams per minute to be taken on the same card.

c. Two minutes to be devoted to taking cards.

d. Interval between cards, twenty seconds.

It will be noted that by this method on each indicator card there were obtained twelve indicator diagrams; six for each end of the cylinder. The average mean effective pressure of these cards was taken to secure the indicated horse power for the cycle of three minutes above described. This three-minute cycle of 66% card indication, was practised several days until perfect runs were obtained between Woodlawn and New Haven, east and west. Then five continuous east and west runs were made for both express and express local service, and an average indicated horse power per ton for each class of service was obtained. By this method of continuous indication throughout all parts of the division, both east and west, the results would seem to be accurate.

5. *A Sufficient Number of days of Continuous Test to Secure Accurate Results.* Eighteen days were considered sufficient.

TABLE 3.

	Ton-miles per annum	Tons of coal steam traction	Tons of coal electric traction	Cost of coal steam traction	Cost of coal electric traction	Saving of electric over steam traction
Express...	592,240,000	57,447	29,870	$183,830	$89,620	$94,210
Express loc	348,000,000	58,300	28,600	186,560	85,800	100,760
Express frt	2,223,000,000	187,844	139,010	563,530	417,030	146,500
						$341,470

The test was conducted during the month of August. The track and temperature were favorable to steam locomotive traction.

Table 3 shows the relative amounts of coal required for electric *vs* steam locomotive traction. In the former case the coal as measured in the electric power house; in the latter as measured in the fire-boxes of the locomotives. The cost-item is interesting in this table, indicating that the New York Division when operated by electricity will show a saving by coal alone of $341,470.00 per annum.

It is to be noted that the pounds of coal per indicated horse power hour is not simply the weight of coal used to accomplish an individual engine run, but the weight used in an all-day service of 24 hours, which includes the time the engine is idle. As the engines are indicated for a given revenue run, this weight of coal might be well termed: The pounds of coal per revenue indicated horse power hour.

showing
motives

Eng. No.	Yea buil
FREIGHT.	
300	190[illegible]
301	190[illegible]
306	190[illegible]
325	190[illegible]
373	190[illegible]
382	190[illegible]
383	190[illegible]
386	190[illegible]
448	190[illegible]
453	190[illegible]
PASS., MAY	
832	190[illegible]
841	190[illegible]
1210	190[illegible]
1258	190[illegible]
1262	190[illegible]
1271	189[illegible]
1272	189[illegible]
1282	189[illegible]
1571	189[illegible]
1574	189[illegible]
FREIGHT	
300	190[illegible]
301	190[illegible]
306	190[illegible]
325	190[illegible]
373	190[illegible]
382	190[illegible]
383	190[illegible]
386	190[illegible]
448	190[illegible]
453	190[illegible]
PASS., JULY	
832	190[illegible]
841	190[illegible]
1210	190[illegible]
1258	190[illegible]
1262	190[illegible]
1271	189[illegible]
1272	189[illegible]
1282	189[illegible]
1571	189[illegible]
1574	189[illegible]

otal cost repairs aintenance er mile n cents
7.23
6.11
4.69
3.90
3.58
2.74
6.47
18.71
13.84
8.41
12.06
9.52
97.26
8.10
10.21
2.89
3.39
16.63
3.14
3.95
5.69
2.76
4.36
4.64
4.78
4.83
67.27
5.60

howing
ssenger

Table 5 is a complete compilation of the twelve months of locomotive repairs and maintenance.

This investigation leads me to the two following conclusions:

1. For a mixed freight and passenger service the same gross draw-bar can be produced by the single-phase method of traction for 60% of the coal required by the steam method of traction.

2. Locomotive repairs are between three and four times as great for steam as for electric locomotives.

L. B. Stillwell and H. S. Putnam (by letter). The paper which we had the honor to present at the two hundred and thirteenth meeting of the American Institute of Electrical Engineers, as stated in its first paragraph, had four objects. 1, To record certain facts relative to heavy electric traction which had been established by experience; 2, to present calculations of relative costs of steam and electric traction in railway service based upon these facts; 3, to point out the transcendent importance of standardizing electric railway traction equipment as rapidly as may be consistent with progress; and 4, to raise the question whether a frequency of 25 cycles per second or 15-cycles per second should be adopted in railway operation by alternating-current motors.

Our purpose in working out and presenting detailed calculations of relative costs of operation by the steam locomotive and the single-phase motor was to secure for ourselves and others a comprehensive view of the great problem which railway engineers to-day are called upon to consider—a comprehensive view being obviously a requisite first step toward an adequate and satisfactory general solution. To realize the magnitude of the problem and the advantages in respect to increased earnings and decreased operating costs which in general will result from the substitution of the motor for the steam locomotive, is to recognize the fact that railways are destined to use electricity upon a scale which demands a general solution and to appreciate the importance of prompt standardization of the frequency chosen for alternating-current work.

While expressing the belief, that as compared with 25-cycles "a frequency of 15-cycles is preferable and should be adopted for heavy electric traction," we stated that our object was rather to present the question of frequency for discussion than to advocate the adoption of any particular frequency, and we suggested a careful consideration of this very important question by the Institute through its Standardization Committee or a special committee.

The oral discussion which followed the presentation of the paper was conclusive, beyond our expectation, as regards frequency. So far as the general practice of engineers who may adopt the single-phase alternating current is concerned, we regard the matter as practically settled by the facts and opinions brought out by the discussion. The designing engineers of both the Westinghouse and General Electric companies testified empha-

b. Locomotive Repairs. Table 4 is a typical sheet showing the scheme of accounts kept on each of the twenty locomotives

TABLE 5.

		Mileage made by locomotive	Total cost of repairs in $	Cost of repairs per mile in cents.	Total cost of maintenance in $	Total cost of maintenance per mile in $	Total cost of repairs and maintenance per mile in cents
Freight	Aug. '06	22,342	1323.	5.92	292.	1.31	7.23
	July '06	22,843	1140.	4.99	257.	1.12	6.11
	June '06	26,570	920.	3.46	326.	1.23	4.69
	May '06	32,678	825.	2.52	451.	1.38	3.90
	Apr. '06	22,500	438.	1.95	367.	1.63	3.58
	Mar. '06	24,984	351.	1.40	335.	1.34	2.74
	Feb. '06	24,788	1254.	5.05	353.	1.42	6.47
	Jan. '06	29,848	5150.	17.26	433.	1.45	18.71
	Dec. '05	24,017	2961.	12.33	362.	1.51	13.84
	Nov. '05	29,528	2029.	6.87	455.	1.54	8.41
	Oct. '05	19,523	2050.	10.50	305.	1.56	12.06
	Sept. '05	19,825	1568.	7.91	320.	1.61	9.52
	Total...	299,446	20009.	80.16	4256.	17.10	97.26
	Average per mile...		6.68	6.68	1.42	1.42	8.10
Passenger	Aug. '06	32,409	2674.	8.25	638.	1.96	10.21
	July '06	32,199	373.	1.15	561.	1.74	2.89
	June '06	35,272	612.	1.74	583.	1.65	3.39
	May '06	34,833	5129.	14.70	674.	1.93	16.63
	Apr. '06	31,395	429.	1.37	554.	1.77	3.14
	Mar. '06	33,332	743.	2.23	575.	1.72	3.95
	Feb. '06	26,428	1040.	3.93	475.	1.76	5.69
	Jan. '06	37,008	385.	1.04	637.	1.72	2.76
	Dec. '05	31,977	830.	2.63	552.	1.73	4.36
	Nov. '05	43,485	1338.	3.08	681.	1.56	4.64
	Oct. '05	37,394	1172.	3.13	615.	1.65	4.78
	Sept. '05	41,304	1376.	3.33	621.	1 50	4.83
	Total...	417,036	16121.	46.58	7166.	20.69	67.27
	Average per mile...		3.88	3.88	1.72	1.72	5.60

for a period of one year. The sheets selected are those showing the maximum and minimum months for freight and passenger engines.

Table 5 is a complete compilation of the twelve months of locomotive repairs and maintenance.

This investigation leads me to the two following conclusions:

1. For a mixed freight and passenger service the same gross draw-bar can be produced by the single-phase method of traction for 60% of the coal required by the steam method of traction.

2. Locomotive repairs are between three and four times as great for steam as for electric locomotives.

L. B. Stillwell and H. S. Putnam (by letter). The paper which we had the honor to present at the two hundred and thirteenth meeting of the American Institute of Electrical Engineers, as stated in its first paragraph, had four objects. 1, To record certain facts relative to heavy electric traction which had been established by experience; 2, to present calculations of relative costs of steam and electric traction in railway service based upon these facts; 3, to point out the transcendent importance of standardizing electric railway traction equipment as rapidly as may be consistent with progress; and 4, to raise the question whether a frequency of 25 cycles per second or 15-cycles per second should be adopted in railway operation by alternating-current motors.

Our purpose in working out and presenting detailed calculations of relative costs of operation by the steam locomotive and the single-phase motor was to secure for ourselves and others a comprehensive view of the great problem which railway engineers to-day are called upon to consider—a comprehensive view being obviously a requisite first step toward an adequate and satisfactory general solution. To realize the magnitude of the problem and the advantages in respect to increased earnings and decreased operating costs which in general will result from the substitution of the motor for the steam locomotive, is to recognize the fact that railways are destined to use electricity upon a scale which demands a general solution and to appreciate the importance of prompt standardization of the frequency chosen for alternating-current work.

While expressing the belief, that as compared with 25-cycles "a frequency of 15-cycles is preferable and should be adopted for heavy electric traction," we stated that our object was rather to present the question of frequency for discussion than to advocate the adoption of any particular frequency, and we suggested a careful consideration of this very important question by the Institute through its Standardization Committee or a special committee.

The oral discussion which followed the presentation of the paper was conclusive, beyond our expectation, as regards frequency. So far as the general practice of engineers who may adopt the single-phase alternating current is concerned, we regard the matter as practically settled by the facts and opinions brought out by the discussion. The designing engineers of both the Westinghouse and General Electric companies testified emphatically to the great increase in power of motors which can be realized by reducing the frequency, and while several speakers questioned the wisdom of now adopting a standard, no one came forward to argue that the higher frequency is preferable.

Mr. Lamme to whom, more than to any other man, we owe the single-phase motor, stated that at 15 cycles the output of a given motor is from 25% to 40% greater than at 25 cycles and that his company had verified this by actual test.

Mr. Storer testified that:

> You can get at least 30% greater output from motors with 15 cycles than with 25 cycles.

Mr. Slichter, the engineer of the General Electric Company, who has immediate charge of the work of designing single-phase motors, said:

> There seems to be a unanimous opinion that the output of the motor may be increased some 30 to 35% by a decrease in frequency from 25 to 15 cycles.

Mr. Potter, chief engineer of the railway department of the General Electric Company, after pointing out some of the difficulties in the way of the adoption of 15 cycles, said:

> I do not think, however, that we can look for the ultimate development of the single-phase motor of 25 cycles.

In his written contribution to the discussion of the paper, Mr. Frank J. Sprague says:

> It may be advisable in the end to adopt for alternating-current operation about this periodicity, and months ago I ventured to predict that the largest 25-cycle railroad enterprise now being installed would adopt a lower frequency.

Mr. Calvert Townley alone, among all who have orally or by written communication discussed the paper, advances arguments in favor of 25 cycles, but even in this case the position taken is one advocating suspension of judgment rather than asserting superiority of 25 cycles, as is shown in the following statement with which he concludes his letter:

> In the light of the foregoing the following seem to me clear:
> 1. That it would be wrong to establish a standard frequency for single-phase railway operation at the present time.
> 2. That even after it has been credited with all the estimated advantages claimed for it, a 15-cycle frequency has not yet made out a case entitling it to general preference.

The paper and the discussion have established the fact that the increase in cost of the power-house equipment consequent upon the suggested reduction in frequency is far more than offset by the reduction in cost of electric equipment of rolling stock consequent upon the adoption of 15 cycles.

As regards power-house and sub-station cost, we estimated that the difference in favor of the higher frequency is about $10,000,000, assuming that all the American railroads now operated by steam should adopt electricity.

As regards cost of the electric locomotives, Mr. Storer stated that the difference in favor of the lower frequency would approximate $5,000 per locomotive. In naming this figure, doubtless he had in mind the present cost of electric locomotives, while in our estimates we have assumed that this cost, which is now approximately $30,000, will be reduced to $25,000. Making a corresponding reduction in Mr. Storer's estimate, it appears that the saving per locomotive, in the opinion of the chief engineer of the railway department of the Westinghouse Electric & Manufacturing Company, will approximate $4,000 in favor of the lower frequency.

The question whether 24,000 electric locomotives would do the work of approximately twice that number of steam locomotives now owned by the railroad companies is certainly open to discussion. If the actual number required be greater than the number assumed, the argument in favor of the lower frequency is strengthened. In our paper we expressed the opinion that work equivalent to that now done by approximately 48,000 steam locomotives could be performed by electric locomotives numbering from one-half to two-thirds of that figure, and in showing that the change to the lower frequency would effect a saving in first cost of aggregate equipment we used the smaller figure in order to be entirely fair to the higher frequency. Adhering to the figure, 24,000, as representing the aggregate of electric locomotives required, and taking Mr. Storer's figure of $4,000 as representing the difference in cost per locomotive, it appears that while the adoption of the lower frequency would involve an increase of about $10,000,000 in cost of power-house and sub-station equipment, it would save $96,000,000 in cost of rolling stock equipment; both of these figures having reference to equipment of the entire existing railroad systems of the United States. The point made by Mr. Storer, therefore, greatly strengthens the argument in favor of the lower frequency.

The practical unanimity of competent opinion evidenced in respect to the advantages of the lower frequency, and the fact that practically every American designing engineer who has participated actively in the development of single-phase railway apparatus was present and joined in the oral discussion, would seem to have established definitely and finally the wisdom of adopting the lower frequency. It is possible that special cases may arise in which local conditions are sufficient in weight to justify the use of the higher frequency, but it is perfectly clear that hereafter the engineer who in single-phase alternating-current railway work adopts 25 cycles will accept serious responsibility and should be able to base his decisions upon concrete and local factors such as will be found to exist in very few cases.

The fact that the Oerlikon Company, of Switzerland, and the Siemens-Schuckert Company, of Germany, in manufacturing single-phase motors of the type adopted by the Westinghouse and General Electric companies are adopting 15 cycles, is an interesting point presented by Mr. Lamme and is excellent evidence in favor of the lower frequency.

Aside from the interesting discussion of the question of frequency, the paper has resulted in the presentation of certain facts of material value and of numerous opinions, many of which deserve respectful consideration. Among the facts of special value may be mentioned the data presented by Messrs. Lamme and Potter relative to comparative slip of wheels at 15 and 25 cycles. It is highly desirable, however, that these facts be supplemented by further experimental determinations. Mr. W. S. Murray has contributed data of especial value in the shape of costs of steam locomotive operation on the New York, New Haven and Hartford Railroad, these costs being in certain respects analyzed more thoroughly than is usual in the locomotive performance records of our steam railroads. Mr. Slichter's figures showing how the cost of electric equipment in certain cases would be affected by the suggested change in frequency, are of particular interest. Mr. de Muralt's discussion of certain comparative characteristics of single-phase, three-phase and direct-current motors is also of value. It is to be regretted that the comparative merits of the two frequencies under consideration were not discussed from the standpoint of the induction motor. The point was referred to in our paper, and Mr. Ralph D. Mershon in his printed communication expresses the opinion that in the near future this consideration will have greater weight than is now generally recognized. It is certainly desirable to have additional light upon this aspect of the subject, and it is to be hoped that if the advocates of the induction motor for traction purposes have in their possession any facts of importance not yet published they will see their way to present such facts at an early date.

Aside from the discussion of the question of frequency and the presentation of test data, the oral discussion and the written communications subsequently contributed bring out the following facts:

1. That Mr. Frank J. Sprague, and possibly a few other engineers, are inclined to believe that the high-potential direct-current motor, (for example, 1200 or 1500 volts) is perferable to the single-phase motor.

2. That a considerable number of engineers feel that the time to standardize has not yet arrived.

Such advantages as the direct-current motor possesses in the general railway field disappear rapidly when we consider this field as a whole rather than regard special cases in which the reasons for electrification are so weighty as to overcome even the comparative disadvantages of a system apparently limited to 1200 or 1500 volts, and necessarily limited by the interposition of synchronous converters between generators and motors no matter what the ultimate voltage for which direct-current motors may be designed. They also shrink materially when we compare the direct-current motor with the 15-cycle motor instead of the 25-cycle motor.

In the course of the discussion, Mr. Sprague made the following interesting statement:

I am going to make a prophecy—that on a large number of lines which can by any stretch of imagination be considered as subject to a reasonable prospect of electrification, that 1200 or 1500 volts will on, any present development known, give better results in every way than the alternating-current 15- or 25-cycle overhead system.

It is to be hoped that Mr. Sprague will present facts and figures upon which this interesting prophecy is based. Meantime, however, it may be pointed out that he limits the alleged superiority of the direct-current system to:

A large number of the lines which can, by any stretch of imagination, be considered as subject to a reasonable prospect of electrification.

The imagination of one man may stretch more than that of another, and in effect Mr. Sprague proposes the plan of special solution. The growth of traffic will constantly operate to bring roads now outside what he considers the practicable field, within that field. Obviously, it will not do to treat this problem as limited to roads having to-day certain density of traffic or limitations of length which may enable the direct-current system to make a good showing. Problems which ten years ago were on the remote horizon are solved and behind us, while problems which twenty years ago were regarded only by the poet are now in the hands of the operating superintendent.

The position which we take in this matter may be stated as follows:

a. A general view of the railway field, including freight as well as passenger traffic, obviously shows that for anything approximating a general solution the single-phase alternating-current system is decidedly superior to the 1200- or 1500-volt direct-current system. This conclusion is corroborated by calculations easily made and based only upon established facts.

b. The admitted advantages of electricity in respect to increased earning power and decreased cost of operation are such as in the near future assure rapid increase in the use of electricity by railway systems now operated by steam.

c. The necessity of standardizing frequency rests practically, although less directly, upon the same arguments as have induced railways to standardize track-gauge, height of draw-bar, location and couplings of air brake, train-line, and steam-line.

In other words, the significance of our estimates of comparative operating costs is that the results, viewed in connection with admitted facts in respect to increased earnings, indicate that a general electrification of important railway divisions, and even of trunk lines, is coming much more rapidly than has been realized, even by electrical engineers; and the lesson to be drawn from this conclusion is that we must standardize as promptly as possible everything essential to convenient interchange of rolling stock.

As regards multiple-unit control equipment, to which Mr. Sprague refers, it will be absolutely necessary to standardize this, at least so far as the train-line connection is concerned, if the time should arrive when freight trains are to be operated by electric locomotives located at intervals throughout the train.

Undoubtedly this possibility now appears remote, by reason of the fact that it would call for a general equipment of the freight cars used by all railways in the United States. It is precisely by this method, however, that the greatest possible advantages of electrification might be obtained. The enormous gain resulting from the ability to operate freight trains of any desired length without increasing the strain on draft-gear, and by a system permitting instant and effective train control at the will of the motorman on the leading locomotive, is obvious to every railway engineer or operator; and it is probable that in no other way could the ability of some of our trunk lines to handle the freight traffic which to-day is overcrowding their existing track facilities be more economically increased. Not many years ago railway operators, in general, regarded the proposition that freight cars be supplied with air-brake equipment as an impracticable dream; to-day the supposed dream is a reality in respect to more than 85 per cent. of this class of rolling-stock equipment. Similarly the idea of equipping all cars with automatic couplers was opposed as impracticable, but to-day such couplers are in general use. In view of these facts, and of the enormously valuable results which might be attained in the case of many trunk lines by employing the multiple-unit system, we contend that the argument in favor of the selection of a standard system of electric supply for railway operation is materially reinforced by the possibility that multiple-unit control may be used in the not very distant future in the operation of freight trains.

It is suprising to find Mr. Armstrong and a few other engineers opposing the idea of standardizing ordinary railway practice. The explanation of their attitude must be found either in the fact that they have inferred more than was intended by our use of the word "standardization," or that they have failed to realize an adequate general view of the railway problem which confronts electrical engineers.

Our paper proposed that standards of practice be agreed upon in respect to: *a*, location of third rail; *b*, location of overhead conductor used with single-phase alternating-current systems; *c*, frequency of alternating traction systems. We remark also that it is clearly desirable but probably less easy to agree upon a standard system of multiple-unit control for train operation.

As reported in the stenographic notes of the discussion, Mr. Armstrong said:

It is not a case of types of apparatus, or a question of frequency. Each case has to be considered by itself. In ten years from now we will still be disputing over the question of frequency, alternating-current or

direct-current operation. Looking back on the history of the steam locomotive, we have no standard. You can talk to the representatives of the different roads, the master mechanics and different engineers, and they have their own ideas about various matters in connection with their locomotives. * * *

Undoubtedly ten years from now the master mechanics and engineers of electrically operated railroads will still have their own ideas about various matters in connection with their locomotives. As regards all things essential to interchange of rolling stock, however, it is safe to assume that practice will be uniform; and the earlier uniformity is attained, provided that system best fitted to survive is selected, the better for all concerned.

The question whether it be wise or unwise now to agree to set aside as inadequate for the solution of the general railroad problem all direct-current systems, depends upon the question whether we now possess adequate knowledge of the possibilities and limitations of the contrasted systems. It is our contention that such knowledge is now available.

In 1890 the standard frequency of 60 cycles was chosen for lighting purposes. This choice was based upon knowledge certainly not more complete in respect to the requirements of the field of use, and the limitations and possibilities of apparatus applicable thereto, than is now available to enable us to make a wise choice of frequency for railway apparatus. In 1890, 60 cycles was not a case of the survival of the fittest. As a matter of fact, when it was chosen as the standard frequency to supersede the higher frequencies previously in use, it had never been embodied in a commercial plant in actual operation. Nevertheless it appears to have withstood successfully the test of time.

Similarly in 1890 the Westinghouse company selected as standard for work in which synchronous converters were to be employed extensively, the frequency for 30-cycles. About two years later, and before any important plants using 30-cycles had been installed, this was changed to 25-cycles, owing primarily to the fact that the Niagara Falls Power Company had arranged to install turbines operating at 250 rev. per min.—a speed which did not permit the development of 30-cycle current by alternators directly connected to the turbine shafts.

The frequency, 25 cycles, when adopted for the Niagara installation, was not selected as the survival of the fittest among a number of alternative frequencies preferred by various engineers and experimented with in commercial service at the expense of the purchaser. At the time it was chosen, knowledge of the facts essential to a wise choice was far less exact and comprehensive than to-day is our knowledge of the considerations which should enable us to predetermine and select that frequency which is best fitted to survive in railway service.

In his exceptionally valuable contribution to the discussion, Mr. H. M. Brinckerhoff takes the position that the essential condition of interchangeability of through equipment does not prevent the selection, locally, of a variety of motive power systems:

Provided the present degree of standardization common in steam railway practice is adhered to.

The question is very important, and it is a fortunate fact that electric rolling-stock equipment offers many interesting possibilities of operation over lines supplied with electric motive power of various types. Such operation, however, as illustrated by the equipment of the New York, New Haven and Hartford Railroad, which is adapted not only to the 11,000-volt single-phase overhead system chosen by that company, but also to the direct-current third-rail system of supply used in the Forty-second Street terminal, implies, necessarily, a degree of complication expensive, and, from the operating standpoint, very undesirable.

If some of our railways are to use 6,600-volt overhead trolley systems of supply, others 11,000-volt systems, still others 1,500-volt direct-current systems, 600-volt third-rail systems, and any other systems which ingenuity can suggest, no conceivable complication of rolling stock equipment will permit operation of motive-power units over the railway lines of the country as a whole.

As regards the necessity of standardization in order to avoid confusion and loss as the zones of electrification of our railway systems are extended, the following considerations, not specifically mentioned in the paper or in the discussion, and apparently overlooked by some who have discussed our paper, may be referred to:

1. The effect of consolidations. The doctrine of special treatment of individual cases of electrification now presented to the electrical engineer, if adopted, will lead to needless expense and great inconvenience in operation in cases where properties equipped with different systems may be consolidated at some future date. The same is true in case of a transfer or sale of a section of line by one railroad property to another.

2. In emergency, in case of accidents blocking the line, our steam railways not infrequently send their trains to destinations by using lines belonging to neighboring railways under different management. If one line is to use the 1200-volt direct-current system, and another the alternating-current system, such accommodation will be impossible.

3. At junction points and terminals the use of different systems in permitting interchange of rolling stock is in many cases practically prohibitive. Every terminal in the city of Chicago is in use by two or more trunk-line railways, and in such a case as this obviously uniformity of systems, frequency, etc., is essential.

It appears unnecessary to elucidate further the reasons which from an operating standpoint argue so strongly against the idea of special solutions of individual cases. Every experienced railway man will recognize their force without argument.

It has been suggested that the adoption of a standard system of supply for railway lines may retard progress by limiting, or checking, the spirit of emulation and competition of inventors and engineers. This question, it will be noted, is not raised by our suggestion that the frequency, 15-cycles, be adopted as a standard for alternating-current railway work. Obviously the opportunities for improvement and development are quite as great at 15 cycles as they would be at 25 cycles.

The question is pertinently raised by our expressed opinion, that for a general solution of the broad problem of railway electrification only alternating-current systems are deserving of serious consideration, and those who believe that direct-current systems may be capable of development to a point which will make them, or one of them, effective and satisfactory for the solution of the general problem, are justified in making the point referred to. For ourselves, the arguments in favor of the alternating-current system are such as justify the setting aside of direct-current systems and concentration of effort in the prompt standardization and more rapid development of the alternating-current system, which, by its essential characteristics, is obviously best adapted to the solution of the general problem.

It is pointed out that the existence of a certain number of 25-cycle generating plants, sometimes owned by the railway, and possibly available as a source of power supply for emergencies, is a consideration of weight in some instances. The answer to this is that undoubtedly in each specific case of contemplated electric installation the problem should be carefully studied with reference to local as well as to more general considerations, and it is not impossible that in some cases the weight of local considerations may justify departure from the general standard. This obvious fact, however, does not argue against the general adoption of a standard. So far as it has weight, undoubtedly it argues in favor of 25 cycles, but it in no way supports the position, which some have taken in opposition to our contention, that a standard should be promptly agreed upon.

One or two contributers to the discussion have criticised our use of the *Statistics of Railways*, issued by the Interstate Commerce Commission, on the ground that these reports are not reliable. For our purposes and as used by us they are, on the contrary, entirely adequate and convincing. The fact that they are not complete in detail does not materially affect their value for our purposes, as we are dealing with the ratio of the individual items to the total operating expense. Obviously, the ratio of saving indicated by our calculations cannnot be applied to individual roads indiscriminately. It could be so applied only to a railway which might happen to represent exact average conditions. It is hardly necessary to explain that the management of any railroad contemplating the adoption of electricity must study the problem with reference to its detailed and carefully analyzed conditions and costs of operation. In attempting to fix comparative costs of the various items of operating expenses, moreover, we have used not only the reports of the Interstate Commerce Commission, but the annual published reports of many railroads and also detailed unpublished reports kindly furnished by officials of the Pennsylvania, the Erie, Missouri Pacific, Denver and Rio Grande, and other railroad companies.

One or two critics have considered it unfortunate that, in connection with our calculations of comparative operating costs, we did not include an estimate of the capital charges involved in the case of electric equipment. This omission was deliberate. To include capital charges is in no way essential to the purposes of our paper, and to do so would raise questions tending to divert attention from the object which we had in view. For example, the treatment of the question of " depreciation " is one which might well become the subject of a paper of considerable length, and the methods of financing railroads in America are so far from having attained a standard of practice that we have deemed it best to show only the calculated saving in operating costs per mile of line as compared with interest on the cost of required electric equipment, exclusive of rolling stock.

Several gentlemen who discussed the paper expressed the opinion that, while the apparent reduction in operating costs, as shown by our analysis, is 18% (exclusive, of course, of capital charges), roads in general will not make the change in order to effect this economy, but will be influenced to a much greater extent by the increased earning power resulting from the change. This consideration is not new to the authors. One of them recalls pointing it out to the president of the Manhattan Railway Company some ten years ago.

The results of our estimates, in which we have endeavored to compare the operating expenses under a system of electric traction with the actual grand averages of operating expenses throughout the United States, are more favorable to electric traction than we had anticipated when this work was undertaken, but it is hardly necessary to point out that no competent engineer would infer from these results that every railway in the United States is likely to be electrified in the immediate future. The possible economies effected by such substitution, however, when considered in connection with the increase in earning power to be anticipated, leads to the conclusion that the electrification of our railways is destined to be carried on much more rapidly than is realized to-day by the average engineer, and emphasizes the necessity of prompt standardization of everything essential to convenient exchange of rolling stock.

The communication from Mr. A. H. Babcock is interesting, but has no particular bearing on the general railway problem under consideration. He objects to our expressed opinion that alternating-current equipment is the only class of equipment deserving serious consideration in connection with the general problem of heavy traction. He has found an alternating-current installation comprising three passenger cars and two work cars weighing about 40 tons each. These cars are operated by 25-cycle single-phase current obtained from a 60-cycle source through the interposition of a motor-generator set. The energy is metered and paid for on the three-phase side of this set. The conditions of service are in no way defined, but the limited equipment suggests a very low load-factor and consequently very low efficiency of conversion from 60 cycles to 25 cycles.

Mr. Babcock asserts that if the 1200-volt direct-current system were used the energy per ton-mile would be 30% less. This is easily conceivable, particularly if Mr. Babcock has based his calculations upon the use of synchronous converters in this case as against a motor-generator set as in the other. The case to which he refers is obviously one of ordinary interurban trolley operation, with frequent stops; and in this field many cases of direct-current practice might be adduced in which the energy consumed per ton-mile, owing to special and local conditions, is comparable to that which he has found in this particular instance of alternating current. Obviously, the point which he attempts to make is not one which will materially influence general conclusions in respect to the problem of heavy traction. Mr. Babcock asserts his intention:

To reserve the right to choose for every specific case the type of apparatus best adapted.

In the interest of the great railway property for which he is retained as electrical engineer, it is to be hoped that he will bestow further consideration upon this very important question of engineering policy. The 1200-volt direct-current system is probably capable of attaining excellent results in a limited field, such as the electrification of a terminal, but generally speaking the system adopted for the electrification of a terminal should be one adapted to future extension to the railway division or even to the trunk line.

The substantial accuracy of the general results of our calculations relative to reduction of operating expense resulting from the substitution of the electric motor for the steam locomotive has not been seriously questioned. Our estimates of the aggregate output and cost of power-house equipment which would be required for the operation of the entire system of the United States rest primarily upon certain stated assumptions as to length of line supply from a given power house, and to this fact some reference has been made in the discussion.

We therefore avail ourselves of the opportunity to supply, in the form of an appendix to our paper, an explanation of methods used in determining power-house output and load-factor, a statement relative to the effect of resistance due to grades, and also a brief statement relative to recuperation.

Clarence Renshaw (by letter): Mr. A. H. Babcock has contributed to the discussion of the Stillwell-Putnam paper by letter. He describes his observations on a visit to a single-phase electric railway. I have been intimately conversant with the operation of this railway through engineering reports from those who have had charge of the installation and initial operation of the apparatus.

Mr. Babcock has neglected to mention a number of facts which materially affect the conclusions which should be drawn from the material which he does give. To overcome certain specific faults in insulation and workmanship, which developed in operation, the motor armatures were rewound. A number of the men whom Mr. Babcock mentions were presumably engaged upon this work, as the normal number which is now employed is very much less.

During the month to which it is presumed Mr. Babcock refers, the total car-mileage of the road was 15,797 miles, including trailers and freight cars. The total motor-car mileage was only 13,009 miles, or approximately 87 miles per car per day. The cars were operated at a schedule of approximately 19.5 miles per hour between terminals, so that the daily mileage of a car represents only about 4.5 hours actual running. Under such circumstances, the load-factor in necessarily very low and the power consumption, on a car-mileage basis, from the 60-cycle circuit, where the power measurements referred to by Mr. Babcock were taken, is necessarily high. This was further accentuated by the fact that, at the time of his visit, polyphase generators which were not well adapted for this service were used for supplying single-phase current. These have since been modified by rewinding them for single-phase operation. Since this modification, one generating set is ordinarily ample for operating the road, whereas two motor-generator sets in parallel were usually required during the month to which Mr. Babcock refers. Consequently, the conversion losses in the sub-station were abnormally high.

Even the figures which are given—153 watt-hours per ton-mile—are not unusual when the load-factor is low. I have a test giving the actual measurements on a road through synchronous converter sub-stations. Three cars of 28 tons operating on this road required 202 watt-hours per ton-mile during the month of January, 1906. This illustrates the high power requirements per ton-mile when there are but few cars and the load-factor is low. A comparison of these two examples shows the marked advantage of single-phase operation under such conditions.

It may be noted that the company operating the road to which Mr. Babcock refers has given a favorable judgment on the operation of the road, as indicated by considerable extension and an increase of more than 100 per cent. in their car equipment.

A paper presented at a meeting of the Schenectady Branch of the American Institute of Electrical Engineers, Schenectady, N.Y., January 31, 1907.

LINE CONSTANTS AND ABNORMAL VOLTAGES AND CURRENTS IN HIGH-POTENTIAL TRANSMISSIONS

BY ERNST J. BERG

With a large number of the very high voltage transmission systems being planned at present, the information readily available in regard to capacity, inductance, etc., of transmission lines, is not sufficient to pass upon some of the important questions which necessarily will be brought up. Below are given, therefore, the equations from which these constants can be determined.

$$L = \frac{161}{10^3}\left[2\,{}^{n}lg\,\frac{2D}{d} + \frac{1}{2}\right]$$

where L is inductance per mile of wire (single phase or three phase) expressed in millihenrys; D is the distance between centre of wires;* d is the diameter of wire in the same unit as D.

The capacity between one wire and neutral, whether single- or three-phase circuit, is

$$C = \frac{890\,k}{10^4\;{}^{n}lg\;\frac{2D}{d}} = \frac{386\,k}{10^4\;{}^{10}\log\;\frac{2D}{d}}$$

Where C is expressed in microfarads per mile of wire against neutral, D and d in the same units as before. k is the specific inductive capacity, which for air is 1.

Neglecting the quantity $\frac{1}{2}$ inside the parenthesis in the in-

*To be absolutely accurate, D is the distance between the center of one conductor and the surface of the other.

ductance formula, which is permissible if the distance between the wires is large compared with their diameter, we get

$$L = \frac{742 \, {}^{10}\log \frac{2D}{d}}{10^8}$$

$$C = \frac{386 \, k}{10^4 \, {}^{10}\log \frac{2D}{d}}$$

We see at once that the product of inductance and capacity is constant, regardless of the distance between wires or their diameters; or

$$L \, C = \frac{286}{10^4}$$

where L is expressed in millihenrys, and C in microfarads, both referring to one mile of wire; or

$$L_1 \, C_1 = \frac{286}{10^{13}}$$

If L_1 and C_1 are expressed in henrys and farads; therefore, if M = number of miles of wire, we get:

$$L'_1 \, C'_1 = \frac{286 \, M^2}{10^{13}}$$

where L'_1 and C'_1 are the total inductances and capacities of each wire in the system.

The natural period; that is, the frequency at which the system oscillates due to its own constants, depends only upon the inductance and capacity, as long as the resistance is reasonably low so that oscillation can occur.

With concentrated inductance and capacity, it is expressed as $f = \frac{1}{2 \pi \sqrt{L \, C}}$.

With distributed capacity, Steinmetz has shown that the frequency is expressed by $\frac{1}{4 \sqrt{L \, C}}$ where L and C are given in henrys and farads.

Since, as shown above, the product $L\,C$ is independent of distances of conductors or their size, it is therefore evident that the natural frequency is also independent of these constants and depends only upon the distance of transmission.

Generally, when discussing the natural frequency of a line, we mean the frequency which the line would have if charged above the ground potential by atmospheric influence, and suddenly relieved of the charge. In this case we should consider the inductance and capacity against ground. These are found by the following equations:

$$L_0 = \frac{2\times 161000\,M}{10^6}\;{}^n lg\,\frac{4\,D}{d}$$

$$C_0 = \frac{178000\,M}{2\times {}^n lg\,\frac{4\,D}{d}\;10^{12}}$$

where L_0 and C_0 are given in millihenrys and farads; M is number of miles of wire; D is distance of the conductor above the ground; and d is the diameter of the conductor.

The frequency so obtained is, of course, the same as when using the inductance and capacity between wires. A ready way to determine the natural frequency of the line is to calculate it from the fact that the length of the line constitutes one-quarter of the wave, so that, since the velocity of electrical propagation is the same as that of light, the frequency, for instance, for a line 150 miles long, is

$$\frac{187000}{4\times 150} = 312 \text{ cycles.}$$

It is, of course, important that the fundamental frequency, or that of any prominent harmonic, shall not be the same as the natural period of the line, since, when that is the case, destructive resonance phenomena are likely to happen.

It has hardly been appreciated that, of the higher harmonics, the third cannot exist in a three-phase line, although it is the most prominent in the generator. (Unless the YY connection of transformers is used, which is not good engineering. But even in that case the triple harmonic appears only in the potential against ground, never in the voltage between the lines.) We need, therefore, consider the fifth harmonic more particularly;

so for instance, in a line 150 miles long, the frequency of the fifth harmonic is obviously five times that of the fundamental. Consequently, in a 60-cycle circuit we have 300 cycles, which is very closely the same as the natural period of the line. 60 cycles would therefore not be feasible unless the line were artificially loaded.

It is perhaps opportune to give an average value of inductance and capacity in high-potential lines. By assuming the inductance as 1.75 millihenrys per mile of wire, and a capacity of 0.0165 mf. per mile of wire, an error of more than 15% can not well be made, when referring to transmissions of from 30,000 to 100,000 volts and conductors from 0.25 in. to 1 in. in diameter. Since, furthermore, in these high-potential lines it is always necessary to have at least two lines in parallel, it is well to bear in mind that in doing so the ohmic drop is the same, whereas the inductive drop is one half and the charging current is twice as large as with one line. The reactance corresponding to certain inductance is expressed by the following formula:

$$\text{The reactance } x = \frac{2\pi n L}{10^3}$$

The charging current I_0 is expressed by the following formula:

$$I_0 = \frac{2\pi n C E}{10^6}$$

where n is the frequency, L is the inductance in millihenrys, C is the capacity in microfarads, and E is the voltage to neutral.

If L and C correspond to one mile of wire, x and I_0 obviously also refer to the same.

It is interesting to note in connection with this, that, since the voltage to the neutral in a single-phase system is one-half and in a three-phase system = 0.58 of the line voltage, the charging current per wire for a given line voltage is 16% greater in a three-phase system than in a single-phase system.

With the help of these constants, we can now readily calculate some of the abnormal phenomena.

1. Abnormal Voltage and Current in Opening or Closing a Circuit

To determine this it is necessary to calculate the stored energy. The energy in joules (watt-seconds stored electromagnetically) is $0.5 L I^2$. The energy in joules stored electrostatically is $0.5 C E^2$. Where L and C are given in henrys and farads.

Therefore, if the line is disconnected at the moment the current has a given value I, energy is stored which must be spent in some way. The only path for the current is formed by the line capacity, therefore the line becomes charged to a certain voltage depending upon its constant; next it discharges through the inductance of the line, so charges again, etc. A current oscillates in the system until the energy is dissipated by the resistance of the line. Therefore, with low resistance there will be many surges; with high resistance, few.

The two energy equations become:

$$0.5 L I^2 = 0.5 C E^2 \qquad \text{thus} \qquad E = I \sqrt{\frac{L}{C}}$$

or

$$I = E \sqrt{\frac{C}{L}}$$

Substituting the average values given above we get

$$E = 325\, I \qquad \text{and} \qquad I = \frac{E}{325}$$

We see from this that the electromotive force induced on opening a circuit is independent of the length of the line.

Opening a switch at full-load instantaneous value of current. In a 60,000 volt transmission of 20,000 kw. the rise will be 60,000 volts per phase; consequently, the total voltage will be almost trebled. Interrupting the charging current will, however, give a very low rise, since the current is so small that there is no difficulty to be anticipated by disconnecting such line.

But, in connecting the line the moment the electromotive force is maximum, *a very considerable instantaneous current will flow*, namely, $\frac{E}{325}$. Consequently, with a voltage between the lines of 60,000, when the voltage per phase is 34,700, the current would be about 100 amperes; whereas the charging current is probably about 10 amperes.

It is also evident from this that we must use such circuit-interrupting devices as open when the current is small, preferably zero. From a great number of oscillograms we have found that our oil-switches break at zero value of current, and we find that no rise in voltage will occur when they are used. Indeed, from some oscillograms that have been made in which the circuit has been opened by air-switches, it would seem as if, when the line voltage is sufficiently high, the arc will keep on until the current value is decreased to such a small amount that, at the time of break, there is no serious rise in voltage. A gust of wind might, however, cause the circuit to be broken when the current is large, when, of course, a rise would take place.

It is also interesting to note that, since the rise in voltage is independent of the line voltage, we are likely to have relatively worse stresses with low-voltage systems; although, to be sure, if the voltage is sufficiently low, the likelihood of the current being interrupted at any point but the zero point is slight. These phenomena of large currents and high voltages in a line apply to grounded as well as non-grounded systems.

2. Abnormal Currents and Voltage Stresses in Connecting a Transformer to a System

Outside of the ordinary stresses between adjacent turns, and winding against ground, there is a very high potential stress between the first few turns of the primary winding when the transformer is connected to a live line. The very first instant that connection is made, one part of the winding is raised to line potential, whereas the rest of the winding is still at ground potential. Consequently, the full voltage exists between the first turns. It is therefore necessary to insulate the first few turns extremely well as compared with the succeeding turns.

It is also evident that when being thrown on the line the transformer may sometimes take a much *larger current than the normal exciting current.* If the transformer when last used was disconnected from the circuit when the flux was at its maximum value, the density will decrease after a short time to about 70% of the maximum value, as can be seen by studying the hysteresis loop. If now the transformer is connected to the circuit at such a point of the potential wave as requires increasing flux, the magnetizing current must be very large, since the iron is already at 70% of the saturation point. At the next instant, however, the magnetic condition will adjust itself, so that the current is normal. The first large current is, of course, of very short duration, but might well be twenty times the exciting current or two or three times full load.

3. Abnormal Voltage in a Non-Grounded System

There has been a great deal of discussion about grounding or not grounding the neutral of transmission lines. For the very high voltages considered at present, I doubt very much if anything but a grounded system can be considered. When operating at such very high voltages, the difficulties of protecting a transmission, and indeed of building and installing the apparatus, increases materially. In the wiring and line itself, a minimum size of conductor, which already is quite large, is necessary in order to prevent corona effects. This corona involves loss in power and is a likely producer of nitric acid, which is detrimental to adjacent insulation.

Investigation of corona effects in parallel conductors—

Let I = current flowing in conductor.

Magnetomotive force per unit length in zone $= \dfrac{I}{2\pi x}$

field intensity $= 4\pi \times$ m.m.f. $= \dfrac{4\pi I}{2\pi x} = \dfrac{2I}{x}$

and magnetic flux in the zone $= \dfrac{2I}{x} \times l \times dx$

thus total magnetic flux between wire and zone

$$= \int_r^R 2Il \frac{dx}{x} = 2Il\,{}^{n}lg\,\frac{R}{r}$$

neglecting flux inside of wire,

thus $L = \dfrac{\text{flux}}{I} = \dfrac{2l}{10^9}\,{}^{n}lg\,\dfrac{R}{r}$ henrys.

Therefore we can write the electromotive force corresponding to this flux $E = k\,{}^{n}lg\,\dfrac{R}{r}$

The flux between x and R is

$$L_x = 2l\,{}^{n}lg\,\frac{R}{x}$$

and corresponding electromotive force

$$E_x = k\, {}^n lg \frac{R}{x}$$

therefore,

$$\frac{E_x}{E} = \frac{{}^n lg \frac{R}{x}}{{}^n lg \frac{R}{r}}$$

The potential gradient is

$$\frac{d\,Ex}{d\,x} = \frac{1}{x} \frac{E}{{}^n lg \frac{R}{r}}$$

Therefore the potential gradient at the surface of the conductor is $S = \frac{E}{r\, {}^n lg \frac{R}{r}}$ and at the inside of the outside sphere representing ground potential:

$$S_1 = \frac{E}{R\, {}^n lg \frac{R}{r}}$$

The stress is therefore as much greater at the conductor than at the shell as R is larger than r.

Obviously, when applying this to parallel conductors, we should use as R one-half the distance between conductors, and as E the voltage to neutral.

From a number of experiments, it looks as if the maximum stress that can be permitted in air is 100,000 volts per inch. Thus $S = 100{,}000$. Based upon this value we obtain the following voltages of corona:

	No. 10 B&S	No. 4 B&S	No. 000 B&S		
	$r=0.05$ in.	$r=0.10$ in.	$r=0.20$ in.	$r=0.5$ in.	$r=1$ in.
R	E	E	E	E	E
5 in.......	23000	39000	64000	115000	161000
10 in.......	26500	46000	78000	150000	230000
20 in.......	30000	53000	92000	184000	300000
50 in.......	34500	62000	110000	230000	390000
100 in.......	39000	69000	124000	264000	460000
500 in.......	46000	85000	156000	345000	620000

We see, for instance, that in a 60,000-volt ungrounded system, where the potential to ground can readily be 64,000 volts, the smallest wire that could be used in carrying the line through a wall having a hole 10 in. diameter is No. 000 B. & S. Any smaller wire would give corona affects. No. 4 B. & S. would,

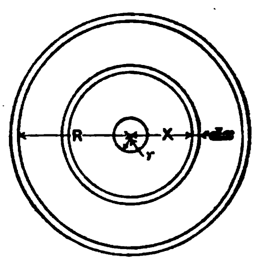


Fig. 1

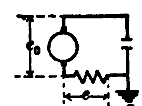


Fig. 2

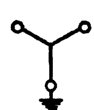


Fig. 3

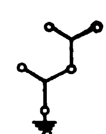


Fig. 4

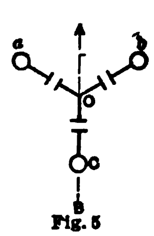


Fig. 5

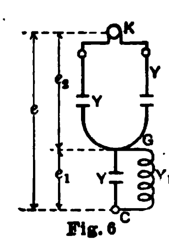


Fig. 6

at the same voltage, require a hole of about 100 in. diameter.

It is also evident that if, as often is the case, the high-potential bus-bars are carried in compartments within but a few inches of ground, we must expect corona effects, especially where there is a sharp bend in the wires, whenever for some reason the voltage is increased above normal. Incidentally, we see the desirability of using large round bus-bars instead of small rectangular bars.

The dielectric strength of insulating materials is greater than that of air, so for instance, from a number of experiments, it seems that insulation of strips of rubber has a strength of about 350,000 volts per inch; oil of about 200,000 volts per inch; and varnished linen or paper between 250,000 and 300,000 volts per inch. It is evident from this that we cannot subject this insulation to higher stress than this without causing deterioration. In the following table is calculated how much insulation is necessary with various sizes of wires and materials of various dielectric strengths.

It is interesting to see that even with rubber insulation we should insulate a wire of 1 in. diameter with about 8 in. of insulation if subjected to 500,000 volts potential to ground. At 300,000 volts we should need 2.27 in. of insulation.

At 150,000 volts we should need 0.68 in. of insulation.

At 60,000 volts we should need 0.20 in. of insulation.

This would give no safety factor whatever. At 500,000 volts the smallest wire that can be insulated is about 1 in. in diameter; at 300,000 volts, 0.5 in. in diameter; at 150,000 volts, 0.20 in. diameter; and at 60,000 volts, a very small wire.

But limiting the stress to 140,000 volts per inch we find that:

For 500,000 volts the wire should be more than 2 in. in diameter.
300,000 volts the wire should be about 2 in. in diameter.
150,000 volts the wire should be just a little less than 1 in. in diameter.
60,000 volts the wire should be 0.20 in. or No. 000 B. & S.
30,000 volts the wire should be 0.10 in. or No. 10 B. & S.

It is evident from this that it is very essential to keep the maximum voltage down when considering voltages from 60,000 to 100,000 volts. By grounding the neutral we limit this to 58% of the voltage between lines.

Apparent erratic voltage between terminal and ground. When measuring the voltage between any of the terminals and ground, it is observed that it is not definite but depends, essentially, upon the resistance in the circuit. This, however, is natural, as can be seen from the following reasoning:

Let e be the voltage from terminal to ground; that is, the voltage across the resistance.

THICKNESS OF INSULATION IN INCHES WITH VARIOUS STRESSES AT SURFACE OF CONDUCTOR

r	$S=70,000$	$S=140,000$	$S=200,000$	$S=350,000$
	500,000 VOLTS TO GROUND			
0.05	5×10^{59}	5×10^{28}	2506×10^{16}	1256×10^{6}
0.10	1×10^{29}	3163×10^{10}	708×10^{6}	158500
0.20	6325×10^{10}	1125×10^{3}	53220	251.6
0.50	792400	628.9	73.46	8.189
1.00	1258	34.49	11.16	3.169
	300,000 VOLTS TO GROUND			
0.05	7925×10^{31}	1991×10^{13}	5236×10^{7}	1377000
0.10	3981×10^{12}	1995×10^{4}	322500	324.8
0.20	3991×10^{4}	8934	3598	14.29
0.50	2623.5	35.72	9.7	2.273
1.00	71.45	7.512	3.478	1.355
	150,000 VOLTS TO GROUND			
0.05	1991×10^{13}	99760000	161800	262.4
0.10	1995×10^{4}	4666	179.8	7.1444
0.20	8934	42.07	8 283	1.502
0.50	35.72	3.755	1.739	0.677
1.00	7.512	1 918	1.112	0.535
	60,000 VOLTS TO GROUND			
0.05	1380000	263	20.04	1.488
0.10	325	7.15	1.904	0.4546
0.20	14.3	1.5	0.6954	0.271
0.50	2.28	0.68	0.4108	0.2043
1.00	1.35	0.54	0.35	0.187
	30,000 VOLTS TO GROUND			
0.05	263	3.6	0.9525	0.2273
0.10	7.15	0.752	0.34477	0.1355
0.20	1.5	0.384	0.2232	0.1041
0.50	0.68	0.27	0.1748	0.0934
1 00	0.54	0.24	0.162	0.09
	15,000 VOLTS TO GROUND			
0.05	3.6	0.37		
0.10	0.752	0.192		
0.20	0.384	0.14		
0.50	0.27	0.12		
1.00	0.24	0.11		

e_0 be the generator voltage per phase,
x = capacity reactance of the system,
r = the resistance between the capacity and the terminal.
We have then:

$$\text{current flowing} = \frac{e_0}{r + j\,x}$$

and voltage across the resistance:

$$e = \frac{e_0\,r}{r - j\,x} = \frac{e_0\,r}{\sqrt{r^2 + x^2}}$$

With a generator disconnected from any line, the charging current against ground is, of course, very slight, so that x is very large. Therefore, for moderate values of r, compared with the values of x, we see that changing the resistance does not materially change the denominator, but the voltage e is proportional to the resistance, thus there is a constant-current effect. The more resistance is put in circuit the higher is the voltage. With infinite resistance the voltage is

$$\frac{e_0}{\sqrt{3}} = 0.58\,e_0$$

Effect of slight leaks in switches, etc. Assume next that the terminal of one phase through a slight leak is connected to ground, the voltage between the other phases and ground will then be almost doubled, being $e\sqrt{3}$

If there are two sets of generators running independently, and there is a slight leak from one terminal of one to that of the other, and also a slight leak to ground, there will be at times 3.5 times as great potential to ground as when the neutral is grounded. This condition might well occur when synchronizing machines or transformers. In circuits of moderate voltage, these voltages might not cause undue stresses, but with a normal voltage of 100,000 it is quite different.

But grounding a terminal does not always give the same results. A positive "good" ground does not cause the "statics" of an arcing ground. The reason is as follows: no matter how or where the circuit is made, as long as there is an arc there is a circuit. Usually this contains resistance, reactance, and capacity.

With a positive ground, the frequency impressed is that of the generator, and it would be but a chance if the values of capacity and reactance should be such as to cause more than slight resonance. With an arcing ground, on the contrary, the circuit is disconnected, and can, and will, oscillate at its own frequency, which is such as to give resonance, which means such as to give the maximum voltage and current.

To be sure, if, as in our lightning-arrester, the oscillations are damped out by a judicious use of resistance, no dangerous voltages occur, but, with accidental slight leaks or grounds, it is quite different. The voltages from ground might then be almost anything. Some protection is, of course, to limit the rise by grounded neutral.

In an ungrounded system, grave danger exists under almost all conditions of disturbed service. For instance, a lightning stroke disables some apparatus so that inductance is introduced in the accidental ground. Before the accident we had a perfectly balanced system, where the neutral, or ground potential, is symmetrical in reference to the line conductors, and governed entirely by the ground capacities represented in Fig. 5 as three condensers. If now one line is grounded by an impedance, the neutral will be displaced along line *AB*.

For convenience in demonstrating, we can change the diagram to a single-phase system, making due allowance, however, in the final conclusions—we will reconstruct the system to another shown in Fig. 6.

Let Y represent the admittance of each condenser and Y_1 the admittance of the impedance connected to ground, which is electrostatically the same as connecting impedance between the line and the point of neutral potential.

We have then the joint admittance between C and $G = Y + Y_1$, therefore the joint impedance $= \frac{1}{Y + Y_1}$. The joint admittance between G and K is $2\,Y$, therefore the corresponding impedance is $\frac{1\,Y}{2}$. The total impedance is therefore:

$$\frac{1}{Y+Y_1} + \frac{1}{2\,Y} = \frac{3\,Y+Y_1}{2\,Y\,(Y+Y_1)}$$

The current is therefore, $\frac{2\,e\,Y\,(Y+Y_1)}{3\,Y+Y}$

$$E_1 = \frac{2\,E\,Y\,(Y+Y_1)}{3\,Y+Y_1}\;\frac{1}{Y+Y_1} = \frac{3\,Y+Y}{2\,e\,Y}$$

$$E_2 = \frac{2\,e\,Y\,(Y+Y_1)}{3\,Y+Y_1}\;\frac{1}{2\,Y} = \frac{e\,(Y+Y_1)}{3\,Y+Y_1}$$

$Y = g - j\,b$, where g is energy component of current; b is wattless component of the current in the condenser.

$$Y_1 = \frac{r}{Z^2} + \frac{j\,x}{Z^2}$$

where r is energy component of electromotive force and x is wattless component of electromotive force.

We will assume that there is no leakage in the line, therefore $g = 0$ and $Y = -j\,b$.

We will also assume that there is no resistance, but only reactance in the accidental ground of the line.

Thus $r = 0$ and $Y_1 = j\dfrac{1}{x}$

We get then $e_1 = \dfrac{2be}{3\,b - \dfrac{1}{x}}$ and $e_2 = \dfrac{\dfrac{1}{x} - be}{\dfrac{1}{x} - 3\,b}$

If x_1 = condenser reactance, then

$$e_1 = \frac{2\,e\,x}{3\,x - x_1} \quad \text{and} \quad e_2 = \frac{x_1 - x}{x_1 - 3x}\,e$$

1. Ground made by infinite reactance. (No ground.)

We have then $x = \infty$, $e_1 = \dfrac{2e}{3}$ and $e_2 = \dfrac{e}{3}$

Therefore in our diagram, the neutral lies at O, and the ground is symmetrical in reference to the three lines.

2. $\dfrac{1}{x} = b$, thus $e_2 = 0$, and $e_1 = e$

In this case the neutral lies midways between the two other conductors, and 0.870 from the grounded line.

3. For $\frac{1}{x} = 3\,b$. e_1 and e_2 both become infinite showing that, under such condition, the system would be subjected to infinite potential.

b is the susceptance of the condenser, therefore $\frac{1}{b}$ is the condensance or capacity reactance. We see, therefore, if one line is grounded by a reactance of one-third the condenser reactance, the system is subjected to infinite stresses, even at normal frequency. Energy losses, however, limit the value considerably.

We might, for instance, in such accident have the line conductors 3 ft. apart and separated by 6 ft. from any wall, and yet upon inspection find that each line was connected through flames to the wall, but that there was no flame between the conductors.

Obviously, if the impedance had been grounded through an arc, high voltages would have resulted, almost independent of the relation between capacity and inductance. The remedy, in that case, would have been a grounded neutral.

Static stresses of generator and transformer windings introduced by accidental ground. A ground might well cause serious breakdowns by the static effect only. Consider, for simplicity's sake, a single-phase system, consisting of a generator, a transformer, and a line.

There is, of course, a certain capacity between primary and secondary of the transformer winding. There is also a certain capacity between the generator winding and the frame, which is the ground.

With the two lines symmetrical and well insulated, there is a balanced capacity against ground, thus the high-potential coils of the transformer are at ground potential; consequently, the low-potential coils and the armature windings are also at ground potential. If now one line becomes grounded, the potential of the coil against the ground is obviously one-half of the line voltage. Consequently, the low potential winding acting as the other plate of the condenser, is also charged to a certain potential, the magnitude of which depends upon the relative capacity of the generator winding to ground and the capacity between the transformer windings. If they are the same, then one-half of the line voltage is divided equally between the primary and secondary of the transformer and the generator winding to ground. If the capacity between transformer coils is twice that of the generator winding against ground, then the generator winding will be subjected to $\frac{2}{3}$ times $\frac{1}{2}$, or $\frac{1}{3}$ of the line potential.

We can readily see from this, when a ground occurs, how the generator might possibly break down, and how in such cases it is important to get at all facts. The remedy is a system with grounded neutral.

How to ground the neutral. Must we ground the neutral perfectly, or can we use resistance or reactance? Without going further into the question, it is evident from the preceding instance that a reactance in the ground connection is not advisable; there are, indeed, several good reasons, but resistance needs some further discussion.

In moderate voltage systems, say up to 15,000 or 30,000 volts, perhaps even higher, resistance is feasible, since under normal operation the stresses are those of a grounded system. When, however, one line is grounded and the current is limited by this resistance, its function as a neutral ceases, and, as far as voltage stresses are concerned, the system might as well not be grounded. It saves, however, a shutdown and permits the systems being rearranged without interruption of service. For transmissions of very high voltage I believe, however, that a good solid ground is best, since any considerable rise might strain the insulation above its safe limit.

Discussion on "Line Constants and Abnormal Voltages and Currents in High-Potential Transmissions".

Frank G. Baum (by letter): The writer gave approximate rules for determining the rise in voltage, due to interrupting a given current, at a meeting of the Pacific Coast Transmission Association in 1902 and before the Electrical Congress at St. Louis in 1904. The rule given was

$$E = 200\,I$$

where I is the actual value of the current in amperes at the time of interruption. This does not exactly agree with the rule given by Mr. Berg. The important fact shown is that the higher the voltage the smaller the excessive strains due to switching, etc. The approximate rule will undoubtedly explain many things happening on lower voltage systems that are charged to lightning, etc.

Surges or resonance occur in any transmission system independently of how the transformers are connected. The statement that certain transformer connections eliminate resonance should be qualified, as it is liable to be wrongly interpreted.

A paper presented at the 215th Meeting of the American Institute of Electrical Engineers, New York, March 1, 1907.

ALTERNATING-CURRENT ELECTROLYSIS*

BY J. L. R. HAYDEN

A. Contents

The development of the single-phase railway motor lead to the introduction of grounded alternating-current systems, in which the current is returned over the rail. With rail-return, necessarily more or less current strays through the ground, reaching gas and water pipes, lead cables, etc. When using direct current for railroading, lead cables, etc. are protected against electrolytic corrosion by connecting them to the negative terminal of the circuit, so that the stray current enters the cable from the ground, but does not leave it; that is, the cable is always at a negative potential against ground. With alternating currents this method of protection evidently is not feasible, since the potential difference constantly reverses.

An investigation was therefore undertaken to determine whether, and to what extent, alternating currents passing between any metallic conductor and the ground would produce electrolytic corrosion. These tests were started in the spring of 1906. and carried on practically continuously throughout most of the year.

These tests were extended to the investigation of different current-densities and different frequencies. First, several series of tests were made with diluted solutions of such salts as may be expected in the ground. Then different kinds of

* In arranging this investigation, laying out the tests, and working up their results, and in recording them in the present paper, I am greatly indebted to Dr. Charles P. Steinmetz, in whose laboratory the investigation was made, and to the General Electric Co., which supplied the means and facilities for carrying out the work.

soils were investigated, and then tests made on a typical soil by adding different substances—carbonates, sulphates, organic matter, etc., and noting their effects. Ultimately, the possibility of protection against electrolytic corrosion was investigated.

In the first sets of tests, lead and sheet-iron were investigated; in the last tests only lead plates were used, as the first tests proved the relative unimportance of iron.

B. Method of Test

Plates of 1.25-in. width and 2.5-in. height were used; that is, with about 6.25 square inch exposed area, of very thin and pure sheet-lead, so-called "test lead." These plates, after cleaning, were weighed on a chemical balance, reading accurately to about 0.5 milligrammes, then immersed in the electrolyte or the soil, the current passed through for a time varying from 60 hours to 390 hours; then the plates were taken out, washed with water and diluted acetic acid, (about 10%) dried. and again weighed. The total weight of the plate was about 6 grammes, and the amount dissolved usually several hundred milligrammes. Check tests showed that the amount of lead which can be dissolved chemically by acetic-acid washing does not exceed 1 or 2 milligrammes. The iron plates were cut to the same size, from transformer iron of 10 mils thickness, having an average weight of 2.5 grammes. They were treated in the same manner, except that very dilute hydrochloric acid was used for washing.

As containing vessels, glass tumblers were used of about 250-cu. cm. volume, and the soil was kept moist by replacing the evaporation with distilled water. A number of tumblers were connected in series with an alternating-current circuit, and immersed in a water bath. The same number of tumblers with similar contents but not connected to the electric circuit were immersed in the bath, and used as a check to determine the spontaneous corrosion due to chemical action of the soil.

As source of 60-cycle current were used the lighting mains of the City of Schenectady; as source of 25-cycle current, a small inverted single-phase converter changing from direct to alternating current; as source of direct current, a mercury-arc rectifier operated from the 60-cycle circuit.

To give quantitative values, all the results are expressed in percentage of direct-current electrolysis; that is, the amount

TABLE I.

MAY 1 TO JUNE 18, 1906. LEAD PLATES. 6.25 SQ. IN. SURFACE. 1% SALT SOLUTIONS.

Electrolyte	Frequency cycles	Current amperes	Duration of test hours	Milligrammes lead dissolved per hour			% direct-current electrolysis		Ratio of total corrosion to chemical corrosion	Ratio of current to frequency
				chemical	total	electrolysis	total	electrolysis		
a	b	c	d	e	f	g	h	i	j	k
Ammonium Nitrate				2.18						
	60	0.3	60		3.14	0.96	0.271	0.084	1.44	5.0
		0.09	139		2.61	0.43	0.753	0.122	1.20	1.5
	25	0.3	150		10.65	8.47	0.918	0.737	4.88	12.0
		0.09	147		2.98	0.80	0.860	0.228	1.37	3.6
Ammonium Carbonate				0.102						
	60	0.3	60		2.14	2.04	0.184	0.176	21.0	5.0
		0.09	139		0.41	0.31	0.118	0.088	4.0	1.5
	25	0.3	150		6.70	6.60	0.578	0.570	65.8	12.0
		0.09	147		0.83	0.73	0.240	0.210	8.2	3.6
Sodium-Potassium Nitrate				0.553						
	60	0.3	63		5.05	4.50	0.436	0.390	9.15	5.0
		0.09	140		1.90	1.35	0.547	0.392	3.43	1.5
	25	0.3	150		7.57	7.02	0.653	0.607	13.70	12.0
		0.09	149		2.66	2.11	0.765	0.610	4.82	3.6
Sodium Potassium Carbonate				0.535						
	60	0.3	77		0.73	0.20	0.063	0.017	1.37	5.0
		0.09	140		0.54	0.005	0.156	0.001	1.01	1.5
	25	0.3	150		0.67	0.14	0.058	0.012	1.25	12.0
		0.09	147		0.37	—0.16	0.107	—0.046	0.69	3.6
Sodium-Potassium Chloride				0.270						
	60	0.3	78		1.42	1.15	0.122	0.097	5.26	5.0
		0.09	140		1.08	0.81	0.312	0.234	4.00	1.5
	25	0.3	150		1.46	1.19	0.126	0.103	5.41	12.0
		0.09	147		1.09	0.82	0.314	0.234	4.03	3.6
Sodium-Potassium Sulphate				0.316						
	60	0.3	79		0.75	0.43	0.065	0.037	2.38	5.0
		0.09	140		0.595	0.28	0.172	0.079	1.88	1.5
	25	0.3	150		0.92	0.60	0.079	0.052	2.92	12.0
		0.09	147		0.65	0.33	0.187	0.095	2.06	3.6
Mixture				0.170						
	60	0.3	79		4.54	4.37	0.392	0.377	26.7	5.0
		0.09	140		1.35	1.18	0.390	0.338	7.9	[illegible]
	25	0.3	150		3.14	2.97	0.271	0.257	18.5	[illegible]
		0.09	147		1.58	1.41	0.455	0.408	9.3	3.6

TABLE II

May 1 to June 18, 1906. Iron Plates. 6.25 Sq. In. Surface. 1% Salt Solutions.

Electrolyte	Frequency cycles	Current amperes	Duration of test hours	Milligrammes lead dissolved per hour: chemical	Milligrammes lead dissolved per hour: total	Milligrammes lead dissolved per hour: electrolysis	% direct-current electrolysis: total	% direct-current electrolysis: electrolysis	Ratio of total corrosion to chemical corrosion	Ratio of current to frequency
a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*
Ammonium Nitrate				1.841						
	60	0.3	63		3.77	1.93	1.21	0.62	2.05	5.0
		0.09	162		2.76	0.92	2.96	0.99	1.50	1.5
	25	0.3	143		3.66	1.82	1.18	0.586	1.99	12.0
		0.09	145		2.66	0.82	2.85	0.88	1.44	3.6
Ammonium Carbonate				0.						
	60	0.3	63		0.50	0.50	0.161	0.161		
		0.09	162		0.	0.	0.	0.		
	25	0.3	143		0.017	0.017	0.005	0.005		
		0.09	145		0.	0.	0.	0.		
Sodium-Potassium Nitrate				0.220						
	60	0.3	66		0.570	0.350	0.184	0.113	2.59	5.0
		0.09	162		0.283	0.063	0.304	0.068	1.29	1.5
	25	0.3	143		0.613	0.393	0.197	0.126	2.78	12.0
		0.09	145		0.462	0.242	0.496	0.260	2.10	3.6
Sodium-Potassium Carbonate				0.						
	60	0.3	68		0.	0.	0.	0.		
		0.09	162		0.	0.	0.	0.		
	25	0.3	143		0.007	0.007	0.002	0.002		
		0.09	145		0.014	0.014	0.015	0.015		
Sodium-Potassium Chloride				0.299						
	60	0.3	69		0.59	0.290	0.190	0.093	1.97	5.0
		0.09	163		0.307	0.008	0.330	0.009	1.03	1.5
	25	0.3	143		0.606	0.307	0.195	0.099	2.02	12.0
		0.09	145		0.439	0.140	0.471	0.150	1.47	3.6
Sodium-Potassium Sulphate				0.371						
	60	0.3	70		0.415	0.044	0.134	0.014	1.12	5.0
		0.09	163							
	25	0.3	143		0.644	0.273	0.207	0.088	1.73	12.0
		0.09	145							
Mixture				0.787						
	60	0.3	71		0.97	0.183	0.312	0.059	1.23	5.0
		0.09	163							
	25	0.3	143							
		0.09	145							

of metal dissolved per ampere-hour by alternating-current electrolysis is given in terms of the amount which 1 ampere-hour direct current should dissolve by Faraday's law: 3.86 grammes lead and 1.035 grammes iron per ampere-hour, assuming the valency of both metals as 2. In some tests, plates of one-half or one-quarter of these sizes were also used, in series with full-size plates, to determine the effect of various current-densities.

C. Tests With Salt Solutions

One per cent. solutions in distilled water were used of those salts which may be expected in the soil.

1.	1%	ammonium	nitrate.		
2.	1%	"	carbonate.		
3.	0.5%	sodium	nitrate and 0.5%	potassium	nitrate.
4.	0.5%	"	carbonate and 0.5%	"	carbonate.
5.	0.5%	"	chloride and 0.5%	"	chloride.
6.	0.5%	"	sulphate and 0.5%	"	sulphate.

7. 0.25% ammonium nitrate, 0.25% ammonium carbonate,
0.125% sodium chloride, 0.125% potassium chloride,
0.125% sodium sulphate, 0.125% potassium sulphate,

referred to in the following as " mixture."

Eight sets of tests were made; four with lead plates and four with iron plates, under the following conditions:

a.	60	cycles	0.3	amperes,	or	0.048	amperes	per	square	inch
b.	60	"	0.09	"	"	0.0144	"	"	"	"
c.	25	"	0.3	"	"	0.048	"	"	"	"
d.	25	"	0.09	"	"	0.0144	"	"	"	"

It is interesting to note that considerable quantities of lead were found in solution only with ammonium nitrate, and small traces of lead with sodium-potassium carbonate. No lead went into solution with the other salts.

The results of the four sets of tests made with lead plates are given in Table I; the results of the tests with iron plates in Table II.

As indicated by Tables I and II, the electrolytic corrosion due to alternating current is very small compared with the electrolytic effect due to direct current, as shown by columns *h* and *i*; in no case did it equal 1%, in fact it rarely exceeded ½% of the direct-current electrolysis.

In general, then, iron is attacked less than lead. It therefore seems that, in general, with iron, alternating-current electrolysis is less to be feared, except in extreme cases; that is, with large currents passing between rails and iron pipes. With lead cables, the amount of corrosion indicated by Table I, would in many cases lead to a rapid destruction of the relatively thin cable sheet. The effect of alternating current on lead cables is therefore the more serious problem.

As shown in Table I, no general relation exists between the chemical corrosion, column *e*; that is the corrosion taking place without any current, and the electrical corrosion, column *i*, resulting from the passage of an alternating current. For instance, the chemical corrosion is about the same with sodium-potassium nitrate as with carbonate solutions;

TABLE III.

LEAD PLATES.

Electrolyte	Chemical corrosion mg. per hour	Total Corrosion % direct-current electrolysis			Electrical Corrosion % direct-current electrolysis		
		25	60	avg.	25	60	avg.
a. ammonium nitrate	2.18	0.889	0.512	0.700	0.483	0.103	0.293
b. ammonium carbonate	0.102	0.409	0.151	0.280	0.390	0.132	0.261
sodium potassium nitrate	0.553	0.709	0.491	0.600	0.608	0.391	0.500
" " carbonate	0.535	0.083	0.110	0.096	0.017	0.009	0.004
c. " " chloride	0.270	0.220	0.217	0.218	0.169	0.166	0.167
d. " " sulphate	0.316	0.133	0.119	0.126	0.074	0.058	0.066
Mixture	0.170	0.363	0.391	0.377	0.333	0.358	0.345
Avg. of *a, b, c, d*	0.717	0.413	0.250	0.331	0.279	0.115	0.197

Ammonium nitrate: large quantities of lead in solution.
Sodium potassium carbonate: traces of lead in solution.
Ammonium carbonate: very small traces of lead in solution in chemical, but none in electrolytic corrosion.
All others, including sodium potassium nitrate and chlorides: no traces of lead in solution

while the electrical corrosion is very high with nitrates, and practically neglible with carbonates.

High current densities sometimes increase the electrical corrosion, as with ammonium salts, sometimes it decreases the corrosion, as with chlorides; but usually the current density has no appreciable effect.

In general, electrolytic corrosion is greater at lower frequency, but this is not always the case. For instance, with carbonates, where the electrolytic action is very low, high frequency seems to corrode more than low frequency; but with alkali nitrates, chlorides, and the mixture of salts, frequency has no appreciable effect.

Interesting is the comparison of the last two columns, *j*, the ratio of the total corrosion to the chemical corrosion, and *k*, the ratio of current to frequency; that is, the electric quantity per half wave. In most cases these two columns correspond closely; that is, the higher the quantity of electricity per alternation the greater the corrosion.

To investigate these relations still further, Table III gives the average values of corrosion, chemical, electrical, and total for 25 cycles and for 60 cycles. Table IV gives the average values for high- and for low-current densities, and their averages.

In the last row of these tables is given the corrosion which should be expected from the mixture, calculated as average of the corrosion due to its components. As seen, the mixture of

TABLE IV.

LEAD PLATES.

Electrolyte	Chemical corrosion mg. per hour	Total Corrosion % direct-current electrolysis			Electrical Corrosion % direct-current electrolysis		
		0.3 amp.	.09 amp.	avg.	0.3 amp.	.09 amp.	avg.
a. ammonium nitrate	2.18	0.595	0.806	0.700	0.410	0.175	0.293
b. ammonium carbonate	0.102	0.381	0.179	0.280	0.373	0.149	0.261
sodium potassium nitrate	0.553	0.545	0.656	0.600	0.498	0.501	0.500
" " carbonate	0.535	0.061	0.131	0.096	0.014	0.022	0.004
c. " " chloride	0.0270	0.124	0.313	0.218	0.100	0.234	0.167
d. " " sulphate	.0316	0.072	0.180	0.126	0.045	0.087	0.066
Mixture	0.170	0.332	0.422	0.377	0.317	0.373	0.345
Avg. of *a, b, c, d*	0.717	0.293	0.369	0.331	0.232	0.161	0.197

different salts gives a very much lower chemical attack than the average attack of the components; that is, some salts, as the sulphates or carbonates, protect the lead against the attack by the nitrates. Electrolytically, however, the reverse is the case; this protective action of one salt against the attack by another does not seem to exist.

The conclusion herefrom is, that it may be possible to protect lead cables chemically against spontaneous or chemical corrosion by surrounding the cables with alkali sulphates, for instance, but this affords no appreciable protection against electrolytic action by alternating current.

In Table I, the data on the electrical corrosion by ammonium nitrate are not very reliable, since ammonium nitrate attacks and dissolves lead chemically so rapidly that the additional attack by the alternating current cannot be determined accurately. In all other cases, the chemical corrosion is rather less than the electrical.

TABLE V.

Lead Plates—Order of Chemical Corrosion

	mg. per hour
1. Ammonium nitrate	2.18
2. Sodium-potassium nitrate	0.553
3. Sodium-potassium carbonate	0.535
4. Sodium-potassium sulphate	0.316
5. Sodium-potassium chloride	0.270
6. Mixture	0.170
7. Ammonium carbonate	0.102

Table V, gives the order in which lead is attacked chemically by the different solutions. Nitrates attack the hardest, next come the alkali carbonates, and last is ammonium carbonate, and the mixture of salts, in which some salts act as a protection against the others.

TABLE VI.

Lead Plates. Order of Alternating-Current Electrolytic Corrosion

Total Corrosion					Electrical Corrosion				
Cycles		Amperes		Average	Cycles		Amperes		Average
25	60	0.3	0.09		25	60	0.3	0.09	
1	1	1	1	1	2	2	2	2	2
2	2	2	2	2	1	6	1	6	6
7	6	7	6	6	7	5	7	5	1
6	5	6	5	7	6	7	6	1	7
5	7	5 }	4, 7	5	5	1	5	7	5
4	4	4 }		4	4	4	4	4	4
3	3	3	3	3	3	3	3	3	3

Table VI gives the order of attack by alternating current, the total corrosion, and the electrical corrosion. The different solutions are given by their numbers in Table V; that is, the numbers in Table VI represent the order of chemical corrosion.

As seen, the nitrates give the greatest corrosion, chemically as well as electrically. The other salts act electrically practically in reverse order to their action chemically: the alkali carbonates give the greatest chemical and the least electrical attack, next come the sulphates, then the chlorides.

TABLE VII

LEAD PLATES—ORDER OF TOTAL CORROSION

		% direct-current electrolysis	
	Number:	Total:	Electrical
Ammonium nitrate and sodium-potassium nitrate	1,2	0.650	0.397
Mixture, and ammonium carbonate	6,7	0.329	0.303
Sodium-potassium chloride	5	0.218	0.167
Sodium-potassium sulphate	4	0.126	0.066
Sodium-potassium carbonate	3	0.096	0

The approximate order of electrical corrosion of the different solutions is given in Table VII. Comparing Table VII with Table V, it is evident that, with the exception of ammonium nitrate and sodium-potassium nitrate, the order of attack is reversed.

TABLE VIII.

LEAD PLATES. RATIOS.

Solution	Net corrosion, by current only					
	Low / high frequency			High / low current		
	0.3 amp.	0.09 amp.	avg.	25	60	avg.
1. Ammonium nitrate	8.77	1.87	4.69	3.23	.69	2.34
2. Ammonium carbonate	3.23	2.38	2.95	2.71	2.00	2,51
3. Sodium potassium nitrate	1.56	1.56	1.56	0.995	0.995	0.995
4. " " carbonate						
5. " " chloride	1.06	1.00	1.02	0.435	0.41	0.427
6. " " sulphate	1.41	1.20	1.28	0.55	0.47	0.517
7. Mixture	0.68	1.21	0.93	0.63	1.11	0.848
8. Avg. of 1, 2, 5, 6			2.43			1.44

Table VIII gives the ratio of electrical corrosion at low frequency to that at high frequency, and the ratio of corrosion at high current-density to that at low current-density; that is, gives the effect of frequency, and of current-density.

ORDER OF RATIOS

Frequency ratio: high current	1	2	3	6	5	7
low "	2	1	3	7	6	5
average "	1	2	3	6	5	7
Current ratio: low frequency	1	2	3	7	6	5
high "	2	7	3	1	6	5
average "	2	1	3	7	6	5
Total average	2	1	3	7	6	5

Or, order of ratio: $\frac{\text{low}}{\text{high}}$ frequency, or $\frac{\text{high}}{\text{low}}$ current, that is, $\frac{\text{high}}{\text{low}}$ quantity of electricity per half wave:

Ammonium nitrate and carbonate.
Sodium-potassium nitrate.
Sodium-potassium sulphate, and mixture.
Sodium-potassium chloride.

As seen, the effect of frequency varies from 4.69 with ammonium nitrate to 0.93 with the mixture, and the effect of current density from 2.51 with ammonium carbonate, to 0.427 with alkali chlorides. In general, then, the order of salts in the two cases is similar; that is, decreasing frequency and increasing current-density have similar effects.

These tables show, however, that the effects of frequency and of current-density depend very largely on the chemical constitution. Ammonium salts show a very great increase of corrosion with increasing current-density, or decreasing frequency; whereas chlorides and sulphates show little effects of frequency, and a decrease of corrosion with increasing current-density. In general, the conclusions of the tests with lead plates in salt solutions are:

1. Chemical as well as electrical corrosion is greatest with nitrates. With other salts or mixtures of salts, the electrical corrosion is not proportional to the chemical corrosion, but, with the salts investigated, rather inversely proportional thereto; that is, where the chemical attack is considerable, the electrical action is more completely reversible than with a chemically less active electrolyte.

2. Current-density in general has no decided effect. High current-density increases the attack with some compounds, as ammonium salts, and decreases it with others, as chlorides and sulphates, provided the current density is not so high as to give

an appreciable increase of temperature, which then increases the corrosion.

3. Low frequency usually attacks more than high frequency. But the increase of corrosion due to lower frequency, entirely depends on chemical constitution, being largest with ammonium salts, and practically negligible with chlorides and sulphates.

4. Mixtures of salts frequently give a greatly reduced chemical corrosion, but give about the same or a higher electrical corrosion than their components; that is, chemical protection fails to protect electrolytically.

5. Iron is less attacked than lead, and is practically not attacked at all by carbonates.

D. Experiments with Different Soils

Tests were made with different soils.

1. Garden soil, a clay loam, taken from Dr. Steinmetz's garden.

2. Street mud, collected from the surface of Schenectady's main street (State Street railway crossing), where the New York Central Railroad crosses the trolley line, and thus containing the accumulated effect of foot, horse, electric, and steam traffic.

3. Sub-soil, a sandy soil collected from below the street surface in the older part of Schenectady, where people lived for over 200 years, the soil containing the seepage of centuries.

4. A mixture, in equal volume, of these three soils.

The soil was kept moist by replacing evaporation with distilled water. It was considered that these three soils are about representatives of the more severe conditions to which lead pipes and cables in the soil are exposed. Four sets of tests were made, of lead plates, and of iron plates, with 60 cycles and with 25 cycles, all at one-tenth ampere current. The same size of plate was used as before and tested in the same manner. The results of these tests are abstacted in Table IX.

Very marked, however, is the effect of frequency. While at 60 cycles the electrical corrosion is very small, averaging less than 0.05% with lead plates, it is quite considerable at 25 cycles, averaging 0.222%.

The chemical corrosion of lead plates averages 0.148 milligrammes per hour, with 6.25 square inch plate surface. The total corrosion averages 0.085% at 60 cycles, and 0.216% at 25 cycles, and the electrical corrosion averages 0.047% at 60 cycles and 0.22% at 25 cycles. Especially marked is the enormous increase of corrosion with increase of temperature, which is investigated later.

Comparing the relatively small differences found in Table IX for different soils, with the great variations in the attack due to different salt solutions, in Table I and II, it was thought sufficient in the further investigations to use only one form of

TABLE IX.

JUNE 21 TO JULY 17, 1906. TESTS WITH DIFFERENT SOILS.
Plates, 6.25 sq. in. total surface; 0.1 ampere.

Electrolyte	Frequency cycles	Dur. of test hours	milligrammes dissolved per hour chem.	total	elec.	% direct-current electrolysis total	elec.
a	*b*	*c*	*e*	*f*	*g*	*h*	*i*
Lead Plates.							
Garden soil	60	254	0.115	0.227	0.112	0.059	0.029
	25	244		0.908	0.793	0.235	0.205
Street mud	60	254	0.130	0.311	0.181	0.081	0.047
	25	244		1.250	1.120	0.324	0.290
Sub-soil*	60	254	0.224	0.462	0.238	0.120	0.062
	25	244		0.642	0.418	0.167	0.108
Mixture	60	254	0.121	0.310	0.189	0.080	0.049
	25	244		1.221	1.100	0.317	0.285
Iron Plates.							
Garden soil	60	254	0.078	0.169	0.091	0.163	0.088
	25	244		0.252	0.174	0.243	0.168
Street mud	60	254	0.036	0.099	0.063	0.095	0.061
	25	244		0.159	0.123	0.154	0.119
Sub-soil*	60	254	0.092	0.98	0.89	0.945	0.86
	25	244		1.99	1.90	1.93	1.83
Mixture	60	254	0.044	0.092	0.048	0.089	0.046
	25	244		0.087	0.043	0.084	0.042

* Appreciable rise of temperature by $I^2 r$.

soil as typical—the mixture referred to above, but to investigate the effect of the addition of different substances.

E. SALT SOLUTIONS IN SOIL

Tests were therefore made by moistening the soil, not as before with distilled water, but with very diluted solutions of nitrates, and nitrites, carbonates, sulphates, and their mixture, to determine whether the presence of nitrates increases the corrosion, and the presence of carbonates or sulphates exerts a protective action. These experiments were made only at 25 cycles, 0.1 ampere, with the same size of lead and iron plates, of 6.25 square inch total surface, and are abstracted in Table X and XI.

The following solutions were used.

1. City water, (Schenectady) containing appreciable quantities of bicarbonate of calcium.

2. Solution of 0.1% potassium carbonate and 0.1% sodium carbonate in distilled water, a total of 0.2%.

3. Solution of 0.1% potassium sulphate and 0.1% sodium sulphate, in distilled water, a total of 0.2%.

TABLE X.

JULY 23 TO AUGUST 3, 1906. MIXED SOIL AND SALT SOLUTIONS.

25 cycles, 0.1 ampere, 6.25 sq. in. total plate surface.
Duration of test, 219.5 hours.
Mean temperature of water bath, 23.7° cent.

Electrolyte	Milligrammes dissolved per hour			% direct-current electrolysis	
	chem.	total	elec.	total	elec.
a	*e*	*f*	*g*	*h*	*i*
Lead Plates.					
City water	0.106	0.851	0.745	0.221	0.194
Potassium sodium carbonate	0.104	0.304	0.200	0.079	0.052
Nitrates and nitrites	0.166	0.716	0.550	0.186	0.143
Carbonates, nitrates and nitrites	0.128	0.481	0.353	0.125	0.092
Iron Plates.					
City water	0.073	0.262	0.189	0.253	0.183
Potassium sodium carbonates	0.117	0.288	0.171	0.278	0.165
Nitrates and nitrites	0.100	0.203	0.103	0.196	0.100
Carbonates, nitrates and nitrites	0.112	0.365	0.253	0.353	0.245

4. Solution of 0.1% ammonium nitrate, 0.05% potassium nitrite, and 0.05% sodium nitrite in distilled water, a total of 0.2%.

5. Solution of 0.1% potassium carbonate, 0.1% sodium carbonate, 0.1% ammonium nitrate, 0.05% potassium nitrite, 0.05% sodium nitrite, a total of 0.4%.

6. Solution of 0.1% potassium sulphate, 0.1% sodium sulphate, 0.1% ammonium nitrate, 0.05% potassium nitrite, 0.05% sodium nitrite, a total of 0.4%.

A comparison of Tables X and XI well illustrates the erratic character of the phenomenon of alternating-current electrolysis.

These two tests were made immediately after each other, under as nearly identical conditions as possible; the same frequency, current-density, etc., the same kind of soil, and practically the same temperatures. The chemical corrosion in both tests is about the same. In the second test it is somewhat less with lead plates, and somewhat more with iron plates, than in the first test. Wide differences are found in the electrical corrosion, not only in the numerical values, but also in the character of the effect produced by the different electrolytes.

In the first test, nitrates and nitrites exert a marked protective action on iron plates, which, however, disappears in the presence

TABLE XI.

AUGUST 7 TO 23, 1906. MIXED SOIL AND SALT SOLUTION.

25 cycles, 0.1 amperes, 6.25 sq. in. total plate surface.
Duration of test, 333.5 hours.
Mean temperature of water bath, 22.3° cent.

Electrolyte	Milligrammes dissolved per hour			% direct-current electrolysis	
	chem.	total	elec.	total	elec.
a	*e*	*f*	*g*	*h*	*i*
Lead Plates.					
City water	0.065	1.160	1.075	0.300	0.278
Sulphates	0.073	0.505	0.432	0.131	0.112
Nitrates and nitrites	0.101	1.911	1.810	0.495	0.469
Sulphates, nitrates and nitrites	0.108	2.048	1.94	0.530	0.503
Iron Plates.					
City water	0.102	0.212	0.110	0.204	0.107
Sulphates	0.145	0.370	0.225	0.357	0.217
Nitrates and nitrites	0.158	0.483	0.325	0.466	0.313
Sulphates, nitrates and nitrites	0.155	0.642	0.487	0.618	0.469

of carbonates. In the second test, nitrates and nitrites greatly increase the corrosion of iron plates. This may have something to do with the possibility of a passive state of the iron, and needs further investigation.

Carbonates exert a marked protective action on lead plates, which is reduced if nitrates and nitrites are present; even then it is considerable. Sulphates also exert a protective effect on lead plates, but this protective action disappears, and the corrosion is increased in the presence of nitrates and nitrites. This agrees with previous experience in the tests with salt solutions. With iron plates, sulphates increase the corrosion.

It seems then that a certain protective action against alternating-current electrolysis of lead plates is exerted by carbonates and by sulphates. Since alkali salts are excluded from practical use by their solubility, a series of tests was undertaken to determine the effect that calcium carbonate and sulphate—chalk and gypsum—have on alternating-current electrolytic corrosion, when mixing these salts with the soil surrounding the lead cables.

F. Calcium Salts in Soil

Tests were made on the effect produced by mixing 5% chalk or 5% gypsum, or both, with the soil used in alternating-current electrolysis. Some tests were also made by adding 5% Portland cement, and by adding 5% fertilizer, containing nitrates,

TABLE XII.

August 25 to Sept. 9, 1906. Lead Plates.

25 cycles, 0.1 ampere, 6.25 sq. in. total plate surface.
Duration of test, 362 hours.
Mean temperature of water bath, 23.1° cent.

Electrolyte		Milligrammes dissolved per hour			% direct-current electrolysis	
Solid	Liquid	chem.	total	elec.	total	elec.
a		e	f	g	h	i
Mixed soil.	City water.....	0.116	1.256	1.140	0.326	0.296
Mixed soil.	Salt solution*..	0.117	0.794	0.677	0.206	0.176
Mixed soil. +5% Chalk. + 5% Gypsum	City Water.....	0.079	0.245	0.166	0.0635	0.043
Mixed soil. + 5% Chalk. + 5% Gypsum.	Salt solution*..	0.126	0.704	0.578	0.182	0.150

* 0.5% solution of mixed potassium, sodium, ammonium, nitrates, nitrites, chlorides, as described above.

phosphates, and ammonium compounds. Only lead plates were used, of the standard size of 1.25 in. by 2.25 in., with a current of 0.1 ampere.

Tests were made at 60 cycles, as well as at 25 cycles, to determine the effect of frequency. Some tests were made with plates of half and quarter size, in series with full-size plates, to determine the effect of current-density. The 60-cycle and 25-cycle tests, and the tests with full-, half-, and quarter-size plates, were made simultaneoutly, with the tumblers immersed in the same water bath so as to have the same temperature in all these tests.

Tests were made with the mixed soil, and also with the same soil by adding: 5% chalk, 5% gypsum, 5% Portland cement, 5% fertilizer: containing nitrates, phosphates, ammonia, 5% fertilizer, 5% chalk, and 5% gypsum. City water was used as liquid, except in a few tests, in which 0.5% salt solution was used, of the following constitution: ammonium nitrate 2, potassium nitrite 1, sodium nitrite 1, potassium chloride 1, sodium

TABLE XIII.

SEPT. 17 TO OCT. 3, 1906. LEAD PLATES.

0.1 ampere, 6.25 sq. in. total plate surface, half and quarter thereof.
Mean temperature of water bath, 22.7° cent. and 19.5° cent. respectively.

Liquid: City Water.

Electrolyte 22.7° cent. *a*	Frequency cycles *b*	Duration of test, hours *d*	Milligrammes dissolved per hour chem. *e*	total *f*	elec. *g*	% direct-current electrolysis total *h*	elec. *i*	Ratio of attack 25–60 *l*
Mixed soil	25	277	0.159	1.451	1.292	0.376	0.335	
	60	306		0.996	0.837	0.258	0.217	1.54
Mixed soil + 5% chalk	25	277	0.155	1.088	0.933	0.282	0.242	
	60	306		0.711	0.556	0.184	0.144	1.68
Mixed soil + 5% gypsum	25	277	0.180	1.843	0.663	0.478	0.431	
	60	306		0.435	0.255	0.113	0.066	6.53
Mixed soil + 5% chalk + 5% gypsum	25	277	0.134	1.544	1.410	0.400	0.365	
	60	306		0.499	0.365	0.129	0.095	3.84
Mixed soil + 5% Portland cement	25	277	0.247	0.485	0.238	0.125	0.062	
	60	306		0.512	1.265	0.132	0.068	0.91
19.5° cent.								
Mixed soil + 5% fertilizer	25	217	0.301	2.481	2.180	0.642	0.565	1.86
	60	234		1.474	1.173	0.383	0.304	
Mixed soil + 5% fertilizer + 5% chalk + 5% gypsum	25	217	0.303	3.638	3.335	0.940	0.864	
	60	234		2.483	2.180	0.643	0.564	1.53
Mixed soil, ½ size plates	25	217	0.162	1.289	1.127	0.334	0.292	
	60	234		1.119	0.957	0.290	0.247	1.18
Mixed soil, ¼ size plates	25	217	0.064	1.839	1.775*	0.476	0.460	
	60	234						

* Lead plates eaten to pieces. The pieces were collected as far as possible, but no doubt some escaped, hence this value is probably somewhat too large.

chloride 1, water 1194. Each tumbler contained about 120 cu. cm. of liquid, in addition to the soil.

The three sets of tests are given in Tables XI, XII and XIII.

Table XII seems to show that the very diluted salt solution rather reduces the electrolytic corrosion.

The addition of chalk and gypsum to the soil exerts a marked protective action, which, however, practically disappears when a mixed salt solution is used instead of water.

Table XIII shows a moderate protective action against electrolytic corrosion, exerted by the addition of chalk to the soil.

Gypsum exerts a marked protective action only at 60 cycles, but increases the corrosion at 25 cycles.

Addition of chalk, as well as gypsum, gives the same effect as gypsum: a reduction of the corrosion at 60 cycles, but an increase at 25 cycles.

Organic materials, as fertilizer, greatly increase the electrolytic corrosion, and the addition of chalk and gypsum in this case still further increases the corrosion.

The effect of Portland cement is interesting: while the chemical corrosion is greatly increased by cement, from 0.159 to 0.247 milligrammes per hour, the electrolytic corrosion is greatly reduced and becomes very small at either frequency.

The current-density seems to have very little, if any, effect, since half-size plates, with the same current, give practically the same corrosion as full-size plates.

Especially interesting is the effect of frequency. In general, at lower frequency the corrosion is greater; but the order in which it varies with the frequency very largely depends on the chemical character of the soil. With soil only, the corrosion increases with decreasing frequency, but not any where near inversely proportional to the frequency. The addition of chalk or fertilizer seems slightly to increase the effect of frequency, but not to any great extent. Gypsum very greatly increases it, so that 60-cycle electrolysis nearly disappears, and the 25-cycle electrolysis is more than six times the 60-cycle electrolysis. Inversely, cement reduces the effect of frequency, so that both frequencies give practically the same attack.

It is worth noting the high values of electrolytic corrosion observed in soils containing fertilizer, especially when chalk and gypsum are added. These reach nearly 1% of direct-current corrosion at 25 cycles, and exceed one-half per cent at 60 cycles.

G. Conclusions

From the data recorded in Tables IX to XII, a number of comparisons on the effect of different constituents in the soil can be made. These are given in Tables XIV, XV, and XVI.

In these tables, the relative values of chemical, total, and electrical corrosion are given.

Table XIV. Effect of nitrates, nitrites, and similar compounds, as fertilizer. The corrosion is considerably increased, the chemical corrosion in all cases, the electrical corrosion in most tests, by an average of about 60%.

TABLE XIV.

Effect of Nitrates, nitrates and fertilizer:	Table No.	Frequency cycles	Corrosion: relative		
			chem.	total	elec.
Mixed soil only			1	1	1
Alkali nitrates and nitrites	X	25	1.56	0.84	0.74
Alkali nitrates and nitrites	XI	25	1.19	[illegible]	1.69
Alkali nitrates, nitrites and carbonate	X	25	1.21	0.57	0.48
Alkali nitrates, nitrites and sulphate	XI	25	1.27	1.77	1.81
Fertilizer	XIII	25	1.90	1.71	1.68
Fertilizer	XIII	60	1.90	1.48	1.40
Fertilizer and chalk and gypsum	XIII	25	1.91	2.50	2.57
	XIII	60	1.91	2.49	2.60
Average			1.61	1.63	1.62

TABLE XV.

Effect of carbonates, etc.	Table No.	Frequency cycles	Corrosion; relative		
			chem.	total	elec.
Mixed soil only			1	1	1
Alkali carbonates	X	25	0.98	0.36	0.27
Chalk	XIII	25	0.97	0.75	0.72
Chalk	XIII	60	0.97	0.71	0.66
Portland cement	XIII	25	1.56	0.33	0.19
Portland cement	XIII	60	1.56	0.51	0.31
Mixed soil containing gypsum			1	1	1
Chalk	XIII	25	0.75	0.84	0.85
Chalk	XIII	60	0.75	1.14*	1.14*
Mixed soil containing nitrates or fertilizer			1	1	1
Alkali carbonates	X	25	0.77	0.67	0.64
Chalk and gypsum	XIII	25	1.01	1.46	1.53
Chalk and gypsum	XIII	60	1.01	1.68	1.85

* Ratios of two small values, therefore less reliable.

The presence of nitrates, fertilizers etc., in the soil is therefore objectionable.

Table XV. Effect of carbonates, and, in general, alkaline compounds.

Carbonates and alkaline compounds, as far as observed, always reduce the electrolytic corrosion of lead, and also the chemical corrosion; that is, they exert a protective action. This is most pronounced with alkali carbonates and cement, the latter, however, greatly increasing the chemical corrosion.

The protective action of carbonates seems to decrease in the presence of sulphates, nitrates, etc., and is in general not sufficiently large to give promise of a method of chemically protecting lead plates against alternating-current electrolysis, by surrounding them with calcium carbonate or hydrate.

Table XVI. Effect of sulphates. Sulphates sometime exert a protecting action, but sometime increase the corrosion. The latter seems to be the case in the presence of nitrates.

TABLE XVI.

Effect of sulphates, etc.	Table No.	Frequency cycles	Corrosion; relative		
			chem.	total	elec.
Mixed soil only			1	1	1
Alkali sulphates	XI	25	0.86	0.44	0.40
Gypsum	XIII	25	1.13	1.27	1.29
Gypsum	XIII	60	1.13	0.44	0.30
Chalk and gypsum	XII	25	0.68	0.20	0.15
Chalk and gypsum	XIII	25	0.84	1.07	1.09
Chalk and gypsum	XIII	60	0.84	0.50	0.44
Mixed soil containing nitrates or fertilizer			1	1	1
Alkali sulphates	XI	25	1.07	1.07	1.07
Chalk and gypsum	XIII	25	1.01	1.46	1.53
Gypsum	XIII	60	1.01	1.68	1.85

In Table XVII are calculated the tests made with soil only, without additional protective or destructive compounds. These give an average spontaneous or chemical corrosion of 0.117 milligrammes per hour, or 0.0188 milligrammes per hour and square inch plate surface, and an average total corrosion, at 25 cycles, of 0.312%, or an electrical corrosion of 0.280% of direct-current electrolysis.

Assuming the specific gravity of lead as 11.4, under these conditions, by chemical corrosion, in 10 years a layer of lead of 0.009 in. thick would be consumed. That is, under average conditions, chemical corrosion of lead cables could be neglected.

Electrically, at a current-density of 1 ampere per square foot, 25 cycles would, in 10 years, destroy an additional layer of lead 0.07 in. thick. In the worst case observed this would increase to 0.22 in. or nearly one-quarter inch; that is, would eat through the cable armor long before this time.

With a current-density of 10 amperes per square foot, a cable armor ⅛ in. thick would in average be eaten through in 1.8 years, but in the extreme case may be eaten through in 0.57 years, or 7 months.

H. Effect of Temperature

Since in the preceding tests, especially in the first set of tests, before a water bath was used, it was noticed that the values of alternating-current electrolytic corrosion were high, when-

TABLE XVII.
Lead Plates. Mixed Soil. 25 Cycles.

	Corrosion:		
	chemical	total	electrical
Table No.	Milligrammes per hour	% direct-current electrolysis	
IX........	0.121	0.317	0.285
X.........	0.106	0.221	0.194
XI.......	0.085	0.300	0.278
XII.......	0.116	0.326	0.296
XIII......	0.159	0.376	0.335
XIII......	½ size	0.334	0.292
Average...	0.117	0.312	0.280
Maximum corrosion observed..	0.303	0.940	0.864

ever the temperature of the cell is increased by its $I^2 R$ loss, some tests were made on the effect of temperature by heating the water bath in which the cells were immersed. The temperature of the bath fluctuated between 36° and 42° cent. with an average of 39.5° cent.

Tests were made with mixed soil, and with mixed soil and 5% fertilizer added, at 0.1 ampere, 25 cycles, and without current, and gave the results recorded in Table XVIII.

As seen from Table XIX, and comparing these results with the average values of previous experiments, the chemical as well as the electrolytic corrosion is very greatly increased by the increase of temperature.

I. Conclusions

The following conclusions seem to be warranted from the preceding investigations.

1. Alternating-current electrolysis is not a phenomenon like direct-current electrolysis, on which definite quantitative general laws can be formulated; but is of the character of a secondary

TABLE XVIII.

Oct. 20 to 29, 1906. Lead Plates.

25 cycles, 0.1 ampere. 6.25 sq. in. total plate surface.
Duration of test, 208 hours.
Water bath heated electrically, mean temperature 39.5° cent.
Liquid, city water.

Electrolyte	Milligrammes dissolved per hour			% direct-current electrolysis	
	Chemical	Total	Electrical	Total	Electrical
a	e	f	g	h	i
Mixed soil	0.296	4.11	3.81	1.065	0.987
Mixed soil + 5% fertilizer	0.393	4.53	4.14	1.175	1.075

effect; that is, the action of the positive half wave is not quite reversed by the action of the negative half wave, leaving a small difference, rarely exceeding one-half percent of the electrolytic action of an equal direct current.

Under the conditions of the investigation, which were chosen

TABLE XIX.

Electrolyte	Temperature degrees centigrade	Corrosion % direct-current electrolysis			Corrosion, ratio		
		chemical	total	electrical	chemical	total	electrical
Mixed soil	22.3°	0.117	0.312	0.280	1	1	1
	39.5°	0.296	1.065	0.987	2.53	3.41	3.52
Mixed soil +	19.5	0.301	0.642	0.565	1	1	1
5% fertilizer	39.5	0.393	1.175	1.075	1.30	1.83	1.90

to represent as nearly as possible actual service conditions of lead cables, alternating-current electrolysis varies from practically nothing to somewhat less than 1% of direct-current electrolysis. Since electrolytic action of the alternating current appears as a small difference between two large and nearly equal quantities, the action of the positive and of the negative half wave, a very small variation in the action of either half wave makes a very large difference in the result, and this probably accounts for the very large variation in the electrolytic action of alternating current compared with the constancy of the electrolytic action of direct current.

2. Alternating-current electrolysis, when expressed quantitatively, or in per cent, of the action of an equal direct current, varies very greatly with the chemical character of the electrolyte. The nitrates and similar compounds, as fertilizers, tend to increase electrolytic corrosion; carbonates and, in general, alkaline reaction of the soil, decreases the corrosion; that is, exert a protective action.

This protective action against alternating-current electrolysis is decreased by the presence of nitrates, etc., and is hardly sufficient to be of practical use for protecting lead cables against attack by alternating current.

3. In general, lead is more attacked than iron, and the latter shows still more erratic behavior than lead, probably due to the existence of a passive state.

4. Alternating-current electrolysis under conditions representing as nearly as seems feasible the conditions of lead cables in the soil, does not appreciably depend upon the current-density, but is practically independent thereof, except indirectly, in that very high current densities may by an increase of temperature give an increased corrosion.

5. In general, electrolytic corrosion by alternating currents increases with decrease of frequency. This increase with decreasing frequency does not follow a general law, but depends largely upon the chemical character of the electrolyte. It may be enormous; that is, 25-cycle current gives many times greater corrosion than the same current at 60 cycles. Or it may be very small and negligible. In some instances, 60-cycle current seems to give a somewhat greater attack than 25-cycle current.

In general, ammonium salts and nitrates seem to give a very great increase of electrolytic corrosion with decreasing frequency, while carbonates and soils with alkaline reaction, as containing cement, may give little or no increase of corrosion with decreasing frequency.

6. Chemical corrosion by the soil, and electrolytic corrosion by alternating current increases very greatly with increasing temperature of the soil.

J. Electrical Protection

Since the attempt to find a method of protecting lead chemically against alternating-current corrosion by mixing compounds as chalk, etc. with the soil surrounding the lead cable did not seem very hopeful, an investigation was made on the possibility of electrical protection against alternating-current electrolysis. With the tests recorded in Table XIV, a test was made on three tumblers, with ordinary mixed soil—one on 25 cycles, one on 60 cycles, and one without current, to check regarding spontaneous or chemical corrosion. In these tests a piece of sheet zinc, of about half the size of the lead plates was connected electrically with one of the lead plates. The idea was that a local action between lead and zinc would produce a direct current between lead and zinc, with the lead as negative, and thus exert a protective action.

The results of this test were:

TABLE XX

Sept. 19 to Oct. 3, 1906.

Total time of immersion of plates, 234 hours.
Duration of test with 60 cycles, 234 hours, 0.1 ampere.
Duration of test with 25 cycles, 217 hours, 0.1 ampere.
Temperature of water bath, 19.5° centigrade average.
Size of lead plates, $1\frac{1}{4}$ in. by $2\frac{1}{2}$ in., or 6.25 sq. in. total exposed surface.
Size of zinc plates, about $\frac{1}{2}$ in. by 3 in.
Electrolyte, mixed soil, city water.

No. of tumbler	No. of plate	Material	Frequency cycles	Duration of test, hours	Weight of plate before test (in grammes)	Weight of plate after test (in grammes)	Difference total mg.	Electrical cor. mg.	Dissolved per hour elec. mg.	% Direct-current electrolysis
7	13	lead	25	217	5.565	4.960	605	523	2.41	0.62
	14	lead			5.883	5.792	91	9	0.0415	0.0107
	14[1]	zinc			5.885	5.685	200			
8	15	lead	0	234	5.095	4.992	103	avg.		
	16	lead			5.892	5.831	61	82	(.351)	
	16[1]	zinc			5.734	5.067	67			
9	17	lead	60	234	5.046	4.709	337	255	1.09	0.282
	18	lead			5.900	5.817	83	1	0.0043	0.0011
	18[1]	zinc			5.769	5.649	120			

While with a zinc plate connected to the lead plate a decrease of the attack should be expected—since the alternating current divides between the zinc plate and the lead plate, and the lead plate receives only a part of the total current—still the difference between the electrical corrosion of the lead plate protected by contact with the zinc plate, and the unprotected lead plate, is startling.

At 25 cycles the unprotected lead plate gives 0.623%, at 60 cycles 0.28%, of the electrolytic attack of a corresponding direct current, while the lead plate in contact with the zinc plate is practically completely protected; that is, is attacked practically no more than it would without any current, by the chemical action of the soil.

To investigate this action still further, a series of tests was made in which a small direct current was superimposed upon the alternating current. A transformer was interposed between the inverted converter which gives the 25-cycle alternating current, and the electrolytic cells, to separate the alternating-current circuit electrically from the direct-current circuit, and a small direct current sent through the cells in a divided circuit.

The 25-cycle alternating current consisted of 0.1 ampere; 0.005 ampere direct current was used, divided so that some of the cells received 1.14 milliamperes, while the others received 3.86 milliamperes, and the undivided direct current of 5 milliamperes passed through some cells without alternating-current. Resistances were inserted in both the alternating-current and the direct-current circuit, and a very high reactance of about $x = 50{,}000$ ohms, in the direct-current circuit.

The same kind of mixed soil as in the former tests was used as an electrolyte and also this soil mixed with 5% Portland cement, and this soil mixed with 5% fertilizer. City water was used as liquid. In some tests, half-size and quarter-size plates were used to get the effect of current-density. Results of the test are given in Table XXI.

The results of tests in Table XXI are extremely interesting. As seen, in many of these tests the electrical corrosion is negative: the total corrosion is less than the chemical corrosion; or in other words, if upon the alternating current a very small direct current is superimposed the total corrosion of the lead is reduced below the value which would exist with no current at all flowing.

With a direct current equal to 3.86% of the alternating current added thereto, the protection is complete; that is, in every case the lead is attacked less, sometimes less than half as much as it would be attacked spontaneously by the chemical action of the soil. Even with a direct current of only 1.14%, or about 1/90 of the value of the alternating current, the protection is

TABLE XXI.

OCT. 9 TO 14, 1906. LEAD PLATES

25-cycle alternating current, and direct current. Duration of test, 111 hours.
Time of immersion, 114 hours. Mean temperature of water bath, 18.2° cent.

No. of tumbler	Electrolyte	Size of plate	Amperes		Mg. lead dissolved		Mg. dissolved per hour		% direct-current electrolysis		Ratio of total corrosion to chemical corrosion
			A.C.	D.C.	total	elec.	total	elec.	total	elec.	
1	Soil............	¼	0.1	0.00114	481 48	449 16	4.28 0.428	4.08 0.144	1.11 0.111	1.035 0.0373	1.530
2	Soil............	½	0.1	0.00114	565 67	519.5 21.5	5.08 0.594	4.68 0.194	1.32 0.154	1.215 0.0503	1.485
3	Soil............	1	0.1	0.00114	583 88	512 17	5.23 0.776	4.61 0.153	1.355 0.201	1.195 0.0397	1.245
4	Soil and cement..	1	0.1	0.00114	621 90	503.5 —27.5	5.57 0.785	4.54 —0.248	1.445 0.204	1.175 —0.0643	0.760
5	Soil and fertilizer..	1	0.1	0.00114	605 69	534 —2.	5.43 0.605	4.81 —0.018	1.41 0.157	1.245 —0.0047	0.973
6	Soil............	¼	0.	0.	33 31		0.280				
7	Soil..............	½	0.	0.	41 50		0.400				
8	Soil..............	1	0.	0.	71 71		0.623				
9	Soil and cement....	1	0.	0.	138 97		1.033				
10	Soil and fertilizer...	1	0.	0.	71 71		0.623				
11	Soil..............	1	0.1	0.00386	1844 65	1773 —6	16.6 0.569	16.0 —0.054	4.30 0.147	4.15 —0.014	0.915
12	Soil and cement....	1	0.1	0.00386	1759 50	1641.5 —67.5	15.8 0.425	14.8 —0.608	4.10 0.110	3.83 —0.158	0.411
13	Soil and fertilizer...	1	0.1	0.00386	1911 29	1840. —42	17.2 0.245	16.6 —0.378	4.46 0.064	4.30 —0.098	0.393
14	Soil..............	1	0.	0.005	2366 87	2205 16	21.3 0.767	20.7 0.144	110.5	107.5	1.235
15	Soil and cement....	1	0.	0.005	2356 93	2238.5 —24.5	21.2 0.812	20.2 —0.221	110.0	104.5	0.788
16	Soil and fertilizer...	1	0.	0.005	2580 49	2509. —22.	23.2 0.425	22.6 —0.198	120.0	117.0	0.583

practically complete, and the additional corrosion due to the alternating current is small compared with the chemical attack, or even negative; that is, the total attack is decreased.

This protection by a small direct current is especially effective under these conditions of the soil, where the electrolytic or chemical attack is especially great. With fertilizers, or with cement in the soil, a direct current of 1/90 the value of the alternating current reduces the corrosion below the value which it would have without any electrolytic action.

Comparing the results of Table XVII with those of XXI, it follows for mixed soil and a 25-cycle alternating current of 0.1 ampere:

Electrolytic corrosion by 25-cycle alternating current Table XVII, 0.280% of direct-current electrolysis.

Electrolytic corrosion by 25-cycle alternating current with the addition of 1.14% direct current, reduced to 0.042% of direct-current electrolysis.

Electrolytic corrosion by 25-cycle alternating current with the addition of 3.86% direct current, reduced to - 0.014% of direct-current electrolysis.

It must be noted, however, that the spontaneous or chemical corrosion in the test Table XXI, was, with mixed soil, considerably higher than the average of the previous tests.

Regarding the effect of current-density, Table XXI again shows this to be absent. The electrolytic corrosion for current-densities varying from 1 to 4; that is, with full, half- and quarter-size plates and the same current of 0.1 ampere, is of the same order.

Quarter-size plates, with a current-density of 0.1 ampere per 1.6 sq. in. or 9 amperes per sq. ft., give 0.0373% of direct-current electrolysis.

Half-size plates, with a current density of 0.1 ampere per 3.2 sq. in., or 4.5 amperes per sq. ft., give 0.0503 % of direct-current electrolysis.

Full-size plates, with a current density of 0.1 ampere per 6.25 sq. in. or 2.3 amperes per sq. ft. give 0.0397% of direct-current electrolysis.

These values do not point to a definite variation of the attack with the current-density.

The last three tests, 14 to 16, were made with direct current only, and show an electrolytic attack which is greater than the theoretical calculated from Faraday's law; that is, the corrosion of lead by direct current is greater than the theoretical value, and the direct current does not only dissolve the theoretical amount of lead, according to Faraday's law, but also increases the spontaneous corrosion due to the chemical action of the soil, especially in the presence of nitrates, etc.

Regarding the protective action of a small direct current, against alternating-current electrolysis, it must be understood that this is not due to maintaining the lead negative against the ground. It is obvious that the lead would be protected against corrosion, if upon the alternating current a direct current were superimposed sufficiently large to maintain the lead always negative. This, however, would require a direct current more than $\sqrt{2}$ times the alternating current, which is not practical. From the previous tests, it appears that a direct current of 1.5% of the alternating current gives practically complete protection against the electrolytic action of the alternating current. Such a small direct current would not appreciably change the duration of the successive half waves of alternating current, but the lead would still be positive for practically half the time; and with such a current graphically superimposed upon the alternating current, the eye would hardly see the difference in size of the two half waves of the resultant current.

It seems that a very small increase of the negative half wave over the positive half wave of the current is sufficient to make the negative half wave completely reverse and thus neutralize the action of the preceding positive half wave.

To investigate this phenomenon further in an experiment of larger magnitude, the following test was made. A lead plate was used, of 10¾-in. width, and 13¾-in. height, giving a total surface of about 2 sq. ft. It was immersed between two sheet-iron plates, as other terminal, of 5 in. by 14 in. each, in a large earthenware vessel. The lead plate was cut in two vertically, and the two halves spread apart, and in the space three small lead plates, of about 6 sq. in. each, inserted in the soil without any electrical connection, to serve as check for the chemical corrosion, due to the soil.

As an electrolyte, I used garden soil, a clay loam, with some sand, a considerable amount of street mud, and some fertilizer added. Four-ampere, 25-cycle alternating current was used and superimposed thereon, 0.06 ampere or 1.5% direct current.

The current was kept on the circuit for 20 days, from Oct. 20th to Nov. 9th, 1906, during which time the alternating current varied between 3.8 and 4.0 amperes, while the direct current remained constant at 0.06 ampere.

During the test the temperature of the soil was about 10° higher than that of the air and averaged 27.0° cent. Masses of marsh gas, with a considerable quantity of sulphuretted hydrogen, were evolved; that is, decay of organic matter took place in the soil. Evaporated water was replaced.

After the test, the lead plates were found covered with a black deposit, to which the sand stuck so that it could not be washed off, even with boiling water. With very diluted HCl, this black deposit was dissolved with the evaporation of large quantities of H_2S, and the acid was colored greenish black, as if iron had been carried across by the current and deposited as sulphide.

The test gave the following results:

Size of lead plates, both sides:	294 sq. in.		
Total weight, before test	208.756 grammes		
" " after "	206.975 "		
Weight dissolved	1.781 "		
Duration of test	470 hours		
Average 25 cycles current	3.9 amperes		
A. Ampere-hours, alternating current	1833		
" " direct current	28.2		
Dissolved per ampere-hour alternating current	.972 mg.		
Theoretical attack per ampere-hour direct current	3860 mg.		
Total corrosion, per cent. of direct-current electrolysis	0.0252%		
B. Weight dissolved per hour and sq. in.	0.0129 mg.		
Check plates, number	1	2	3
Location	top	middle	bottom
Surface, sq. in. both sides	6.24	6.72	6.72
Weight before test	4.575	4.797	4.763
" after "	4.527	4.759	4.722
" dissolved	48	38	41
" " per sq. in. and hour	0.0160	0.0118	.0127
Average	–0.0134 mg.		
Leaves as electrical corrosion, per sq. in. and hour	–0.0005 mg.		
Amperes per sq. in., 25 cycles	0.0132		
Electrical corrosion, per cent. direct current electrolysis	–0.001%		

It seems to follow herefrom that a direct current superimposed on the alternating current and equal to 1.5% of the alternating current, perfectly protects the lead plates against electrolytic attack by 25-cycle current; so that the corrosion of the lead plates in the soil is reduced to the value of corrosion which would take place spontaneously by the chemical action of the soil, or even less.

From Table XIX it follows that the average electrolytic corrosion in ordinary soil, by 25-cycle alternating current, is 0.280% (in soil containing fertilizer, as in the last test, it is greater).. 1833 ampere-hours would therefore dissolve electrically

$$1833 \times 0.0028 \times 3.86 = 19.85 \text{ grammes of lead.}$$

With a chemical corrosion of 0.0134 mg. per square inch an hour, observed, 294 sq. in. would lose in 478 hours,

$$0.0134 \times 294 \times 470 = 1850 \text{ mg} = 1.85 \text{ grammes.}$$

Without protective action by superimposed direct current, the total corrosion of the lead plates during the 20 days' test therefore should be 21.70 grammes.

By the superposition of 28.2 ampere- hours direct current, or 1.5% of the alternating current, this was reduced to 1.78 grammes, or to 8.2% of its former value, showing strong protective action of the superimposed direct current.

A paper presented at the 214th Meeting of the American Institute of Electrical Engineers, New York, March 1, 1907.

ELECTROLYTIC CORROSION OF IRON AND STEEL IN CONCRETE

BY A. A. KNUDSON

In these days of wide and rapidly growing use of reinforced concrete and hydraulic cements in all kinds of structures, the question often comes up as to whether concrete will afford to iron and steel the same protection from stray currents of electricity that it does from ordinary corrosion or rust. In the practice of investigating movements and results of currents upon underground pipes and other structures, several instances have come to our notice where damage has been caused by electrolytic action upon metals covered or incased in concrete or Portland cement.

During the last year we have frequently been asked about the probability of electrolysis upon various underground structures where the use of cement or concrete was being considered or had been used. In view of the importance of this question, therefore, we have thought it would be of service to those who are interested in the subject if more light were thrown on the true value of concrete as a supposed insulator. With a desire to obtain some definite data as to the amount of current and time necessary to cause corrosion upon metals encased in concrete or hydraulic cements, and also to test their value as electrolytes, we have made some laboratory experiments, and herewith give the results, trusting they may be of some value.

In March, 1903, blocks of concrete containing iron tubes were prepared by the writer for this purpose. These blocks or samples were made of equal parts of portland cement and sand. They were made in ordinary metal pails slightly larger at the top than at the bottom. In the centre of each block was placed a 2-in. wrought-iron pipe. The dimensions of each block and the surface of iron buried are given in plan and sectional drawing, Fig. 1, and will not require further explanation; the following cuts show blocks and pipes after the tests. A few preliminary tests at this time indicated that a series of tests might bear important results, and as we lacked opportunity for making daily tests and observations, they were sent to the Electrical Testing Laboratories of this city, where excellent facilities were had for making the required measurements. Preliminary tests were made with the object of "feeling our way," and of selecting such strength of current for the series as seemed advisable. These preliminary tests not being especially important, the details are not given; but from the information obtained it was decided to commence a series of tests extending over a time of 30 days with the three blocks immersed, and under the following conditions:

Block 2, Fig. 2, was immersed in fresh water and Block 4 in sea water. These were connected in series, with 0.1 ampere continuously flowing through them. Block 3, Fig. 3, was also immersed in sea water, but no current was sent through it. This was for the purpose of comparison after the blocks were broken open. The arrangement of the circuit is shown in Fig. 4.

These tests were commenced on February 1, 1906, and ended March 2, 1906. The results of importance upon this first group of blocks were found in the gradual disruption of the concrete, as shown by the cracks as time went on, and the appearance of electrolysis and loss in weight of the iron tubes of both No. 2 and No. 4 when the tests were concluded. Block 4 is not shown, it being quite similar to the others. During the test these cracks were noted as follows: on the 17th day a small crack down one side of Block 2 was observed. On the 27th day this crack in No. 2 had a maximum width of ⅛ in. and extended clear down one side, across the bottom, and nearly to the top of the other side. Two cracks also appeared in No. 4. This disintegration of the concrete was a genuine surprise. The report furnished by the laboratory on this first set of experiments concludes as follows:

After the conclusion of this test which extended over thirty days time, the blocks were removed, and after allowing them to dry they were broken open. It was found to be quite easy to break open blocks Nos. 2 and 4 which had already become cracked. Block No. 3 which had not been subjected to electrolysis was broken with the greatest difficulty. Blocks Nos. 2 and 4 showed on their interior strong evidences of electrolytic

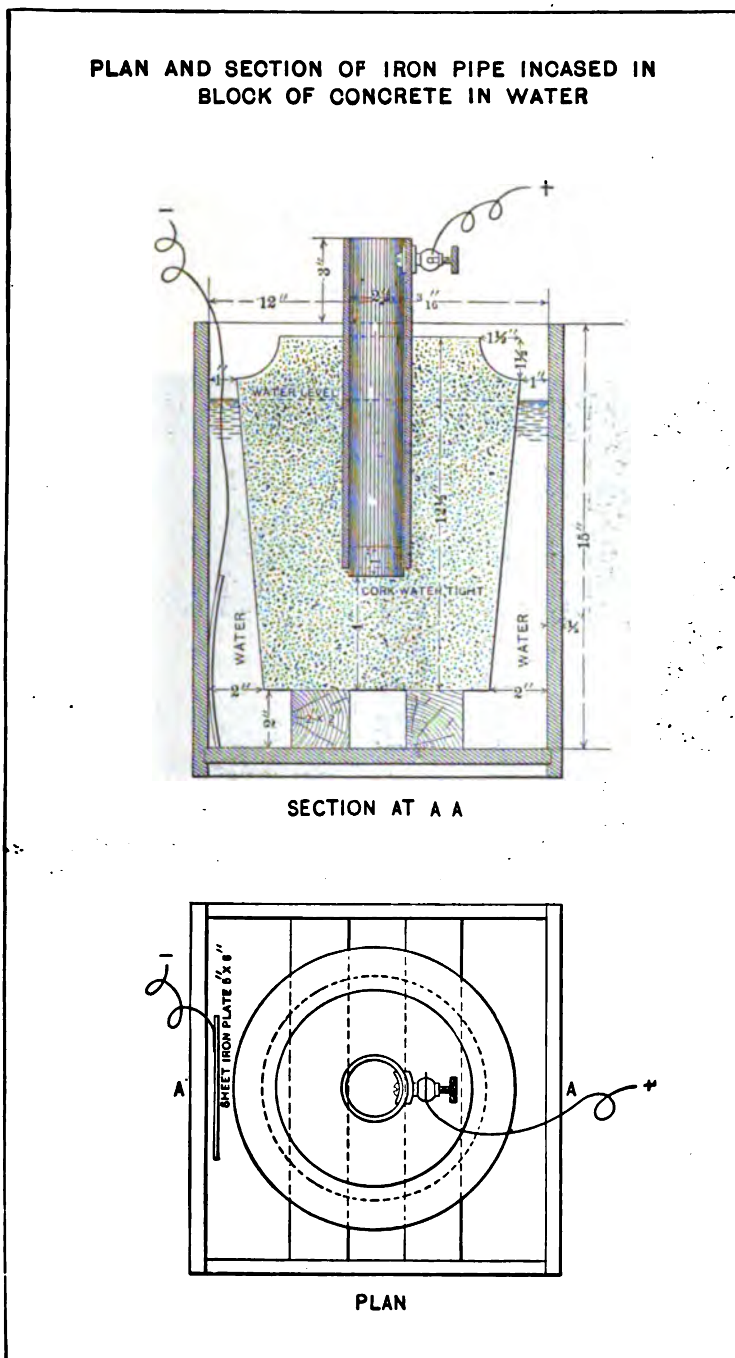

PLAN AND SECTION OF IRON PIPE INCASED IN BLOCK OF CONCRETE IN WATER
WATER LEVEL
CORK WATER TIGHT
WATER
WATER
SECTION AT A A
SHEET IRON PLATE
A
A
PLAN

FIG. 1.

action in the form of what was apparently a deposit of iron rust extending from the pipe toward the outside of the block. Along certain lines which acted like lines of cleavage, the cement was found to be softened so that it could readily be cut or scraped with a knife. This softening was such that the point of a blade of a pocket knife could be inserted into it far enough so that the knife was supported in an upright position. The pipes enclosed in Nos. 2 and 4 were found to be considerably corroded. A portion of the scale on the corroded parts of these pipes was removed and the pipes were weighed. The pipe in Block No. 3 was as bright as a new pipe. The concrete showed no evidences of a deposit of iron rust. An idea may be formed of the condition of the concrete blocks from the photographs given herewith.

(Block 2) FIG. 2.

Weighing of the pipes had been made by Mr. Knudson before casting them in the blocks. Weighings made at the conclusion of the experiment, together with these initial weighings, are given in the following table:

	No. 2 fresh water.	*No. 4. salt water.*
Initial.............	3 lb. 12.50 oz.	3 lb. 7.5 oz.
Final..............	3 " 10.95 "	3 " 6.4 "
Loss	1.55 "	1.1 "

As has been said above, the scale was not entirely cleaned off from pipes Nos. 2 and 4 before the final weighing was made, so that the loss in weight does not represent the entire amount of the electrolysis which had occured.

The results of these experiments seemed so important that it was thought best before drawing conclusions to have the tests repeated, and therefore another set of experiments similar to the first, was made to see how the data would compare.

Second Set of Experiments

In this case two blocks of concrete were prepared, numbered 5 and 6 (Block 6 not shown). These were made the same as the others except that Rosendale cement was used, called in the trade "Brooklyn Bridge Brand." The object of using a different cement was to see if there was any change in the results

(Block 3) (no current)

Fig. 3.

that could be attributed to the use of a different brand of cement. In these tests more careful and more frequent measurements were employed than in the first set of experiments. They were commenced on April 12th, 1906. Two readings were made every 24 hours through the entire 30 days, and the appearance of the blocks was closely watched. The source of current, as in the first test, was from a storage-battery, and the pressure was increased or decreased according to the resistance, in order to maintain a constant current of 0.1 ampere.

The variation of resistance in both blocks during the test of 30 days is important. Such changes are graphically represented in

Fig. 6. The figures showing ohms are given as relative, as they may not quite accurately represent the true values. They were obtained by simply dividing the volts by the 0.1 ampere. It was found in the preliminary trials that resistance measurements by the usual methods, such as the Wheatstone bridge, were not accurate, owing to strong polarizing effects. For this reason the resistances as shown by these curves while not considered absolutely accurate in every case, are sufficiently so for our purpose of examination and study.

The curve in Fig. 7 represents the sudden fall or practical breakdown of concrete as insulation in 48 hours. The measurements in this test were made by the Wheatstone bridge, using

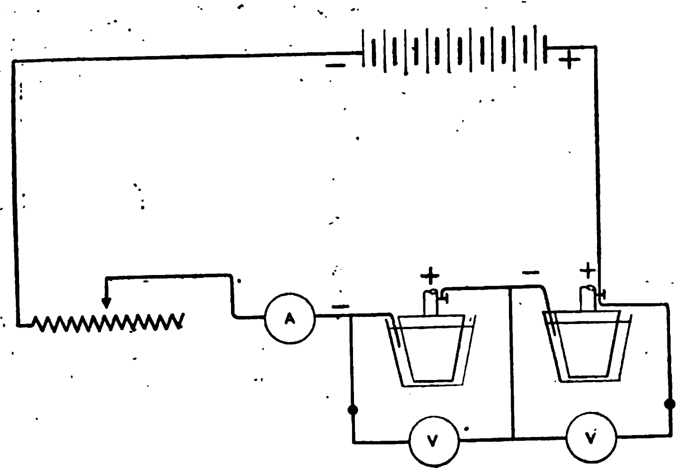


FIG. 4.

alternating current and a telephone receiver. They are considered fairly accurate.

Quoting from the report on this second series of tests, the following notes are of interest:

Second day of test. Water appeared around the pipe of No. 5, having soaked through the concrete.

Sixth day of test. Cracks were observed in both samples of concrete, those in No. 5 being the most prominent. A small amount of water was found standing in the bottom of pipe No. 5. None in pipe No. 6.

Seventh day of test. The cracks in the concrete are increasing in the case of both samples.

Ninth day of test. A yellow frothy substance appeared at several points at the top of the concrete, close to the iron pipe of sample No. 6. Later this turned rust color.

Eleventh day of test. Same rust colored deposit observed around pipe of sample No. 5. The cracks of both samples have increased in prominence.

Eighteenth day of test. The cracks have assumed such proportions that it appears as though the concrete might easily fall apart, being $\frac{1}{8}$ to

(GROUP 1)
(1st series)

FIG. 5

$\frac{3}{16}$ of an inch in many places. There is considerable rust colored, frothy deposit on top of sample No. 5, especially near the pipe.

It appears from these observations that before the ninth day, the process of electrolysis had arrived at quite an advanced stage on both blocks and before the rise in resistance took place, which afterwards in fresh water reached 300 to 400 ohms, requiring some 30 to 40 volts to maintain the 0.1 ampere. We should not, therefore, conclude that because such high readings are not found

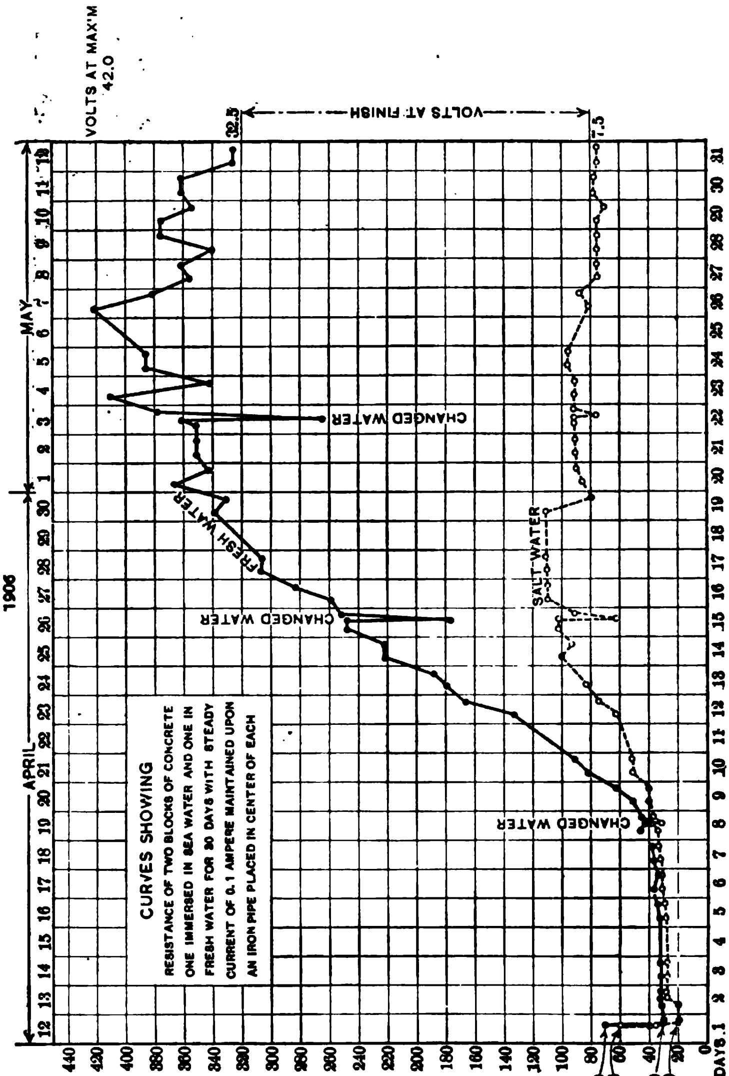


Fig. 6.

in practice, it is a sign that there can be no electrolysis. In the salt-water block it is observed that even to the eleventh day of the test 5.5 volts only were required to pass the 0.1 ampere, and at that time the record states the cracks in both samples have increased in prominence.

This report concludes as follows:

After the conclusion of the test which continued over thirty days time, the concrete blocks were removed from the water and allowed to dry. They were then broken open. Block No. 5 which had been under test in the salt water was found to have a rust colored deposit extending along the sides of a crack from the external surface to the pipe, as shown by the accompanying photograph. The rust colored deposit in sample No. 6 was only about the pipe.

There were spots especially in the fresh water block No. 6 where the concrete had softened to such an extent as to be readily dug out with a knife.

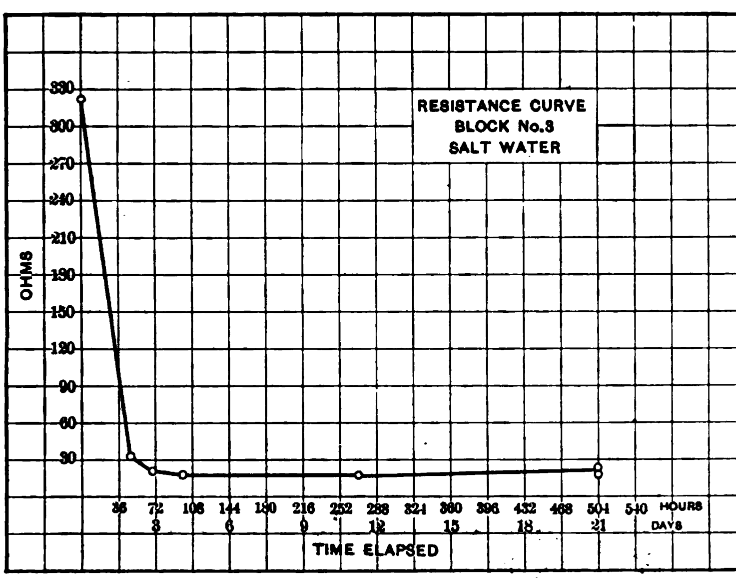


FIG. 7.

The weights of the pipe before and after the tests are given in the following table:

	No. 5 *salt water.*	No. 6 *fresh water.*
Initial	3 lb. 7.1 oz.	3 lb. 6.6 oz.
Final	3 5.5 "	3 5.5 "
Loss	1.6 oz.	1.1 oz.

Since the scale was not entirely removed for the final weighing, the loss in weight indicated does not represent the actual total amount of electrolysis which had occurred. However, all scale that could be readily removed was removed by Mr. Knudson before the final weights were taken.

This second series of tests shows results very similar to the first, only more pronounced; and we believe it also shows that the results would be practically the same with concrete

(GROUP 2)
(2d series)
FIG. 8.

made up with any of the different brands of cement found in the market, or made with different proportions of sand, or made of brick, or stone masonry.

The photographs of the different pipes show to some extent the effects of electrolytic action upon their surfaces which were in the concrete, except No. 3, Fig. 5, which had no current. No. 5, Fig. 8, which was in the salt-water block, shows the most severe case, having a hole through the iron. This hole is one inch long and three eighths of an inch wide at its widest part, as genuine a case of electrolysis as any we have seen in larger pipes removed from a street.

Referring to the photographs of the blocks, all but No. 3 (which had no current) show the discoloration made by the iron rust, extending in most cases through what were cracks to the outside surface. No. 3 shows a perfectly clean and hard interior surface. As the report states, there was no evi-

(Block 5) FIG. 9.

dence of corrosion. It was like breaking open a piece of granite, and required the services of a "hard-handed son of toil" with a sledge-hammer and chisel. The other blocks which were under test could be pried apart with an ordinary screw-driver inserted in the cracks.

Attention is called to block 5. Fig. 9 (sea water) where one of the cracks is shown at the back and about the centre of the curve from which the iron tube was removed. The object of using sea water in our tests, as well as fresh water, was to ascertain and compare the resistances shown in the curve sheet, and also to conform as nearly as possible to conditions found in practice, such as bridge-piers and other structures located on water-fronts.

These tests and experiments go to show that only a small fraction of an ampere is necessary to cause electrolytic action. The element of time being always with us, it is only necessary where electric currents are present of sufficient voltage in the proper direction to cause even a very small amount of current to pass that will in time cause corrosion upon interior steel structures, whether placed in concrete, brick, or in granite masonry. It is not expected, however, that large granite piers would develop cracks, but electrolysis to interior steel work and to bridge anchorages may go on just the same. Cracks may develop, however, in concrete piers of small bridges, such as those which cross creeks or canals.

By way of a practical illustration, there is a bridge in this city of this description over the Gowanus canal, South Brooklyn, at Hamilton avenue. A portion of the Bridge Commissioner's report ending June 30, 1906, referring to this bridge, is as follows:

HAMILTON AVENUE BRIDGE.

Since construction, the foundation walls of this bridge have developed some rather serious cracks, occurring on both sides of the canal, and there has been a movement of the walls towards the centre of the canal. During the last three months this movement has amounted to half an inch. Previously the movement totaled about, three and one-half inches. From October to March there was practically no movement. A continuation of this movement for several inches more will result in the necessity of alterations in the centre of the leaves, as they will interfere before the bridge can be fully closed.

With a view of ascertaining the electrical conditions, we have made a few tests at this bridge. The voltmeter readings show the steel structure to be positive to the canal, positive to water-mains in the street, and positive to the trolley-rails on the bridge, ranging from 0.5 to 1.5 volts. These readings were taken when the car-traffic was light. Some of the cracks on the concrete had been plastered over, but others were quite visible. The tests indicate that the trolley tracks on the bridge are in connection with the steel structure. Tests were also made on another bridge of the same construction a little farther north over the same canal, at Ninth street. The readings here were exactly the reverse of those found at the Hamilton avenue bridge, the structure being negative to canal, to water-mains and tracks. There were no visible cracks in the concrete of either foundation. Although the cracks in the concrete of the Hamilton avenue bridge are attributed to other causes in the Commissioner's report, we believe these tests and observations point strongly to electrolytic action from trolley currents as being the true cause. This seems to us the more reasonable cause for these cracks, in view of the results of our laboratory experiments just described. Ordinary care would suggest that costly structures of this kind in this or other cities should be periodically inspected for evidence of electrolytic action upon the interior steel work, especially if located contiguous to water, or in the vicinity of electric railways or railway power stations as in the case just cited. Furthermore, this question should be carefully considered when such structures are planned, and tests made at locations of proposed bridges or other structures to ascertain the electrical conditions and the possibilities of injury due to electrolysis from stray currents.

This question of electrolytic corrosion of interior steel in the construction of high buildings, however, has not been entirely neglected. There is at least one case, that of the *New York Times* building, where provision has been made in advance as a protection. In the Building Supplement, issued by that paper, dated January 1st, 1905, an interesting description is given in detail of the entire construction of that building. The following extract, referring to electrolysis, will be of interest:

> The danger that in the case of the steel frame, rust and the disintegration of electrolysis would hasten the process of dissolution so much as to make structures of this kind prematurely unsafe through the destruction of their supports, was recognized in time to permit of ample safeguarding in the case of the steel frame of the Times building. It is axiomatic that columns to which moisture has no access will not be impaired by rusting, and that those effectually insulated from vagrant electrical currents will not be affected by electrolysis. The first consideration was to keep the basements dry. Hence the thorough waterproofing and draining of the retaining walls already described, which was carried under the floor of the press room, occupying the great area of the sub-basement. As a further safeguard, all the steel members up to the street level are incased in Portland cement mortar, to the minimum thickness of three-fourths of an inch. This is effectual protection against rust deterioration. Under these conditions electrolytic disintegration is deemed impossible, but the probability of its occurrence in even microscopic degree is rendered still further remote by as perfect insulation as can be provided. There is sufficient grounding to relieve any electrical tension which may exist in any part of the steel frame by drawing off the current at points where electrolytic action cannot be set up.

This is the first instance we have noticed where a large corporation has recognized this danger and has taken steps beforehand to avoid it. The protection of steel structures already constructed, however, is a different matter. While plans may be made to provide insulating methods and water-proofings, before construction, it is not easy to prevent corrosive action, when the conditions are favorable, after construction.

Another point which may have an important bearing on this subject is the great pressure upon pillow-blocks, and upon piers supporting as they do enormous weights, which serve to make excellent electrical contact with concrete or masonry on which they stand, and, therefore, offer further opportunity for inviting stray currents.

Figs. 10 and 11 are photographs of the underside of two water meters which were practically destroyed by electrolysis while in

FIG. 10.—300 ft. from nearest track. FIG. 11.—675 ft. from nearest track

service in the cellars of dwellings in a distant city. They were discovered during a survey by the writer in October last. They are shown as an illustration of how railway currents will follow a service pipe for a considerable distance from the tracks, enter a building, and find an outlet to ground in the damp soil of a cellar. This furnishes an opportunity for current to pass into the iron foundations of large buildings where such service pipes, either water or gas, are connected, as they usually are, to the framework of such structures.

These illustrations are by no means isolated cases. We have discovered many similar cases of current straying into buildings in different cities in this country. There were three meters found destroyed in this way in different sections of the city from which they were taken. They were from one to two miles apart. The distance from the tracks of Fig. 10 was

300 ft., and of Fig. 11, 675 ft. All of these meters were on side streets, at right angles to the car tracks.

IN REGARD TO REMEDIES

Coatings of various kinds of paints or varnishes will be of little use as an insulation, for it must be borne in mind that not only a moisture resistant is required, *but an insulation that will resist continual moisture*, and also that will stand the pressure of great weights.

From these laboratory experiments, as well as observations in practice, we draw the following conclusions.

1. Steel structures are well preserved from ordinary corrosion by concrete if placed either in salt or fresh water. This, however, has long been known.

2. If but a small fraction of an ampere of electricity passes from an interior metallic column or structure into concrete or masonry as usually made, there will be corrosion of the metal and disintegration of the concrete or masonry.

3. Structures of steel in concrete that are subject to sea water are in more danger from electrolytic action than those in fresh water, by reason of the lower resistance of concrete in sea water as shown by the laboratory experiments.

4. In no sense can concrete be considered an insulator, and, as shown, it is from all appearances just as good an electrolyte as any of the soils found in the earth.

Other investigators in this field have given valuable information on this subject. Mr. Maximilian Toch, in a paper before the American Electrochemical Society in June last, gives an interesting account of some experiments conducted by himself with steel in concrete, and although on somewhat different lines to our own, arrives at practically the same results.

Mr. M. P. Wood, in his excellent work entitled " Rustless Coatings, Corrosion, and Electrolysis of Iron and Steel," refers to this subject as follows:

> It is a false reliance that masonry, mortar, concrete, or cement are impervious to moisture and incapable of acting as an electrolyte such as would induce electrolysis. They are not insulating substances, or at the best only in the smallest degree under the most favorable circumstances. They are positively porous and in nearly every case, whether tested in large or small mass, are permeable to all waters or moisture and gases, and in but a few exceptional cases ever become thoroughly dry.

It is therefore to be expected that so long as the single trolley with its grounded return is in general use, just so long may we look for electrolytic action in some form upon various underground structures; and reinforced concrete is no exception to the rule.

It is not at all surprising that such currents are busy at steel work of bridge-anchorages. Whether enclosed in concrete or masonry, these materials, as we have endeavored to show, are no protection from straying railway currents when the conditions are favorable for electrolytic action. In view, therefore, of these items presented and the enormous use to which concrete and hydraulic cements are now put, it would seem that this question should receive due consideration by those who have to do with planning and constructing important public works and buildings, as well as those who are entrusted with the care and safety of such structures.

A paper presented at the 214th Meeting of the American Institute of Electrical Engineers New York, March 1, 1907.

SOME THEORETICAL NOTES ON THE REDUCTION OF EARTH CURRENTS FROM ELECTRIC RAILWAY SYSTEMS BY MEANS OF NEGATIVE FEEDERS

BY GEORGE I. RHODES

The subject of earth currents caused by electric railway systems is of such importance that it is believed a few theoretical notes on the relative efficiencies of different return feeder systems in reducing stray currents will not be without interest.

Consider any system, the potential of whose running rails may be represented by the Curve I, Fig. 2, which is plotted with distances from the power house or sub-station as abscissas, and potentials of the rails referred to the negative bus-bar as ordinates. Assume for the time being that all resistance offered to current flowing from the tracks to earth is in the contact between rails and earth.

Let a = contact resistance per foot between rails and earth.
l = distance from power station.
v = potential of rails referred to negative bus-bar.
I_g = total leakage current.

Now if the negative bus-bar is completely grounded, and the earth of uniform potential, as would be the case if it had zero resistance,

$$\Delta I g = \frac{v \Delta l}{a}$$

$$g = \sum \frac{v \Delta l}{a}$$

If a is uniform over the entire line, it is evident that the leakage current will be measured by the area enclosed between the potential curve of the track and the line of zero potential. If the contact resistance is not uniform, the area will not be a true measure, but it will still be indicative of the amount of current flowing from the rails.

If now the negative bus-bar is insulated, the earth will have a potential with reference to it such that the current flowing out of the rails shall be equal to that flowing into them. Under the assumption of uniform contact resistance between track and ground, this potential will be such that the areas enclosed by the curve, above and below the line of earth potential, are equal.

The assumption that the earth is of uniform potential is obviously far from correct, for since its resistance is not zero it is affected to a certain extent by the presence of a grounded conductor of different potential. If the curve is plotted with refer-

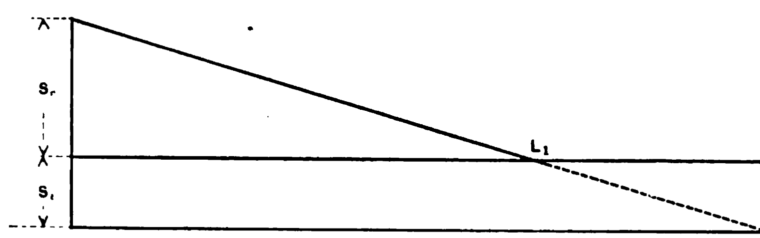


FIG. 1.—Distribution of copper for uniform drop.

ence to the ground in the vicinity of the rails as zero, the area enclosed by the curve will then measure the true leakage current with the above limitations; but if the curve is plotted with reference to the earth at that point where the rails and ground are at the same potential, the area enclosed will not measure the actual leakage, but rather the maximum current that would flow if the earth offered no resistance except at the surface of contact with the rails.

On this latter assumption, then, the following cases will be considered, both with the negative bus-bar thoroughly grounded and insulated. The load is considered to be uniformly distributed over the whole line, which extends in one direction only from the power station.

I. No copper in return circuit.

II. Copper of uniform section bonded to the rails at short intervals.

III. Copper distributed to give uniform drop, bonded to the rails at short intervals.

IV. A single insulated negative feeder connected to rails at middle of the line, and at the power station.

V. A single insulated feeder connecting the rails to the negative bus-bar only at the middle of the line.

VI. Several insulated feeders.

VII. Several insulated feeders with equal potentials at all feed points.

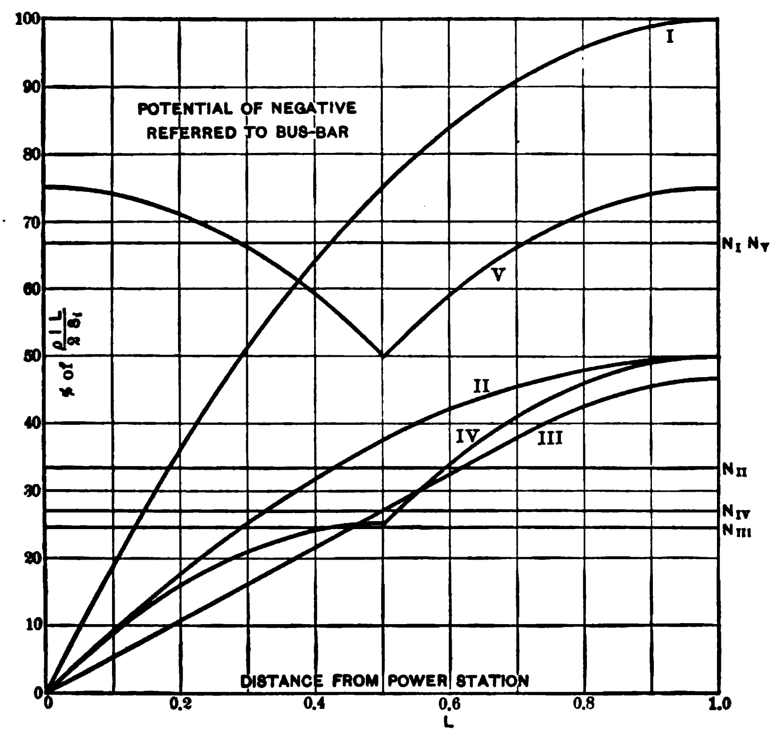


FIG. 2.—Potential Curves, Cases I–V.

The following notation will be used:

i = current at any point on line.
I = total current.
v = potential at any point referred to bus-bar as zero.
l = distance from power station.
L = total length of line.
r = resistance per foot of return.
ρ = 10.30 = resistance per cir. mil-foot of copper.

$$v = \frac{\rho I l}{s_i + s_c} \text{ a straight line.}$$

It is evident that this equation can hold only when l is such that

$$(s_i + s_c)\left(1 - \frac{l}{L}\right) = s_i$$

then
$$l = L_1 = L \frac{s_c}{s_i + s_c}$$

For values of $l > L_1$, the conductivity is uniform and equal to that of the rail return (see Fig. 1).

From $l = L_1$ to $l = L$

$$i = I \left[\frac{L - L_1}{L} - \frac{l - L_1}{L}\right]$$

$$r = \frac{\rho}{s_i}$$

$$v = \frac{\rho I}{s_i}\left[\frac{(L - L_1)(l - L_1)}{L} - \frac{(l - L_1)^2}{2L}\right] + \frac{\rho I L_1}{s_i + s_c}$$

This curve is that portion of the parabola I, Fig. 2, beyond $l = L_1$, dropped until it is tangent to the straight line.

$$v = \frac{\rho I l}{s_i + s_c}. \quad \text{See III, Fig. 2.}$$

The area representing leakage current with the bus-bar grounded can be shown to be

$$A = \frac{s_i (3 s_c^2 + 6 s_i s_c + 2 s_i^2)}{2 (s_i + s_c)^3} \cdot \frac{\rho I L^2}{3 s_i}$$

and with the bus-bar insulated the neutral point is at

$$L_0 = \frac{L}{2} \left\{1 - \frac{s_i^2}{3 (s_i + s_c)^2}\right\}$$

for values of $s_c > 0.815\, s_i$, making $L_1 > L_0$.

This makes

$$a = \frac{s_i (3 s_c^2 + 6 s_i s_c + 2 s_i^2)^2}{24 (s_i + s_c)^5} \cdot \frac{\rho I L^2}{3 s_i}$$

The weight of copper used is

$$W = \omega\, s_c \frac{L_1}{2} = \frac{\omega\, s_c^2\, L}{2\ (s_i + s_c)}$$

In order to compare properly this case with Case II, equal amounts of copper must be used making

$$\frac{s_{c\,\mathrm{III}}^2}{2\ (s_i + s_{c\,\mathrm{III}})} = s_{c_{\mathrm{II}}}$$

$$s_{c\,\mathrm{III}} = s_{c\,\mathrm{II}} + \sqrt{s_{c_{\mathrm{II}}}^2 + 2\, s_i\, s_{c_{\mathrm{II}}}}$$

IV. Single insulated return feeder from middle of line. Connection to rails at power house.

By the use of Kirchoff's laws it can be shown that

From $l = o$ to $l = \frac{L}{2}$

$$i = I\left(1 - \frac{3\, s_c}{4\, (s_i + s_c)}\right) - I\,\frac{l}{L}$$

$$r = \frac{\rho}{s_i}$$

$$v = \frac{\rho I}{s_i}\left\{ l\left(1 - \frac{3\, s_c}{4\ (s_i + s_c)}\right) - \frac{l^2}{2\,L}\right\}$$

From $l = \frac{L}{2}$ to $l = L$

$$i = \frac{I}{2} \quad \frac{I\left(l - \frac{L}{2}\right)}{L}$$

$$v = \frac{\rho I}{s_i}\left\{ \frac{\left(l - \frac{L}{2}\right)}{2} - \frac{\left(l - \frac{L}{2}\right)^2}{2\,L} + \frac{L}{2}\left(\frac{3\, s_i}{4\,(s_i + s_c)}\right)\right\}$$

Both curves are portions of the parabola of Case I (see IV, Fig. 2).

The area representing leakage current can be shown to be

$$A = \left\{1 - \frac{27\, s_c}{32\ (s_i + s_c)}\right\} \quad \frac{\rho\, I\, L^2}{3\, s_i}$$

1. No connection to rails at power station, and distance between feed points twice the distance from the power house to the first point, and from the last point to the end of the line. (See Fig. 3.)

2. Connection to rails at power house with the distance between feed points, and from the power station to the first feed point equal to twice the distance from the last point to the end of the line. (See Fig. 4.)

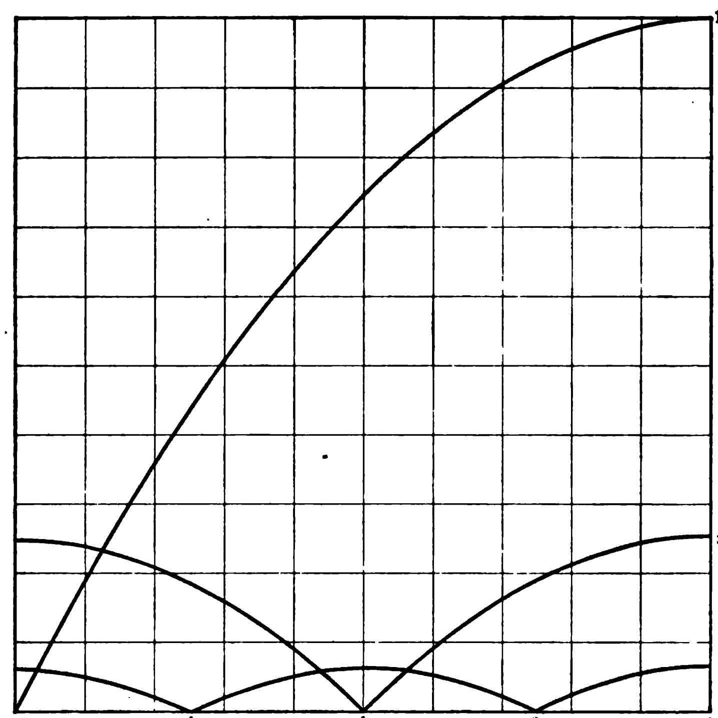


FIG. 3.—Potential of negative referred to bus-bar.—Case VII.

1. With a single feeder and no connection at power house, the feed point for equal maxima will be at the centre of the line. (See Fig. 3.) the potential curve being made up of the upper portions of the parabola of Case I, also shown in Fig. 3.

With the bus-bar grounded the area beneath this curve is

$$A = 2 \times \frac{2}{3} \times \frac{L}{2} \times \frac{1}{4} \frac{\rho I L}{2 s_i} = \frac{1}{4} \frac{\rho I L^2}{3 s_i}$$

With two feeders the feed points will be ¼ and ¾ of the distance from the power house and the area will be

$$A = 4 \times \tfrac{2}{3} \times \frac{L}{4} \times \tfrac{1}{16} \times \frac{\rho I L}{2 s_i} = \tfrac{1}{16} \, \frac{\rho I L^2}{3 s_i}$$

With n feeders the feed points will be at

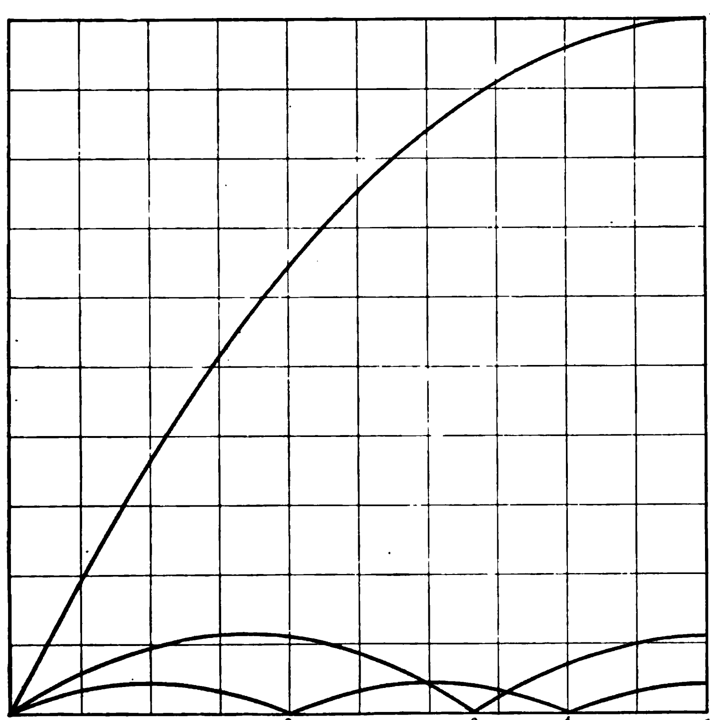


Fig. 4.—Potential of negative referred to bus-bar.—Case VII.

$$\frac{1}{2n}, \; \frac{3}{2n} \; \ldots \; \frac{2n-1}{2n}$$

of the distance from the power house to the end of the line, making

$$A = 2n \times \tfrac{2}{3} \times \frac{L}{2n} \times \frac{1}{(2n)^2} \times \frac{\rho I L}{2 s_i} = \frac{1}{4n^2} \, \frac{\rho I L^2}{3 s_i}$$

Fig. 7 gives the relative leakage currents with the bus-bar insulated.

Fig. 8 gives the relative leakage currents for Case VII with bus-bar insulated, plotted with the number of feeders as abscissas, the points representing half feeders being as explained above.

It is at once apparent that insulating the negative bus-bar very much decreases the leakage current in all cases, the re-

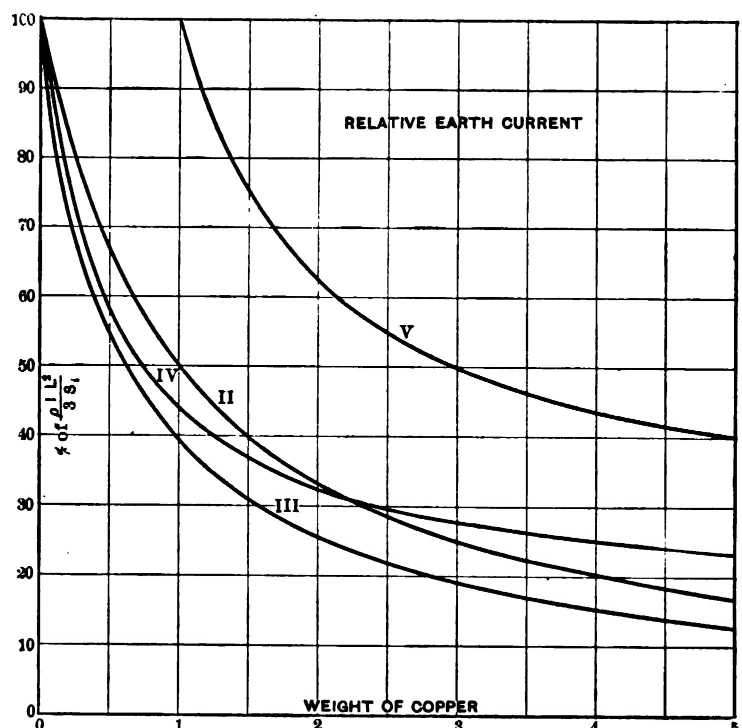


FIG. 6.—Relative earth current. Negative bus-bar grounded.

duction being in the neighborhood of 80%. Further than this, it is unnecessary to consider the case of a solid ground at the power station.

With the bus-bar insulated, it is seen that the leakage currents with copper distributed either uniformly or for uniform drop, are identical. The equations do not represent the same line but they agree so nearly that the curves are identical within a very few per cent.

With a single feeder to the middle of the line and a connection to the bus-bar at the power station, it is seen that for large feeders, the results are poorer than for any other method, the divergency becoming greater as the amount of copper is increased; but with a single feeder and no other connection between bus-bar and rails, the leakage is independent of the amount of copper used and equal to 4.8% of the original leakage with the bus grounded and no copper in the negative circuit.

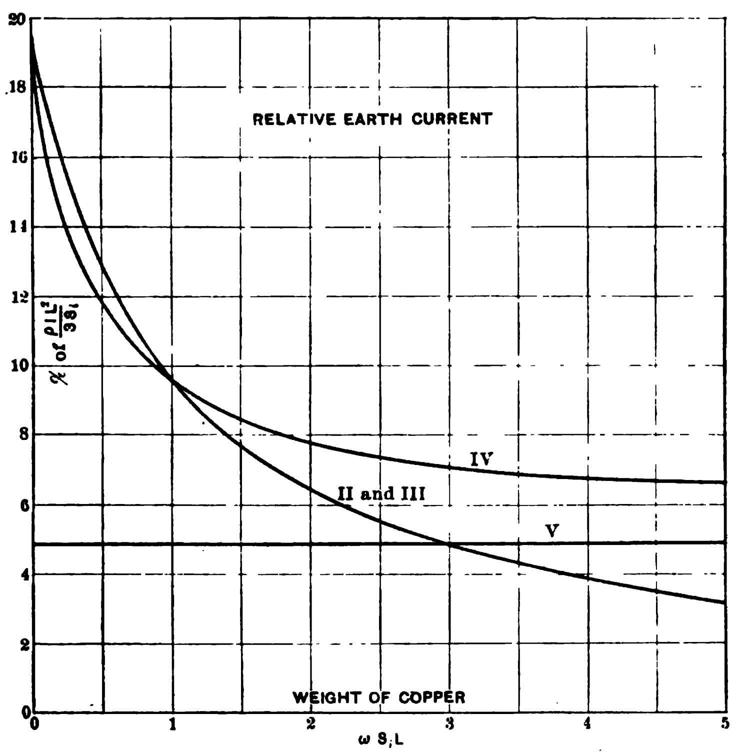


Fig. 7.—Relative earth current. Negative bus-bar insulated.

This latter is really covered by Case VII. The great superiority of the boosted negative feeder method of reducing earth currents is at once apparent, two feeders reducing the leakage to 1.2% of its original value with the bus-bar grounded, or about 6.2% of its original value with the bus-bar insulated. Very little is gained by using more than two feeders.

In conclusion, a few figures as to the amount of copper required to reduce the leakage to one half with the bus grounded may be of interest. Let us consider a double-track road with 100-lb. rails. The equivalent conductivity of each rail is about 1,200,000 cir. mils of copper if well bonded, making $s_i = 4{,}800{,}000$.

If the copper is to be of uniform section 4,800,000 cir. mils must be used the entire length of the line.

If the copper is to be distributed to best advantage it must

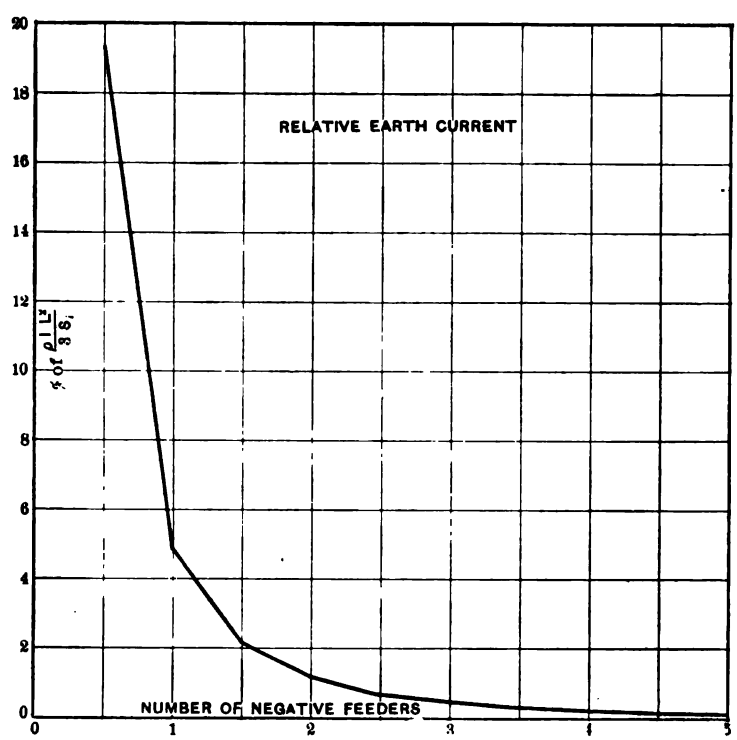


FIG. 8.—Relative earth current. Bus-bar insulated.—Case VII.

be of a section 9,120,000 cir. mils at the power station, being reduced uniformly to zero at a point 65.5% of the distance to the end of the line. The total amount of copper used will be 62% of that in the first case.

If an insulated feeder to the centre of the line is used, with a connection at the power house it must be of a section 7,200,000 cir. mils making the weight of copper 75% of that in the first case.

If the bus-bar is now insulated the 4,800,000 cir. mils of copper extending the entire length of the line will reduce the leakage to 9.7%; 62% of this copper distributed to best advantage will reduce the leakage to 12%; while a single feeder with a connection at the power house, using 75% of the copper will reduce it to 10.4%. Using a weight of copper determined only by its carrying capacity and the cost of power, in two boosted feeders, will reduce the leakage to 1.2% with no connection at the power house and by using 20% more copper in longer feeders, to 0.77% with such a connection.

Discussion on "Electrolysis," at New York, March 1, 1907

L. B. Stillwell: The results of Mr. Hayden's comprehensive and painstaking tests are particularly gratifying to all interested in the extensive use of electricity for railway purposes. While they show, however, that the electrolytic damage to subsurface metallic structures which alternating currents are liable to cause is practically negligible under ordinary circumstances, they illustrate also the fact that here, as elsewhere, special conditions may exist which call for the adoption of preventive measures. The method of protecting cable sheaths which Mr. Hayden suggests is ingenious and interesting. Quantitatively considered, however, his results indicate that it will rarely be necessary to adopt his plan of superimposing a continuous potential upon an alternating potential.

Mr. Knudson's paper and that of Mr. Rhodes have to do with electrolysis by continuous current. This subject is an old one and in the nature of things it is always with us. Unfortunately in its discussion the lawyer generally has been rather more prominent than the engineer. Too often also the engineers who have been retained by one or the other parties interested in litigation or threatened litigation, over actual or alleged damage by electrolysis, have approached the subject from a radically partisan viewpoint. Engineers representing the owners of water pipes or gas pipes have seriously recommended that street railway companies should be compelled to provide complete metallic circuits for their current, absolutely insulated from rails and ground. On the other hand, street railway companies, in many instances, have installed their plants apparently with absolute disregard of the effect of stray current upon the property of their neighbors; even going so far as deliberately to connect their track return to lead service pipes wherever opportunity offered.

Engineering is applied science; science is knowledge of facts. Nowhere better than in the meetings of this Institute can the essential facts ascertained by experiment or deduced by correct theory be discussed frankly and fairly, and nowhere better can engineering methods minimizing or preventing damage be worked out in a spirit of fairness to all concerned.

In the suit of the city of Dayton against the street railway company for alleged damage to water pipes owned by the city, Judge O. B. Brown in rendering his decision, admirably stated the rights and duties of the respective parties in the following words:

> The use of the streets for water works purposes is obtained by legislative authority. The right of an electric railway to use the streets is from like authority. Each of these uses is beneficial to the public and each is entitled to use its respective rights, without interfering with the other, and it is clear that no conflict can occur between the two if each would remain within its own sphere and exercise its powers with

due care and prudence. It is not necessary in arriving at a proper decision in this case to determine which should give way to the other. Both are legal, and both are important and of almost equal necessity to the inhabitants of the city.

* * * * * * * * *

Each should exercise its functions for the general good, exercising due care not to interfere with the duties and rights of the other.

There can be no question that in many of our cities and towns damage due to electrolysis is in progress which might be prevented by reasonable application of known principles and methods. That the prevention is not employed is due, in part, to our engineers, but perhaps still more to the general unwillingness of the management of electric railway companies to spend money in preventing damage which is not seen. This unwillingness to incur expenses in correcting conditions not realized by the executive management of the companies is naturally to be expected. The duty of the engineer is to exercise his influence to secure a realization of the fact that an ounce of prevention is worth a pound of cure, and to induce his client to take timely precautions to protect the interests of his neighbors, and, by so doing, to protect his own.

Mr. Rhodes' paper is an excellent theoretical discussion of the possibilities of an apparatus probably destined to do much more work in the future than it has in the past. Properly applied, it is of the greatest value in minimizing electrolytic damage underce rtain conditions. The plans of the Hudson companies contemplate the use of boosters to prevent possible electrolytic damage to the metallic shells of the tube tunnels destined to connect the Borough of Manhattan and the New Jersey shore. The Interborough Rapid Transit Company is also proposing to use them for a similar purpose in connection with its tunnels under the East River.

While the papers of Messrs. Hayden and Rhodes are convincing and of special value, that of Mr. Knudson would seem decidely to require revision of methods employed before satisfactory conclusions can be drawn. As regards Fig. 6 of this paper, the method employed; namely, the increase of potential to keep current constant, notwithstanding the apparent tendency of the reinforced concrete to protect itself, seemingly makes the conclusions reached of little value. No proof whatever is presented that the splitting of the concrete blocks was due to electrolytic action, as no effort had been made to exclude other possible causes, for example, expansion due to chemical change in the concrete itself. It is important to ascertain the facts as regards electrolytic corrosion of iron or steel in concrete, but the paper as presented fails to establish them.

Frank N. Waterman: We all know that electrolytic phenomena are so essentially mysterious to the average mind that it is almost impossible for the public to distinguish between true statements and false. Electrical engineers should, therefore, be extremely cautious about making statements that might mislead the layman. It is therefore peculiarly important that the discussion of the subject by the Institute should be careful and scientific, since its utterance will be regarded as authoritative. The papers by Messrs. Hayden and Rhodes are most gratifying in this respect, but the paper by Mr. Knudson contains much that cannot be considered as the last word on the subject.

Iron encased in concrete is like a battery electrode in a porous cup so far as insulation is concerned; of course current can be sent through it, and it can be made to take iron with it. Cement as a protector of iron acts both mechanically and chemically. If a current is introduced into the midst of it no protection is to be expected, unless by chemical action with the initial products of the decomposition a protective or highly resistant coating is formed which will restrict the flow of current. In Mr. Knudson's paper five samples of cement were used, but the author has not told us about the physical or chemical properties of the cement, how long it had been cast, or its age or condition when cast. Whether it contained free lime tending to make it develop expansion cracks, or whether its constitution predisposed it to shrinkage cracks, are not set forth. These facts are important, and should be carefully considered in accounting for the cracking of the blocks.

I should like to know the condition of the iron surfaces before weighing and casting—whether they were turned or filed bright or were coated with oxide grease and dirt; and, too, did the same person that did the original weighing do the final weighing? And how was the cement removed from the iron surface? It appears that the coating on the surface was not dissolved off but was scraped, in the case of the samples subjected to current, while the single specimen not subjected to current was not scraped. Therefore, I think it would be interesting to learn how much of the material set down as loss was original oxide and dirt, how much was natural corrosion, and how much good iron filings? The maximum depreciation as given is about 1.5 oz. in 3 lb. 7 oz., or less than two-thirds of the expected loss.

In the passage of current through the samples, Mr. Knudson says that a constant current was sent through, the voltage being remorselessly raised 1400% to effect the result. It seems to me that the raising of the voltage to that extent would in itself baffle the efforts to determine the utility of cement as a protector.

We are told that the cement cracked, it would be interesting and valuable to know whether a current will have such an effect on cement and if so to what particular action or influence it is due.

Fig. 6 suggests that the samples subjected to current very soon began to protect themselves, and that to maintain the current flow, the voltage had to be raised to 42 volts, or 14 times the minimum energy; that is, to 4.2 watts. The surface of the pipe was about 0.45 sq. ft. or about 9.5 watts per square foot of iron if the resistance was concentrated at the surface. In the case of the salt-water specimen it seems that the voltage was increased 5.5 times.

Were these tests made with regard to temperature or the rise of temperatue due to the current? This, I think is worth considering, as the energy was so large as to cause foaming and evident heating.

So far from indicating that iron encased in concrete will be injured in practice, these curves seem to suggest that had the samples been subjected to anything like natural conditions they would promptly have protected themselves against damage. Under such conditions, voltages are not raised to many times normal values in order to force a definite current through; temperatures are kept at low and relatively constant values, the opposite electrode is not usually brought up to within a few inches of the iron, and the current concentrated along a radial line through the concrete as in these experiments.

If iron will protect itself against electrolytic action when encased in concrete, as the paper seems to indicate, the fact is interesting and important. If, on the other hand, it will not be materially protected, that fact is also interesting and important. But the paper gives us no basis for a positive opinion. The measurements seem to indicate that the iron will tend to protect itself, but unfortunately the method of experiment makes it quite impossible to say whether it will or not.

The author's conclusions on these experiments are most sweeping. Thus he concludes:

> If but a small fraction of an ampere of electricity passes from an interior metallic column or structure into concrete or masonry as usually made, there will be corrosion of the metal and disintegration of the concrete or masonry.

What the author calls a small fraction of an ampere amounted in fact to nearly 0.25 ampere to the square foot, or for the sake of comparison to 5,000 amperes per mile of 30-in. water main; in other words, a current which is extremely large compared with those likely to exist in practical conditions except under very exceptional circumstances. There does not seem to be any ground for the assumption that the current had anything to do with the cracking of the concrete, much less that it would under practical conditions have such an effect.

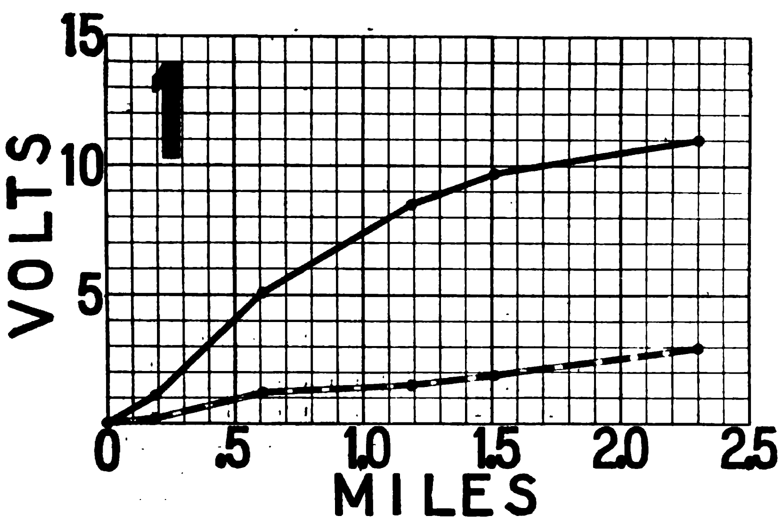
We are shown a picture of a corroded water-meter, but just what a corroded water-meter has to do with the subject of the paper is not quite clear. That an iron shell resting on the earth floor of a damp cellar for a sufficient period will be destroyed whether there is electric current in the neighborhood or not, is well known. Not the slightest proof is offered that this sample was in any way affected by current.

One thing in Mr. Rhodes' paper seems to me a very picturesque way of stating what all of us have encountered; namely, the enormous quantity of copper required appreciably to reduce the drop where the feeders parallel the track. The unit which he takes is the weight of copper of conductivity, equal to that of the rails. It is an impressive thing when one has had occasion to figure what that means. The natural result in such cases, where reduction of drop is necessary, is the negative booster. Unfortunately, we do not deal with the negative booster on the simple lines of the paper. We are not given roads which run straight from the power-house, and are uncomplicated by branches or network. Some systems can be reduced to a plurality of such lines, but the majority will involve a more or less complicated network. The distribution of current in a network is determined by constantly changing bond resistances, particularly where special work is not kept up. The negative booster offers an extremely interesting possibility in that connection. It gives the means, with reasonable watchfulness, of controlling the distribution of current in that network. The paper dealing as it does only with the single-trolley line, naturally does not bring that out. It shows the enormous gain in respect to reduction of earth currents, but does not show the other possibility of the negative booster; namely, the control of the distribution of the return current in the network, which is a feature in many cases of very great value, particularly in making it possible to reduce to a minimum the track drops in those regions where such current, as has escaped to the earth, is returning to the rails, thus giving a current density of minimum value in the pipes, at points where current is leaving them, that is where they are positive to the rails.

Paul Winsor: We think we have a pretty good railroad in Boston; well bonded, a good deal of return copper, and we follow it pretty closely. But in certain places we have bad conditions; the trouble we have had, unknown or unlooked for trouble, has taken place near the Harvard power station, where there is a marsh of salt water, and beyond which, about a mile away, is the first car track in that direction. A large number of water mains are located near by, but a careful study of the situation has reduced the electrolytic trouble most materially. The telephone people have taken great pains to survey their cables, and when they find a place where they think there is danger of electrolysis, they consult with our engineers, and we put in either a negative feeder or a connection to our rail. This removes the trouble. On our own cables we have cut the lead in many places, made special connections, and got rid of the trouble. The Metropolitan Water and Sewerage Board have some large pipes running into Boston. We studied the matter carefully with them, and finally put eleven insulating joints in those pipes. Some of the joints are of rubber, and some are of wood, ordinary bell and spigot joints, with $\frac{5}{8}$ in. to $\frac{3}{4}$ in. of pine calking.

Some time ago we made some experiments in operating certain portions of our road on the three-wire system. Some of the data we got regarding the current in the neutral back to the station; that is, the return currents through the rails and underground structures, seem to me of interest in connection with the present discussion. As we thoroughly appreciate the practical difficulties of operating stations on a three-wire system, the matter is not offered as a panacea for the cure of electrolytic troubles, nor even as a practical method of operating; It is offered simply as of interest in the general discussion. Mr. Corning will present this part of the discussion.

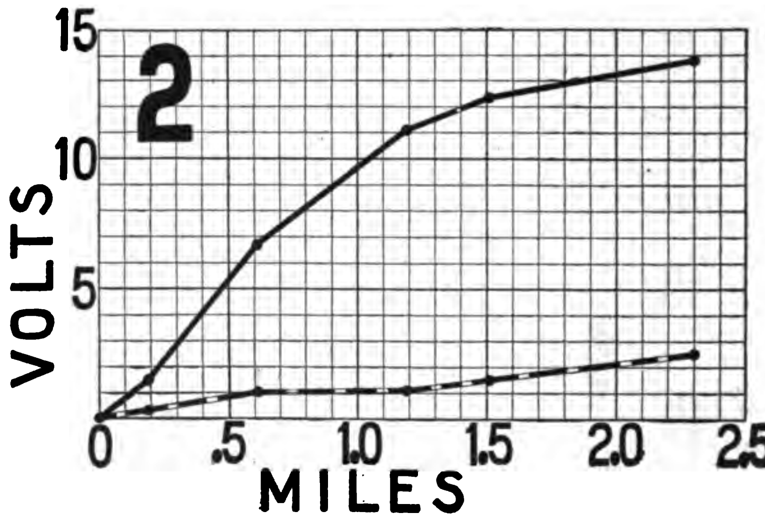
J. W. Corning: A few years ago in connection with the study of some power problems on our system, Mr. Winsor suggested that we investigate the feasibility of using the thiee-wire sys-

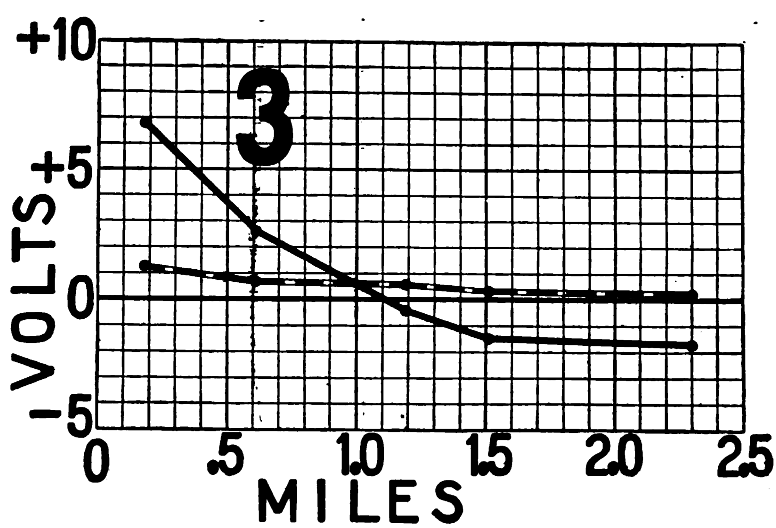


tem. Some experiments were made, and in view of the papers to be presented this evening it was thought that a part of the results obtained would be a matter of interest to the members of the Institute. These results appear in graphical form in Figs. 1 to 15.

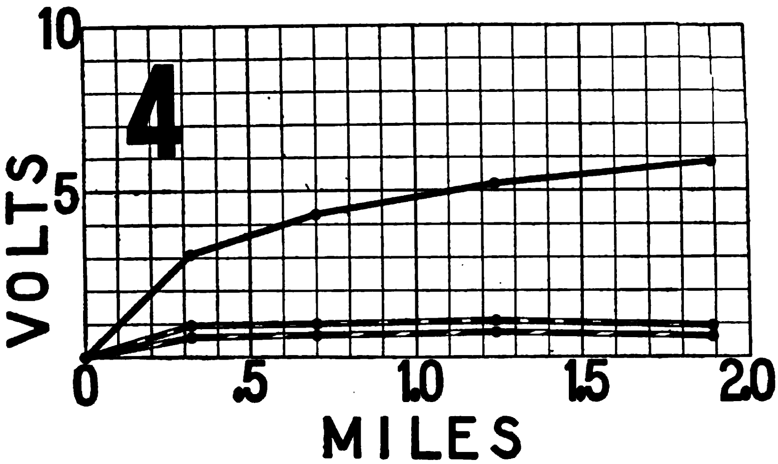
Our system is supplied with power from ten power stations and is divided into upwards of 70 feeder sections. In order to explain these results more intelligently, I will call your attention to Figs. 14 and 15 comprising nine of these feeder sections fed by the Harvard power station in Cambridge. You will notice from these maps that the dash lines indicate the boundaries of the feeder sections, the numbers of which appear. The heavy lines indicate tracks. Passing through this district from one side to the other will be seen depicted some 48-in. water mains The power station location is indicated by the star (*).

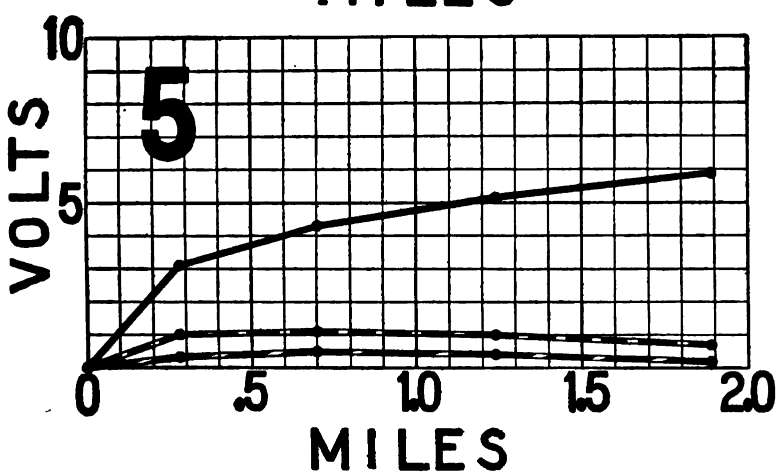
We operate on the two-wire single-trolley grounded-return system. Fig. 14 represents the ordinary relation between feeder sections with this system. Referring now to Fig. 15, it will be noted that certain of the feeder sections have been shaded.

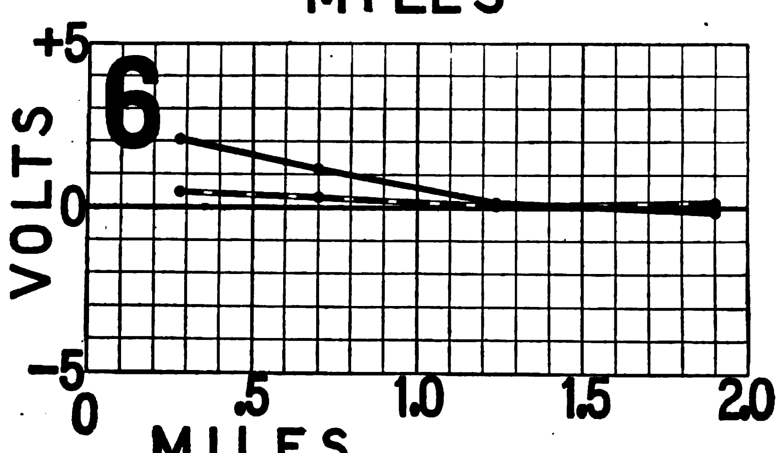


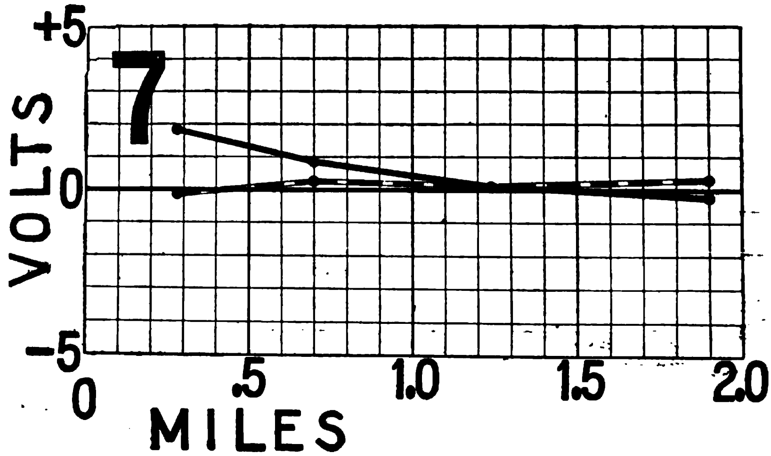


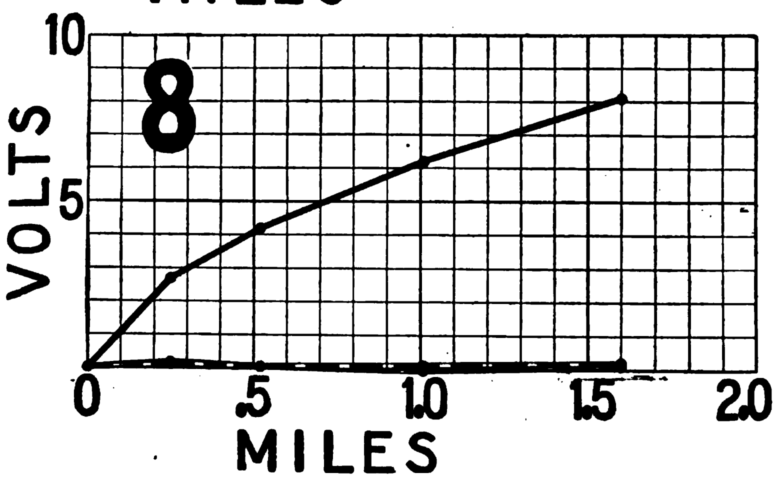
In the experiments referred to, these sections were supplied from this power station by current from a generator connected in three-wire relation with the rest of the station. No line change was made in the feeder sections beyond installing an

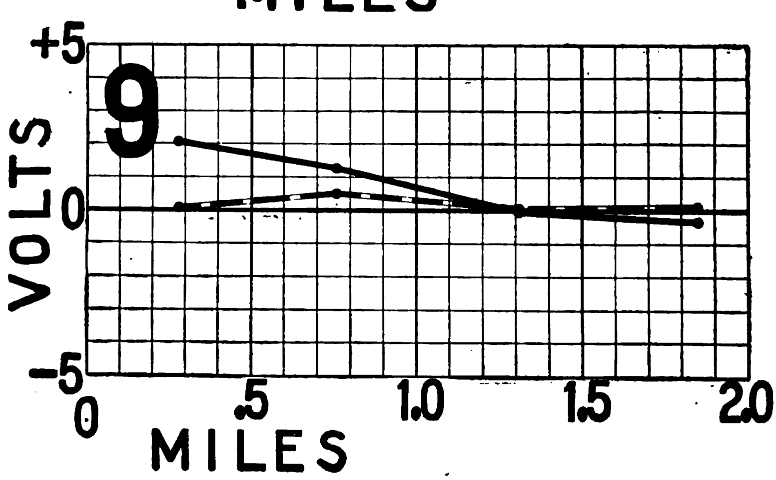

4
10
5
0
VOLTS
.5
1.0
1.5
2.0
MILES


5
10
5
0
VOLTS
.5
1.0
1.5
2.0
MILES


6
+5
0
−5
VOLTS
0
.5
1.0
1.5
2.0
MILES


7
+5
VOLTS
0
−5
0
.5
1.0
1.5
2.0
MILES


8
10
VOLTS
5
0
.5
1.0
1.5
2.0
MILES


9
+5
VOLTS
0
−5
0
.5
1.0
1.5
2.0
MILES

additional set of insulating joints in the trolley wire at the points of intersection of positive and negative sections.

For the purpose of our investigations, test-wires were run from the power station in three directions for a distance of from 1.5 to 2.5 miles, and simultaneous readings taken at several points along the line, under both two-wire and three-wire operation. The observations that are interesting in connection with the subject this evening are:

a. Return drop,

b. Potential difference between pipe and rail.

c. Current flowing on pipe.

The observations under two-wire and three-wire operation were taken about two hours apart for a period of one-half hour each, the endeavor being to have the loads on the individual feeder sections as nearly as possible the same throughout both sets of observations.

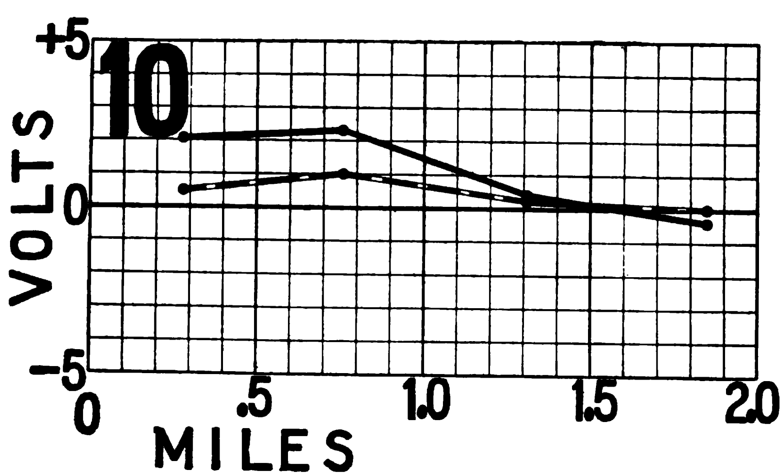
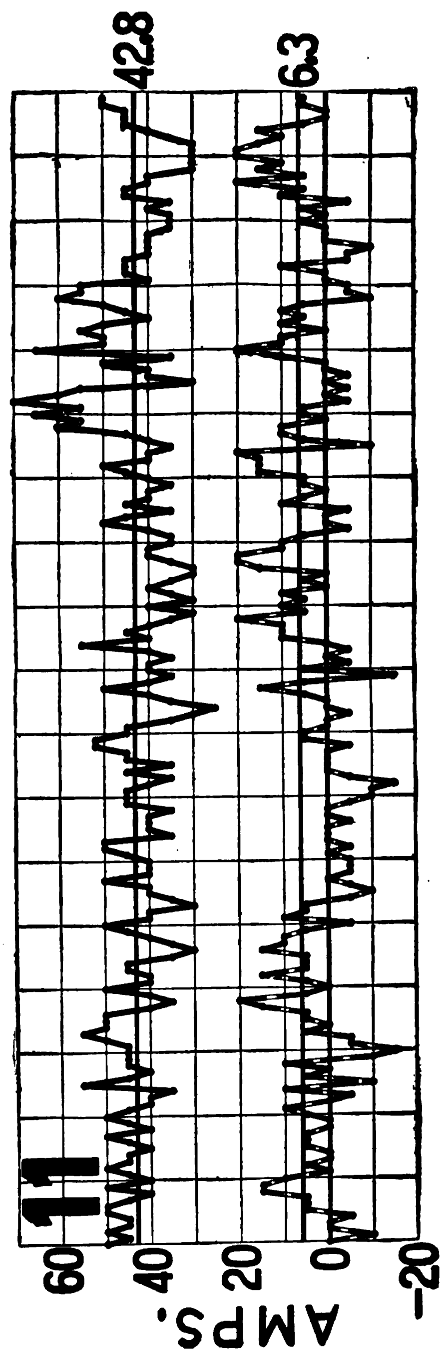


Fig. 1 shows the return drop to the power station from a point about 2.25 miles distant, under two-wire and three-wire operation. As before stated, the results are averages of readings taken at intervals of 10 seconds throughout a period of 30 minutes. The load on the shaded sections of Fig. 15 under two-wire and three-wire operation are as shown in the following table:

TABLE 1

Average load on section.		
Section.	Two-wire.	Three-wire.
70	246.0	222.0
71	183.6	133.2
73	263.6	251.9
90	413.0	411.0
91	271.0	249.0
Totals.....	1377.2	1267.1


42.8
6.3
11
60
40
20
0
-20
AMPS.

From this table it will be seen that the conditions with respect to load are almost identical in both cases. It will be noted that the return drop under two-wire operation, represented by the full line, was reduced to that under three-wire operation, represented by the dash line, the drop throughout this length being reduced by about 83%.

Fig. 2 gives the results of a test which was repeated on another day in which practically the same results were obtained. The following table gives the loads in the several feeder sections:

TABLE 2

Average load on section.		
Section.	Two-wire.	Three-wire.
70	278.3	305.2
71	196.9	303.2
73	272.6	275.0
90	488.0	516.0
91	325.0	339.0
Totals.....	1560.8	1738.4

Fig. 3 gives the potential relation between pipe and rail along the line of the first test-wire. The full line represents the relation under two-wire operation, and the dash line the relation under three-wire operation, values above the zero line referring to positive condition of pipes, and those below the line to negative condition of pipes. It will be seen that the high reading obtained near the power station has been reduced very materially, although at the same time the pipe has been rendered positive throughout the whole length under consideration, by a gradually decreasing amount. The loads in the several shaded feeder sections under two-wire and three-wire operation while the above test was being made are shown in Table 3.

TABLE 3

Average load on section.		
Section.	Two-wire.	Three-wire.
70	245.2	266.6
71	145.2	189.2
73	231.0	295.2
90	524.0	527.0
91	378.0	329.0
Totals.....	1523.4	1607.0

Figs. 4, 5, 6, and 7 give results obtained along the second test-wire. Figs. 4 and 5 show return-drop relations on two different days. The current relations in the several shaded feeder sections for Figs. 4 and 5 are as shown in Tables 4 and 5

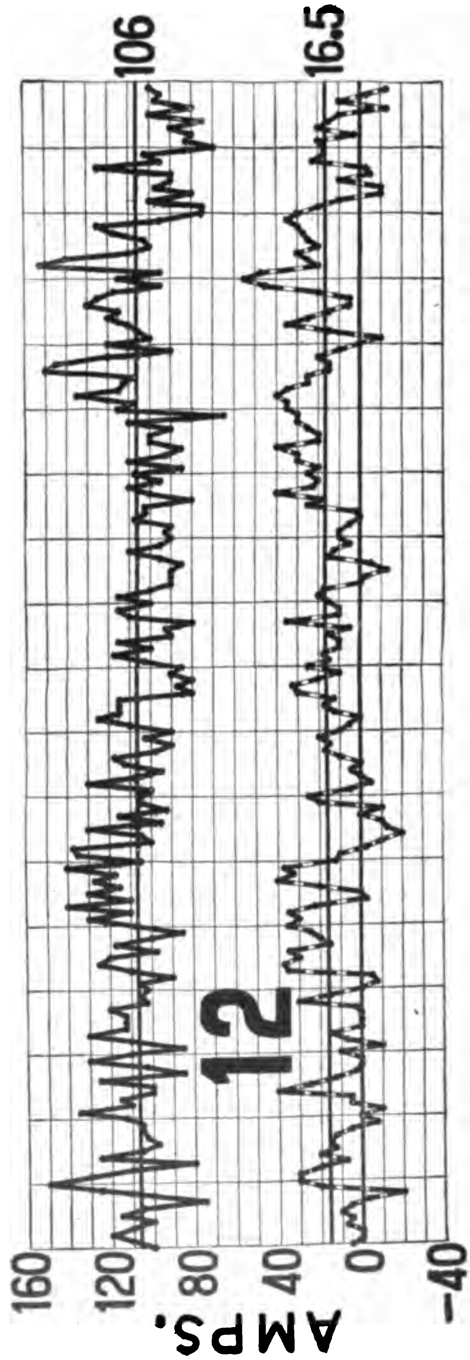

106
16.5
12
160
120
80
40
0
-40
AMPS.

TABLE 4

Average load on section.		
Section.	Two wire.	Three-wire.
70	215	208
71	136	149
73	241	262
90	480	454
91	266	300
Totals.....	1338	1373

TABLE 5

Average load on section.		
Section.	Two-wire.	Three-wire.
70	224.6	181.9
71	152.6	134.6
73	232.4	232.6
90	455.6	464.0
91	264.0	302.0
Totals.....	1329.2	1315.1

Attention is called to two sets of results, in each case under three-wire operation. While the upper set of observations was being taken, section 70 was feeding in the usual manner; whereas, while the lower set of observations was being taken it was fed from the other side of the three-wire system.

Figs. 6 and 7 show the potential relations on the pipe along the line of the second test-wire under two-wire and three-wire operation, and it is clearly seen that in these cases the potential differences between pipe and rail have been almost eliminated. The load relations of the sections while these observations were being taken are shown in Tables 6 and 7

TABLE 6

Average load on section.		
Section.	Two-wire.	Three-wire.
70	234	199
71	113	111
73	284	285
90	445	404
91	249	277
Totals.....	1325	1276

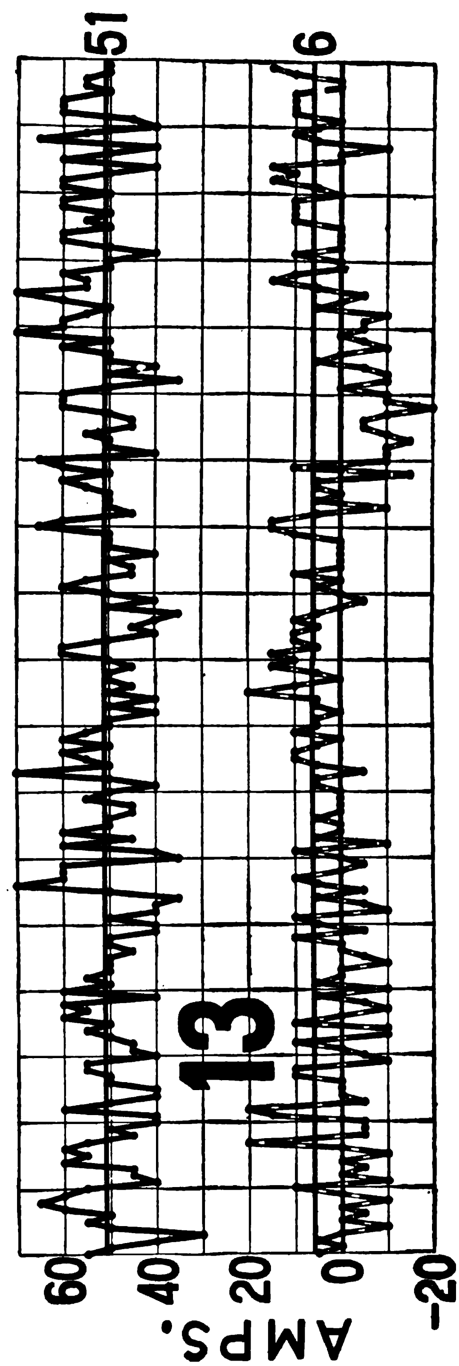

51
6
13
60
40
20
0
-20
AMPS.

TABLE 7

Average load on section.		
Section.	Two-wire.	Three-wire.
70	205	267
71	190	199
73	301	235
90	488	536
91	384	370
Totals.....	1568	1607

Fig. 8 gives the return drop along the line of the third test-wire. While the three-wire system was in operation, section 70 was fed part of the time from one side and the rest of the time from the other. The results are as shown. It will be seen that the return drop in this case was practically wiped out, the three-wire potential curve practically coinciding with the zero line. The effect of reversing section 70 in this case was not as great as it was in the last instance, but is just noticeable. The load on the several sections while these results were being taken is shown in Table 8:

TABLE 8

Average load on section.		
Section.	Two-wire.	Three-wire.
70	286.	321
71	170.6	199
73	280	236
90	627	600
91	372	380
Totals.....	1735.6	1736

Figs. 9 and 10 show the effect on the pipe potential in this district of three-wire operation, as compared with two-wire operation, and similar relations of potentials are observed as have been observed in the previous cases.

I would now call your attention to Figs. 11, 12, and 13, which show readings of current flowing on the large mains which traverse the district in question, under two-wire and three-wire operation. These readings were taken for a period of 30 minutes at intervals of 10 seconds. It will be seen in Fig. 11 that under two-wire operation the average current flowing on the pipe was 42.8 amperes, with a maximum of 70 amperes. Under three-wire operation this current was reduced to an average of 6.3 amperes, and a maximum of 20 amperes. On Fig. 12 an average current of 106 amperes, with a maximum of 155 amperes is reduced by three-wire operation to an average of 16.5 amperes and a maximum of 55 amperes. In Fig. 13 an average current of 51 amperes, with a maximum of 70 amperes under two-wire operation, is reduced by three-wire operation to an average of 6 amperes and a maximum of 20 amperes. The results in each one of these last three figures were taken at a different point on these pipes, the current being calculated from the resistance of the pipe, and the potential drop along

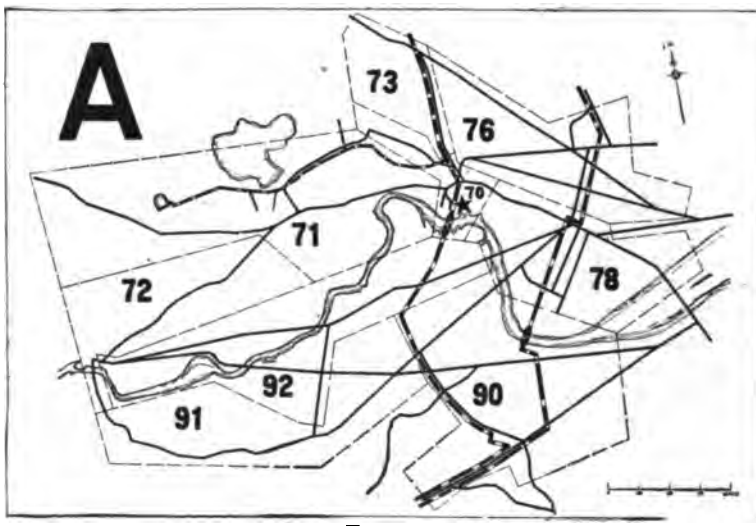


Fig. 14.

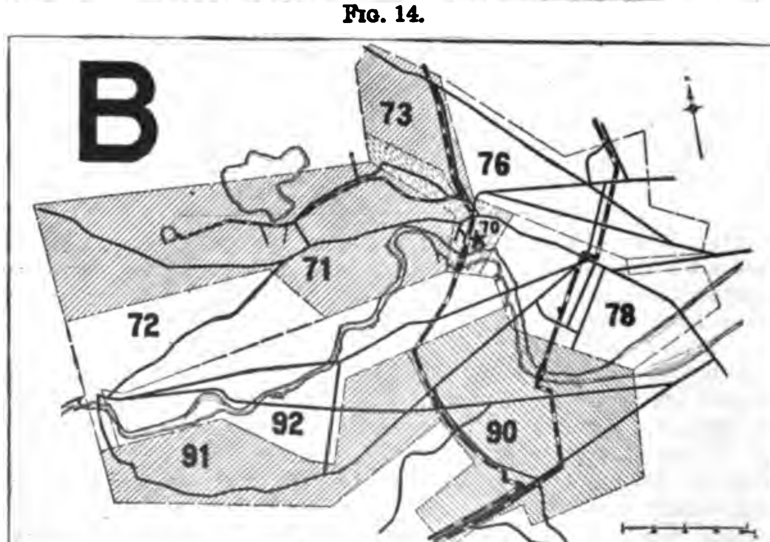


Fig. 15.

a single length, not including joints. In the case of the three-wire operation, the averages given are averages of all observations, those below the line being taken with a positive sign. In these three cases the three-wire operation shows a reduction in current flowing on the pipe of 85, 85, and 88% respectively.

S. M. Kintner: It is satisfactory to find that the results of Mr. Hayden's tests agree with the results of tests that I made some two or three years ago.* I made tests quite similar to those reported by Mr. Hayden, though not so many different kinds of solutions were tried. The laboratory tests showed the following results:

1. That the loss was not directly proportional to the ampere-hours, as repeated weighings of the same plates after equal ampere-hours of current action failed to show equal losses.

2. That the shape of the plates had a very decided effect upon the results obtained, the edges being by far the most active part of the terminals. The best results were obtained with terminals mounted so as to form two sides of the box containing the electrolyte, the rest of the box being of impregnated wood. The terminal plates were approximately six inches square.

3. That it was necessary to have a duplicate cell for every one subjected to the alternating-current electrolysis, the duplicate being used to determine the chemical action alone. Attempts to reduce the corrosion loss to so much per unit surface, and thus correct for losses in various size cells, gave very inconsistent results.

4. That the loss on the so-called "gain plate" of a cell in which a sodium chloride solution and iron terminals were used, when subjected to the action of a direct current, was greater than the losses on similar plates subjected to alternating currents.

5. That the residue in cells, such as the last described, showed a very marked difference when analyzed chemically. The analyses of residue for the cells subjected to chemical corrosion only, and those subjected to the alternating current action, were very similar, while that of the direct current cell was very different.

Laboratory experiments in which cells were used were carried on for several months, with results somewhat similar to those obtained by Mr. Hayden. The broad general conclusions reached were that:

a. For iron and steel there was in general little or no loss greater than the chemical corrosion.

b. But for lead and tin-lead, such as employed in cable sheaths, there was a slight loss which varied from one quarter to one half of one per cent. of what would be obtained from direct current under similar circumstances.

A long-time test was then undertaken in which pipes of from 4 to 6 feet in length were buried for a period of one year. During all this time an alternating current of 25 cycles and 25 volts was applied between each pair of pipes. In this test, pairs of pipes of wrought iron, cast iron, and lead were used. Each pipe was carefully weighed and marked before it was buried,

*Electric Club Journal, November, 1905.

and was weighed again after one year's test. The losses in weight of the several pipes were not materially different, it being on the average the same for the pipes subjected to the alternating current as for those subjected to corrosion only. It is believed that a test of the kind just mentioned is much more representative of operating conditions than any that can be carried out in a laboratory.

Careful visual inspection of the pipes as they were removed from the ground failed to show any difference between those subjected to the alternating currents and those which were not.

Referring to Mr. Hayden's conclusions regarding the electrolytic effect of current densities in amperes per square foot, I think that the current densities mentioned by Mr. Hayden are very unlikely to exist in actual service. I found that it required about 260 volts to force only 30 amperes of current between two terminals each of 20 square feet of surface. The terminals were only 6 feet apart and the earth was exceedingly moist; the water was also very impure, as a large part of it was surface drainage. Another test with similar size terminals placed in a less favorable location gave only about 7 amperes for 260 volts. It is the writer's opinion that the alternating current, so far as practical service conditions are concerned, will not cause serious electrolytic damage to pipes.

Calvert Townley: With reference to general electrolytic problems, I think we have all been too much afraid of them. When attacked with the same vigor that is commonly brought to bear on other problems connected with the generation and distribution of electricity, electrolytic questions show themselves no more difficult of solution. While not desiring to belittle the damage which may occur from neglect to take proper precautions against the electrolytic action of direct currents, I do think it is time to discourage giving them disproportionate importance, and timidity in their handling. The public has been led to believe that electrolysis going on secretly and continuously under our feet is much to be dreaded; but if those who have to do with underground structures liable to electrolytic attack, and those who have to do with the generation of current which is likely to attack such structures, will jointly take pains to ascertain by suitable measurements what the existing conditions are, and will take such reasonable precautions to minimize the troubles as the state of the art permits, I believe that the seriousness of the situation will be largely, if not entirely, eliminated. As engineers, our efforts should be to bring the facts before all interested parties, and let it be known that, treated intelligently and carefully, electrolytic troubles can be largely prevented.

I get much encouragement from Mr. Hayden's paper. I have not known much about alternating-current electrolysis, but have had a general feeling that it was insignificantly small. Mr. Hayden's paper, as well as Mr. Kintner's discussion, greatly strengthens this feeling. As far as I know, there is yet to be reported the first case of trouble anywhere in practical service from electrolysis due to alternating currents.

I understand that in protecting the lead sheathing of their cables from direct-current electrolysis, the telephone companies have adopted a method which they have found to be entirely satisfactory; namely, where the cable is positive to the return circuit they connect the lead sheath of the cable to that circuit by a metallic conductor or bond, so that any difference of potential that may exist between the lead sheath and the return circuit is practically eliminated. No attention is paid to the sheath where it bears a negative relation to the return circuit; that is, where the tendency of the return current is to flow from, say, the rail of a trolley road to the sheath. But where the tendency of the current is to flow from the sheath to rail, and electrolytic damage may occur in consequence, a bond is inserted. Now the tendency to flow from sheath to rail is not concentrated at any one point. The positive relation frequently extends over a considerable area, although practice has shown that electrolytic damage may be prevented by the insertion of a bond only at some one central location. Obviously, it follows, therefore, that the additional drop in the lead sheath from the outlying territory of the positive area to the central bond can be neglected, although in many cases it must represent an appreciable potential. Mr. Hayden has shown that under the most unfavorable conditions, alternating-current electrolysis will not exceed one per cent., and will seldom equal as much as one-half of one per cent. of the electrolytic action of the direct current of like volume.

In the light of the foregoing, then, it becomes pertinent to inquire whether the total tendency towards alternating-current eletrolytic action is any greater than the residual tendency for such action from direct currents in outlying parts of the positive district, and which it has been found are practically negligible. I think we can all take a great deal of encouragement from the very small amount of electrolytic action found to take place under the most unfavorable conditions of Mr. Hayden's test, and from the interesting comments contained in Mr. Kintner's discussion.

George F. Sever: It is fortunate that we should have so valuable a discussion on this subject from Boston, because our first real knowledge of electrolytic troubles came from Boston some years ago through a valuable paper by Mr. Farnham.* He investigated this subject most thoroughly in the interest of the telephone company, and the West End Railroad of Boston, now the Boston Elevated, assisted him materially in his investigation. Since that time, the subject has been very carefully followed up in Boston, as well as in many other places.

*Transactions, A. I. E. E., 1894, Vol. xi., p. 191.

If the interests in all other cities, such as New York, Philadelphia, Chicago, St. Louis, and Pittsburg, should study this question from an engineering standpoint, we would have but little contention as to the proper methods to apply in remedying the supposed difficulty.

I speak from the standpoint of a municipal engineer, who finds in his city some isolated indications of electrolysis. The engineer, whether he represents the water or gas interests, reports this difficulty, and possibly a suit against the local railroad company results. If the court reaches any decision, whatever it may be, there is no assurance that sub-surface conductors are not incurring further damage In my opinion—and I have carried this out in practice in the city— the only way to handle the situation is for all parties in interest, with their engineers, to agree upon a policy, and to study the situation carefully and together, and endeavor to reduce the difficulty wherever it appears. I think we make too much of electrolytic troubles; I think those who stimulate this idea in the minds of engineers do not realize what electrical engineers can do to remedy the supposed difficulty. Some time ago the American Water Works Association published a long and interesting report signed by three eminent engineers, recommending that every trolley road in the country be changed from the single overhead trolley system to the double-trolley system, as a sure remedy for electrolytic troubles. That interesting document is referred to in almost every electrolysis case; having the opinion of these three eminent engineers behind it, it is very impressive to the authorities. I think the Institute should take some recognition of this report, to the end of pointing out that the electrical engineer, in coöperation with the municipal engineers or water works engineers, can mitigate and cure the difficulty. In one city that I know of, the water system is supposed to be undergoing continuous damage, whereas the gas system owned by the city has not indicated that any damage is occurring to its system.

Mr. Hayden's paper prompts me to cite the result of some tests and investigations made at Columbia University in 1904, on alternating currents as producing electrolytic action. At that time we had available only 60-cycle current. We arranged cells containing certain solutions such as sulphates, chlorides, carbonates, and nitrates of different metals, and passed current through them by means of lead plates. From the results obtained we arrived at the following conclusions:

1. That alternating currents can cause a slight electrolytic action. 2. That the rate of this action is very much slower than with direct currents of the same value. 3. When insoluble or semi-soluble salts are formed, the rate of action with a given current strength decreases with the passage of time. 4. That the resistance of the cell decreases with increasing current strength for alternating current as well as for direct current.

5. That the resistance is not only in the liquid itself, but particularly in the contact layer where the electrode and electrolyte meet.

Variations in the density of the current, or of the electrolyte, unless excessive, have no marked effect. Unless subsequent investigations shall bring to light differences likely to exist in the earth, in which corrosive action is more vigorous than between lead and the common salts of the alkali metals—and no such combinations are known as applied to direct-current railway operation—the corrosive action of alternating currents on sub-surface metal structures may be assumed to be negligible. This investigation is being supplemented by a further one for lower frequencies, and I trust we shall be able later to report the results of that investigation

Albert F. Ganz: The experiments described by Mr. Hayden show that with an alternating-current electrolytic corrosion is generally a very small fraction of that which would be produced by a direct current of the same strength and under the same conditions. The action is explained by the statement that the corrosive effect of the positive half wave of current is not entirely reversed by the reconstructive action of the succeeding negative half wave. The reason for this lies probably in the fact that a portion of the products of the electrolysis, produced by the current during the positive half cycle, diffuses away so that the negative half wave of current does not quite reverse the action of the positive half wave. Since these rates of diffusion vary greatly with different materials, the per cent. of direct-current electrolysis produced by an alternating current varies greatly with different electrolytes. On this theory the effect of increasing the frequency would be to diminish the electrolysis In general this has been found to be the case. The rate of diffusion of the products of electrolysis in the case of metals in the soil may also be governed by other conditions, such as by the amount of moisture present, temperature, etc., and this would seem to be so judging from the widely varying quantitative results which have been found by different investigators.

The suggested protective measure of superimposing a small direct current upon the alternating current so as to add to the effect of the negative half wave sufficiently to neutralize completely the corrosive action of the positive half wave is certainly very interesting, but does not seem to me to be a desirable thing to do in practice, as I understand the proposition, because it would mean deliberately to send a stray direct current through the ground and to have this enter the metal to be protected and return by way of this metal. This stray direct current, while small in percentage of the alternating current to be counteracted, in its passage through the ground may in itself be a source of electrolytic danger to other underground metal.

Referring to Mr. Knudson's paper, the curve shown in Fig. 7 is of importance inasmuch as it shows that concrete absorbs a considerable quantity of water and becomes an electrolytic conductor of comparatively low resistance, so that a few volts of electromotive force between a metal imbedded in wet concrete and the surrounding water or wet soil is sufficient to set up a current. It also explains why attempts to protect pipes from electrolysis by embedding them in concrete have failed.

Mr. Rhodes' paper brings out the very important fact that the disposing of return feeder copper is quite as important as the weight of return feeder copper used in the effort to minimize stray currents. The calculations given show, clearly that the way to obtain a minimum of stray current from the grounded rails of a single-trolley electric road is to insulate the negative bus-bar, and to employ two or more insulated return feeders either so proportioned in resistance or provided with negative boosters as to produce equal potentials at their connecting points to the rails. This method results in minimizing the potential differences in the rails, and for this reason also minimizes stray currents from the rails.

Mr. Rhodes assumes that the only resistance encountered is the contact resistance between the rail and ground, which is on the safe side. as it gives values for the stray currents which are too large; as a matter of fact the soil, especially when dry and sandy, has considerable resistance.

The question of electrolysis from stray railway currents has been very carefully investigated in Germany by a committee of the German Society of Gas and Water Engineers, who have already issued three annual reports. Translations of these reports for the years 1904 and 1905 are published in abstract in the *Report on Electrolysis* of the American Gas Light Association. The German committee have formulated a set of rules for electric trolley roads which are designed to prevent trouble from electrolysis due to stray currents.

These rules require permanent bonding of the rails so that the resistance of the finished track does not exceed the resistance of an equivalent unjointed track by more than 20 per cent. They also require that the resistance between the rail return and the ground be made as great as possible, and to this end forbid the deliberate grounding of the negative bus-bar and of any part of the return system. They also forbid the bonding of the rails to any underground pipes or other metals.

Great stress is laid in these rules upon the installation of return feeders in such a manner as to minimize the rail potentials; the following five of these rules relate directly to the return feeders and I will repeat them here because they bear directly upon Mr. Rhodes' paper:

3. *Potential difference in the rail network.* The potential difference in the rail network must be limited to a certain prescribed amount, which must not be exceeded with the greatest or most unfavorable loading of the return circuit.

The greatest permissible potential difference must be determined for each place separately, for it depends upon local conditions, such as the nature of the soil, the location and resistance of the pipes between points of highest and lowest potentials, the position of the pipes with respect to the rails, etc. In special cases, this greatest permissible potential difference may be different in different sections of a rail system.

For the present this maximum permissible potential difference in the rail network may be taken as *one volt*; this figure to be the average of readings for ten minutes during a period of full load.

4. *Return conductors.* Where the rails alone are not sufficient for the return current, without allowing the potential difference to exceed the prescribed amount, extra return conductors must be provided.

These return conductors must be so numerous and so planned that, in conjunction with good conductivity of the rail network, they prevent the potential difference in the rails from exceeding the prescribed amount.

The points where the return conductors are connected to the rails should be located as far from the pipes as possible.

The return conductors must be insulated and of sufficient size to return the current with only a small drop in voltage; so that, if an occasional change in the distribution of the currents occurs, no excessive difference in the potentials at the connecting-points of the return conductors will be produced.

The return conductors should have a cross-section at least equal to that of the outgoing conductors; where conditions require a number of return conductors, it may be better to make them of larger cross-section than the outgoing conductors.

6. *Adjustability of the return conductors.* An essential condition for minimizing the potential difference in the rails, and therefore the stray currents, is that the potentials be equalized at all points where return conductors are connected to the rails. The resistance of each return conductor must, therefore, be proportional to the strength of current which it has to carry. For this purpose, each return conductor must be provided with an adjustable resistance (or negative booster) so that the product of current and resistance may be made the same for all return conductors.

7. *Negative boosters (Sucker dynamos).* Negative boosters are to be recommended, particularly for the purpose of automatically regulating the rail potentials at the connecting-points of the return conductors in districts where the return conductors are liable to be frequently or seriously overloaded.

8. *Controlling arrangements.* Test wires must be led to the distributing station from all points where return conductors are connected to the rails, and from all points of relatively highest potentials in the rail network (points between two return connections and points at the end of the track). By connecting a voltmeter, it must be always possible to determine the potentials of these points in the rails. Arrangements must also be provided so that the current in any one of the return conductors can be measured at any time, etc.

The laying out of a proper system of insulated return feeders has been frequently neglected in this country, and even where insulated return feeders have been intsalled they have only in rare cases been properly proportioned for equal drop in potential. The usual method is to connect the rails with the negative bus-bar at the station with large copper cables, and in large installations to run out additional return feeders from these bus-bars to points on the rails distant from the station. The drop in potential in each of these long return feeders establishes points of higher potentials in the rails at these connecting points than exist in the rails at the station. The tendency is therefore for currents to leave the rails in these distant points of higher potentials, pass through the ground and buried metals, and return to the rails in the vicinity of the station.

Great improvements in the ground return circuits could generally be obtained in most of our trolley roads if these rules were followed at least to the extent of insulating bus-bars, removing all bonds to pipes, and installing a properly proportioned system of return feeders. The use of adjustable resistances in the return feeders is not a practicable arrangement for the large currents generally used on American roads. The use of negative boosters as suggested by Mr. Rhodes is, however, entirely practicable, and when applied with a judicious number of insulated return feeders will tend greatly to minimize stray currents. This is well illustrated by the curve in Fig. 8 of Mr. Rhodes' paper, which curve shows the percentage of stray current with various numbers of return feeders, and is based on the assumption of equal potentials at the connecting-points of these return feeders.

Mr. Rhodes says that very little is gained by using more than two return feeders. I do not believe that this is so on a large and extensive system. Referring to the curve in Fig. 8 it is seen that three return feeders will reduce by half, the stray current with two return feeders, and four return feeders will again reduce by half the stray currents produced with three return feeders. In a large system the stray currents obtained with two return feeders may still be a dangerous stray current making a larger number of return feeders imperative.

C. P. Steinmetz: Electrolysis is a branch of electrical engineering that has the misfortune to be of special popular interest. It has been exploited very thoroughly by the "yellow" press, gas pipes, water pipes, bridge piers—all these public and private utilities have been attacked and destroyed, in the newspapers, by this electrochemical phenomenon. Fortunately, iron is a material which is not so easily attacked by electrolytic action; wrought iron is not attacked very badly, steel very much less, and cast-iron is hardly attacked at all. For the electrical engineer, the problem of electrolysis is not the problem of protecting the rails —even the gas or water pipes can in general very well look out for themselves—for with a reasonable use of negative or ground feeders there is little danger. The greatest danger of electrolytic action is in the case of the lead cables of the telephone system. The underground metal structures which are suffering most, are the underground lead cables—the telephone cables. The power cables are relatively less affected, because they are better protected in subways, conduits, manholes, etc., and furthermore it is not economical to let a power cable lie idle. As long as it carries current it is at a temperature above that of the ground, and condensation is not likely to occur at or near it. But condensation and consequent electrolytic action do occur at or near a telephone cable.

The telephone companies have worked out, I understand, a system of protection by maintaining the cable negative against ground, by connecting it to the negative terminal. For this protection it is not, as was stated here in the discussion, necessary to see that no current passes between the lead cable and the rail. That cannnot be done, and current may pass; but the protection is perfect and absolute by making the cable throughout its whole extension more negative than the surrounding ground. As long as the lead cable armor is maintained at a potential, however slight, negative against the ground, there is no electrolytic corrosion, although current may pass. In this manner cables have been protected. Where no ground is used at the negative terminal of the dynamo, but only return feeders, by having negative feeders lead to the cables the whole cable system can be maintained at a negative potential against ground; even with a limited number of connections between the cable and negative terminal, the cable can be absolutely protected.

This shows the importance of considering alternating-current electrolysis. It has been stated in the discussion that alternating current electrolysis does not need to be feared, because it is less than one per cent. of direct-current electrolysis. I understand from those who know about the electrolytic attack, and the danger of it, with lead cables, that in many cases an electrolytic corrosion of telephone cables amounting to one-half per cent. of the direct-current action, would in a very short time be destructive. Therefore, fear is expressed that even with the greatly reduced electrolytic corrosion of the alternating-current the corrosion would still be destructive and harmful to telephone cables. It is said that against direct-current the lead cables can be protected, but against alternating-current it does not seem possible. This is the importance of the last section of Mr. Hayden's paper, which shows that even against alternating-current, lead cables can be protected. I believe that with the introduction of single-phase railways this protection will become necessary in many cases, even with an electrolytic action equal only to one-half per cent. of direct-current electrolysis.

It has been stated that the current densities in actual practice between cable and ground may not be as high as chosen in Mr. Hayden's tests. I beg to differ from that. If a cable is laid in the ground through its whole length, the total current from the cable to the ground distributed over the whole surface of the cable would give a low current density, but that is rarely the case with lead-covered cables. Laid in a conduit, the cable is, for most of its length, fairly well insulated from the ground, and it is only in isolated places where moisture condenses, or otherwise the cable comes in conducting contact with the ground, that current enters or leaves the cable to ground. In these spots the current density may be very high, and rapid destruction would take place if no protective action were resorted to. It is true that such a protective direct-current would somewhere else eat up the metal. But this is necessarily so, and when we protect lead cables against electrolysis by making them negative, it means that we prevent the electrolysis at one point by making it take place somewhere else. But this other place will be the rails which can stand it, because even with direct-current electrolysis the total amount of corrosion, when distributed over the whole extent of rails, in the rail return does not amount to anything compared with the mechanical wear. We may well neglect it altogether. It is only in the thin cable sheaths of lead cables at exposed places where damage may result, and the stray superimposed direct-current would not need to be feared in its electrolytic effect on the positive side of the rail return.

As stated, the problem is that of guarding against electrolysis of lead cables. Guarding against electrolysis of iron rails and gas and water pipes is not very difficult and with alternating-currents needs hardly to be considered, except in very extreme cases.

To protect against the alternating-current by a superposed direct-current may be done in the same manner as Mr. Rhodes has shown in his paper—lay out a system of negative feeders for an underground cable system, so as to insure that the total stray alternating current will be within the limits of protective action of the total direct-current superimposed upon it. I think that a further investigation similar to that given by Mr. Rhodes' paper may well be carried out and will result in an intelligent arrangement for protection of the lead cable system against alternating-current electrolysis.

Mr. Knudson's paper has been severely attacked, but it all depends how you look at it. I do not think that this paper can be considered as a conclusive decision on electrolytic corrosion of iron in concrete, but merely as some preliminary experiments which show that a further investigation is very desirable and should be made. All that the paper really shows is that a piece of iron in a concrete block is affected differently if a direct-current is made to flow, than if no current is made to flow. The next questions to answer would be: what is really taking place? How does it take place? What is the meaning of it? How can we guard against it? The paper does not state what is taking place; why the cement block cracked. It may be electrolytic corrosion of the iron, the formation of oxides which occupy a larger volume and so increase the size of the iron, and cause mechanical destruction by the irresistible force of the increase of volume which leads to cracking. It may also be electrolytic action resulting in the production of chemical compounds. We may think of chlorine attacking the concrete and softening it, or it may be still other actions; in short, the action of cement requires further investigation. In Mr. Hayden's paper also cement is mentioned; there the curious effect, where cement is not used by itself as in a concrete block, but added to soil, is that it increases the spontaneous corrosion of lead. That also may be a chemical action exerted by the cement on the soil. It also affects greatly the electrolytic action, different at 60 cycles from that at 25 cycles. In short, the whole phenomena resulting from stray currents on concrete structures may well be further investigated in view of the importance of concrete as structural material in the ground.

In regard to the protection, by negative feeders and the permissible potential drop against ground, the specifications of the German engineers are certainly very safe. If the potential difference between rail and ground in the return circuit is kept below one volt, there will be no trouble from electrolysis, because the pressure is below the dissociation voltage of water. This recommendation deserves to be classed with the recommendation of the American Water Works Association Committee of Engineers, in which they recommend the double-return trolley. The German recommendation is not quite as practicable, however, because one volt potential difference is impossible. I understand in England that the rail return drop has been restricted to seven volts. Those who have figured on negative feeders for any railway system know how handicapped the electrical railroads are with regard to this specification of seven volts return. To restrict it to one volt, if that is really the recommendation of the German engineers, would appear ridiculous. I do not think it can be done commercially, and I do not see any reason for it, since those metal structures which are most liable to be attacked are iron and they are always massive, and fairly well protect themselves. Lead requires special protection and can be protected by maintaining it negative against ground. I believe a more sensible specification would be not to limit the return drop at all, but to require that the underground metal structures which it is desirable to protect must be made negative and maintained negative against the rail, and then let the railroad company look out for their rails, which would be the only structure in which attack takes place. All the water and gas pipes should be connected to the negative terminal of the dynamo, and maintained negative. That is a complete protection for them.

J. L. R. Hayden (by letter): Confirming Mr. Kintner's statement under 3, I also found that it is necessary to have a duplicate cell for every test, to determine the chemical corrosion. I found, too, that special care must be taken to keep this control cell at the same temperature as the electrolytic cell. A water bath was used in all later tests for this purpose.

My experience does not quite agree with Mr. Kintner's 2, "that the edges of the plates were by far the most active part of the terminals." The plates were usually corroded fairly uniform all over, even on the back, and the edges not more than should be expected from the higher current density existing there.

Mr. Kintner's statement that the current densities assumed by me are very unlikely to exist in actual service conditions, I believe has been fully answered in the discussion by Dr. Steinmetz. Dr. Steinmetz shows that with a cable laid in a duct, and thus partly protected, the current density over the surface of the cable is distributed very unevenly; therefore, fairly high local current densities must be expected.

Regarding the voltage required to produce such current densities, I originally intended to record the voltage per cell also, but found that it was too low to be read accurately with the available voltmeters, in which the scale below 20 volts was not very reliable, and so I had to give it up. Usually from 6 to 8 cells were connected in series with a rheostat, in a 120-volt circuit, and herefrom it follows that the voltage per cell was well within the range of rail-return drop commonly found on American railways. In alternating-current railways at 25 cycles the resistance of the rail return is from 5 to 8 times greater than with direct current, due to unequal current distribution in the rail. The higher trolley voltage permits a higher voltage drop in the circuit, and in this case, even higher rail-return drops may be expected than with direct-current.

Philip Torchio (by letter): Will Mr. Corning please explain how it happened that with feeder districts of alternative signs of potential all the potential-drop readings obtained from water mains were shown on each and all curves all of one sign? One would expect to find negative and positive zones along the water mains traversing the territory, because if the current must practically all flow to the station by the way of trolley wires, this current must at certain points of the water main leave the mains as well as enter them at other points. Were the readings taken at random and the results accidental, or were the points of reading purposely selected?

John W. Corning (by letter): The points at which the readings of potential difference between pipe and rails were taken, were so chosen on account of accessibility to pipes at these points without excavation, and the length of line over which conditions were investigated was limited by the number of observers available at the time.

The feeder sections that were supplied with current from the negative pole of the generator to trolley were, as a rule, not the sections farthest from the power stations, but were midway between the inner and outer sections, so that the average condition of potential difference between pipe and rail would not reverse. Had feeder sections farthest from the power station been chosen it is probable that positive potentials on pipes would have been encountered.

A. M. Schoen (by letter): I am much interested in Mr. Knudson's conclusions, drawn from a thirty-day test with current flowing over pipes buried in concrete blocks which were in turn immersed in water. I have never made any detailed laboratory tests of this character, but some years ago while making a general survey in one of our larger cities, for the purpose of determining to what extent water pipes had suffered damage due to electrolytic corrosion, I had an excellent opportunity to note these points in the practical operation of a trolley system. The city was inland, hilly, and well drained, under which conditions the concrete road bed should naturally not be subjected to excessive moisture, the run-off leaving it ordinarily fairly dry. There were in operation in the city two independent overhead trolley systems with track return, one having an 18-in. concrete roadbed, the other having only cross-ties embedded in the soil. The track under which there was no concrete was in many places badly bonded, with resultant heavy. leakage to water pipes; after leaving the water pipes much of this stray current found its way back over the better bonded tracks of the line having the concrete roadbed. In many places I found heavy damage done both to lead services and cast-iron mains under the tracks of the company using no concrete, while in no single instance, although a large number of excavations were made, did I find damaged even a lead service lying under the concrete. Instances were found where such corrosion had taken place just beyond the edges of the concrete, indicating that this was due to surface leakage. I attribute these results to the fact that the concrete being less porous than the earth, and, owing to good drainage, not continually soaked in water, formed a fairly good insulator and provided considerable protection for the pipes beneath it. With the concrete continually saturated with water, the results would naturally be different.

W. R. C. Corson (by letter): The facts brought out by the experiments recorded in the papers by Messrs. Hayden and Knudson will prove, I believe, valuable additions to engineering knowledge, and while some of the conclusions reached by the writers are probably assailable they serve a valuable purpose in giving direction to new thoughts on an old subject.

My interest has, however, been especially aroused by the paper presented by Mr. Rhodes, and I wish to pay the tribute of appreciation to his ingenious treatment of the subject. The mathematical demonstration of the relative values in the several methods of return feeder distribution is one which will prove of great assistance in the study of the measures to be taken for relief from the effect of stray earth currents.

While I have not had time as yet to follow in detail the various steps through which the demonstration is carried, one conclusion, which seems to be proved and which was touched on but briefly during the discussion, appears worthy of emphasis by repetition; this is, that all methods of return-feeder distribution are more effective in reducing earth currents when the negative bus-bar at the power station is not grounded.

Now the negative feeders from the rail, if run underground in an uninsulated condition, form a more or less perfect ground for the negative bus-bar; and in proportion to the perfection of the ground so formed must reduce the efficiency of the relief from ground currents which they should afford. A corollary to the conclusions of Mr. Rhodes' paper would be therefore that, for efficient relief from earth currents return feeders must be insulated from earth.

It has usually been considered that the measures which a street railway company would naturally take in its own interest to reduce the amount of lost energy on its return system would be effective also in reducing the stray currents on other metallic structures in the streets. Mr. Rhodes' paper clearly shows that the different methods of feeder distribution would not be equally effective for both purposes. For instance, Case II of the paper represents perhaps the most economical method of reinforcing the conductivity of the rail for the purpose of reducing the drop in potential in the return circuit, but this method is shown to be least effective in diminishing earth currents. Again, a single feeder connecting the negative bus-bar to the middle of the track is very effective in reducing earth currents, and, as the effect is independent of the copper in the feeder, an installation of this method might be made without improving in any way the conductivity of the return circuit. The more one studies the question, the more forcible is the impression that the street railway's interest and that of other co-occupants of the streets are not equally served by any one measure of improvement.

This conflict of interest has been appreciated by all concerned for many years, although its existence has never been shown so clearly as by Mr. Rhodes' paper. Water and gas associations have received reports from committees appointed to investigate remedies for electrolytic troubles, and these reports have almost invariably demanded changed methods in the construction of street railways, changes which their economical operation prohibited. On the other hand, remedies have been suggested by the electrical interests such as the application of "drainage systems," the insertion of insulating joints in pipe lines etc., which while effective in certain cases, or in certain classes of systems, have been almost universally condemned as unfit by electrical engineers who have under their charge the care of long lines of lead jointed pipe.

It cannot but be a fact that all operating and most consulting engineers have to give the matter of electrolytic corrosion consideration from some point of view. In view of this it appears to me a proper time to suggest that the Institute has an especial opportunity of enlarging its field of usefulness by lending the weight of its authority to a set of recommendations governing the matter of relief from the effects of stray railway currents.

During the discussion, extracts were read from a report made to the American Gas Light Association, which contained the regulations governing the installation of return systems of conductors formulated by a body of German engineers. As I heard these regulations read they appeared for the most part of a reasonable nature, though certain of them were doubtless difficult of attainment. I did not understand, however, from the reading with what authority these engineers acted. If they represented a committee duly appointed by a national non-partisan association of engineers the regulations must have weight in their country and should doubtless prove the basis for "good practice" in installations of the nature covered by them.

In this country no association is so well qualified to take up this matter as our Institute; its membership is representative of the best talent in all fields of electrical engineering; it comprises the men who have been most responsible for the wonderful development of our street railway systems, and whose opinions on the requirements of such systems have become authoritative; it contains also those men who have devoted their abilities to a study of the damage which the railways have done or are doing to underground metallic structures; and men who have under their care the protection of lead-sheathed cables for the conveyance of electrical energy. These men have accumulated from extended experience and study a fund of data and general information on the subject in question, and a committee selected from such a membership would be particularly qualified to examine the whole subject and sift the good and practical from the bad or unwise methods of relief which are in vogue or have been advanced. The recommendations of such a committee modified or amended by a general discussion at an Institute meeting would unquestionably form an authoritative standard of practice which would not only tend to improved conditions of our buried structures, but would redound to the credit of our Institute and increase its prestige.

F. A. C. Perrine (by letter): The results of Mr. Knudson's experiments have been brushed aside by those who have discussed the paper on account, I believe, of a fear that there may be some truth in his statements that will put an additional burden on the street railways of the country. Unfortunately, particularly in reference to the Hamilton avenue bridge, Mr. Knudson has drawn some conclusions from his experiments which are probably not warranted by the facts.

I have no doubt but that a current sent through concrete will not only crack it, but will make it soft. In the case of the Hamilton avenue bridge, however, there is no evidence from the paper that the concrete was softened, and I understand from the engineer's report on the bridge that the cracking of the concrete was due to settling of the foundations. This is particularly emphasized by the fact that certain building foundations in the same neighborhood have also settled. But I agree with Mr. Knudson's conclusions that blocks of concrete will crack and are made soft by the passage of electric current, because I have had similar experience on quite a large scale with current passed through concrete. In some experiments made about a year ago to determine the efficiency of a large generator, the water rheostat was contained in a concrete basin. After a test lasting about twenty four hours the electrodes were taken from the concrete basin and the water pumped out for the purpose of making some changes in the machinery. Much to the surprise of all concerned, the concrete basin was found to be badly cracked, although during the time of passage of the current from one electrode to another a considerable quantity of water was kept flowing through the basin. The electrodes were three in number, each about four inches in diameter and set about two feet deep in the water, clearing the bottom of the basin by about six inches. The test stopped about 5 o'clock in the morning, and by 8 o'clock in the morning, after the water had been removed from the basin, the concrete was found to be hot and cracked badly, some of the pieces coming out being half as big as a man's body.

The concrete was found to be quite soft, so that it could be whittled like soapstone. This softening ran up along the side of the concrete basin. The damage seemed to have been done by currents passing through the concrete in their path from one electrode to another. I believed at the time, and still believe, that the damage was due to the heating of the concrete as the current passed through it, although this does not quite explain the softening of the concrete itself. In parts where the current must have passed in small amounts the damage to the character of the concrete seemed to be greater than would have resulted from boiling the concrete in water. As was stated earlier in the discussion, enough energy was passed through the concrete by Mr. Knudson to develop an appreciable amount of heat, and if this energy resulted in the dissociation of even a small amount of the water contained in the concrete, the cracks would naturally result. Furthermore, if this water in the concrete so dissociated were water of crystallization, not only would the concrete have been cracked, but it also would have been softened, as described.

I do not believe that there is real danger to buildings on account of this phenomenon, for the simple reason that the conditions for a current passing through concrete to a building frame are not generally present when the concrete is sufficiently wet to afford a ready path for the current; at the same time I have not the slightest doubt but that if the current passed through the concrete, the results described by Mr. Knudson would follow, although I question whether the results may properly be called results of electrolysis. I think that this subject is worthy of much more careful study than has been given it. I believe though that such a study will reassure, rather than discourage those owning concrete buildings.

A. A. Knudson (by letter): The tests shown in the paper are the first of the kind attempted by the writer, or by anyone else so far as the writer is aware, consequently the data are confined to what may be termed initial experiments. Had these tests been conducted over a much wider range as suggested, including an analysis of the many brands of cements, and the effect of currents upon each, it is doubtful if there would have been any practical difference in the results. Both the Portland and the Rosendale cements used in the concrete blocks were samples of brands commonly used in building all manner of structures.

The wrought-iron tubes were not turned or polished before being set in the concrete, but were well cleaned.

The weights in the tables are in avoirdupois ounces; all of them were made in the presence of the writer, and on a very delicate scale.

It has been claimed that no proof is presented that the splitting of the concrete blocks was due to electrolytic action. This question seems to have resolved itself into a difference of opinion as to what is proof. In the absence of other reasons for the splitting of the blocks, it may be said that blocks which had current flowing through them were split open, and the block which had no current showed no cracks of any kind, nor the first sign of corrosion upon the tube. The tests were repeated with practically the same results.

Dr. Steinmetz' remarks on this subject confirm my own view of the case. He said:

> It may be electrolytic corrosion of the iron, the formation of oxides which occupy a larger volume and so increase the size of the iron, and cause mechanical destruction by the irresistible force of the increase of the volume which leads to cracking; it may be also electrolytical action resulting in the production of chemical compounds.

Mr. Waterman said:

> Iron incased in concrete is like a battery electrode in a porous cup, so far as insulation is concerned.

Porous cups are not made to adhere to an electrode as is the case of iron in a concrete block. If this were the case they would doubtless crack open in a few hours. It is only where the tests show that a separation from the electrode was caused by the concrete splitting open that there is a similarity. Here probably is the cause of the increase of resistance after the cracks began to show; for as the cracks increased in size, and the concrete separated from the iron, the resistance increased.

In regard to the "restriction" of the flow of current due to a "highly resistant coating" upon the iron; it is pointed out in the paper that electrolytic action had progressed to the point that cracks appeared on the sixth day, and it was not until the ninth day that the rise in resistance really commenced, consequently there could have been no restriction of current flow until *after* considerable corrosion of the iron had taken place and the damage had been done. This test might have been terminated at the ninth or tenth day, so far as establishing the two points are concerned; namely, that concrete is no protection to iron against a current of electricity, and that concrete will be cracked and softened by such current. The voltage, however, was "remorselessly" raised to determine what the final effect would be on blocks in both fresh and salt water. Mr. Waterman said further:

> Just what a corroded water meter had to do with the subject is not clear.

It is distinctly stated in the paper that the two illustrations were placed there as an example of how currents do actually stray into buildings, or piers, and cause damage. Mr. Waterman also said:

> The corrosion of the meters was probably caused by *iron rust.*

As a matter of fact the meters were made of bronze, and the currents that caused their destruction were in each case traced from the car tracks.

Referring to Dr. Steinmetz' remarks:

> Fortunately iron is a material which is rather stable, and least attacked by electrolytic action. Even wrought iron is not attacked very badly, and steel much less, and cast iron is hardly attacked at all. The problem of protection against electrolysis is not the problem of protecting the rails or gas or water pipes. The underground metal structures which are suffering most are the underground lead cables, and there again it means the telephone cables.

This statement is quite surprising in view of the many instances of pipe destruction which are so generally well known. Even Mr. Corning, representing one of the finest electric railway systems in this country, has stated frankly that they were having a good deal of trouble from electrolysis in one part of their system on the large 48-inch cast-iron mains, and other mains of the Metropolitan Water Works, and they had installed a number of insulating joints in the attempt to prevent electrolytic action.

This is only one illustration from one city of damage by electrolysis to piping systems and other property. This information from Boston was furnished by railroad men. Their statements I can corroborate for I have personally been on the ground and taken measurements in company with others.

Future experimenting with electric currents and steel in concrete will doubtless show further points of interest. The present paper giving the results of experiments is intended as a warning that concrete is no protection to iron or steel when electricity is passing through it.

H. W. Fisher:* Over ten years ago, when the first cases of electrolysis of the lead covering of cables were reported, I made a series of tests to determine the conditions both favoring and preventing electrolytic action on lead-covered cables. As anticipated, I found that only when the lead is positive to ground does injurious electrolysis take place. I also found that electrolysis is not prevented by the addition of 3% tin to the lead, nor by covering the lead with a weatherproof tape or braid saturated with insulating compound. In the latter case, electrolytic action is apt to be concentrated in spots, and thus eat through the lead cover more quickly. For the same reason, I also found that lead-covered cables laid in wooden boxes filled with pitch or bitumen deteriorate rapidly under electrolytic action. As a result of these tests, and others made on cables working under practical conditions, it was found that the amount of electrolytic action depends upon:

1. The proximity of cables to electric railroads.
2. The distance the cables parallel electric railroads.
3. The quality of the electric railroad construction work providing a path for the ground-return current.
4. Numerous other things, including the polarity of the ground return current, the conductivity of the soil, and the position of low soil or water resistance, either along the route of the cables or leading toward the power house, the proximity of the cables to water and gas pipes, the dry or damp condition of the ducts containing the cables, and the chemical constitution of the earth.

From the above data it is evident that the manufacturer of cables cannot guarantee them against electrolysis. He should, however, always be ready and anxious to prescribe such remedies as in his judgment will prevent electrolysis on cables which he has sold. With this end in view, at least one of the cable companies has printed literature dealing with the subject of electrolysis and giving preventive methods and remedies which have proved effective through repeated trials.

The introduction of the single-phase alternating-current railroad system with grounded return brings up the question of electrolysis with alternating currents, and I have been making some experiments to determine whether under any conditions the lead covers of cables may be destroyed by alternating-current. My experiments so far have not been very comprehensive, but I have found that under certain conditions destructive electrolytic action may occur with alternating currents operating at a frequency of 60 cycles.

The solution I employed for the electrolyte was water containing common salt and sal ammoniac, all of which may occur in

*Presented originally at a meeting of the Pittsburg Branch, December 12, 1905.

and around duct systems. I found that with a current density of 0.1 ampere per square inch of lead there was no electrolytic action. With 3.04 ampere per square inch of surface, the amount of lead destroyed per ampere per hour per square inch was 0.004 grammes. With 11.8 ampere per square inch, the amount of lead destroyed per ampere-hour per square inch was 0.136 grammes. With 17.9 ampere per square inch, the amount of lead destroyed per ampere-hour per square inch was 0.237 grammes. In this last case, a large hole was eaten through the lead, and the surface exposed to electrolytic action was nearly one square inch. These tests were made without any attempt at great accuracy. The results show very plainly, however, that if the current density per square inch of surface is sufficiently great, destructive electrolytic action can take place with alternating currents.

Thinking that the action might be due to the large amount of energy dissipated over a small area, I repeated the experiments with direct-current of slightly larger density per square inch, applying the negative side to the lead cover. No lead was destroyed. It may be possible that with other ingredients in the soil or ducts, the alternating-current action may be greater than that here given. While in many cases the current density per square inch of surface may not be sufficiently great to cause destructive action on the lead covers of cables, yet while there is a possibility of such action occurring, the cable companies cannot guarantee their cables against electrolysis from alternating currents.

The apparent remedy is to make the difference of potential between the lead cover and ground so small that the current density per square inch of surface is not sufficiently great to cause destructive action. This may be accomplished in different ways, depending on local conditions. With a frequency of 25 cycles, the alternating-current action would probably be greater than that shown by my tests.

R. A. L. Snyder: The name telephone cable is inseparably connected with the subject of electrolysis. No underground construction has suffered from the ravages of electrolytic corrosion quite so severely as the telephone cable. Our company's experience with this subtle destroyer has been a very sad one. In the early days of telephony we installed a large underground cable plant, and this plant, which cost us $150,000, was entirely destroyed by electrolysis. The plant was known as the " solid system " in distinction from our later plant, now in use, known as the " drawing-in-system."

The solid system was very carefully laid in order to prevent electrolysis. A wooden box was installed and the cables laid in the box on a layer of mineral pitch. The box was then filled with the pitch so as completely to surround the cables. A layer of pitch at least one inch thick separated the cables from the box on every side. Another precaution was taken, by attaching grounding plates to some of the cables at regular intervals; but with all this elaborate protection electrolysis destroyed the system.

At first very little trouble was experienced, for the reason that the electric roads did not become prevalent until about 1894. Before this time Pittsburg's longest street car line was a cable road. During 1896–7 our troubles increased rapidly, but thanks to the new drawing-in-system which we had started in 1893 we were able to replace the solid system very rapidly.

When one of these solid-system cables would show trouble, we had to locate it as closely as possible and then dig up the streets. This was a very expensive operation, especially when the trouble occurred in two places, which meant that we were obliged to open the street for a distance of three or four hundred feet. When the cable was uncovered, the sheathing would be found pitted in many places. Our first solid-system cables laid to the East End exchange had to be abandoned after operating only a few years.

So much for the solid system. The next problem after getting our cables installed in the new system was how to prevent them going the way of the old cables. The electric roads were increasing the size of their plants and the leakage of current was becoming greater. It was generally conceded that the best plan was to make the cables negative to earth as in the old system, as it was noticed that corrosion generally took place where the cables were positive to earth; but there were records showing that cables strongly negative to earth often generated chemicals which reacted to destroy the lead sheathing. This was especially true where the current was shut off during the night.

Some years ago a mass of slimy matter was taken from beneath the electric car rails on Boylston Street, Boston, and sent to the Massachusetts Institute of Technology to be examined, where it was found to consist mostly of sodium hydrate with particles of metallic sodium distributed through it. These particles of sodium burst into flame when thrown into water. Sodium chloride or common salt was used to melt the ice along the rails. This may have been turned into sodium when acted upon by currents flowing into the rail.

As the law at this time apparently furnished no protection to our property from the traction company's stray currents, we decided to go to the expense of running long bond wires to the negative poles of their generators, thus making the cables negative to earth. The result of this course has been very satisfactory compared with our former experience, but we have still had our troubles. At times our cables would carry so much current that they would arc to well-grounded conductors, burning holes through the cable sheathing. At Twenty-first Street and Spring alley the arcing was severe enough to set fire to a terminal pole and required the services of the fire department to extinguish the flames. In the neighborhood of Twentieth street, we had a number of cable terminals burnt where they passed through the pole pipes. This trouble became so bad that in several places we insulated the cable terminal from the pipes with rubber hose.

Several years ago, we had our cable system bonded to the traction company's negative return on Twentieth street with three No. 0 copper wires. These wires carried enough current to heat them to a temperature of 212° fahr. About this time we noticed a change in the electrolytic condition of our cables and upon investigation found that the wires were burned off a short distance from the manhole.

In some cases where our cables are positive to ground at distant points from the power houses, we have allowed them to eat away rather than to go the expense of running a bond wire. Our record of losses from electrolytic corrosion for the past few years is as follows:

1901—One case
1902—Two cases
1903—Two cases
1904—Two cases
1905—Seven cases.

Our troubles appear to be increasing, yet we have spent more money running bond wires during the past year than ever before, despite the fact that the traction company have electrically welded their rails. We have done everything known to the art to prevent electrolytic corrosion of our cables.

The drop in potential between our Grant office building and the cable sheathing at Twentieth street and Spring alley is often over twenty volts. Sometime ago we had some spare cable conductors grounded to the cable sheathing at Twentieth street and the current was used in our laboratory to run a small motor. There was enough current to light a 50-candle power 50-volt lamp to a bright red.

The anchors holding our aerial cables have also suffered from electrolytic corrosion. They have to be made negative to ground by running bond wires. This occurs in almost every town in our territory, and when an anchor breaks, the cables fall to the ground, causing a big repair bill.

For a long time the Ben Venue power house was run only for a few hours each day In this neighborhood we had much trouble from the continually changing conditions. I understand that the Pennsylvania Railroad had to replace their signal air-pipes in this neighborhood several times.

In conclusion, I would say that our present policy is to maintain all parts of the cable system free from electrical contact with underground steel and iron structures; to keep the parts well bonded together, and most of all to have them slightly negative to earth. I would advise all owners of underground metal construction to do likewise, until the traction company adopts some method of carrying return currents in its own conductors.

A paper presented at a Special Meeting of the American Institute of Electrical Engineers, New York, March 22, 1907.

MOTOR-GENERATORS *vs.* SYNCHRONOUS CONVERTERS

WITH SPECIAL REFERENCE TO OPERATION ON LONG-DISTANCE TRANSMISSION LINES

BY P. M. LINCOLN

GENERAL

The particular problem to be considered in this discussion is the following: wanted, direct-current power of approximately constant voltage; for instance, for railways 500 to 700 volts, for an incandescent lighting system, 100 to 275 volts, for an electrolytic process, any direct-current voltage. Given as a source of power, a long-distance alternating-current transmission system, which may be either 25 or 60 cycles, may have a varying voltage at point of delivery, may have the variation occur either on account of the load taken by our particular station or independent thereof, and may have a somewhat variable frequency. Problem, what shall be used for making the desired transformation; synchronous converters? motor-generator sets with synchronous motors? or motor-generator sets with induction motors?

In this discussion a comparison will be made between these methods in regard to the following points, these points being placed, in the opinion of the writer, in the order of their relative importance.

1. Reliability.
2. Voltage regulation.
3. Corrective effect.
4. Efficiency.
5. Cost.
6. Parallel operation.
7. Starting.

These points will be taken up in the order named. As a matter of simplification, it will be assumed that the line voltage is too high for a revolving machine and must be transformed before utilizing.

1. Reliability.

In this connection, the term " reliability " is taken to mean simply freedom from accident, or, in other words, capability of performing normal functions continuously without interruption. Without this element of reliability, it is evident that no plan of transformation can be a success. To those charged with the responsibility of the operation of such a plant, there will be no question but that this feature deserves the first place.

As to reliability, it is evident that the synchronous converter has a very decided advantage in that there is only one machine to get out of order, whereas either of the others involves two. Further, we are forced to use a low voltage on the synchronous converter so that its insulation is normally called upon to stand a maximum of not more than 700 volts; whereas with the motor-generator sets other conditions may dictate a very much higher motor voltage, and, therefore, a lower factor of safety in insulation. Both the synchronous converter and the synchronous motor-generator set suffer the disadvantage that a momentary removal of the voltage from their terminals—a short-circuit on the transmission line for instance—will cause them to drop out of step and make it necessary to start them over again. In this respect the induction motor-generator has an advantage in that it will resume operation automatically after such a temporary cessation of incoming power.

As to " bucking," this is a fault that is more commonly attributed to synchronous converters than to direct-current generators, but the reason for it is that the converter is more widely used under conditions that will cause " bucking " than is the direct-current generator. The usual cause of " bucking " is the sudden occurrence and removal of heavy overloads; as, for instance, when a circuit-breaker blows. The ideal conditions for this occur on the average interurban road, where the sub-stations are relatively small compared with the maximum loads carried. A direct-current generator of the same size and exposed to the same conditions would probably give rise to about the same amount of " bucking." Exception is made in the case of the 60-cycle converter, which is admittedly somewhat more sensitive in this respect than the 25-cycle converter, chiefly on account of its necessarily short distance between brushes.

As a relative comparison of the reliability of the methods under consideration in railway work, the following is advanced as a personal opinion. The number given indicates the relative number of hours that the apparatus would be out of service within a given time on account of defects inherent in the apparatus.

25-cycle synchronous converter...............	10 hours.
Induction motor-generator...................	14 "
Synchronous motor-generator.................	17 "

2. Voltage Regulation

The term " voltage regulation " here will be confined to the changes that may take place in the direct-current voltage. The term embraces at least three distinct features:

a. Automatic change in voltage with change in load.

b. Ability to adjust the initial voltage.

c. Variations in direct-current voltage with variations in incoming line voltage and frequency.

Automatic Change in Voltage with Change in Load. In this respect all methods under discussion are equal. Rising or drooping characteristics of an adjustable value can be obtained with either the synchronous converter or the direct-current generator. The converter suffers the disadvantage that the power-factor of the current supplied must vary with varying loads, whereas with the motor-generator sets the direct-current voltage compounding adjustment is independent of the alternating-current circuit. This point will be further discussed under subsequent headings.

Ability to Adjust the Initial Voltage. It is in this respect that the synchronous converter suffers its greatest handicap. In the motor-generator sets the direct-current voltage is absolutely independent of the incoming alternating-current power. With the synchronous converter, on the other hand, the only way to adjust the direct-current voltage is to make a proportionate adjustment of its alternating-current voltage. There are several methods of accomplishing this end, which may properly be discussed under this heading.

One method is to insert a reactance in the alternating-current circuit of the converter. By changing the field strength of the converter, adjustments of the voltage applied to the collector rings can be obtained within limits, depending upon the amount of reactance and available field adjustment. The disadvantage of this scheme is that the alternating-current voltage is thereby made interdependent upon the power-factor of the incoming alternating-current power, and that the high-tension line voltage is dependent upon the direct-current voltage adjustment to an extent depending upon the relative reactance in transmission line and in the local converter circuit.

Another method is to use an alternating-current booster having the same number of poles as the converter and mounted upon the same shaft. This is approaching motor-generator conditions, except that the generator involved has to take care of only a small percentage of the output of the set under consideration, and the range of voltage adjustment instead of being from zero to the required amount remains between limits depending upon the relative output of converter and booster. This really makes a more logical arrangement so far as initial voltage adjustment is concerned than the motor-generator, since adjustment down to zero is never required in practice. The maximum range of adjustment ever required is the range of incoming voltage fluctuations plus the initial range required.

Still another method is the use of taps on the transformer stepping down to the converter, or of an induction or other type of alternating-current voltage regulator. These in general have the same effect as the booster just described. It is outside the range of this paper to discuss their relative merits. The addition of any of these means of voltage regulation makes the converter equal to the motor-generator set as far as ability to adjust initial voltage is concerned.

Variations in Direct-current Voltage with Variations in Incoming Line Voltage and Frequency. The difference between the converter and the motor-generator set in this respect consists in the fact that the converter responds only to changes in the incoming voltage and the motor-generator only to changes in the incoming frequency. This last statement may be modified slightly by recognizing that the slip of the induction motor depends upon the voltage, but the normal variations of voltage are so small that this feature can be safely neglected. For a given percentage change in incoming line voltage, there will be an equal percentage change in the direct-current converter voltage. For a given percentage change in incoming line frequency there will be a greater percentage change, nearly double, in the direct-current voltage of a motor-generator set. However, changes in incoming line voltage will under normal conditions be much greater and sharper than those in frequency, so that in this respect the converter will probably suffer by comparison with the motor-generator.

There are cases where, on account of voltage regulation, a straight synchronous converter would be absolutely unusable as, for instance, where a steady direct-current voltage for lighting is desired and the voltage of the alternating-current supply is varying due to causes other than the direct-current load under consideration.

The conditions which dictate the choice between converters and motor-generators with respect to direct-current voltage regulation are so variable that no attempt will be made to give any estimate of relative merits in numerical values.

3. Corrective Effect

By " corrective effect " is meant in general the results that may be obtained in respect to the voltage regulation of a transmission line by means of a change in the power-factor of the current taken. Only the synchronous motor and the synchronous converter need to be considered, since the power-factor of the induction motor is not adjustable.

It is desirable in any transmission line,

a. That the voltage shall remain as nearly constant as possible independent of the variation of load, and

b. That the voltage shall be capable of adjustment within limits at the will of the operator at any point.

So far as corrective effect is concerned, the synchronous motor has a distinct advantage over the synchronous converter in that the corrective effects may be obtained without involving the direct-current voltage. In the converter the corrective effect and the direct-current voltage are interdependent. On the other hand, when a converter is adjusted for a rising direct-current voltage characteristic, the tendency is to correct, in part at least, for the transmission-line drop caused by its own load. Thus it tends to fulfil condition (*a*) stated above. The synchronous motor can be made to fulfil condition (*a*) to the same extent by causing the direct-current generator current to flow through series coils on the motor field.

As to condition (*b*), both converter and motor field can be so adjusted by hand as to accomplish this end, but in the case of the converter not without making a simultaneous adjustment in the direct-current voltage. In order to secure the same independence of action with converter as with synchronous motor, it is necessary to have some means of adjusting the converter alternating-current voltage independent of simultaneous power-factor adjustment; as, for instance, the synchronous booster or voltage regulator described under the previous heading.

There is another point of view that should be presented before dropping this subject. A sub-station using the apparatus under discussion may or may not be under the control of the transmission-line operator. If it is, then its corrective effect can be used as transmission line conditions may dictate. If it is not under his control, the possession of corrective effect may not only be of no advantage, but also a positive menace to the proper voltage regulation of the line. If it is not under his control, he is probably better off with the induction motor-generator set, since it is neutral and possesses no power of changing line voltage at the caprice of an uncontrolled individual.

From the standpoint of corrective effect, therefore, the synchronous motor-generator has decidedly the advantage over the straight converter while the induction motor-generator is entirely neutral. No attempt will be made to give comparative numerical values since this depends, not only upon specific conditions, but also upon the point of view.

4. Efficiency

At the end of a transmission line power is usually sold by the kilowatt hour, or some other function that is proportional to it. The amount of the monthly bill will be proportional to the meter-reading, and the efficiency of the transformation therefore enters as a direct function in the cost of power. In this respect the converter has a decided advantage. It is a case of the losses in one machine as against those in two, and, moreover, the losses in the converter are somewhat less than in either element of the motor-generator set. The full-load efficiency of a converter of, say, 500 kw. capacity, may be put approximately at 95%, the synchronous motor-generator set, 89%, and the induction motor-generator set, 88%. The all-day efficiency will be considerably less than the above. As a reasonable estimate of the all-day efficiency under about 75%

load, the following is submitted. In submitting these the writer has in mind units of 500 kw. capacity or thereabouts:

25-cycle synchronous converter	93%
Synchronous motor-generator	85%
Induction motor-generator	84%

The following calculation based on the above is somewhat surprising. Assume a station using a 500-kw. unit an average of 18 hr. per day at 75% average load. Assuming power to cost one cent per kilowatt-hour, the saving in power bill per year of converter over motor-generator is $2100.00. Capitalized at 6%, this represents $35,000.00. In other words, one could afford to pay $70.00 per kilowatt more for converters than for motor-generators.

5. Cost

In regard to cost, the synchronous converter has an immense advantage. Here again, as in efficiency, it is the cost of one machine against two; and the cost of the converter is not far different from that of each machine that goes to make up the motor-generator. An approximate idea of relative cost is given in the following:

Synchronous converter	60%
Synchronous motor-generator	100%
Induction motor-generator	100%

6. Parallel Operation

The two points to consider in parallel operation are:

a. Proper division of direct-current load between units.

b. Proper operation so far as alternating-current ends are concerned, such as freedom from "hunting," etc.

As to division of direct-current load, there is no question either on direct-current generator or converters. In fact, it is perfectly possible by proper adjustment to operate converters and motor-generator sets of both kinds all in multiple.

As to operation on the alternating-current ends, the induction motor-generator is the least liable to trouble, since "hunting" or "pumping" cannot take place on that type of machine. The synchronous motor and converter are on a par in regard to hunting. However, with the modern construction of synchronous machines, including as they do heavy dampers, there is so little probability of hunting that it may be entirely neglected. The only places in which hunting is apt to occur are in cases where antiquated generators are used and where the ohmic line drop is very high. Neither of these is apt to occur in practice.

7. Starting

In starting the desirable features are:

c. Minimum draught of current from line of starting from alternating-current end.

b. Ease of synchronizing.

a. It is difficult to make any of the apparatus under discussion of such design that it will start readily from the alternating-current end. Good running characteristics invariably mean poor starting characteristics. The inherent starting characteristics of the synchronous motor and converter are bad on account of the large air-gap. The converter has the advantage of only having one-half the mass of the motor-generator to start. The induction motor-generator set has the advantage of better starting characteristics, but it suffers in comparison with the converter in having double the mass. If started from the collector rings, the converter suffers by liability of damage to commutator by burning and sparking. A draught of full-load current or less from the line is usually sufficient for starting any of the sets.

If it is essential to keep down starting current, a starting motor can be employed. In this case the converter again has the advantage of one half the mass as well as one-half the losses of the motor-generator set. The same advantage applies to starting from the direct-current end, but is partly off set in the converter by the shunting effect of the static transformers, if these be connected.

b. In synchronizing, the induction motor has a great advantage in not requiring synchronizing at all. As between the converter and the synchronous motor, the converter suffers the disadvantage of having a commutator connected to the winding being synchronized, and, therefore, liable to injury by careless manipulation.

Altogether, there is not much choice in the starting qualities of the three methods, but what there is would cause them to be arranged in the following order:

1. Induction motor-generator.
2. Synchronous converter.
3. Synchronous motor-generator,

Summary

On three of the preceding seven counts; namely, 1, 4, and 5, the converter has a distinct advantage.

On one more, 6, all methods are taken as being on a par.

On the remaining three, 2, 3, and 7, one of the other methods has the advantage. In one of these, 7, the disadvantage of the converter is not marked. The converter's disadvantage on the other two largely disappears with the addition of a means of voltage regulation.

This analysis, therefore, would seem to indicate that there are but few cases where the motor-generator should be used in preference to the synchronous converter.

DISCUSSION ON "MOTOR-GENERATORS *vs.* SYNCHRONOUS CONVERTERS, WITH SPECIAL REFERENCE TO OPERATION ON LONG-DISTANCE TRANSMISSION LINES." AT NEW YORK, MARCH 22, 1907

A. H. Armstrong: In regard to the use of motor-generators or synchronous converters, the question seems to me to be one of voltage regulation. The requirements of a railway system fed from a general transmission system are best met as to first cost and efficiency of operation by the adoption of the synchronous converter, and its almost universal use in railway installations would seem to leave no room for argument. The requirements of a direct-current lighting load can also be best met by the adoption of the synchronous converter, provided the distribution system is used for lighting only. Where, however, the distribution system supplies a mixed lighting and railway load (or any other load occasioning extreme fluctuations) the lighting system should be fed through motor-generator sets in order to smooth out the effect of unavoidable voltage fluctuations. Taking this broad view of the situation, there is a well-defined field for both synchronous converters and motor-generator sets, the question of voltage regulation determining the choice of either type of apparatus.

W. L. Waters: The reliability of operation of these different classes of machines is mainly a question of the care they get in operation. The induction motor is the only one that presents any disadvantages as regards actual construction of the machines. The small clearance between the rotor and stator with which these machines operate makes them more liable to mechanical troubles, and the small slots which it is necessary to use in the stator make it more difficult to make a satisfactory job of a high-voltage winding.

On the question of flashing over, the synchronous converter is decidedly more sensitive than the direct-current generator. The fact that the alternating- and direct-current sides of the converter are so intimately connected, combined with the fact that there is no armature reaction in such a machine to limit the current on short-circuit, make it peculiarly sensitive to sudden fluctuations on one of the circuits. For carrying overloads, the converter is superior to the direct-current generator, but it will not stand short-circuits or violent fluctuations on either circuit so well.

If voltage regulation is of importance, it is practically impossible to use a synchronous converter. With a synchronous converter we are dependent for voltage regulation upon the voltage supplied on the alternating-current side. If the synchronous converter is the only machine on that particular line, then by introducing artificial self-induction into the line and putting a series winding on the magnets of the converter, we can compound the line and so to a certain extent make the voltage change automatically with the load; but this means varying the power-factor of the converter and of the system within quite wide limits, and also that this change of voltage on the line affects all other apparatus on that line. The only other way of adjusting the voltage delivered by a converter is by introducing some sort of an alternating- or direct-current voltage regulator or booster, which of course means extra complication, extra cost, and lower efficiency.

As regards corrective effect for power-factor, this can practically be obtained only by the use of a synchronous motor-generator. On account of its low power-factor, an induction motor is very undesirable at the end of a transmission line and would not usually be considered unless it were possible to correct this low power-factor by introducing a leading current into the line. This can only be done practically by means of a synchronous motor. A synchronous converter can be made to introduce a leading current into the line, but this would mean varying the direct-current voltage and power-factor of the machine.

In using a motor-generator at the end of a long transmission line, it would undoubtedly be necessary to employ transformers for lowering the voltage before delivering it to the synchronous motor. In this case the synchronous converter has a considerable advantage in regard to efficiency. The value of this difference in efficiency has to be decided in each case by the cost of producing the extra kilowatt-hours. In a steam plant where the cost of fuel is high, this may be quite important, but as most long-distance transmission lines are operated from water power the cost of producing the extra kilowatt-hours is quite small. Practically, the only bad effect of the lower efficiency is that it reduces the capacity of the power-house machinery somewhat.

The relative cost depends a good deal on the particular machine that we are considering. If we consider a 1500-kw., 275-volt, 25-cycle machine, the synchronous converter would run at about 187 rev. per min., as this machine could not very well be built with less than 16 poles, while the motor-generator set could, by using an interpolar design, be built to operate at a speed of 300 rev. per min. or even higher. In this case there would be practically no difference between the cost of a synchronous converter and that of a synchronous motor-generator set. The introduction of interpolar designs in large direct-current work makes the direct-current generator the equal, if not the superior, of the synchronous converter, at the same time it is not subject to the limitation that the speed is dependent upon the number of poles on account of the frequency.

Referring to the question of starting. The induction motor-generator set is undoubtedly the simplest. The synchronous motor-generator only differs from the induction motor-generator in that it is necessary to close the exciting circuit and to synchronize the machine after it is up to speed. The starting of a synchronous converter is considerably more complicated than that of a motor-generator. If the converter is compound wound, we have to short-circuit the series coils when starting from the direct-current side. Then we have to synchronize carefully, and an error in throwing the machine on the line is much more liable to do damage or cause a flash-over than in the case of a motor-generator, as there is nothing to limit the short-circuit currents that would flow. If we start from the alternating-current side, we have to see that the polarity and voltage are correct before we throw them on the direct-current line. Throwing a synchronous converter on the line is a more sensitive operation and one which is more liable to cause damage than the same operation with the motor-generator, and in consequence the operator must be proportionately more skilful.

Speaking generally from the operating standpoint, a motor-generator is preferable to a synchronous converter in almost every respect, except as to efficiency and cost. And even as to cost a motor-generator is cheaper for low voltages and larger outputs, especially if the voltage on the transmission line is not over 15,000 volts, when the synchronous motor could be wound to take the high voltage direct. When comparatively cheap and medium-size units are wanted, and under conditions where close voltage regulation is unimportant, synchronous converters would be used; when large-size units are desired and when the voltage regulation and general flexibility are important, motor-generators would be preferable. In situations where the machines are to run with practically no attention, probably induction motor generators would be perferable to synchronous motor-generators. But the fact that synchronous motors can be used to control the power-factor of the line is of such importance in long transmission lines that the engineer should adopt them wherever possible.

H. G. Stott: In regard to Mr. Lincoln's comparison of the characteristics of motor-generator sets and synchronous converters, my own experience confirms his statements. During the initial period of the operation of a water-power plant, the voltage regulation was fairly good, but the speed regulation was poor; with these conditions, the synchronous converter gave the best results, but later, when the number of generators in service had been increased and the line regulation had become poorer, owing to the increased load, we had to resort to motor-generator sets, in order to obtain regulation suitable for lighting.

In reference to the various methods of starting, it is desirable to remember that any method involving starting from the alternating-current side means a rush of current equal at least to full-load current, at a power-factor of less than 25%; whilst starting from a motor coupled to the shaft, or from the direct-current side involves the use of only 4% of the full-load current, at unity power-factor. The first, or purely alternating-current method, may cause a serious disturbance in the circuit, resulting in hunting, and violent surges of current and voltage if the circuit is in a condition approximating resonance.

With the induction motor-generator set, however, another condition obtains, as when we start it from a separate motor or from the direct-current end, and after bringing it up to full, no-load speed and throwing it on the line, there may be a rush of magnetizing current equal to more than 10 times full-load current. This is the same phenomenon as observed when throwing current into transformers, the value of the momentary current depending upon the point of the cycle at which contact is made, with relation to the point of the cycle at which the current was previously broken. With large induction motors, it is therefore necessary to introduce resistance or inductance at the moment of closing the circuit, but this resistance may be cut out again after a few seconds, as this enormous magnetizing current lasts only for a few alternations.

Ralph D. Mershon: I cannot quite agree with Mr. Lincoln as to the relative reliability of motor-generator sets and synchronous converters. I have been closely associated with one installation where power is supplied in part by 60-cycle induction motor-generator sets and in part by 30-cycle converters. While there has been very little trouble due to either type of machine, such trouble as there has been, is more chargeable to the converters than to the motor-generator sets, although there are a good many more of the latter than of the former. This is in spite of the small air-gaps of the motors. We have not had in the installation I refer to any trouble such as Mr. Stott speaks of in regard to throwing the induction motors on the line though this may be partly due to the higher frequency. I am quite sure that the company supplying the power would make it known if there had been much disturbance when the motor-generator sets were thrown on the line.

It seems to me that in Mr. Lincoln's introduction, and the discussion of it, there has not been enough stress put upon the fact that operation of the motor-generator set is largely independent of the line voltage which it receives, and that therefore it is very well adapted to operation on very long transmission lines, where the full-load voltage at the two ends of the line will differ widely. In some instances this difference of voltage and the consequent variation between no load and full load of the voltage of the converters at the ends of the transmission line will not be a serious drawback. In other cases it may constitute a serious objection, and in any case it certainly is a very attractive condition of affairs to have along the transmission line motor-generator sets whose operation will not be materially affected by considerable variations of transmission line voltage this will apply to both induction motor-generator sets and synchronous motor-generator sets; but it is also a great advantage at times to have the equalizing effects which may be obtained from a separately excited synchronous motor in assisting to maintain an approximately constant voltage on the transmission line. In general, in any engineering problem we must adopt the apparatus to the conditions to be met. Undoubtedly, where the converters can be used without serious disadvantage, there is a very great deal in their favor on the score of efficiency, and also on the score of first cost. I believe with Mr. Waters, however, that if some work were done in the matter of raising the speed of motor-generator sets the difference in cost would largely disappear.

Charles W. Stone: It is simpler to insulate a generator coil than it is a high-voltage transformer coil, for the following reasons: The generator coil is usually small, and when insulated is usually quite stiff and rugged; whereas the transformer coil being comparatively thin and quite wide and flat, making it very difficult to get an insulation which will be continuous and will not be subject to movement and consequent deterioration.

When low-voltage taps on the transformers are used, the starting of converters is much simpler than the starting of a motor-generator set. I have seen machines as large as 1500 kw. started from the alternating-current side and brought up to full speed within 40 seconds. This means, of course, a considerable rush of current, but shows that it is possible in cases of emergency to start a converter quickly; in fact, much more quickly than a motor-generator set of similar capacity.

In regard to the number of hours that the different classes of machines would be out of service, due to defects inherent in the apparatus itself, I do not agree with the order given in the third page of the paper. I should place the synchronous converter first, next the synchronous motor-generator set, and next the induction motor set. I am basing the above conclusions upon a careful study of complaints which have been brought to my attention, and which clearly indicate that there has been more trouble with the induction motor sets than with the synchronous motor sets.

In regard to the relative efficiencies of the different combinations, I would say that the author's table applies only to the 25-cycle synchronous converters, as the efficiencies of the 60-cycle motor-generator set will approach very closely those of the converter sets. The 60-cycle converter will probably cost as much if not more than a motor-generator set.

Mr. Lincoln says that induction motor-generator sets do not hunt. I cannot quite agree with this, as I have seen induction motor-generator sets hunt considerably under certain line conditions. It is possible to make them hunt under test.

The author says, that with the motor-generator set there are two machines to look after. That disadvantage is, I think, somewhat offset by the fact that the converter has very large collector rings and brushes and heavy copper connections. I anticipate as much trouble with the collector rings and brushes as with the synchronous motor end of a motor-generator set.

Mr. Lincoln also says that the induction-motor end of a motor-generator set has an entirely neutral effect on the line. I do not think that this is quite true; it has a very serious effect on the line, and that is in lowering the power-factor.

Charles F. Scott: Mr. Lincoln's paper is excellent in that it gives a general survey of conditons pertaining to a given class of service. Very often engineers are apt to present a certain class of apparatus as the only one which is suitable; one man, for example, advocates the induction motor; another, the synchronous motor, and still another cares for nothing with alternating current in—it each maintaining that his class of apparatus is the one for all cases. A paper of this kind shows the wide field of conditions which exist, and shows that each of several kinds of apparatus may have its own proper place under certain conditions.

The general conditions applying to the three classes of apparatus considered have been presented; the second step in the problem should be to determine the results of experience. What has been the concrete experience with each these different classes of apparatus? Mr. Lincoln has given his opinion in a certain order of preference of the different classes of apparatus, and some others have expressed opinions reversing his order. If we could get from the operators of the several classes of apparatus their different experiences, it would give us some excellent data. For example, when we are told by one gentleman that induction motor-generator sets give greater cause for complaint than other classes, it raises the question: If this is the case, why is it? The simplest kind of apparatus is the direct-current generator on the one hand and the induction motor on the other, but if, however, these are not found in practice to give the best results, it will be interesting to know more in particular just why.

Philip Torchio: I am willing to endorse all of Mr. Lincoln's conclusions as far as applied to existing moderately-high-tension voltage systems operating relatively short lines. I do not think it justifiable, however, by actual experience to apply the same conclusions to the specific conditions of the paper, having special reference to long-distance transmission lines. In this case experience with synchronous converters is very limited, and the author has pointed out two serious drawbacks which, in my opinion, would in most cases preclude the use of converters. One of these drawbacks is the fact that converters fall out of step when the ohmic line drop exceeds a certain percentage, which is generally limited to ten per cent., and it seems to me that any momentary heavy short-circuit at the end of a long transmission line would be a menace to the continuous operation of the converters. The other drawback is due to the independence between line-voltage fluctuations and direct-current voltage regulation. I am certain that with most of the lighting systems this fluctuation would prohibit the use of converters. I would even go a step further and state that with 25-cycle transmission lines, frequency-changers of from 25 to 60 cycles should be installed; not only for the reason of the higher frequency required for good incandescent lighting, but also on account of regulation.

The question of variation of frequency can be remedied at the generating station, but it would be almost impossible to expect the generating station to regulate the distributing voltage with fluctuating loads on the line.

P. M. Lincoln: Mr. Waters says that the synchronous converters would compound the whole line when compounding themselves. This is true to a certain extent only; it is usual in operating converters to place in each individual converter circuit a rather high reactance which has largely the effect of making only the converter compound. Such reactance has the further effect of answering the objection to the large amount of current that a converter would take when short-circuited; the reactance has the effect not only of making the converter compound, but also of limiting the current on the short-circuits. Mr. Waters further says that efficiency is not a very important point, because water power doesn't cost anything. This is an easily answered argument. If power is being paid for, the power wasted has to be paid for as well as that used, and this applies whether the power is generated or bought.

As to the contention that converter speeds are necessarily lower than those of motor-generator sets, I take exception to that statement. I dont see why converter speeds cannot be made as high as motor-generator speeds.

To the statement made in my paper that the induction motor is neutral in its reaction on the line, objection is made that the induction motor is not neutral—that it is highly inductive. Closer reference to my langage will show that my point is that the induction motor is neutral so far as its capability of adjustment is concerned; it takes one position and stays there.

Mr Torchio intimated that trouble might be expected from converters where the ohmic line drop was ten per cent. or more. I should like to raise that limit a little, to something nearer twenty per cent., I know of cases where converters have been successfully operated when the ohmic line-drop was considerably more than ten per cent. Also tests have been carried out which indicate that the converters can, under favorable conditons, be operated with an ohmic line-drop of twenty per cent., and possibly more.

B. A. Behrend: I want to ask Mr Lincoln in regard to the subject of his paper why he has not included a 60-cycle converter in the list of machines out of service for a certain number of hours. How many hours would a 60-cycle, 600-volt synchronous converter be out of service?

P. M. Lincoln: I think it would depend entirely upon the time at which the converter was designed. The design of 60-cycle converters has improved wonderfully during the last decade. If it were designed in the last three or four years, I should put it somewhere between the 25-cycle converter and the induction motor-generator—say 12 hours.

B. A. Behrend: There is another point on which I wish to ask Mr. Lincoln. I quote from his paper:

> However, with the modern construction of synchronous machines, including as they do heavy dampers, there is so little probability of hunting that it may be entirely neglected. The only places in which hunting is apt to occur are in cases where antiquated generators are used and where the ohmic line-drop is very high. Neither of these is apt to occur in practice

I am afraid that this statement is not altogether true. I am quite willing to state that hunting does not occur very often, but it does occur in some cases, and in such cases it is often very obdurate and it is difficult to account for the causes in a satisfactory manner. I should like to know why the ohmic drop has such considerable effect; it, of course, limits the overload capacity of the synchronous machine; it changes the characteristic frequency of the oscillation; and if there exist in the system somewhere forced perturbations of a given frequency, then there may be a resonance effect produced by an increase in line resistance. But even this does not explain thoroughly why line resistance is made responsible for hunting. Mr. Lincoln's statement that hunting in modern synchronous machines can be neglected seems to me somewhat broad, although Mr. Lincoln allows himself a loophole by stating that this is the case only with modern generators and converters of a recent style with heavy dampers. I should like to ask Mr. Lincoln why he considers line resistance responsible for hunting?

P. M. Lincoln: Hunting always means that the rotor of the machine that is hunting is departing from its true mean path—periodically ahead of and behind that path. The magnetic field which flows from the pole into the armature is shifting constantly from one side to the other of the pole. The way to prevent that is simply to put grid dampers upon the iron of the pole, and in that case if there is any tendency for the flux to shift across the pole face. large currents are set up in these dampers which oppose the shifting of the magnetic lines.

The application of grid dampers, judging from the experience has been a complete cure for hunting—the exceptions being accounted for on high ohmic drops.

B. A. Behrend: What is the effect of the ohmic drop in regard to hunting?

P. M. Lincoln: I am unable to give you an exposition of the reasons at this time. We have made experiments to determine the limits of ohmic resistance and have found that under favorable conditions the grid damper would prevent hunting with an ohmic drop as high as 20%. The final limit may be even higher than this.

J. R. C. Armstrong (by letter: I am in full accord with the conclusion stated in the last paragraph of the paper, to the effect that, " there are but few cases where the motor-generator should be used in preference to the synchronous converter".

I understand that the object of this paper is to determine which of the three devices—synchronous converters, motor-generator sets with synchronous motors, or motor-generator sets with induction motors—is the best for transforming alternating current into direct current, and, at the same time, maintaining a constant voltage on the direct-current bus-bars.

It seems to me that the items " Parallel operation " and " Starting " should precede " Efficiency " and " Cost", as these factors are vital to the successful operation of a plant.

Reliability. or continuity of operation is I think the most important condition to obtain, especially at times when the greatest demand is made upon the respective pieces of apparatus.

I believe that undue prominence and stress has been laid on so called " bucking " or arcing over on the synchronous converters. It is true that this occasionally happens, but in a well-designed converter the percentage of trouble in a station due to this cause is very small. When bucking does occur, very little damage results to the converter, due to the highly developed protective switchboard apparatus installed on the alternating-current and direct-current sides of the converter circuits. It is very seldom that a short-circuit on transmission lines, either on alternating-current or direct-current sides, causes the converter to arc over, due to the fact that the overload device on the breakers will operate and thus clear the station bus-bars. A great deal of the trouble experienced in the operation of converters is due to the fact that the negative side of the circuit has been grounded and no attention has been paid to insulating the machine from the ground. It is readily seen that since there is a short distance between the commutator bars and the frame of the machine, there is only this short distance between the commutator bars and the ground when the frame of the machine is thoroughly grounded. Bucking due to this cause can be very easily obviated by insulating the machine from the ground; in other words, installing it on insulating material that will not allow an appreciable current to pass from the commutator bars to the frame.

In my opinion, the time assumed for the synchronous converter being out of service is too high. I think that this figure (10 hours) can be materially reduced.

Voltage regulation. With regard to the statement in the paper on " Variations in direct-current voltage with variations in incoming line voltage and frequency." I do not believe that such great variations may be expected. Should large variations occur, it would be on an exclusively railway system where the fluctuations in direct-current voltage would not be a serious matter; whereas, where a steady direct-current voltage is required, as, for instance, in a lighting system, the period of fluctuations would be quite long, in fact long enough to allow the operator in the generating station to change the field strength on the generator in order to hold the voltage more or less constant. This, I believe, would likewise apply to most systems composed of a combined lighting and railway load. Therefore, I believe that the synchronous converter compares favorably with the motor-generator set and not unfavorably, as mentioned in the paper, for operation under ordinary conditions.

Parallel operation. In the present state of the art of designing synchronous motors and converters, I agree with the writer that "The synchronous motor and converter are on a par in regard to hunting". The question of hunting on the last two mentioned machines may be neglected.

Starting. It might be mentioned in connection with the amount of current that these respective kinds of apparatus take from the line, that the induction-motor set is very bad in this respect. For in the case when a heavy draught of current is taken from the line, thereby setting up line disturbances, the induction motor-generator set is very conducive to this condition.

When new and in good condition, the motor will require a considerable interval of time to bring the machine being started to synchronous speed before switching it on the line. This operation will sometimes take as much as five minutes. A much simpler and quicker method of starting, and one which does not draw a large amount of current from the line, is that of starting from the direct-current bus-bars of the station. This can be accomplished very simply, and no time is lost in waiting to get the machine at the exact frequency of the line. It can be done by sectionalizing the field and connecting the field leads to a multiple-point switch that will introduce into the field circuit when opened a large amount of resistance, thereby largely reducing the normal current flowing in the field, and at the same time causing a very slight increase in voltage on the field windings. With this switch, a tripping device for the direct-current breaker can be operated and connected in such a way that the direct-current breaker through which the machine is receiving its power can be tripped before the high resistance is thrown into the field circuit. A second contact can be attached to this switch for closing the alternating-current circuit on the converter; this operation following immediately the introducing of the high resistance into the field as above mentioned. It will be seen that in the one operation above outlined, three things are accomplished; namely, the cutting off of the starting current, the introducing of a large resistance into the field circuit; and the closing of the oil switch—all three operations following one another in the order named. Then the machine cuts in on the alternating-current side when the armature is practically "floating", due to its own momentum, at approximately synchronous speed, and cut off from the direct-current source of power.

After the above operation has been carried out, the high resistance is cut out of the field circuit by closing the multiple-point switch and the machine is then ready for service. It will be seen that there can be very little strain or jar thrown on the armature in starting a machine by the above method. Units of large size can be started by this method by the ordinary operator in one minute or less. Therefore, I cannot see why the more expensive methods as proposed in this paper for starting machines of the above mentioned type should be employed, except perhaps where one of the above methods might be installed for starting one machine in case of emergency when no direct-current power was obtainable in the station.

The above method of starting machines from the direct-current bus-bars is now employed in quite a number of sub-stations in New York where converters are installed. It has been giving entire satisfaction.

In regard to cost of apparatus for starting, it might be mentioned that the cost of installing a switch as described above is only nominal, compared with the cost of other types of starting apparatus.

The advantages of the synchronous converter over the motor-generator are very marked, especially with respect to reliability, which I believe to be the predominating feature. Further, there is a wider range of application of the synchronous converter than there is of the motor-generator.

A. H. Babcock (by letter): A single qualifying clause should be added to the author's conclusions; that is, provided that the line frequency is not greater than 25 cycles. Experience on long lines in the West, especially where an extensive distribution system is operated, shows plainly that synchronous converters should be barred entirely where frequencies as high as 60 cycles are used.

For railway work, especially where the generating station distribution is under one control, and the frequency can be made 25 cycles or less, synchronous converters are to be preferred.

For 1200-volt lines, the indications are that ordinary 600-volt generating apparatus operated in series will give satisfactory results, although there is no experience in this country, at the present time, on which to base a positive opinion.

F. G. Baum (by letter): This paper assumes that 60-cycle converters are as satisfactory in operation as motor-generators. In any event, the author seems to have had in mind a 25-cycle system.

Assume for example that a given district is to be supplied by direct current at several points, also 60-cycle, 2300 to 10,000 volts for light and power circuits from a 60-cycle power system. The substations feeding the light and power circuits are also to be used for the conversion from alternating to direct current.

In this case, to the cost of the converter there must be added that of a bank of transformers and regulators to supply it; add also the losses of the transformers. This would bring the cost of the converters and transformers to about 80% of that of the motor-generator, and reduce the efficiency of the converter to about 90%.

The extra floor space for the transformers must also be considered. Also the great advantage the motor-generator set has in regulation on the alternating-current side, as well as on the direct-current side. These advantages are of great importance, and, considered in the light of present experience with 60-cycle converters, the motor-generator would generally be selected for the conditions here assumed. The conditions here assumed are those generally prevailing, except where there is a special system for the railroad power.

Ernest J. Berg (by letter): My judgment is that the synchronous converter is likely to play even a more prominent part in the future than at the present time. I quite agree with Mr. Lincoln in regard to the reliability of the converter as compared with the other types.

Regarding the voltage regulation. I do not think it serious that the power-factor is affected by automatic voltage regulation. Considerable control can be had with but slight change.

In most long-distance transmission lines, considerable lagging current is not objectionable at light loads, because the charging current is larger than the lagging current, due to the induction load. In its control of voltage, the converter can be adjusted to take considerable lagging current at no load and practically none at full load. Therefore, the converter might advantageously be operated with such automatic control. In low-voltage transmissions, which however are outside of the scope of this paper, there would be some objections on this score.

I quite agree with the conclusions given under the heading " Corrective effect " and also under the heading " Efficiency." The question of cost I can hardly pass upon, but I recollect some cases in which the cost of the synchronous converter with its transformer was practically the same as that of high-speed induction or synchronous motor-generators.

Regarding parallel operation. My experience leads me to believe that a properly designed synchronous converter operating on a 25-cycle system can be made quite as stable as any synchronous motor-generator, even if the latter is equipped with various kinds of anti-hunting devices.

Regarding the heading " Starting ". I consider that the three systems are practically on a par. Induction motor-generators will take about as much current as any of the others, if special starting devices are omitted.

My conclusions, therefore, agree with those of Mr. Lincoln, that in most cases the synchronous converter offers advantages over the other two kinds of machine. I consider that in high-potential transmissions where there is usually a leading wattless current, the induction motor is preferable to the synchronous motor in every case.

R. G. Black (by letter): This paper refers to matters that interest not only the electrical engineer, but the operating man the capitalist, and the customer. In my opinion it is hard tc consider the various heads under which the paper is discussed for both railroad work and lighting and power work, as what might be entirely satisfactory for railroad work might be otherwise for lighting and power work. From the point of reliability I would say that our experience leads us to differ with the writer of the paper as regards the motor-generator set, as generally designed, resuming operation automatically after temporary cessation of power supply; for if the speed should drop below 50 per cent. it is very doubtful, with the load of incandescent lights, direct-current motors, etc., if the induction motor would resume speed without drawing sufficient current to trip the automatic alternating-current line circuit-breakers. However, with a specially designed coil-wound induction motor, so arranged either by means of a centrifugal device or an electrical device automatically to put resistance in the rotor circuit, should the speed drop, say, 25 per cent. below normal, it is quite possible to arrange a motor-generator station so that the induction motors will automatically resume operation notwithstanding the direct-current load remains on. With motors arranged as above, I should be much inclined to place the induction motor-generator set first on the list, with the 25-cycle synchronous converter second, with about the same number of hours as shown.

Speaking generally, on every point except cost I should be inclined to favor the specially arranged, coil-wound induction motor as being the most reliable, easiest operated, and least objectionable of the three classes of machines discussed. In the matter of cost there is no doubt but that the synchronous converter has the advantage, particularly if its overload capacity is taken into consideration, but unless the operating company controls the transmission company, or has an agreement with them whereby the variation in voltage is not excessive, the cost of a large enough induction regulator brings the cost of the converter, with transformers and regulator, very nearly equal to that of a motor-generator set for a given kilowatt capacity. If the induction motor sub-station is close enough to a terminal station so as not to make transformers necessary, it might in some instances be cheaper than the synchronous converter set.

At one of the plants with which I have been affiliated, which is connected to a long-distance transmission system, arrangements are being made to purchase five 1500-h.p. induction motor-generator sets for lighting and power work in preference to synchronous converter sets or synchronous motor-generator sets, the idea being that they will be much more reliable, easier to operate, and more satisfactory in every way than either of the other types of machine.

Edward P. Burch (by letter): The writer's experience is that 60-cycle converters are not reliable. They are therefore unsatisfactory for 600-volt electric railway service. He would recommend the purchase of the higher price and lower efficiency synchronous motor-generators in place of 60-cycle, 600-volt converters.

H. W. Buck (by letter): On a miscellaneous system of power transmission covering a large territory it becomes very difficult to adjust the voltage throughout the transmission network to suit everybody, where each customer is directly dependent on the line voltage at the point of delivery of the power. This condition becomes more pronounced as the length of transmission lines is increased. With a trunk line, say 200 miles in length, feeding branch lies here and there of considerable length, it is virtually impossible to maintain anything like a uniform potential on all parts of the system, nor is it possible to prevent wide fluctuations in the voltage at any given point. Sudden changes in load are inevitable, together with changes in phase relation. Such power systems should not be closely restricted in regard to line voltage regulation but should be free to deliver power, in the rough, so to speak, with voltage refinements made on the secondary distributing circuits. The power company should be allowed a variation in line voltage of 20% if necessary, or 10% above and below a mean. Such fluctuations might not be objectionable for many classes of power work, but would, of course, be prohibitive on lighting circuits. It becomes necessary, therefore, under these conditions to have the voltage of the secondary distributing circuits rendered independent of the line voltage, and motor-generators must be installed.

It is true, as pointed out by Mr. Lincoln, that frequency variation with a motor-generator installation disturbs the distributing generator voltage; but on large transmission systems having a heavy and diversified load, as is usual, good frequency regulation is not difficult. The loads on various portions of the system, and consequently the voltage at such points, may fluctuate widely, but in general the total resultant load at the main power house remains either practically constant or else changes so gradually that the governors can compensate for it with small change in generator speed.

As to the comparison between induction and synchronous motor-generators, while the induction type has certain advantages in starting, the synchronous type has other advantages of equal importance. In cases of momentary short-circuits on the system there will be a tendency for all the motor-generators and converters to drop out of step, due to the consequent drop in voltage. In the induction type the torque drops as the square of the drop in voltage, and a heavily loaded induction motor may therefore break down at a comparatively small reduction in impressed voltage. In the synchronous type, the field current of the motor being proportional to line frequency only, will remain constant under drops in line voltage, and will tend to keep up the voltage at the motor terminals, and maintain the torque. In this regard the converter has the same characteristics as the induction motor, in that its field current falls with the voltage of the line. In the writer's experience the motor-generators of the synchronous type hold in step better under line short-circuits than either converters or induction motor-generators.

The absolutely independent control of the voltage of the distribution circuit possible with the motor-generator combination affords many operating advantages, all of which cannot be listed on paper. The possibility of independent phase control with the synchronous type is of special advantage. On every alternating-current power system there must of necessity be many small induction motors in operation, and compensation for their low operating power-factor can only be obtained by means of some large synchronous motors on the lines. The introduction of single-phase railways as customers on large power systems, with the low power-factors of their circuits, makes this corrective influence all the more demanded.

O. B. Coldwell (by letter): Mr. Lincoln places " Reliability of operation " at the head of the list of points to be considered when making a selection of the most suitable machine for the connecting link between the high-tension transmission line and the low-tension direct-current distributing system. Unquestionably this is the point of most importance to those entrusted with the operation of a plant using such apparatus.

It has not been the experience of the writer that the converter has a decided advantage over a motor-generator set, on account of there being but one machine to get out of order rather than two. A converter is necessarily provided with slip-rings on the alternating end—six rings in the case of large converters—and even with the best of attention there will occasionally be trouble on this side of the machine. This feature is entirely absent in the motor-generator set.

The induction set is driven by a unit that, when once in operation, has a decided tendency to remain so in spite of momentary disturbances on the high-tension system which would invariably cause the synchronous motor and the synchronous converter set to drop out of step. Due to the intimate relation existing between the alternating-current supply circuit and the direct-current end of the converter—both being connected to the same set of armature windings—and to the fact that the sliding contacts on the alternating-current side are to be taken into account as well as the commutator, I should consider the converter as the least reliable machine when inherent defects in the apparatus are used as a basis of comparison.

I should therefore revise the table of relative reliability due to defects inherent in the apparatus to read as follows:

Induction motor-generator 10
Synchronous motor-generator 14.
25-cycle synchronous converter 17.

I agree with Mr. Lincoln that it is an advantage to be able to control the voltage independently of the supply circuit. Undoubtedly the converter is handicapped in this respect. In railway work this is not of such importance as in the case of lighting apparatus.

As to the "corrective effect," the synchronous motor-generator set is the only unit under consideration that can be used for the purpose and at the same time not suffer a disturbance of the direct-current voltage. Unless the "corrective" features of the synchronous motor and converter are applied intelligently, more harm than good may result.

The synchronous converter is the best machine as regards efficiency. Mr. Lincoln's calculation is apt and shows very plainly the advantage enjoyed by the converter in this respect.

Regarding cost, the writer is of the opinion that 60% is somewhat low for the converters, as it is necessary to consider the step-down transformers, the voltage regulators, the blower for air, cooled transformers, and the more expensive construction due to the necessity for an air chamber under the transformers.

Parallel operation is equally good for all machines.

The induction motor-generator set is the best as regards starting, as no synchronizing is required. In some of the larger sets, however, it is customary to start them on direct current and bring them to speed before connecting them to the supply circuit, thus avoiding any serious shock on throwing on the line.

No mention is made of the use of half or one-third or two-thirds taps for starting the converter on the alternating-current side. This is undoubtedly the quickest way of starting a converter and connecting it with the line. It is successfully used.

The use of the storage-battery in central sub-stations where a large direct-current, low-tension lighting system is installed, as well as a direct-current railway system, for the purpose of acting as a relay on the alternating-current supply from long-distance transmission lines, should in some cases have a bearing upon the selection of apparatus. In such case the battery could carry, during times of trouble, the low-tension system directly and the railway system indirectly, the transformer machinery being operated inverted.

While converters have been and are operated inverted, they are not so successful in this respect as the synchronous motor-generator set.

It is the writer's opinion that a selection of apparatus should be made only after a very careful study of all the operating features of the particular case in hand. It is quite possible that the best results could in some cases be obtained by using both converters and motor-generator sets. A discussion of this particular feature should bring out some interesting points.

W. R. C. Corson (by letter): The problem of determining the best method for converting alternating to direct current for any particular case must, of course, be largely dependent on the governing conditions of supply and the purpose of the derived current. Mr. Lincoln's treatment of the subject, by classifying the operating requirements of such apparatus, and noting the points of relative vantage which the several methods possess in each class, is an analysis which aids in a solution of the problem. But it is, after all, a problem which is not susceptible of a general solution. The several classes of operating requirements should be given differing relative values in considerations involving the choice of apparatus for differing purposes or conditions. The summary of Mr. Lincoln's paper, which seems to establish the preëminent excellence of the converter because it is found superior in a majority of counts, is, however, really of little assistance and serves only to establish an explanation for its present almost universal employment for the conversion of alternating to direct current. There are conditions of operation in which the synchronous converter falls behind its competitors in filling the essential requirements, and any conclusion that will help us in a limitation of these conditions will be useful.

Under the head of reliability, the synchronous converter is given the highest award, because but a single machine is involved as against a unit of two machines. The conclusion would follow that the converter is therefore twice as reliable as any method of double conversion, were it not for the further numerical values for the relative reliability advanced by the author. Now the relative reliability can hardly, it seems to me, be measured by the number of hours that the apparatus would be out of service within a given time, even if we could all agree on a basis for estimating the probable hours of breakdown. A more reasonable valuation of reliability would be the ratio of operating time to that of breakdown; but here again any exact assignment of values would be so much a matter of personal opinion that no definite conclusion could be reached. The mathematical chance of pure accident is greater in a unit of two machines than in a simpler apparatus, but reliability, from the practical viewpoint, should involve other considerations than the mere mathematical chance of accidents from unforeseeable causes. We must take the risk of accident, in this sense, in almost any responsibility we assume, and can rarely place a value on such risk.

Reliability, for the purposes of this discussion, should cover the broader field of ability successfully to operate under adverse or abnormal conditions, and the weight attached to the measure of reliability, as thus defined, possessed by any class of apparatus should be in proportion to the probable diversion from normal of the conditions for which a selection is to be made. Reliability, in other words, should be understood as the possession of robust characteristics as opposed to those sensitive to adverse conditions.

For general ability to withstand the hard knocks of fluctuations of voltage, frequency, or load, or of heavy overload, and to operate with a minimum of attention under all circumstances, the induction motor is without a peer. A direct-current generator coupled to it to form conversion apparatus can be designed to possess the best characteristics of such a machine uncompromised by the conditions imposed by the alternating-current supply. From the point of view of reliability I should, therefore, place the induction motor-generator set in first place; the synchronous motor-generator in the second; with full appreciation of its merits under proper environment, I should give the synchronous converter the lowest mark of the three.

The characteristics of the several types of converters as affecting the control or regulation of the direct-current voltage is considered by Mr. Lincoln, and his conclusion that relative numerical values of merit should not be attempted on account of the variable conditions dictating a selection is correct. He points out one case in which the synchronous converter can not be used; as no case appears against the other types, perhaps in this particular group of characteristics the converter must also take last place.

The corrective effect of the converting apparatus on the line is a matter of importance in the proportion which the capacity of that apparatus bears to the total load on the line. It is clearly shown in the paper that circumstances of control make this effect a desirable or undesirable characteristic. The induction motor-generator, having no corrective effect, may be, therefore, in this count, either utterly worthless or preëminently excellent, but under either consideration the converter seems to have second place.

In efficiency, the converter is undoubtedly the superior of either of the other types with which it is compared, and it is unquestionably its superiority in this respect which influences most largely its almost universal selection. It does not seem quite fair, however, to allow to the converter quite the measure of superiority credited by Mr. Lincoln's figures for efficiency. These, I understand, are admittedly made on the assumption that the line voltage is "too high for a revolving machine and must be transformed before utilizing." This assumption is of a condition which is usually necessary to converter operation but by no means so to that of its competitors. To give them the benefit of the doubt, it would be fair to decrease the figure representing the economical superiority of the converter by an amount determined by the static transformer losses. If this were admitted, the relative economy of the different types would be represented by the following values:

Synchronous converter	91
Synchronous motor-generator	85
Induction motor-generator	84

The first cost of a synchronous converter installation is much less than that of the other types, but again the cost of step-down transformers, and usually of additional switching equipment, should be included with that of the converter itself in the comparison.

The parallel operation of all types of machine under consideration can be accomplished successfully under normal conditions. Under certain abnormal conditions, however, either type of synchronous apparatus is more sensitive than the induction motor-generator.

In starting characteristics, Mr. Lincoln's analysis places the induction motor-generator set at the head of the list, the synchronous converter second, and the synchronous motor-generator last. The reasons for this rating appear sufficiently obvious.

In his summary, Mr. Lincoln concludes that as the synchronous converter excels in his analysis in counts 1, 4, and 5 and is practically at par with the best in count 7, there would seem to be "but few cases where the motor-generator should be used in preference to the synchronous converter." From my rating of the characteristics of the types considered, it appears that in counts 1, 2, 3, 6 and 7 a form of motor-generator is inherently superior to the converter, while only in counts 4 and 5 does the converter take unconditionally the first place. But counts 4 and 5 are usually factors of prime importance in the choice of apparatus, and the characteristics required by the other counts are possessed in sufficient degree by the converter. The conclusion is undoubtedly true, then, that but comparatively few cases exist where it should not be used. In fact the conclusion is so obvious that this discussion would be of little value, did it not, as it does, indicate by its analysis the conditions which would determine the selection of other apparatus in these few cases.

Where the synchronous converter is but one portion of an electrical system designed, installed, and maintained as a whole, for the particular purpose of the direct-current supply, the conditions most suitable for converter operation will be provided. The frequency, voltage, regulation, etc. will be selected with particular reference to the purpose of the conversion, and the control of all apparatus will be subject to one management, or at any rate to a common interest. In installations of this character, reliability of performance, adjustment of voltage, corrective effect on line, etc. will be maintained within the limitations of converter characteristics by the provisions of the entire system, and the manifest economy and low cost of such machine will secure its selection.

On the other hand, where the purpose of the conversion is merely incidental to the general purposes of the whole system, conditions less favorable to converter characteristics are more prevalent, and problems of selection will arise. In such cases, independence of purpose of demand and supply may often be best served by the electrical independence of the machine utilizing the supply and that supplying the demand.

So far as any general conclusions may be drawn from a discussion of this character, therefore, I would advance the proposition that the criterion of utility of either of the conversion methods considered lies in the degree of community which the purpose of the supply bears to that of the demand.

Henry Floy (by letter): It must be borne in mind that Mr. Lincoln's conclusions are very general and may not apply to any particular or individual case. A paper of this character is so frequently accepted as conclusive and universal application attempted, that I desire to show how unsuited these general conclusions may be in some cases. For example, it is practically impossible to use a converter, without storage-battery, to supply satisfactory lighting service at the end of a long transmission line that also serves alternating-current motors carrying large fluctuating loads, because the motor load will disturb the alternating voltage which directly affects the direct-current voltage. A motor-generator would therefore be necessary, regardless of the general conclusions, or the advantages claimed for the converter. Again, if the voltage of the transmission circuit were not so high as to prohibit the use of motor-generator sets without step-down transformers, a considerable investment, always necessary with a converter installation, would be saved.

Under the item of "cost" it seems to me that Mr. Lincoln has not clearly indicated the relative investment necessary, because the converter must be provided with some voltage-control apparatus that, from the comparative figures given, do not seem to be included in Mr. Lincoln's costs; moreover, if a motor-generator can be used without transformers, the converter installation with transformers and regulators will usually make the total converter cost higher than that of the motor-generator.

In a section where lighting is troublesome, I believe an induction motor-generator will be found much more satisfactory than a synchronous motor or a converter, because the induction motor will frequently pick up its load again without the shut-down of the other machines that will ordinarily result from the short-circuit caused by a lightning flash.

I do not agree with Mr. Lincoln in regard to the reliability of the different types of machines, for although the converter is but a single unit, it is twice as liable to some causes of breakdown as either a motor or a generator, because it is connected to two circuits—on its alternating and its direct end—and would therefore suffer, for example, from lightning coming in through either circuit.

Clarence E. Gifford (by letter): It goes without saying that insulation of apparatus operated from a motor-generator can not suffer directly from "surges" on the line from which power is supplied to the motor.

It is equally true that direct-current apparatus operated from converters often has its insulation subjected to very severe strains by such surges, especially surges that arise from momentary grounding of one of the lines of the supply system.

It will be readily seen how such a ground, or a permanent one, were it permitted to remain, may, and generally does cause a strain between the earth and any conductor connected with the secondary winding of a transformer supplied from a system upon which such ground occurs, or with any portion of a transformer or successive series of transformers which are operated by current received from said secondary. And this condition does not necessarily imply any change in voltage between the primary lines, one of which is grounded, although a change would doubtless occur.

The surge is transmitted through a transformer or series of transformers in the same manner as through a condenser; or in case of a ground of more than momentary existence, the entire secondary system would have its insulation from earth subjected to a series of strains recurring with the same frequency as that of the current. The primary and secondary windings of a transformer would in this case correspond to the plates of a condenser, and the action is not likely, in most cases, to be greatly modified by the core, unless it be well grounded.

Numerous experiences prove that the strain between earth and a direct current 220-volt system operated from a converter receiving power from a 22,000-volt system through three step-down transformations, often rises momentarily, when no preventive measures are adopted, to thousands of volts, and at a season of the year when the power company cannot say "lightning." In one instance two direct-current motors grounded at the same instant that the power company lost a cable, and from appearances one not familiar with such occurrences or with the circumstances would certainly have pronounced it the work of lightning. Incidentally, it is interesting to note the inventive faculty displayed by the "experts" of some power companies in assigning any cause but the true one for these expensive occurrences.

The best protection against such effects that the writer has found, and it has proved remarkably satisfactory in a trial extending over many months, is to place at various points in the direct-current system, notably near the converter, near the extremities of long trolleys and near stationary motors, carborundum resistances of 1000 to 1200 ohms (for a 220-volt system) bridged between the lines and having the center well grounded.

Ordinary resistance rods of a resistance of 250 to 300 ohms, such as used in lightning arresters serve well. Each one may have terminals of No. 10 or No. 12 copper wire attached by winding the wire once or twice round the copper plated terminal of the rod, twisting it down tightly and soldering it by dipping. The resistance of each, in ohms, is then determined marked upon it plainly with paint.

They are then sorted and made up in series of four, with all joints soldered, in such manner that the resistance between the center and one extremity of any series does not differ from that between the center and the other extremity of the same series by more than two or three ohms. Any other style of leakage devices used for the same purpose must of course be practically non-inductive, rugged, and so proportioned that when a dead ground occurs on one side of the local system the current flowing through the device shall be just safely below a point that would injure the device or its connections.

As before noted, the best protection for any local system operated from long-distance lines, is likely to be secured by distributing a number of such leakages at points where theory and experience indicate the greatest need. Unless the current value of a surge exceeds the ordinary, the potential between the system thus protected and the earth will not rise to a dangerous point.

As an indication of this fact, one plant in mind required five to eight new lamps per month for a ground detector, the lamps receiving normally only one-half full voltage, and this was not due to ordinary grounds on the system.

Since leakages, as described, have been provided, the detector lamps escape destruction, and crane operators cease to fear being knocked nearly senseless, as has occurred in the past, but the most noticeable result is the great decrease in number and seriousness of motor troubles.

Wm. B. Jackson (by letter): Under the list of "points" which are considered in the paper, it seems to me that the subject of "*Parallel operation*" should either be omitted entirely and considered as being covered by the subject "*Reliability*", or that it should be placed second in the list. Without perfect parallel operation "*Reliability*" as considered in the paper would be of little value.

1. *Reliability*. In this matter I take direct issue with some of the statements made in the paper. It is true that the the synchronous converter comprises but one machine, but it it is equally true that this machine is the weakest brother in the entire family of alternating-current and direct-current machinery. It is formed from a combination of a revolving armature alternating-current synchronous motor which, considered as an alternator, is no longer an acceptable piece of machinery, and of a direct-current generator which has been designed, not as the best possible direct-current generator, but as the best generator that can be made a component part of a synchronous converter.

The argument against the motor-generator set on account of pressure and insulation would be more nearly correct if reversed, for there can be no reason for using a higher voltage on the alternating-current side of a motor-generator set, unless it has evident advantage over the lower pressure. Furthermore, a first-class stationary armature induction or synchronous motor can be safely insulated for several times the pressure that can be employed in a synchronous converter armature with equal safety.

Although, as stated in the paper, the fault of "bucking" is not one of very serious moment in present day practice, yet this fault can be eliminated with greater ease and certainty in a simply direct-current dynamo than in one which must also work in with an alternating-current frequency of even 25 cycles, and this fact is emphasized if 60 cycles is considered.

2. *Voltage regulation.* I am unable fully to agree with the conclusions arrived at under this heading. I do not consider that, "All methods under discussion are equal" for "automatic change in voltage with change in load" for the reason that the automatic results that can be obtained in the synchronous converters are dependent upon various extraneous conditions while such results are obtained in motor-generator sets with the same simplicity as in any direct-current dynamo, for the direct-current side of the machine, and in the synchronous motor-generator set very effective regulation on the alternating-current side can be obtained with simplicity and without interaction with the direct-current operation of the machine.

In considering the "ability to adjust the initial voltage" it is impossible to accept the statement that the introduction of an alternating-current booster on the converter shaft is a more "logical arrangement so far as initial voltage is concerned than the motor-generator." Such an arrangement with its regulating rheostat and switches certainly does not constitute so logical an arrangement for voltage regulation as a simple rheostat in the field of a direct-current generator.

In considering "variations in direct-current voltage with variations in incoming line voltage and frequency" I agree in general with the conclusions arrived at, though I consider that too much relative importance has been given to the difficulties arising from variable frequency. In most up-to-date transmission plants where the "line voltage is too high for a revolving machine and must be transformed before utilizing", the problem of maintaining uniform frequency has been solved, though this cannot be said as regards the problem of uniform delivered voltage.

Under "Corrective effect" my views agree with those expressed in the paper, though it should be added that in the case of almost all high-tension transmission plants there is direct telephone connection between the power house and all sub-stations containing current-transforming apparatus. As these sub-stations usually require continual attendance, they thus become a valuable adjunct of the transmission system, and especially so if synchronous motor-generator sets are used therein.

4. *Efficiency.* There appears to be an error in computing the additional value of synchronous converters as compared with motor-generator sets, when considered simply from

the standpoint of relative efficiency. The capitalization of the saving due to the higher efficiency of the synchronous converter is made upon a basis of 6 per cent, while in fact 10 per cent. is the least figure that should be used in this connection. This would be upon the basis of 5 per cent. interest upon the money involved and of 5 per cent. for depreciation or sinking fund.

There are some factors that enter into this consideration which have advantageous bearing upon the motor-generator set, and have not been considered in the paper. In sub-stations supplying mixed service, uniform step-down transforming apparatus can frequently be used for all classes of service when motor-generators are employed, while two ratios of transformation must be used if synchronous converters are operated. Also in the case of very large converter units, the handling of the great quantity of alternating current at from 350 to 450 volts which is required is sometimes a factor of considerable importance.

There are also cases where, even for plants of the class here considered, an extra set of transformers must be provided for synchronous converters that would properly be omitted in the case of motor-generator sets. Such a condition is presented where the high transmission voltage must be reduced at the outskirts of a city to permit of carrying the current into the distributing stations located in the city.

5. *Cost.* Under this heading the same additional considerations that are presented under "*Efficiency*" should be taken into account to arrive at a fair analysis of the relative importance of synchronous converters and motor-generator sets, when considered from a broad point of view.

6. *Parallel operation.* Although it is true that troubles from imperfect paralleling qualities are not of frequent occurrence in up-to-date transforming machinery, yet the motor-generator sets have the advantage. In fact during those times when unending troubles seem to come upon the operating superintendent in a bunch, as they sometimes do in the best regulated plants, the synchronous converters are usually the first to show signs of distress, and this is especially true in plants of higher frequencies, while motor-generator sets are not so prone to crankiness. In motor-generator sets, troubles arising in the direct-current side of the system cannot have magnetic or electrical effects upon the alternating-current side, nor can troubles arising in the alternating-current side have such effect upon the direct-current side. This cannot be said of synchronous converters.

7. *Starting.* The question of starting has been well presented, but considering that an error in starting is likely to cause vital trouble in the synchronous converter on account of its commutator and collector rings, and also that the revolving-field synchronous motor properly connected to a high-class direct-current generator is a more robust piece

of apparatus to withstand synchronizing mistakes, it does not seem fair that the synchronous converter should be placed ahead of the synchronous motor-generator set as regards starting qualities.

Summary. In the foregoing, I have more particularly considered the advantageous qualities of the motor-generator set, as it had seemed to me that the advantageous features of the synchronous converter have been very fully presented in the paper. There has been no thought of belittling the field of usefulness of the synchronous converter. At the same time, I do not feel that the phrase in the "*Summary*" "that there are but few cases where the motor-generator should be used in preference to the synchronous converter" should go unchallenged. In fact, there are large appropriate fields of usefulness for both the motor-generator set and the synchronous converter, though it is fair to admit that the conditions will doubtless warrant a greater number of synchronous converters than of motor-generator sets being put into service.

R. S. Kelsch (by letter): The writer has used both motor-generators and synchronous converters. There can be no rule which makes one better than the other. Local conditions, class of service, number of units, and the characteristics or nature of the system from which they are operated entirely govern the advisability of using one or the other.

Farley Osgood (by letter): We are operating ten converters driven by current from our power station and transmitted about 60 miles at 33,000 volts at a frequency of 60 cycles. Four of these converters are 30 miles, three are 45 miles, and three are about 60 miles from the power station, and are placed in three different sub-stations, and, at times, all operated together.

These being 60-cycle machines, I presume they are the most sensitive type of synchronous converter in use. We find that these machines are very reliable, and, generally speaking, the interruptions to service are caused by the flashing-over at the brushes on the commutator. These machines have been in service for three years.

The first year's experience with the converters brought them into ill repute as regards reliability; but a careful study of the situation showed that the real difficulty was the lack of voltage regulation on the generating end. Regulation conditions were bettered by means of the water-wheel governors, and the installation of a voltage regulator. Since the correcting of the voltage regulation, or during the last year and a half, the ten converters have thrown themselves out of service less than ten times, giving an average of better than once per year per converter. I think this is as good a record of running as can be shown by any other type of machine driven from a source of power of high voltage and used for railway work.

These machines are 430 volts on the alternating-current side, and furnish 600-volt current on the direct-current side. They are connected with the high-tension system of 33,000 volts by means of a step-down transformer with a reactance coil in series between the transformer and converter.

Our experience shows that converters with bad voltage regulation on the alternating-current side are the worst things an operator can have; but with good voltage regulation, which with existing regulating appliances is wholly possible, the converter is entirely satisfactory and preferable to the other two types of machines under discussion.

Our experience with the converter also brings out the fact that although a sudden rise of 10 per cent. of the voltage from the generating source is liable to make the converter flash-over, a very great drop in the generating voltage may occur without affecting the converter.

Three times we have had a generator oil-switch stick so that the machine was thrown in and out of service several times in rapid succession, and so disturbed the line voltage as to lower it on the indicating voltmeter from 110 to about 65, and yet on none of these occasions were the 60-cycle converters thrown out of step so that they went out.

Concerning the "*Corrective effect*". When the load of our system is so arranged that the power and lighting load is carried on one transmission line, and the railway load on the other; in other words, when there are only induction machines on one line, we have materially to increase the voltage on this line in order to bring about any satisfactory power-factor. In mixed service work, therefore, the converter will help the voltage at the generating end by bringing about a more satisfactory power-factor. We find that an induction load only will perhaps require an increase in potential of from three to five per cent. at the generating end, but by placing converters with the induction motors satisfactory results are obtained on the receiving end without this increase in potential, This is simply an actual operating condition mentioned to bear out a well-known theoretical supposition.

Concerning "*Efficiency*". The experience on the system here, which carries converters at three sub-stations at a total transmission length of 60 miles, shows that with the proper arrangement of load we can obtain the power-factor as indicated by Mr. Lincoln; namely, 95 per cent.

Concerning "*Parallel operation*". We find no difficulty in operating our 60-cycle converters in parallel, not only with each other in the same sub-station, but in parallel with other converters in other sub-stations. At first the converters did not all appear to be of equal efficiency; it was found, however, merely to be a matter of adjustment, the large apparent differences of efficiency being easily done away with

One noticeable feature in a converter, which, however, is probably a well-known fact, is that the different phases of any one converter will not require the same amount of current, and that the various phase requirements vary.

As we use single-phase recording watt-hour meters to measure the current taken by the converters, we can very easily observe the current requirements of each phase of the machine. Often the meter will change its speed in favor of another phase of the converter sufficiently to be observed by a man watching the meter discs. The daily record of consumption taken from these meters shows swings from one phase to another from one day to another.

In summing up these discussions, I would say that I would not recommend any type of machine other than a converter for railway work from a high-tension source of power.

John C. Parker (by letter): The writer has been much interested in the particular phase of voltage regulation that bears on the distribution of load between various machines and between systems fed by distant hydroelectric generating stations on the alternating-current lines and engine-driven or local hydraulic plants on the direct-current lines.

In any large works or city distribution, it is customary to generate at a high voltage, 2500 to 11,000 volts, and distribute by means of this voltage to various sub-centers, where transformation to either the railway or light and power circuits is effected. The motor-generator set possesses, in such a case, one decided advantage over the more ordinary form of synchronous converter, in that the load taken on by any one station may be varied by manipulating the field excitation of the generator without influencing the power-factor of the alternating-current lines, and vice versa. Thus, during a period of maximum activity in any one section of the distribution system, the direct current voltage may be depressed, causing more distant subcenters to feed into and relieve this particular district by means of the direct-current network, whereas with synchronous converters the tendency is for the converter nearest the concentrated load to assume increasingly greater proportions of the load until its automatic apparatus cuts it out of service. Of course, the inherent regulation of the converter can be made so bad as to give a strong drooping characteristic even at a good power-factor, but this is evidently at the expense of the copper efficiency and leads to voltage variations which are manifestly objectionable—especially on lighting systems. With the motor-generator set, the load fluctuation can be guarded against and the direct-current voltage regulation at the same time kept reasonably near what it should be, by designing the generator so that the voltage will progressively rise with increasing loads, until at any desired load point it begins to drop and thence rapidly decrease to a value below the no-load voltage, thereby causing current to flow in from distant transformation points which may be less heavily loaded.

Inasmuch as hydraulically generated power must be sold on what is in all cases the equivalent of a peak-load basis, we often find installations in which 24-hour power is received from a distant hydroelectric plant and is supplemented, on the peak, by a local steam generating plant. In such a case the vagaries in the transmission voltage or momentary peaks in the load demanded on the direct-current system may result in a heavy overload in the alternating-current transmission. A few of these peak overloads will heavily affect the consumer's bill. Here again the synchronous converter suffers a disadvantage that cannot be obviated otherwise than by juggling with the power-factor, which is manifestly prejudicial to the distribution system. A motor-generator set having a slightly rising voltage characteristic on the generator up to normal load, followed by a rapid droop, tends to take a more nearly constant load. Such characteristics are additionally important when the voltage regulation of the steam-driven local plant is bad.

It should be pointed out that the alternating-current booster or induction regulator referred to under caption two of Mr. Lincoln's paper, permits the application of automatic relays to the system for accomplishing such load control, and indeed permits a more direct regulation of load than can be obtained with motor-generator sets. On the other hand, this introduces additional elements of unreliability into the system, one of which, the relay, is especially delicate, while the induction regulator must be very substantially designed if it is to stand up under the severe treatment to which it is subjected. It is obvious that neither of these methods permits so nearly instantaneous operation in the division of load as does a motor-generator.

The elements of relative efficiency and cost would seem to be a function, more or less, of the specific voltage used in distributing to the various transformation units. If, for example, it were necessary to use such a subsidiary distributing voltage as 2500 or 11000 volts for works distribution, or for entrance to and distribution underground in a city, the element of transforming cost would be eliminated in the case of the synchronous or induction motor-generator which might operate directly at either of the voltages mentioned, while additional transforming equipment would have to be used with the synchronous converters. In all probability, this would still leave somewhat of a margin in both the matter of efficiency and of cost in favor of the synchronous converter, but probably not a very large margin. If in addition, an alternating-current booster or induction regulator were installed, the efficiency and cost, as well as the reliability of the converter, would suffer somewhat additionally. The complexity of the equipment would also be materially increased. The writer is inclined to feel that a distributing system of 2500 volts would show a worse case for the synchronous converter than would a distribution voltage of 11,000, inasmuch as this higher voltage would react much more prejudicially on the cost, efficiency, and reliability of the synchronous motor than it would on the transformers which would probably—following the modern practice—be made oil-insulated for this voltage.

In a number of cases a material advantage accrues to the motor-generator set from the less room it occupies as against the synchronous converter, step-down transformer, and—if this feature were included—the alternating booster or induction regulator. Whether this and a few other elements mentioned would throw the balance one way or the other between the two types of apparatus, would seem to be a question controlled by the special considerations in any given installation, such as the size of units and voltage on the distributing alternating-current transmission system.

H. F. Parshall (by letter): The synchronous converter is the more advantageous machine to use when the conditions of transmission and distribution are such that the ratio between direct-current and alternating-current voltage is more or less fixed. When the line drop is considerable, and a constant or increasing direct-current voltage, according to load, has to be maintained, the synchronous converter is at a disadvantage. When however, the reverse is the case, the synchronous converter has the advantages of higher efficiency, less first cost, and, in favorable cases, greater capacity for extreme overload. The motor-converter stands in an intermediate position between the motor-generator and the synchronous converter. It has not the flexibility of the motor-generator in the matter of voltage transformation and has not the high efficiency of the synchronous converter. Now that the development of computating machines for high speeds to suit the requirements of turbo-machines, is assuming a satisfactory status, it appears very reasonable to suppose that, in most classes of long-distance transmission, the balance of advantages will lie in the use of motor-generator sets. In other cases, however, where the ratio of transformation can, from the nature of things, remain more or less constant, the balance of advantages will lie with the synchronous converter, so far as efficiency and first cost are concerned.

A. C. Pratt (by letter): While Mr. Lincoln's analysis of various means of obtaining direct current from transmitted alternating current is fairly stated, it must be borne in mind that the choice of a proper medium will depend largely on the governing conditions of the particular installation. In all systems reliability is essential. While 25-cycle converters are satisfactory, 60-cycle converters may be termed successful. But they are not always a comfort to the operating engineer and are certainly more apt to develop internal troubles or go out of step when slightly unfavorable conditions arise, than are induction or even synchronous motor-generators.

In the operation of converters there seems good reason for providing separate motor-driven exciters, in which case voltage fluctuations not accompanied by change of speed will have much less effect on the operation.

In many long transmission systems voltage regulation or corrective effect, singly or together, are the governing conditions when designing a sub-station. If converters are used, either one of these features may be provided for with reasonable success; but it is by no means easy to cover both at once in such a way as not to affect other branches of the system unfavorably.

A poor power-factor in the transmission system may readily cause a greater drop in over-all efficiency than the difference between the efficiency of converters and motor-generators, provided the latter results in a good power-factor in the system. The ideal system transmits power current only; the idle current needed at various consuming points is generated at these points; permitting less capacity in generators, transformers, and transmission line, and better regulation at the consumer's end. The synchronous-motor generator in large size units with a motor of unusually ample size offers means of attaining closely the ideal system.

Steadiness of speed is usually much better maintained than steadiness of voltage on a transmission system; therefore the generator of a synchronous motor-generator set will regulate well, and a first-class regulator applied to the exciter of the motor will afford the corrective effect for the alternating system. Under these conditions, alternating-current lighting and direct-current railroad load can often be supplied from the same bus-bars with excellent results. It must be borne in mind that the synchronous motor-generator requires slightly more intelligent supervision than induction motor-generators, but not more than the converter. For best results, therefore, the synchronous motor should be used under immediate supervision of the transmission company.

Another item for consideration is the character of the direct-current load as regards inertia effects. Some loads, like lighting, store no energy, while some motor-driven loads store a large amount of energy when coming up to speed. Assuming a load of the latter type, supplied from induction motor-generators, and a momentary short-circuit cleared by time-limit circuit-breakers on some one feeder out of the sub-station. During the short-circuit the induction motors will slow down much more than will the generators at the power station. The sudden removal of the short-circuit will cause a sudden rise of voltage, which in turn will cause a rush of current to the induction motors; these, hampered by large inertia, will very likely trip their breakers before attaining normal speed, or the speed will have dropped so low that the motor torque is reduced to a point below full-load torque, in which case there is little probability of recovering the load.

Under the same conditions, if the short-circuit is not too severe, a synchronous motor having a high " pull out " torque will stay in step and hold its load. This observation applies also with especial force to induction motors, of relatively low " pull out " characteristic loaded with heavy shafting or air compressors, in which case the load torque is not reduced as speed is reduced The same motors would show entirely different results when driving centrifugal pumps.

Leo Schüler (by letter): It may be interesting to discuss the subject of this paper from the European point of view, as there is so distinct a difference between American and European practice. I dare say that on this side of the Atlantic the number of converters in operation does not exceed one-tenth the number of motor-generators, while I think that in the United States the opposite ratio may safely be assumed. As a matter of fact, I do not consider the author's conclusions, which are generally in favor of the converter, to be quite impartial, and for the following reasons:

I see no reason to assume "a somewhat variable frequency." Governors for all kinds of prime movers can certainly be obtained so as to keep the speed constant within one or two per cent. and with proper care variations of frequency of more than one per cent., can certainly be avoided. We may therefore safely assume a virtually constant frequency.

The author assumes "the line voltage to be too high for a revolving machine." this means more than about 15,000 volts; as such voltages are only employed in long transmission lines, it seems only fair to assume further that a considerable drop of pressure takes place on the line, say 20-25 per cent. It should be well understood, that with a lower pressure the comparison would be more in favor of motor-generators, as static transformers could be avoided.

1. *Reliability.* I do not understand why "with the motor-generator, other conditions may dictate a very much higher motor-voltage," as static transformers are distinctly specified.

It is true that under normal conditions the possibility of "bucking" is about equal with 25-cycle converters and direct-current generators. It must be kept in mind, however, that the sparkless running of the commutator in a generator depends only upon the direct current taken from it, while in a converter it is also affected by the conditions of the alternating-current system. The 60-cycle, 600-volt converter has necessarily such a high pressure between adjacent commutator segments that it must be set quite at the other end of the reliability list.

As I consider the synchronous-motor to be a little more reliable than the induction-motor, in consequence of larger air-gap, I should figure the reliability to be about as follows:

25-cycle synchronous converter Synchronous motor-generator	12 hours.
Induction motor-generator	14 hours.
60-cycle synchronous converter	25 hours.

2. *Voltage regulation.* There can be no doubt but that the direct-current voltage supplied by a motor-generator depends only upon the direct current taken from it, while in the case of a con-

verter it is greatly affected by the alternating-current voltage.

It must certainly be assumed that the alternating-current voltage supplied to a sub-station by a long transmission line is variable, not only in consequence of the variable power consumed in this individual sub-station, but it also affected by other sub-stations, starting of motors, working of lightning-arresters etc. in any other point of the system. As the effect of all compounding arrangements, with or without reactance or boosters, is based on the magnetizing effect of the direct current taken from the converter, they certainly will not respond to independent fluctuations of the alternating-current voltage. It is therefore impossible with converters to obtain automatically a constant direct-current voltage with a variable alternating-current voltage; this reason alone, I think, simply forbids the use of converters for lighting purposes in connection with long transmission lines.

Summary. As the converter has certainly a distinct advantage with regard to efficiency and costs, while there is practically no difference with regard to starting, I would summarize as follows:

For 25-cycles, railway or other motor circuits, converters are always preferable. For 60-cycles, motor-generators are more reliable and should be adopted if costs and efficiency are not prohibitive, especially if the primary pressure is low enough to allow omission of static transformers.

For lighting circuits, converters are applicable only if the alternating voltage itself is sufficiently constant for lighting purposes.

Carl Schwartz (by letter): *General.* Synchronous converters are extensively used where three-phase alternating current of high potential and a frequency of 25 cycles is to be transformed into direct current. For the other higher standard frequency of 60 cycles, this type of machine is not nearly so satisfactory in operation as a motor-generator. As reliability is of prime importance, particularly in long-distance transmission, and as a synchronous or induction motor-generator is much more reliable, the converter does not need to be further considered in case of this or similar high frequency.

Mr. Lincoln clearly and briefly enumerates the various advantages and disadvantages of the three types, but on account of the great amount of detail to be considered it is impossible to balance the characteristics of the different constructions entirely against each other without taking specific cases; therefore the choice of one type or the other will always be governed by the prevailing conditions. If this were not the case, the choice could be left to the purchasing agent instead of to the engineer.

The following suggestions are offered to illustrate that a somewhat different point of view may change some features of one type to the advantage of the other.

Reliability. Mr. Lincoln considers the converter the most reliable machine, quoting as an advantage that there is only one machine instead of two, and that a low alternating current voltage has to be applied. As it is assumed that in both cases step-down transformers are to be used, there seems to be no reason for applying an unsafely high voltage in case of a motor-generator; in this respect, then, both types should be considered equal, inasmuch as the voltage for a motor-generator could be much higher than for the converter, without impairing its safety beyond the comparable limit. The chances of a breakdown may seem twice as great, because the motor-generator contains two rotors and two stators, while a converter has only one armature, and one set of field coils. The machines are, however, practically alike otherwise, assuming that the motor-generator has two bearings only. If the case warrants, spare armatures and field coils can be kept in stock, minimizing the consequences of a break-down.

An induction motor is less affected by line troubles than either of the other two constructions; on a long line this motor is most undesirable, and in figuring on this type of machine, the increased investment in copper or capitalized line losses should be charged against it.

Voltage regulation. With reference to voltage regulation, the converter is at a serious disadvantage. Boosters, potential regulators, or other devices in connection with the converter are undesirable additions, and influence items 1, 4 and 5, and, to a certain extent, item 3, in favor of the motor-generator. These complications were apparently not taken into account when comparing the machines in regard tor eliability, efficiency, and cost. The efficiency of the converter will be decreased by from one or two per cent., and its cost increased by from ten to twenty per cent., so in trying to make the converter equal to a motor-generator in regard to voltage regulation, its advantages may be counterbalanced to a large extent.

Efficiency. In considering the additional costs of current for the motor-generator against converter, inclusive of the regulator, and assuming an efficiency of 85% and 91% respectively, the following is submitted:

A low efficiency increases the direct operating expenses in coal, water, wages, etc., but not the fixed charges, as the power station will hardly be built larger on account of a slightly lower efficiency of transforming-devices. The cost of current per kilowatt-hour can therefore be estimated perhaps closer to one-half than one cent., decreasing the annual additional costs for current in case of the motor-generator to about $950. In capitalizing this amount, depreciation and other fixed charges should be included, for the reason that if the amount capitalized is invested in equipment it will have to be treated like other portions of the system.

Using 10% to cover all fixed charges, the annual extra costs for current represent an investment of **$9500**, or **$19.00** per kilowatt capacity. The exact amount will depend on local and other conditions, and the difference may be still lower; for instance, in case of a water-power plant, or if the operating costs should otherwise be lower than five cents.

In most instances it will be almost impossible for the engineer to decide definitely which type of machine should be selected, before bids have been obtained, based upon specifications, outlining carefully all requirements, and leaving room for the manufacturer to specify the characteristics of the equipment he is able to offer.

Guido Semenza (by letter): The only point not put forward in this paper is, perhaps, the one excluded by the assumption "that the line-voltage is too high for a revolving machine and must be transformed before utilizing." This is often not the case, at least in Europe, where synchronous motors wound for 12,000 volts are in regular operation. Some firms would not hesitate to construct them for still higher voltages.

In such cases the cost of installation, the floor space occupied, the switching apparatus, and the efficiency of the motor-generator set are not very different from those of a converter with its transformers. Thus for primary voltages up to 8000 volts, in view of its other advantages, the motor-generator is generally preferred.

In Europe the use of converters is not so general as in the United States. This machine has been highly perfected in America, and its advantages have been only lately acknowledged on the old continent. Then again, for countries where hydraulic power is available, and long-distance transmission is the rule, there are special reasons for the preference being given to motor-generators, as I shall try to explain.

In the matter of power transmission and distribution many differences exist between one plant and another. We have, for instance, power plants of the type of the New York Edison Company's, in which the alternating current generated is mainly converted to direct current in a number of sub-stations belonging to the same company. The alternating voltage is then very carefully controled in the power house, in order to obtain the best direct-current regulation, and all systems used in the different sub-stations to control the voltage are there working in the best condition.

Assume, for example, a long-distance power transmission, say 100 miles long, from a waterfall. Consider that the power is sold in the neighborhood of the station, at the end of the line, and along the line. Suppose further, that there is a steam station working in parallel for overcoming the winter peak. We see that these conditions are quite different from those of the first instance, and voltage regulation cannot be done except to take care of the converter sub-stations.

In such a type of plant, rather common in Europe, converters can be put in for railway work, but it would not be very easy to obtain a good direct-current lighting service. In such cases motor-generators are preferred.

In plants of the above kind, the "corrective effect" of synchronous machinery, if any be used, is very important in order to correct the low power-factor given by induction motors. What Mr. Lincoln says on this point is quite right: it is much easier to control the corrective effect with synchronous motors than with converters in which the corrective effect and direct current are interdependent. I would let customers use synchronous motors, and I would not allow them to use converters on a somewhat complicated distribution plant, as they would only take care of their direct-current regulation without paying any attention to the power-factor.

Another matter in connection with long-distance transmission is the parallel running. It is well known that when the ohmic resistance of the line is too high, also good synchronous machines are apt to hunt and sometimes to such a degree as to get out of step. This is an extreme condition, but a certain amount of hunting may easily occur.

It is also known that by adjusting the excitation this hunting may be reduced. It is evident that in these conditions the motor-generator offers a great advantage, as this regulation can be done without affecting the direct voltage.

All these considerations show that the problem proposed cannot be solved in a general way: there are conditions in which the converter is, no doubt, the best adapted machine; there are others in which only a motor-generator ought to be used, and others also in which the use of either is equally as good.

On the comparison of synchronous versus induction motors, I must say that for driving-current dynamos the synchronous motor is in a general way, for many reasons preferable. It is not always true that after a momentary removal of the voltage from its terminals the induction motor will resume operation automatically: if it is well loaded it will often shut down and cause its own circuit-breaker to open when the voltage is restored.

The use of induction motors has to be resorted to only in case starting from the direct-current side is not possible. When starting on the alternating-current side causes too much trouble, and in the case of very long transmission lines where some difficulties are experienced with parallel running.

B. C. Shipman (by letter): *Reliability.* If reliability were the sole requirement of the problem, the induction motor-generator would, in my opinion, be the best transforming apparatus to use. Mr. Lincoln states no defects under this head against the induction motor-generator, except that higher voltages than 700 on the motor may be required by certain conditions. If the choice were between synchronous converters and induction motor-generators on the ground of reliability alone, certainly whatever voltage was available for a synchronous converter would also be available for the induction motor-generator. Therefore there would be no advantage on this point for either piece of apparatus. Of course it might be much more desirable to use a higher voltage, and the induction motor-generator would lend itself readily to this condition. Even so, I think the latter apparatus would still be on a par with the synchronous converter, as it is much more easily insulated and less susceptible to injury than a commutating machine.

The strong point of the induction motor-generator is pointed out in the paper; namely, automatic resumption of operation after an interruption to the service. All the weak points of the synchronous converter, however, are not covered. Synchronizing takes more or less time, certainly more than it takes to get an induction motor on the line, and it has to be done more frequently. "Bucking" of a synchronous converter also takes place more frequently than of a similar direct-current generator, for several reasons aside from the sudden removal of load. "Pumping", or even sudden aperiodic changes of speed in the prime movers, will cause a synchronous converter to "buck". In such cases there is a shifting of the field similar to that caused by the sudden removal of load. A synchronous converter, is also more often reversed by bucking than is a direct-current generator; hence its greater tendency to bucking counts considerably against its reliability as compared with a similar direct-current machine. Therefore I would change the numbers given in Mr. Lincoln's paper showing the relative amounts of time the respective machines are out of service, as follows:

Induction motor-generator	10
25-cycle synchronous converter	14
Synchronous motor-generator	17

Voltage regulation and corrective effect. I concur in all the author's remarks under these heads. I have noted excellent regulation of direct-current voltage from a synchronous converter equipped with an induction regulator, when supplied from generators whose other load was street railways.

Parallel operation. Of course with similar units, parallel operation presents no difficulties or disadvantages of one type over another. Sometimes, however, if a synchronous converter or a synchronous motor-generator is operated in parallel with an induction motor-generator, there is trouble in making the units divide the load properly throughout the full range. Assuming a constant frequency and voltage, the induction motor-generator will have to be compounded decidedly more than the direct-current end of either synchronous unit. A variable frequency or voltage, or both, will interfere with any fixed adjustment, so that under the conditions laid down in the paper under discussion, hand regulation would probably be necessary to effect good distribution of load between units.

Summary. In general, I agree with the author that in the majority of cases with conditions under discussion, the synchronous converter has the advantage.

Miles Walker (by letter): I am interested in Mr. Lincoln's paper on account of the discussion which has recently taken place in England between the advocates of the converter on the one hand, and the advocates of the motor-generator and the cascade motor-converter on the other.

It is mainly in the case of 50-cycle and 40 cycle-transmissions that difference of opinion exists as to the merits of the various types of machines. In the case of 25-cycle transmission the superiority of the converter for most purposes is generally admitted.

The Bruce Peebles-La Cour cascade motor-converter is now much used in England for transforming 50-cycle alternating power into direct-current power. On the other hand, the 50-cycle converter is also widely used, and the excellent performance and great stability of modern designs are fast overcoming the prejudice which existed in England against high-frequency synchronous converters.

In most cases where the matter is discussed in England, it is not permissible to assume that the line voltage is too high for a revolving machine and must be transformed before utilizing, because generally the line voltage is only 6,600 or 11,000, and with motor-generators the use of transformers is obviated. Notwithstanding this advantage in favor of motor-generators and motor converters, it can generally be shown that the use of transformers and converters is preferable on account both of reliability and economy.

Reliability. The risk of breakdown of a converter and its transformers is less than that of a motor-generator set. If one transformer out of three breaks down, it is possible to run with only two, and it is easy to substitute a spare transformer. It takes a long time to rewind a motor-converter.

I have seen a 50-cycle converter take six times full-load current momentarily without " bucking " or getting out of step, so it cannot be said that it is a delicate machine. It will not, however, stand a dead short-circuit.

I know of a case where three 1000-kw. 40-cycle converters have been installed for electrolytic work where continuity of service is of vital importance, because in case of a shutdown some hundreds of cells of molten electrolyte have to be refilled from a furnace at enormous cost. The plant has now been in operation six months without any failure on the part of the converters, although some motor-generators alongside of them have already been out of service more than the 17 hours allotted to them by Mr. Lincoln.

Voltage regulation. I agree with what Mr. Lincoln says in this division of the subject. The method of introducing self-induction into the transformers is applicable to most cases where a range of only 10% is required in the adjustment of the direct voltage. The power-factor on load need not be varied more than between the limits of 95% lagging and 95% leading current. In many cases the required adjustment is only 5% and the power-factor need not depart more than one or two per cent from unity. Very few users object to a leading power-factor, particularly at heavy loads.

Corrective effect. I agree with what Mr. Lincoln says in this division of the subject.

Efficiency. In dealing with this matter in England, we have generally to consider the losses in the transformers as well as in the converters, because these are in competition with cascade motor-converter sets on which very high efficiencies are guaranteed (93% on the 500-kw. size).

The converter and transformers are however still ahead in efficiency. It is safe to guarantee 94% on the 500-kw., 500-volt rating for the over-all efficiency of the converter and transformers and this without rating up the converter so high as to spoil the overload guarantees.

A well-designed 50-cycle converter can take very heavy overloads without commutation or heating troubles. It is therefore safe to keep it loaded to the full in cases where it would not be advisable to keep motor-generators fully loaded on account of fear of sudden demands for power, so that in taking the all-day efficiency of a converter, it is fair to take the efficiency at a higher percentage of the load than with a motor-generator. Here is a case in point: at a certain sub-station belonging to the North Eastern Railway Company the load fluctuates between almost zero and 1600 kw. A load of 1200 to 1600 kw. lasts at times for about one minute. The whole of this load is taken by one 800-kw., 40-cycle converter. Compare the efficiency of this sub-station with what it would be if the converter were replaced by, say, two 500-kw. motor-generators.

J. B. Whitehead (by letter): Under the author's assumption that transformers are used with all three types of machine, his conclusions appear reasonable. Attention may be directed, however, to the many instances of moderate transmission distance and voltage in which it is possible to apply the line voltage directly to either type of motor-generator, but to the converter only through the medium of transformers. The relative position of the motor-generator under such circumstances is bettered, not only as to reliability, but also as to efficiency and cost. Considering reliability, this improvement would be greater in the case of overhead than in the underground transmission in cities. The figure for the efficiency of transformer and converter becomes about 91%, the figures for the motor-generators remaining the same. The relative cost will now be approximately: converter and transformers 82%, motor-generators 100%. In many instances these differences may be sufficient to outweigh the more general choice of the converter, and indicate the motor-generator as the proper machine.

A paper presented at a special meeting of the American Institute of Electrical Engineers, New York, March 22, 1907.

INTRODUCTION TO DISCUSSION ON THE PRACTICABILITY OF LARGE GENERATORS WOUND FOR 22,000 VOLTS

BY B. A. BEHREND

With the increased capacity of individual units of alternating-current generators it is natural that the potential for which these generators are wound should be continually increased. It commends itself to limit the current capacity of generators, as the distribution and conduction of large currents from the generators to the switchboards is cumbersome and expensive. Historically, the increase in voltage with the increased capacity of individual units and of power plants may be briefly summarized. The Niagara generators of approximately 3500 kw. capacity, put into operation about ten years ago, were designed for 2200 volts. The 3500 kw. generators of the Metropolitan Street Railway Company, of New York, were designed for 6600 volts. The 5000-kw. generators installed in the stations of the Interborough Rapid Transit Company, in New York, were designed for 11,000 volts. The large generators for the Brooklyn Rapid Transit Company, of 7500 kw., were designed for 11,000 volts also.

The question of the importance of higher voltages in future plants cannot be discussed without reference to prime movers. The four types of prime mover which are likely to be of great importance in the immediate future are:

1. The hydraulic turbine.
2. The gas engine.
3. The reciprocating steam engine.
4. The steam turbine.

1. The field of the hydraulic turbine for large capacities, by which I mean capacities of 7500 kw. or above in individual units, is not likely to be of great importance at the present.

2. The gas engine has been successfully built for capacities up to 2000 kw. and while it has unquestionably a great future for greater capacities, nothing as yet has been done to allow the application of the gas engine in connection with electric generators of 7500 kw. or above.

3. The reciprocating steam engine still holds its own for

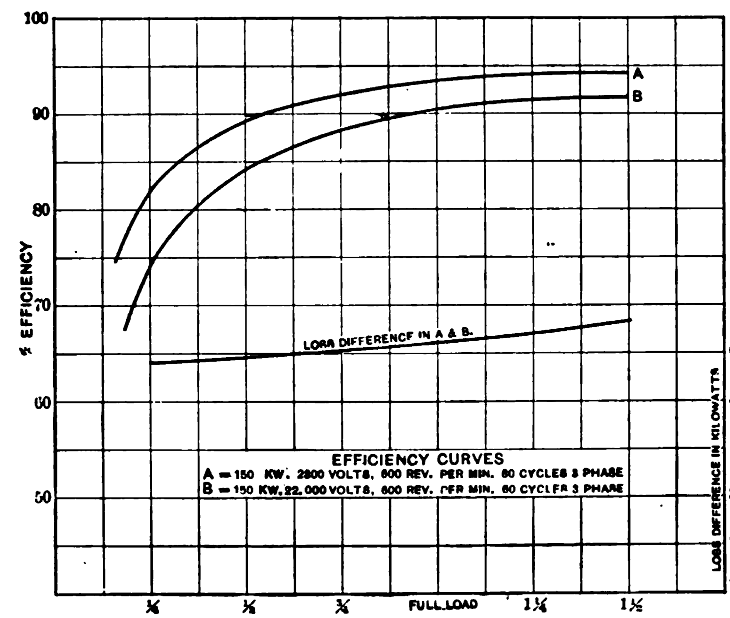


FIG. 1—Comparison of losses in high-voltage and loss-voltage generators.

small capacities, but for the capacities which we are here considering it has been superseded by the steam turbine.

4. The steam turbine in its present condition is pre-eminently adapted to large individual capacities. I should consider a steam turbine of 7500 kw. a comparatively small unit, and I am firmly of the conviction that steam turbines of 10 000 kw. or 15,000 kw., and even of 25,000 kw. will, before long, be developed and put into successful operation.

In thus looking to the steam turbine as the prime mover for generators of large capacity, we have limited our sphere of inquiry to generators of large capacity and high speed·

namely, conditions as best fitted for the operation of steam turbines. The question of high voltage in generators of small capacity and driven by other prime movers than the steam turbine will be referred to in the concluding paragraph.

Steam-Turbine Generators for Large Capacity, 7500 kw. to 15,000 kw. and Above

The difficulties encountered in winding generators for potentials of 20,000 volts or 25,000 volts are primarily mechanical difficulties. A coil containing a large number of small wires does not make a very mechanical piece of work. It would, therefore, appear to me desirable for the reasons here mentioned and some others, that the individual coils should consist of as few conductors as possible and that these conductors should be of such size as to enable the making of mechanically and electrically strong coils. Let us take a concrete example. A certain 7500 kw. turbo-generator wound for 11,000 volts and operating at 750 rev. per min. at 25 cycles, has six conductors per slot. A 7500 kw. generator wound for 22,000 volts, if designed along similar lines, would have twelve conductors per slot. Increasing the capacity of the generator from 7500 kw. to 15,000 kw. would enable the generator to be designed with six conductors per slot, and the difficulty produced by the higher voltage would be that of insulating the coils for the higher potential against ground. and against one another.

The insulation of the coils against ground is easier to obtain than against one another. The question of insulating the coils from one another is particularly difficult in turbo-generators on account of the crammed conditions of the winding space, but at the present state of the art it is possible to obtain the necessary insulation for 22,000 volts, although this can be done only with considerable expense. As soon as there will be a demand for large units wound for 22,000 volts, this demand will be met by machines carefully designed for these conditions.

The question of reliability of service is closely allied to that of quick repairs. It will be urged that not only is the danger of the breakdown of a 22,000-volt generator greater than that of a 11,000-volt generator, but also the repairs, consequent upon a breakdown, will be more difficult to make on the 22.000-volt generator. While this statement is perfectly true, a plan can readily be devised so as completely to defeat this argument. In a large power house in which a number of units of large capacity of the steam-turbine type are installed, the only rational way to make quick and satisfactory repairs consists in the carrying of spare parts. It will commend itself to the operators of power stations to carry a spare revolving field for one of these units and a complete set of spare armature coils. It must be insisted upon that the armature coils of these high-potential generators can readily be replaced, and, unless the

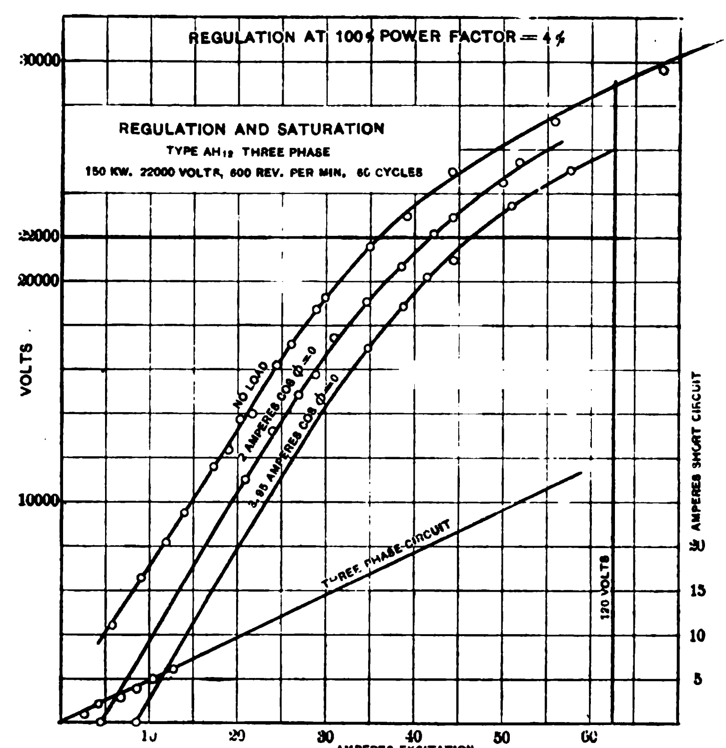


Fig. 2—Regulation curves of a 22,000-volt gaterator.

machines are designed to permit this, it would be necessary even to carry a spare stator completely wound, which would be almost equivalent to having a spare unit in the power house.

Economy Obtained by the Use of Generators Wound Directly for 20,000 Volts

The chief gains obtained by winding generators of large capacity directly for the high potential required for distribution consist in the simplification of the power plant and, probably, in a slightly reduced first cost. The question of reduced cost should certainly be considered a very minor factor, as reliability of service should be the criterion either in favor of, or against, the adoption of generators wound directly for high potential. Calculations of relative cost are here omitted on that account.

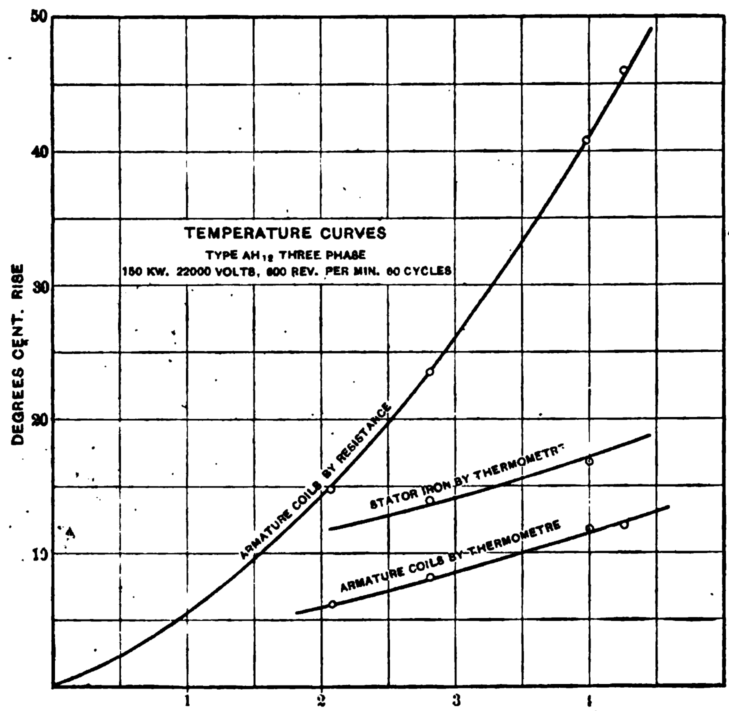


FIG. 3—Heating of armature coils.

GENERATORS, REGARDLESS OF SIZE, FOR 20,000 VOLTS

For the sake of ascertaining the feasibility of insulating coils for 25,000 volts, the writer has had in operation a 150-kw. generator wound for 25,000 volts, 60 cycles, 600 rev. per min. This generator has been in operation for months, operating day and night under full load. Regulation curves and other data are illustrated in the accompanying diagrams. There is no doubt that there may be a limited field for units of small capacity wound for potentials above 11,000 volts, and the object of this paper is to call to the attention of the engineering profession the feasibility of generators of as small capacity as 150 kw., being wound for as high a potential as 25,000 volts. That the regulation, the heating, and the efficiency of this machine are very satisfactory is amply shown by the curves accompanying this paper. Should such machines be used in the future, it must always be insisted upon that the exchange of coils can readily be effected. In the 150-kw. generator referred

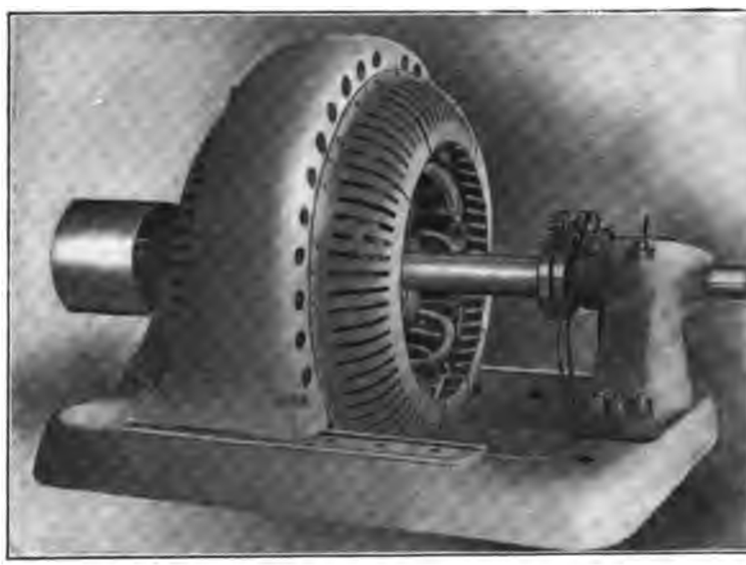


Fig. 4.—A 22,000-volt, 150-kw. generator.

to in this paper, it has so far not been necessary to replace any of the coils on account of defective insulation.

Summary

Where individual units of very large capacity are installed in power plants, a potential of 20,000 volts is feasible, and it is to be recommended in units of 10,000 kw. capacity and above.

Where individual units of small capacity are needed for a potential of 20,000 volts, the conditions can be met in most cases, even down to capacities of 150 kw.

DISCUSSION ON "THE PRACTICABILITY OF LARGE GENERATORS WOUND FOR 22,000 VOLTS," AT NEW YORK, MARCH 22, 1907.

B. A. Behrend: I stated that hydraulic turbines for large capacity, of 7500 kw. or above in individual units, are not likely to be of great importance at the present. The extensions at Niagara Falls may contain such large individual units; I hardly think that for the Victoria Falls of the Zambesi, units of 7500 kw. will be installed. Our chairman, Mr. Mershon, will probably bear me out when I say that the units for Victoria Falls will be about five thousand kilowatts. In all these cases the line potential will be high, and, therefore, the generators will not have to be wound for very high potentials. I believe, therefore, that my statement, that water-wheels need not seriously be considered as prime movers for large generators wound for high potential, is correct.

Let us take for example the system of the Interborough Rapid Transit Company of New York, in which generators wound for 11,000 volts are used; if the capacity of this system were larger and the area of distribution greater, 22,000 volts would have been seriously considered as the potential of the generators, rather than install units of 6600 volts or 11,000 volts transforming from this voltage to 22,000 volts. It must be distinctly understood that the potential of the generators is altogether dependent upon the conditions of the system of distribution.

I agree with Mr. Lincoln that reliability is more important than cost. To be able to keep a plant going is, in my opinion, the most important thing from the standpoint of the manufacturing and operating engineers. I want to call attention to the fact that repairs on high-speed generators are more difficult to make than on low-speed generators, as the coils are larger and more difficult to handle. This relates especially to turbo-generators and it forms, therefore, another weighty consideration against the use of high voltage in turbo-generators. Small hydraulically operated power plants in which 600 or 800 kilowatts are generated, will be simpler if no oil-filled transformers have to be used. As these plants are sometimes located in the mountains, this may be an advantage in certain cases. These generators are usually easy to repair, whereas repairs on oil-filled transformers take considerable time. Few power plants, therefore, care to depend upon repairs of transformers, but prefer to use a spare transformer. The 150-kw. generator which has been referred to in this paper was wound in two days, including the making of all connections. In Fig. 1 of this paper there are shown two efficiency curves, the one marked "*A*" referring to a 150-kw., 2200-volt, 600-rev. per min., 60-cycle, three-phase generator, and the other marked "*B*" referring to a 150-kw., 22,000-volt, 600-rev. per min. 60-cycle, three-phase generator. I have also plotted a curve which represents the difference in losses between "*A*" and "*B*". This loss corresponds to the loss in transformers used in connection with the 2200-volt generator, therefore, the efficiency of the high-voltage generator would be approximately equal to the efficiency of the low-voltage generator with the transformers. As far as I can see, the efficiencies are nearly the same in both cases. In Fig. 2 there will be found the regulation curves of the 22,000-volt generator, showing a regulation of 4 per cent. at a power-factor of 100 per cent. The temperature rise of the armature coils at 3.5 amperes is 16 or 17 degrees by resistance, and only 10 degrees by thermometer. I want to call particular attention to the difference in temperatures between the outside of the coil and the inside, so that, the temperature rise on the inside being, for instance, 60 degrees, the temperature on the outside might be only 30 degrees.

C. E. Skinner: The feasibility of using generators of 20,000 to 25,000 volts has been of very great interest to me for a number of years. In my opinion there are three main factors which must be considered in any discussion involving the use of these higher voltages directly on the generator: 1. cost of installation; 2, reliability of service; 3, performance of plant.

Cost of installation. I do not agree with Mr. Behrend that the question of cost can be left out of the discussion. I put the question of cost of first importance. Generators of 20,000 volts and above would hardly be considered at all for use in transmitting directly without the use of transformers unless there were some gain in cost. The decreased cost of such an installation of generators where 20,000 to 25,000 volts are used results from the omission of transformers, and some switchboard apparatus, and the requirement of less space for installation. Generators for a given output will be larger for the higher voltages, more lightning protection will be needed, and, according to Mr. Behrend's figures, a larger amount of money will be tied up in spare parts, particularly with relatively small plants. It is difficult, if not impossible, to make a general statement as to the relative cost of the two systems, as much depends on the size of units, the amount of power to be delivered, and the general requirements for handling the system. Without having made actual calculations, I believe that there are many cases where the cost of installation would be equal, if not greater, with high-voltage generators than with low-voltage generators and transformers where sufficient margin is allowed in spaces to insure the same reliability of service.

Assuming a plant of 10,000 kw. total, with generating units of 10,000 kw., the capacity of machinery installed would have to be double the output on account of requiring spare parts. If units of 5000 kw. are used, 50% must be added to the equipment. If the same plant is equipped with low-voltage generators and step-up transformers, it is my opinion that no spare generator would be required. If but one unit is used with three transformers in delta, it will be impossible, in case one transformer breaks down, to operate without additional transformers—using two transformers in V. If the transformers are star-connected, one-third additional capacity in transformers would be required if a spare transformer is carried. Many plants operate year in and year out without spare transformers, and with much higher voltages than it is possible at the present time to use directly on the generators.

The constructional difficulties of high-voltage machines are much greater than with low-voltage machines and transformers. In a unit of any given size the number of conductors increases approximately in proportion to the voltage, and the cross-section of the conductor decreases inversely as the voltage. Armature coils are therefore mechanically much weaker, and, where the coil-throw is long—as in low-frequency machines, particularly low-frequency turbo-generators—the question of coil supports becomes more difficult as the voltage is increased.

Static and lightning troubles increase as the voltage increases; consequently, even for the same number of volts per turn, the insulation between turns must be greater with the higher voltages. The outer insulation increases approximately in proportion to the voltage. As a result the copper space in a given size of slot rapidly decreases and will eventually disappear. Very large slots are therefore necessary, and, to further the economy of insulation, the coils must be reduced to the lowest possible number.

Reliability of service. High-voltage machines are necessarily more subject to break down from all causes than are low-voltage generators; they are also harder to protect from lightning discharges of the same voltage. Repairs for the average machine are more difficult to make than for the average transformer of the same voltage. This feature has, no doubt, influenced Mr. Behrend in making the statement that it is necessary to carry complete spare parts for high-voltage generators.

The question of lightning protection is of great importance in any transmission system, and I believe the concensus of opinion among experienced engineers is that a generating station consisting of low-voltage generators with step-up transformers will be far easier to protect than a similar station using high-voltage generators, assuming the generator voltage to be between 20,000 and 30,000 volts. I have recently visited two stations using generating voltages between 20,000 and 30,000. The first has been in operation for some time, delivering power to the Valtellina Railway near Lecco, Italy. The generators are 20,000-volt, 3-phase, 15-cycle, direct connected to water wheels. That the lightning problem is a serious one at this station is proved by the fact that even though a large variety of lightning-arresters is installed, on several occasions the burning out of a generator has resulted from lightning discharges. At the time of my visit, additional types of lightning-arresters were in the station ready for installation in the hope that they would give relief from this difficulty. The second station referred to was not in operation; this is the Subiaco-Rome transmission, the generators being water-driven and the generating voltage 28,000. The whole installation including generators, switchboard, etc., is beautifully simple, but it remains to be seen whether this simplicity will exist after one or two seasons of operation.

Performance of plant. As before stated, high-voltage generators necessarily require open slots, the slots must be larger than those for low-voltage generators; and for economy of insulation the minimum number of coils must be used. This results in relatively high iron-losses and relatively poor regulation. At the present time there seems to be very little demand for 20,000- to 25,000-volt apparatus, except as additions to plants built some years ago.

Mr. Behrend says that steam turbines of 10,000 to 15,000 kw. and even 25,000 kw. will soon be developed and put into successful operation. There are already in operation a number of units which, while not rated at 10,000 kw. are, virtually of this capacity, and there are under construction steam-turbine units of 10,000 kw., with an overload guarantee. From 11,000- to 13,200-volt generators are in successful operation in this country; and one plant, the Los Angeles Edison Company, has been operating 7500-kw., 16,500-volt generators for some time.

I agree with Mr. Behrend that generators wound for voltages of from 20,000 to 25,000 are entirely feasible and that as soon as there is any real demand for such machines they can be successfully made. As before stated, it is chiefly a matter of cost, and it is also a question whether or not they are worth while. It is well known that a well-distributed winding gives better results both as to the performance of the generator itself and of other apparatus on the circuit, especially synchronous apparatus. The high-voltage generator plant is therefore at some disadvantage as compared with the low-voltage generator, step-up transformer plant in this regard. If large amounts of power are to be transmitted some distance, there will be used voltages higher than it is possible to use on generators at the present time. If for transmitting relatively small amounts of power within distances which can be reached by 20,000-volt transmission, the individual case must be considered. The cheapest outfit that will give equal reliability of service will, without doubt, be selected in every case. The use of such transmission plants would be limited to districts where large amounts of power are to be transmitted comparatively short distances; for instance, for railway service in large cities such as the present system installed in New York City, this being at the present time 11,000 volts. Increasing this voltage of 11,000 to 25,000, involves the subject of cables, etc., and requires very careful working out in order to determine whether or not there would be real economy in the increased voltage. For transmitting smaller amounts of power to greater distances, it is my opinion that the most popular method for some time to come will be the low-voltage generator with step-up transformers.

In regard to possible size of steam turbines, I think that units of 25,000 kw. are even now within reach. The steamships Lusitania and Moritania, now building on the river Clyde, will have steam turbines as their motive power, the turbine units to be something like 30,000 h.p. If such machines can be built for steamship service, they are, of course, available for the driving of electric generators, and generators of this capacity will without doubt be developed commercially as soon as there is a real need for them.

W. S. Murray: In matters of this kind cost must ever enter as an important factor. Though it may be possible, by a combination of the generators and transformers, to equip a generating plant for the same money as that required to pay for generators without transformers, yet it seems to me that such a combination should not be considered until necessity makes its development imperative. Also, there is no doubt but that in creating high voltages in a generating apparatus, the active conductors of which are limited to a few coils, there is also created very poor regulation. High-voltage apparatus will therefore drive the designer from well-distributed windings to coil-wound armatures.

I wish to support Mr. Skinner's statement in regard to the protection of the station by means of transformers. If there are great transmission distances, naturally the voltage has to be increased, and under these conditions there is no better lightning protection than well-designed step-up transformers.

Though Mr. Behrend contends that the repairs on transformers are rather difficult to make, still it should not be forgotten that the cost of equipping a step-up station with spare transformers is much less than that of equipping a station with spare generators.

My conception of a well-designed high-voltage power house—by high voltage I mean 20,000 volts or more—is that of a fort, the ramparts of which are the transformers; they take most of the hard blows. It is not necessary to compare the damage by lightning in a plant having transformers between the generator and the line with a plant that is not equipped in this way.

In view of the fact that the generator-transformer combination affords better lightning protection, I admit that I shall remain heartily in favor of step-up apparatus until a real case is made out for high-voltage machines.

A. H. Armstrong: The design of any type of apparatus must be governed by commercial demands. Generating and transmitting systems may be divided into two broad classes; those centering in and about large cities and operating at from 6,000 to 11,000 volts, and those having an unlimited area of distribution calling for potentials of 33,000 volts, 44,000 volts, or higher.

Mr. Behrend would have us believe that the choice of transmission potentials is dictated by the limitations of generator design and that the installation of 5,000 and 10,000 units offers the opportunity for higher generator potentials, and hence permits the adoption of higher distributing potentials in and about cities. I cannot take this view of the matter, as the potential of city distributing systems is limited by other considerations than those of machine design. To substantiate this statement I would point out that the generators with highest voltages are not the large units used in city generating stations but the smaller units used in interurban railway and general power distribution systems. The manufacturers are perfectly willing and able to build generators for higher potentials than 11,000 volts, but the fact that low potentials are still adhered to in city distributing systems bears out my statement that the potential of such a system is dictated by questions of reliability of cable distribution and the general needs of the distributing system rather than by any inability or unwillingness of manufacturers to construct machines for 15,000 or 20,000 volts.

While generators may be wound for 15,000 to 20,000 volts, these potentials fall far short of the requirements of a general distributing system outside of large cities. The history of such distributing systems indicates a tendency towards large generating stations feeding over considerable areas at the highest practicable potential; and the potentials required are so much in excess of what can be accomplished in generator design that it would seem, considering the transmission problem broadly, that the low-potential generator used in connection with step-up transformers must continue to be considered the best engineering.

Furthermore, both railway and general transmission systems are constantly expanding over increased areas, and the history of such systems has been to call for a much higher potential than that adopted in the original installation. The flexibility provided by low-voltage generators and step-up transformers takes care of the needs of the expanding system, while it is very probable that a high-voltage generator wound for the original transmission potential would ultimately be used in connection with step-up transformers.

W. L. Waters: The best answer to an inquiry as to the practicability of large alternators wound for 20,000 volts is that such alternators have already been built and are in operation. I would modify somewhat the history of high-voltage alternators from that given by Mr. Behrend. The first high-voltage alternators were the 10,000-volt, 1000-kw. Deptford alternators built by Ferranti in 1889. Then in 1897 came the 15,000-volt, 1800-kw. Paderno alternators built by Brown Boveri, and then in 1900 came the 20,000-volt, 1050-kw. alternators built by Schuckert for the Valtellina line.

The practicability of building high-voltage alternators depends entirely on the nature of the workmanship put into them.

The design of such alternators is similar to that of 6600-volt alternators; the only point for the designer to take care of is to make the work on the armature winding as easy as possible for the shop. After this is done, it is altogether a question of careful and skilful work in the armature-winding department. The larger the output of the alternator the easier it is to make a satisfactory high-voltage armature coil, as the conductors per slot are fewer and they are of larger section and consequently more rigid. It is only with alternators of small ampere capacity that serious difficulties arise.

Mr. Behrend mentions a 150-kw. 22,000-volt alternator which has been in operation for sometime. Mr. Behrend is not particularly specific as to the conditions of load under which this machine has been operated. As far as can be seen from the paper, this machine was operated under a steady synchronous motor load. This is not nearly so severe a test as that where an alternator is continually subjected to sudden variations in load, heating and cooling, being taken off and thrown on the line, and possibly short-circuits. It is quite possible that Mr. Behrend would have a different experience with that alternator if it were operated in some small power station on a high-voltage line.

Breakdowns of the insulation to ground or between phases rarely happens. On high-voltage alternators, breakdowns virtually always start as short-circuits between the individual turns of a coil. In regard to their liability to such short-circuits between conductors in the same coil, it is my experience that there is very little difference between 6000-volt alternators and those of higher voltage. These short-circuits are apparently caused partly by sudden surges on the line, and partly by the gradual deterioration of the insulation due to the vibration of the individual conductors in the coil. This gives as a first requisite of a high-voltage alternator, that it must have the insulation on each conductor as good and as permanent and as strong mechanically as possible, and that the conductors must be held perfectly rigid both in the slot and outside. This practically means the abandonment of the scheme of threading the conductors through a closed insulating tube. Though this construction has been standard in Europe for high-voltage work, and has been used to a certain extent in this country, I think we shall find that it will gradually be abandoned in favor of the form-wound and subsequently insulated coil for all high-voltage work. It is almost impossible to make a perfect high-voltage coil out of small wires, such as would be used on a 150-kw. 22,000-volt machine, as such a coil could not very well be made sufficiently rigid to last any length of time. For this reason I think that about 30 amperes is the minimum current capacity for which high-voltage alternators can be constructed; with very careful shop work, 30-ampere alternators can be constructed up to 30,000 volts. With steam-turbine alternators there are liable to be extra difficulties on account of crowded space available for the end-connections, but this crowded space is chiefly due to the demand for small floor space for these alternators, and extra space will probably have to be allowed for 25,000-volt machines. If this were done, there would be no more difficulty with a steam-turbine alternator than with any other alternator of like capacity.

The demand for such high-voltage alternators would practically be limited to systems operating with 20,000-volt lines. If such a system were of comparatively small capacity and operating on overhead lines, 20,000-volt generators would hardly be desirable, as the supervision would probably not be of the best and the danger of operating directly on a overhead line would be too great on account of possible lightning troubles, so that probably in this case the usual system of a low-voltage generator with transformers would be used. For large city power system work, there would be undoubtedly a certain demand for such generators, especially as 20,000-volt cables are now in use. In such a case, a 20-000,volt generator would be somewhat simpler than a low-voltage generator and transformers, and probably somewhat cheaper. If a demand for such 20,000-volt alternators does arise, I think that they can undoubtedly be manufactured to operate as reliably as 6000- and 12,000-volt machines.

H. G. Stott: Mr. Behrend's able and suggestive paper upon the characteristics of high-tension generators raises the point for discussion of whether we need them or not. I believe that the ultimate solution of this matter lies, not in the generator, but in the question of how far we dare go in voltage in underground cables.

With high-tension transmission, oil-cooled transformers are now invariably installed in all cases where the voltage is above 20,000, as the advantages to be gained by the oil acting as insulation are now fully recognized by all.

The transformer as a piece of lightning protective apparatus is a most important consideration, as very few cases are on record of generators being injured by lightning when transformers were interposed between them and the line. If a transformer were destroyed by lightning, it could be cut out in a few minutes, whereas if a generator were struck, the repairs to it would cover several days.

Professor Ryan's classical paper, read before the Institute two years ago*, showed that owing to the concentration of electrostatic stress on a conductor, there was a limiting diameter of copper for each voltage, below which it is not safe to go; so that unless very large quantities of power are to be transmitted, nothing is gained by increasing the generator voltage.

The limit of generator voltage would thus seem to be determined by considerations entirely outside of the machine itself.

* "The Conductivity of the Atmosphere at High Voltages," by Harris J. Ryan. TRANSACTIONS A. I. E. E., 1904. Vol. XXIII, p. 101.

Percy H. Thomas: The practicability of 22,000-volt generators must evidently depend largely upon their capacity and also upon the speed and other features of the design which will be determined by the conditions of the plant. What can readily be done in generators of the size and type of those in the Interborough Rapid Transit Company's 59th street power house, is hardly practicable in a small generator requiring fine wire windings.

Although the high-tension generator eliminates transformers and some switches, and perhaps switchboards, it has the disadvantage in parallel operation that all high-tension lines must be electrically connected; whereas with low-voltage generators and step-up transformers, paralleling may be done on the low-tension bus-bars, thus electrically disconnecting the high-tension circuits from one another where found convenient.

The importance of this point must not be overlooked. Further experience with large high-tension systems will probably demonstrate that a material increase in reliability of operation will be obtained by maintaining electrically separate the naturally separate divisions of the transmission system. For example, where power is transmitted over different routes to the same sub-station, or to an entirely different sub-station, no limitation of capacity will result by paralleling on the low-tension, if as is usual the capacity of a single line is equal to that of one or more groups of transformers. By this arrangement, the direct effect of lightning discharges, grounds, and short-circuits occurring in one of the separate lines is practically nothing on the others; with the present frequent paralleling of the whole system on the high-tension, however, each high-tension disturbance of a severe character equally endangers virtually all of the transmission system.

A good example of the seriousness of this condition is the accident and shutdown described by Dr. Steinmetz before the Asheville Convention, in 1905. In this case a large electrical railway plant operating all its high-tension apparatus from a common bus-bar was shut down for a considerable length of time by several simultaneous failures of cables and other apparatus, presumably all resulting from a single break. This system had high-tension generators; had it been supplied with low-potential machines and step-up transformers and had each sub-station been operating independently on its high-tension lines, or had it been otherwise possible to obtain this electrical independence, it is very likely that this breakdown would have involved only the sub-station in which the original break occurred, leaving the road perfectly able to operate its entire system. I do not mean to express the opinion that under all conditions this is sufficient reason for foregoing all the advantages of high-tension multiple operation or high-tension generators, but simply to say that I believe this condition must be taken into account and that actual experience with high-tension plants is such that it should receive considerable weight.

The matter of insulation must receive the most careful attention in high-voltage generators, not only insulation between windings and core and between overlapping coils of different potential, but between turns of windings especially near the leads. The concentration of potential on the outer turns of a transformer connected to a line subject to "static" is well known. This same condition must, of course, exist in a high-tension generator connected to such a line, and in most cases substantial protection or sufficient insulation between turns is much more difficult to obtain. For instance, the peculiar shapes of the armature coils found necessary for mechanical reasons, renders it difficult to get the high insulation strength between adjacent wires or layers. In view of the inductance of these coils and the capacity of the windings of the core, there will always be a strong tendency for static disturbances to pass between turns in such coils. The chances that such static puncture will result in a short circuit supported by the generator electromotive force are exceptionally good. It is often said that additional insulation may be used in the coils nearest the line to meet this danger; this method is generally impracticable, however, since the increase in strain upon these coils is not of a reasonable magnitude, say two or three times, but may be ten or twenty times the normal strain. The conditions rapidly become more severe as the voltage rises. Personally, I believe that usually on the higher voltage machines the only practicable solution is in protective apparatus. As a matter of actual experience, the short-circuit of coils of high-tension generators connected to lines, except in favorable conditions, such as are often found in very large 10,000 generators, is a serious handicap.

On the other hand, it is usually found that the numerical constants, involving the number of turns and exposed surface of the coil, are such that a choke-coil will be much more effective in protecting a high-tension generator than it will in protecting a high-tension transformer. In many cases it is likely that a static interrupter will be found more economical in space and cost than an equally powerful choke-coil.

It is an unfortunate fact, borne out by examples in actual service, that the short-circuiting of an end-coil in a high-tension generator operating on a transmission line throws the original strain, possibly only slightly reduced in intensity, directly upon the second coil, which will then often break down, and the third coil will in turn be subjected to similar conditions, etc. I have in mind one case where such a discharge passed across coils all the way from one generator lead to another, the marks being traceable in nearly all the coils. In many cases there were pittings of the wires showing the following of current sustained by the generator.

I wish to urge strongly the importance of protecting against the unusual susceptibility of a high-tension generator to short-circuits between turns of the end-coils, when subjected to static strains. A single breakdown in a generator disables the whole machine, whereas one of a group of three transformers in delta may be spared without serious inconvenience.

Philip Torchio: Not long ago I happened to deal with a large water-power proposition in which the conditions seemed to warrant the use of 22,000-volt generators, as the total length of the transmission line was about 15 miles, with a total capacity of 30,000 to 40,000 kilowatts. Manufacturers were asked to make a preliminary study for machines of 2250 kw. 25,000 volts, 3-phase, 60-cycle, 112.5 rev. per min. Under these specific conditions it was found that the costs and efficiencies of generators of different voltages would be approximately as follows:

Voltage of alternator	Relative cost	Relative efficiency
2,300	100%	96%
15,000	130%	95.25
25,000	155%	94.20

From the above it would appear that as far as cost and efficiency are concerned, there would be hardly any difference between the low-voltage generator with step-up transformer and the 25,000-volt generator. On the other hand, if step-up transformers are used, great savings can be made in the copper and transmission line by raising the voltage higher, say, to 44,000 volts, which can now be made as entirely safe to operate as the lower voltage, and probably, in connection with oil transformers, safer than with 25,000-volt generators.

The selection of generator voltages is usually determined by the conditions of distribution Lighting companies have usually been conservative and seldom exceeded 6600–9000 volts. Electric railroads, on the other hand, have adopted 11,000–13,000 volts, but in most instances the extra insulation on cables has almost entirely offset the reduction in their copper cross-section. I think, however, that with proper grading of insulation on cables, one can now get greater economy from higher voltages then have been heretofore realized

Aside from these considerations, if we are unhampered by any restriction, the problem of selection of voltage simmers down to the question of cost of cable wiring and switch-gear at the station, as with large generating units the problem becomes rather troublesome if great amounts of current are to be handled in the station One will readily appreciate these difficulties if he considers that a 20,000-kw. generator with 50 per cent. overload would require switches of about 8,000 amperes' capacity at 2,200 volts. If, however, 12,000 volts are used, 1500-ampere switches can be substituted with the overall dimensions practically unchanged. If the voltage should be doubled the current would be halved, but the difficulties and costs would be greatly increased in getting the proper insulation on cables and the proper spacing of the high-tension switch elements.

Offhand, I would say that in large central stations these considerations would prohibit the use of high-voltage generators. The above applies to large units.

In the case of smaller units I should think the conditions would not materially change the above conclusions.

In connection with high-voltage generators, it may be interesting to mention the fact that Italy was among the first to use high-voltage generators with their water power transmission plants. The Paderno installation was designed between 1895 and 1896, using 2,200-h.p. Brown Boveri units wound for 15,000 volts. Later the Valtelina three-phase railway installed three 1,500-kw., 22,000-volt, 3-phase, 15-cycle, 150-rev. per min. Ganz generators, wound for star connection and tunnel winding. This and other plants have been operated for many years, and I believe that were it not for the difficulties of installation inherent to the type of slot, the service would have been considered satisfactory. With this type of winding the greatest drawback is the length of time that is required to replace a burned out coil. The explanation for the favor of high-voltage generators in Italy lies, in my opinion, in the fact of the relatively short length of transmission lines and the multiplicity of distributing lines, making desirable the use of a moderately high voltage, which happened to be very close to the commercial dividing line between direct-wound generators and generators with step-up transformers.

F. V. Henshaw: In connection with high-voltage, air-cooled transformers, will Mr. Torchio say if he has any information of any case of deterioration of the insulation due to ozone, or chemical action resulting from brush discharge.

Philip Torchio: With a certain type of coil, insulated in a certain manner, from experience with moderately high voltages covering a great number of units operated for many years without breakdowns of any kind except due to mechanical injury, I would take my chances with 20,000-volt coils; I would not bother about the ozone. With some other insulation, I would not take chances with 2200 volts.

C. F. Scott: I have just made some general calculations to determine the field of application for generators of 150 kw., wound for 25,000 volts. The distance of transmission will ordinarily exceed 25 miles, as a less distance would not necessitate so high a voltage. If No. 6 wire be assumed as the smallest convenient practical line wire, we will find that the cost of the transmission line will approximate, say, $25,000. It is desirable, therefore, that such a line transmit considerably more than 150 kw. in order that the cost of the line per kilowatt will be small. Moreover, such a line will transmit 150 kw. with a loss of only about one per cent. Such a line, therefore, has a capacity for transmitting 1,000 kw, or 1,500 kw., and, if this amount of power is to be generated and transmitted, it will usually be advantageous to use a few large machines instead of many small ones. In other words, 150 kw. is too small a unit for the generation of power at 25,000 volts. The application of generators of this kind, as has already been pointed out, would be quite special.

Paul M. Lincoln: What capacity would the generator have if wound for 2200 volts instead of for 22,000 volts, with a regulation of from say, eight to ten per cent?

I agree with Mr. Stott that the oil used in transformers is of great advantage, and enhances the desirability of the transformer combination over the high-voltage generator. Oil has the property of automatically healing insulation ruptures, and for that reason I believe that such a combination would be much freer from lightning troubles than would a high-voltage generator. Another thing that operates against the high-voltage generator, particularly one of good regulation, such as the one mentioned in the paper, is the liability of the winding to bend on sudden short-circuits. The reasons for this are two: first, on account of the turns being many and the wire therefore necessarily thin and weak; secondly, the good regulation causes a much larger rush of current on such a short-circuit, thereby making the bending forces the greater.

B. A. Behrend: I think that my commentators are laboring under the impression that I had chosen the title of this paper for the purpose of advocating broadly the use of 22,000-volt generators for all sorts of purposes. Let me say, therefore, that the subject of this paper was assigned to me by the chairman of the high-tension Transmission Committee, who, knowing perhaps that I am something of a wolf in the fold and might start some discussion, suggested the title of this paper.

Mr Skinner is well known for his good work on insulation, but I confess that I should have relished Mr. Skinner's remarks better if he had, for the time being, forgotten that we are not connected with the same business interests.

Turning, now, to the technical statements in Mr. Skinner's remarks I must say that I really concur with him in everything he has said except the mode in which it was put. Regarding the point already raised by Mr. Mershon and brought up by Mr. Skinner, concerning the relative cost of the apparatus in question, Mr. Torchio has cited an interesting case. Mr. Mershon requested me to give a comparison of prices and, therefore, I sent an inquiry to our sales department with the following result. A 200-kw., 2200-volt 3-phase, 600-rev. per min. generator with three 75-kw., 2200-volt to 22,000-volt. transformers would be sold for $3,849.00. A 200-kw., 22,000-volt, 3-phase, 600 rev. per min. generator would be sold for $3,837.00; the difference is only $12.00 between the two plants. The total shipping weight of the 22,000-volt generator is 31,000 lb., whereas the shipping weight of the combination of generator and transformers is 30,650 lb. Freight charges, therefore, would not seriously interfere with the sale of these machines in far-off districts.

Mr. Skinner and other gentlemen have imputed to me the statement that the voltage of the generator should determine the line voltage; what I did say was that it was the external conditions, the amount of power to be distributed, the area of distribution, and other conditions that determine the line voltage. If the line voltage thus determined happens to be such that the generators can readily be wound for it, the omission of the transformers may seriously be considered.

Mr Skinner referred to the question of money tied up in spare parts. I can argue on this only academically but, as this paper has been written for the purpose of " raising the dust "—in the laying of which we are concerned in this discussion—I may as well raise some more dust. I stated that the carrying of spare parts and the repairing of the generators was a comparatively inexpensive and simple matter. If a single coil breaks down, a repair can often be quickly made by bridging over and cutting out the injured coil. In a small power plant the carrying of a few spare coils is no worse than the carrying of a spare transformer.

I distinctly said, in reading my paper, that 20,000 volts need not be used for distribution in a city of the size of New York; the amount of power and the area of distribution are not great enough. The population of New York will have to be increased before 20,000 volts will be needed on our generators! 11,000 volts is perfectly satisfactory for the area that has to be covered in this city. At the present time, there are no cities large enough in this country to justify a higher potential. But twenty-five years hence the population of New York will be at least doubled, and then the problems which we are now discussing in an academic way will have become actual problems, unless a widely different system should be discovered or invented.

Mr. Murray agreed with Mr. Skinner so thoroughly that I need not reply in detail to his remarks. But I want to say one word or two about a statement that he made three times: he called the 22,000-volt machine, to which I have referred in my paper, " a very very poor piece of regulating apparatus ". So, then, 4 per cent. regulation is " very very poor "! Four per cent. regulation can not be got at all with transformers and low-voltage alternators designed for 8 or 10 per cent. regulation!

Mr. Armstrong said that " Mr. Behrend wants us to believe " that generators should be wound for 22,000 volts and that this voltage, therefore, should be used for distribution and as line potential. And then he proceeded to show that this statement, which I have never made, is absolutely wrong. I referred, while reading my paper, to the power plant in which Mr. Mershon is interested at Victoria Falls of the Zambesi River. The distance from Victoria Falls to the South African mining district is about 600 or 700 miles. The transmission line will be operated at a potential of 100,000 volts or more, and it goes over the heads of Kaffirs and lions, and one certainly would not select generators of 22,000 volts for this transmission line. I thought that I was speaking to experienced electrical engineers who were fully conversant with all these conditions, and I thought that Mr. Armstrong would hardly be misled to believe that the potential of the generators determined the line potential. But I also stated that the conditions external to the power plant determined the choice of the voltage of the generators. A competent engineer must be able to see more than merely the generating plant; he must have a grasp of the conditions of the entire system, including the transmission line and the conditions of distribution and utilization, as these determine the choice of the line voltage and the voltage of the generators.

I heartily endorse Mr. Waters' remarks. Good shop work must be put into high-voltage machines, and there is no use in denying the fact that it is difficult to obtain thoroughly reliable workmen to whom such work can be safely entrusted. Here lies one of the chief difficulties connected with the building of high-potential generators. Mr. Waters is right that good workmanship on high voltage coils is of the utmost importance.

Mr. Stott's remarks contain statements which I should have included in my paper. He emphasized the fact that the insulation of the cables at present forms one of the chief obstacles to an increase in the generator voltage in large power plants. I am completely in accord with Mr. Stott in regard to the great advantage obtained from oil used as an insulator. It has been proposed to use oil for insulating the stator of electric generators for high potential. This appears feasible but, at the present time, I should prefer to instruct our sales department to quote rather high prices on such oil-insulated generators.

Some one has asked about the wave shape of the generator described in this paper. I have not yet had an opportunity to determine the wave shape by means of an oscillograph, but I hope to do so later. The generator which was used for 22,000 volts was a stock machine having the same number of slots as that used for potentials varying from 10,000 to 15,000 volts. There are many machines of this type and size in operation both as generators and as synchronous motors, operating on short and long lines, and there has never been the least trouble with these machines and certainly no trouble due to wave shape.

It was stated that the manufacturer preferred to sell the generator and the transformers rather than the high-potential generator by itself. This point was also raised by our sales department; they were afraid that they would be overrun with orders for 22,000-volt generators, but I assured them they would get none.

Mr. Thomas made some most interesting remarks on the subject of lightning protection, as might be expected from this thoughtful source. I well remember how he called attention several years ago, in his excellent paper before this Institute, to the fact that the strain increases between the end layers of a transformer coil, and, of course, it does likewise in the coils of alternators and synchronous motors. In the discussion of Mr. Thomas' paper,* I showed mathematically and graphically, by the use of Fourier's analysis, this increase in strain—and I want to say, in this connection, that we are always careful in the insulating of our coils to look out for the stresses between layers—I believe that it is quite feasible to insulate individual conductors in the coils closest to the terminals in such a manner that a breakdown from this source is not likely to occur. Mr. Thomas also called attention to the use of choke-coils in connection with lightning protection. Mr. Thomas knows a great deal more about lightning protection than I do, yet I wish to state that in Switzerland and northern Italy, where plants located in the mountains are subjected to considerable danger from lightning, insulation of the frame of the generator is resorted to as a means of lightning protection. Generators and motors are mounted on porcelain insulators and, while this may not appear a very mechanical construction, it has proved an excellent protection against lightning.

Mr. Torchio has stated a case of 2,200-kw. generators wound for 22,000 volts, on the one hand, and wound for 22,000 volts with transformers on the other, and he has remarked that the prices which have been quoted him by different manufacturers for these different types of plant were almost exactly the same. This bears out the statement made by me in this discussion, that there is but little difference in the relative cost of high-voltage generators, and of low-voltage generators and transformers. Mr. Torchio has also called attention to the difficulties at present connected with the use of high-potential cables. I am in thorough accord with what he has said on this subject.

Mr. Scott has asked me where such machines would be used. I have said in this discussion that there are a number of small plants of 300 or 500 kw., in which 22,000 volts would be a satisfactory line potential and, in this case, by winding the generators for 22,000 volts, a considerable simplification of the power house may be obtained. There is also little force to the argument that the manufacturers will refuse to build 22,000-volt machines, as they are special. We actually took a standard 12,000-volt machine, and wound it for 22,000 volts.

I am in accord with Mr. Scott in regard to his statement that some engineers recommend the same system under all sorts of conditions. There is no panacea for all the troubles that are encountered in our work, and I am glad to find Mr. Scott among those who advocate the taking of a broad view, though I fear that Mr. Scott and all the rest of us will be in our graves when

*Static Strains in High-Tension Circuits, and the Protection of Apparatus," by Percy H. Thomas. TRANSACTIONS A. I. E. E., 1902. Vol. XIX, pp. 213–276.

engineers are still persisting in advocating a specific system for all conditions.

W. S. Murray: Does Mr. Behrend really mean that on the high-voltage machine, notwithstanding the fact that the distributed winding must be dispensed with, that the regulation will be as good? If conductors are bunched will there not be a much larger percentage in regulation? Is Mr. Behrend willing to say that he expects this regulation to be just as good without the distributed winding? Regulation is one of the most important things in the design of large transmission plants, and it cannot possibly be overlooked.

B. A. Behrend: In answering Mr. Murray's question, I should like to state the facts. Comparing with one another, a generator having one slot per pole per phase, a generator having two slots per pole per phase, a generator having three slots per pole per phase, a generator having five or six slots per pole per phase—all cases with which I am thoroughly familiar through my own personal experience in designing some million or more kilowatts of such generators—I must state that I have been unable to notice, in spite of most carefully carried on experiments, any appreciable difference in the regulation of these machines. There ought to be, and there probably is, a slight difference in the regulation, but it is too slight to be established with certainty. The armature reaction is less in the generator having few slots, while the self-induction caused by local fields in the armature winding is greater. Thus, the theory of armature reaction shows that below saturation there is no difference in the regulation, while at high saturation there is a slight difference in favor of the machine having many slots. We have a number of generators and synchronous motors operating in parallel with different numbers of slots per pole per phase, and certainly no difficulty has ever been experienced on that score.

W. S. Murray: I understand that it is not entirely a question of self-induction—it is the result of the two. Does Mr. Behrend feel that his remark—that his conclusion—is applicable to very large units and also generators wound for single-phase transmission? That is that 20,000-volt generators will give as good regulation as distributed-wound generators?

B. A. Behrend: To answer Mr. Murray's question I would say that the regulation is practically the same in both cases, understanding by regulation the voltage drop between no load and full load. I have had no experience with single-phase railway work, but I should say that it will be necessary to avail oneself of all possible advantages by designing a generator so as to give as nearly a sine curve as possible, so as to make it as easy as possible for the single-phase motors. Advantage should be taken of everything to make it easier for the single-phase motors.

W. S. Murray: Does the remark of 4% regulation apply?

B. A. Behrend: There should, of course, be good regulation in a single-phase railway plant on account of the large wattless currents. But this regulation depends rather on other factors, as the reluctance of the magnetic circuit, the amount of excitation, than on the number of slots per pole per phase.

Ralph D. Mershon: I hope that Mr. Behrend later on will give us some cost and efficiency figures for such generators as compared with lower voltage generators combined with transformers, as I believe he has such figures at hand.

I was rather surprised to hear Mr. Skinner lay so much stress upon the question of lightning protection. From what I know of his attitude relating to choke-coils, I should have expected him to assume that enough choke-coils would be used in series with the generators to protect them. Contrary to Mr. Stott's experience, I have known of several cases where generators having step-up transformers between them and the line were damaged by reason of lightning discharges. I have known such trouble to occur without any apparent damage to the transformer. In such cases the static discharge which damaged the generator was probably induced in the low-voltage circuit of the transformers by the electrostatic inductive action between the windings of the transformers. In some cases, however, there may have been a break down between the high- and low-voltage windings of the transformers which breakdown repaired itself by reason of the healing action of the transformer oil. I think there is, unquestionably, a place for the high-voltage generator, and this paper of Mr. Behrend's is very timely. I have listened to it with a very great deal of interest indeed, and will receive with even more interest the cost and efficiency figures previously mentioned which I understand he will give us later on.

F. G. Baum (by letter): I take exception to the statement that hydraulic units of or above 7,500 kw. are not to be considered of importance at present. Several installations are under way for hydraulic units of 7,500 and 10,000 kw., and by putting a turbine on each end of the generator shaft, there may be produced units as large as 15,000 kw., or even 20,000 kw.

The disadvantages of winding for a high voltage are:

1. Increased losses.
2. Increased cost.
3. Decreased capacity.
4. Increased danger and risk of breakdown.

The advantage is that reduced space is required, as no transformers are necessary.

In some localities the question would be answered by the cost of space, but, eliminating the space-factor, it does not seem advisable to wind for 22,000 volts. At some point it is folly to increase the voltage on generators. I am inclined to the opinion that this folly point is reached in most cases before 22,000 volts is attained.

Ernst J. Berg (by letter): I quite agree with Mr. Behrend that large turbo-generators lend themselves best to very high voltage windings. At the same time it may be of interest to know that one manufacturing company has built 18,000-volt alternators directly connected to slow-speed engines.

The transmission line voltage has, in my opinion, a bearing on the best generator voltage, since with one of the high-potential lines grounded in a delta system, high static stresses are induced in the generator windings. These do indeed occur even in a grounded star system when power is conveyed over two of the lines and the ground used as a third conductor.

Therefore, it is evident that it is not well to make the generator voltage too low in reference to the line voltage. My judgment would be that it ought to be not less than one-sixth or one-fourth of the line voltage, corresponding to 16,000–25,000 volts in a 100,000-volt transmission system. Judging from the amount of insulation required in transformers, the limit would seem to lie somewhere between 20,000 to 25,000 volts, provided alternators of reasonable wave shapes are demanded.

W. J. Foster (by letter): The question of practicability involves construction cost and efficiency. It may be said that the question of construction is wholly one of insulation. Is it possible to allow the space necessary for the insulation and so to apply it as to insure against breakdowns? This may be answered in the affirmative, with the qualification that large slots are always possible where the pole-pitch is large. Hence, there are certain sizes of generators that are well adapted for such high potentials. It is probable that the simplest way of putting this matter above a certain minimum size is to make the output per pole the criterion, since this eliminates to some extent the consideration of periodicity. It is probable that almost any generator with a capacity of 1000 kw., or more, whose output per pole is at least 100 kw., can be advantageously wound for 22,000 volts. All steam-turbine generators up to 60 cycles belong in this class. There is another type of generator that is admirably adapted to 22,000 volts; namely, the large engine-driven fly-wheel type. Such generators have a large pole pitch, and, consequently, make it possible to select the number of slots that permit of the necessary room for insulation between winding and core. They also make the high-potential machine desirable by reason of the fact that a large percentage of their cost is due to the mechanical parts. Hence the additional cost of the high-potential machine is generally less than the cost of step-up transformers. It is frequently much less. Furthermore, the efficiency of such a generator is much higher than the combined efficiency of the low-potential generator with step-up transformers.

The synchronous motor in motor-generator sets and frequency-changer sets in sizes of 1000 kw. or more, may often most advantageously be wound for 20,000 volts. The majority of these are for low frequency, such as 25 cycles, and for use in sub-stations to drive direct-current generators or alternating-current 60-cycle generators. Winding for 20,000 volts will frequently simplify the sub-station by eliminating step-down transformers;

at the same time it will invariably increase the efficiency of the transformation.

I wish briefly to describe some 5000-kw., 50-cycle, 100-rev. per min. engine-driven, fly-wheel type generators that have been constructed to operate at approximately 20,000 volts, three-phase. The ampere rating of these generators corresponds to a normal potential of 18,000 volts, but the specifications require them to be capable of operating at a maximum of 22,000 volts. Three of these generators are being installed in the plant of the Pacific Light and Power Co., Los Angeles, California.

Floor space required	31 ft by 6 ft. 9 in.
Diameter of stator	28.5 ft.
Diameter of rotor	25 ft.
Radius of gyration	8.8 ft.
Weight of rotor	186,000 lb.
Weight of stator	162,000 "
Weight of accessories	12,000 "
Total weight	360,000 "

The armature coils have stood a high-potential test of 40,000 volts for one minute.

The commercial efficiency is as follows:

1.25 load	96.5%
Full load	96.2%
0.75 "	95.2%
0.50 "	93.5%
0.25 "	88.0%

The class of generators which will undoubtedly make the best showing in the matter of cost to the customer is the large fly-wheel type of low periodicity, such, for instance, as a 25-cycle, 5000 kw., 75 rev. per min. Such a generator wound for 22,000 volts, will not cost the customer more than 15% above the cost of the generator wound for the most advantageous potential with step-up transformers. Step-up transformers will cost about 30% of that of the generator. Hence there is a saving in the initial cost of the apparatus alone of from 10 to 15%. To this should be added the saving in the station due to the elimination of space for transformers. Along with this saving in the initial cost there will accrue to the consumer a continual revenue due to the better efficiency. This will amount to at least 1% at full load and 1.5% at one-half load. Many large water-wheel driven generators might well be wound for 22,000 volts where it is desirable to use that potential on the transmission lines. It would be an interesting study to work out the cost and efficiency of such generators for transmitting Niagara power to Buffalo in comparison with the use of generators with step-up transformers, as at present. There is no doubt in my mind but that a most decided gain would be shown. The 3750-kw. generators on the American side and the 7500-kw.

on the Canadian side are ideal machines for 22,000 volts, by reason of their large capacities and the relations that exist between capacity and the number of poles.

In conclusion, after several years' experience in designing, I am confident that 22,000-volt generators properly selected in the matter of their ratings, offer less difficulties in design and construction than numerous 6,600-volt generators now in operation.

R. S. Kelsch (by letter): In June, 1905, the writer endeavored to purchase 25,000-volt, 3750-kw. generators for a hydroelectric development to consist of five 3750-kw. generators for an 18-mile transmission. Several large companies manufacturing this class of electrical apparatus were asked if they would construct such machines. One company replied that they did not think it feasible; the other companies thought it feasible but were not prepared to supply machines of this voltage at that time.

The plant referred to is now operating, using 3750-kw. generators, step-up transformers, etc. In preparing plans for this installation, and while considering 25,000-volt generators, the following points, for and against the use of such generators, received consideration:

Extra cost. Generators; potential transformers; current transformers, etc.

Saving. Saving of step-up transformers, building for transformers, generator cables, entire low-voltage bus-bar system, switches, etc., the water- and oil-pump system, insurance on transformers and building, interest, and depreciation.

Disadvantages. The 25,000-volt generators would be exposed to line strains, lightning, etc. In case of lightning entering the station, liability of greater damage and serious interruption to service, which might be overcome by extraordinary insulation on generators, and 25,000-volt bus-bar constructed to have had capacity to dissipate abnormal strains.

There is also the disadvantage that with such generators the multiplicity of voltages sometimes required for the high-tension systems could not be obtained as readily as with the step-up transformers.

Advantages. Advantages obtained by using the 25,000-volt generators are; better regulation, simplicity of station wiring, reduced fixed charges, reduced danger from fire due to the absence of oil-cooled transformers.

In Montreal there is one hydroelectric plant containing eight 750-kw., 4400–5000-volt generators, working direct on the transmission lines. In nine years' service there has not been one case of trouble on the high-tension windings of the generators, due to lightning or other abnormal strains. And this plant has yet to record the first injury to an employee or any other person from these 5,000-volt machines.

When this plant was installed, the specifications for these generators called for the insulation to be such as successfully to withstand a 25,000-volt alternating-current breakdown test.

The writer believes that a plant containing a large number of 25,000-volt generators can be successfully and safely operated.

L. Schüler (by letter): There is no doubt that alternators can be wound for pressures over 20,000 volts. As early as 1895 I assisted in the design of a 30-kw. 27,000-volt machine, which was built by the Allgemeine Elektricitats-Gesellschaft, Berlin. It worked satisfactorily. The coils were embedded in troughs of micanite, and the machine was made for the purpose of showing that the possibilities of this new (at that time) material.

Another question is, whether it is advantageous to use such machines in connection with long transmission lines; this I think is *not* the case. Mr. Behrend is quite right to advocate the carrying of spare coils, but it should be well understood that it takes at least a couple of hours to replace coils of an alternator, while practically no time is required to switch in a spare transformer. Even if no spare transformer is available, in case of a breakdown it will very often be possible to carry the load on the other transformers while the broken down one is being repaired. The overload capacity of alternators, and especially prime-movers, is usually not sufficient to do this.

As Mr. Behrend says himself, there would not be much saving in costs by the adoption of such extra high tension generators, I think it would be rather unwise for supply companies to use and for manufacturing companies to sell them.

Farley Osgood (by letter): Without question the operating dangers in a high-voltage machine are greater than in a machine of moderate voltage. The greatest objection the writer has to a machine wound for such a voltage is the uncertainty of protecting it from outside disturbances such as grounded or short-circuited lines, lightning discharges, etc. With step-up transformers, a defence-wall for the generating units is maintained, and the protection afforded is in my opinion worth the additional cost.

No doubt such a generator can be built and will run satisfactorily, but I think that the discussion would finally resolve itself more into one of practical operation rather than electrical or mechanical possibility. As an extreme case, Mr. Behrend cites as possible a 20,000-volt machine as small as 150 kw. capacity; such a machine would of course be built for experimental purposes only, as there is hardly any power problem which would require such an unusual piece of apparatus.

It seems to me that a machine wound for 20,000 volts to be used directly on the power system should receive consideration only where units of enormous capacity are required and where the transmission distance is very short.

H. F. Parshall (by letter): The practicability of winding generators for 22,000 volts would depend largely on the size of the machine. In the case of the proposed installation for the London County Council, where 12,000 to 15,000 kw. turbo-generating sets are in contemplation, the matter was the subject of most careful consideration, the result of which was that 15,000-volt generators were considered practicable and that they would be more satisfactory in practice than low-voltage generators with step-up transformers. Voltages higher than 15,000 were considered, both in the generating and transmission systems, the transmission system in this case being underground and thereby being subject to different considerations from an overground transmission system, and it was found that to transmit the same energy, having regard for all of the conditions, there would be no advantage in the transmission system is a voltage higher than 15,000; in fact, the maximum advantage occurred at that point.

I make particular mention of this in that the installation has been designed to distribute 250,000 kw. over perhaps the widest area that is likely to be encountered in municipal supply. This being, therefore, practically the limit of this class of installation, it would appear there is a natural division between voltages for generation in what may be termed a municipal system and in what may be termed a long-distance transmission system, the limiting commercial voltage for a municipal system placed underground being approximately 15,000 volts, whereas in the long-distance transmission, if overhead, three or four times this becomes commercial. At this higher voltage, direct generation is out of the question. It would appear, therefore, the particular answer would be that in practically every case generators of large size can be wound to meet the requirements of economical transmission in the largest type of municipal plant, but that in the case of long-distance transmission, step-up transformers in the generating station become a necessity.

A. Henry Pikler: The chief object in winding a generator for high voltages is to use it directly in connection with the transmission line and to do away with the step-up transformer, if this in combination with the generator is found more expensive than the high-voltage generator alone.

I assume that 22,000 volts was selected in connection with this paper, because it was thought that this is about the limit for which generators can be wound in the present state of the art. Since, however, there is a large range of transmission voltages still above 22,000—in such cases transformers must be used anyhow—I should more explicitly formulate the question like this: Is it practicable to operate transmission lines from 20,000 to 25,000 volts directly by generators wound for such voltages?

What is meant by practicable? By this term I understand collectively the following elements in question: 1. Whether or not the apparatus can be built at all for such a voltage. 2. Whether or not it is economical to the manufacturer to build it for such a voltage in preference to other solutions. 3. Whether or not such a generator is reliable in the service; that is, economical from the standpoint of the power-plant man.

The very fact that there is some discussion over the practicability of 22,000-volt generators, may readily convey the impression that winding generators, even large generators, for 22,000 volts, is a great feat. Generally speaking it is not. It is not the art of insulating that is at fault in this problem. It is not that materials cannot be found good enough or that we do not know how to do the insulating, in order to have the generators stand the voltage in service.

The author introducing this subject for discussion illustrates very well with his 150 kilovolt-ampere, 22,000-volt generator, operating for months night and day without a break, that this is not the case. Though it is true that the quality of insulating materials has undergone rapid progress during the last four or five years, yet I know of machines wound for 20,000 volts that were installed seven years ago. These machines are not very large. They are horizontal turbine-driven, 150-rev. per min., 15-cycle, 1000-kw. machines. They can operate at 30,000 volts for half an hour without injury and they are operating satisfactorily.

I know of another plant installed about a year ago with 4000-kilovolt-ampere turbine-driven generators wound for 40,000 volts, and they are working satisfactorily. To wind and insulate a generator for 20,000 volts is, then, not out of the question.

The most essential thing needed for winding a generator for high voltages is space, big slots where there is space for the slot insulation, for insulation between adjacent turns or layers, and space on the ends to prevent creeping or breakdown between the ends of coils.

Big slots, however, mean an uneven distribution of magnetic flux, strongly developed higher harmonics, an electromotive force wave-form deviating from the sine wave, a higher excitation. It would be very interesting to know the electromotive force wave-form of the 150 kilovolt-ampere 22,000-volt machine, of which other characteristic curves are shown to advantage in the paper.

This wave-form is a very important matter, the manufacturer should consider it just as much as he does the possibility of a satisfactory insulation or the cost of a machine. There is no doubt but that even a 2000 kilovolt-ampere 300-rev. per min., 20,000-volt machine can be produced at a lower cost than can a combination of a 2300-volt machine and three 700-kilovolt-ampere step-up transformers. Besides, it would greatly simplify the power plant and lessen the responsibilities of the station men. It is doubtful, however, whether such a generator would be as good in every other respect, especially in wave form, as the 2300-volt generator. Besides, selling a generator and transformer, too, means greater profit to the manufacturer.

As to the reliability. A generator if protected by lightning-arresters, choke-coils, or even static-interrupters against abnormal rises in voltage is, to my mind, a safer and simpler proposition than a combination of a generator and transformer;

on the other hand, if a breakdown occurs—in one case the transformer breaks and in the other the generator—there is no doubt but that it will take more time to repair the generator than to cut out the injured transformer and run the other two on open delta, or to repair the transformer, or to cut in a spare transformer.

Which solution is the most economical to the customer is almost solely dependent upon local conditions. For instance, in steel works or ore-smelting works where large blast-furnaces are electrically operated and where in case of a breakdown costly furnaces and valuable ore are affected, it will pay to carry in reserve even a complete generating outfit.

As the practicability in winding alternators for high voltages depends chiefly upon their geometrical dimensions, I cannot accept such a general conclusion as arrived at by the author of the paper. If he had in mind a steam turbine, he is about right, but I am of the opinion that lower generating capacities can be wound and used to advantage for 22,000 volts.

Bertrand P. Rowe: From the standpoint of the man who has to provide for the switching devices, the proposal to wind alternating-current generators for higher voltages than are commonly used at present seems to be a step in the right direction. As the size of unit increases, and the amount of energy to be interrupted becomes greater, it becomes more and more of a problem to build oil-switches that will open the circuits from the bus-bars, because the lower voltages now employed introduce currents of large capacity.

The problem of breaking circuits at high voltage has been successfully solved as far as pressure is concerned. It is a simple matter to open a circuit for any generator voltage that is likely to be determined upon. But if this circuit must carry a large ampere capacity, the problem becomes more difficult; and the higher the generating voltage becomes the simpler will be the problem.

Oil circuit-breakers have been built to open circuits carrying 2000 amperes normally at 13,000 volts pressure, and there have been cases where engineers have asked for circuit-breakers to open 3000-ampere circuits at 13,000 volts pressure. Here we are getting to the point in oil-switch design where it is doubtful engineering at best to build the switch and be ready to guarantee its successful operation.

If it were only the generator capacity that must be taken into consideration, it would be some time before arriving at a point where the switch must break any extraordinary current with present generator voltages. But the fact is that the use of low voltages on the bus-bars means heavy capacities in the junction and tie-in switches, and on circuits feeding large capacity transformer banks. The latter must often be automatic, and when opening on heavy overloads in a station with enormous capacities on the bus-bars, the result may be imagined. As the entire operation of a plant may depend on the success or failure of such switches, connected as they are to the bus-bars, the importance of this phase of the situation is obvious.

The problems involved on account of higher generating voltages in the other switchboard apparatus and the wiring of the station are not worth mentioning. The only appreciable difference will be that the higher potential will have to be provided for in the cables between the machines and switchboards. It is really a installation problem that has already been solved.

Comparing the cost of switchboard apparatus and conductors, everything is in favor of the higher voltage. It may cost a little more for insulated cables, but the oil circuit-breakers, bus-bars, series transformers, and other accessories will be smaller in capacity and much cheaper. It often happens that switchboard apparatus for a 13,000-volt plant with a given ampere capacity can be used without change for a plant of the same capacity at 22,000 volts, for the reason that the manufacturers have one class of apparatus for both purposes.

Summing up the whole situation, the use of higher generator voltages will simplify the problem in the switchboard equipment, and undoubtedly reduce the cost, besides involving nothing that has not been well developed and in successful operation.

A. B. Reynders (by letter): High voltages are independent of the prime mover; that is, the insulation on a 22,000-volt generator would be practically the same whether driven by hydraulic turbine, gas engine, reciprocating steam engine, or steam turbine.

As stated by the author, increase of voltage means increase of conductors. Increase of conductors means increase of insulation; hence, the higher the voltage the greater percentage of slot space occupied by the insulation. This, from a mechanical point of view, is inefficient. In the case of the 11,000-volt generator, cited by the author, it is probable that 50% of the space in the slot was taken up by the insulation, the remaining 50% being copper. Increasing this voltage to 22,000 volts and the capacity to 15,000 kw. will cause the insulation to be doubled; or, in other words, the space occupied by the insulation will be 70% of the total slot space.

When it comes to the insulation on the ends, the distance which the bare parts of the coils will have to project will be about double that required for 11,000 volts. This means that the coils will be extremely weak mechanically, owing to their length. This assumption is based on the fact that peripheral speeds cannot be increased much over the present uses; hence the increased induction must be obtained by lengthening the iron.

The increase in insulation has another very bad feature besides occupying valuable space; namely, it is a non-conductor of heat. All heat generated in the copper must be transmitted to the surrounding cooling medium through the insulation. Under the action of heat all insulation of a fibrous nature tends to deteriorate. Mica and asbestos are exceptions, but these are grave objections to their use unless combined with some fibrous material, such as tape. This deterioration of insulation is reduced by decreasing the heat generated, to accomplish which necessitates an increase in the size of copper. This again tends to decrease the efficiency per pound of gross weight.

As admitted by the author, a 22,000-volt generator is less reliable than one of 11,000 volts. That this is a grave weakness is endorsed by his statements regarding spare parts. He recommends practically an extra machine to provide against breakdowns. The only advantage which can be claimed is in simplicity of the power station by avoiding use of transformers.

Guido Semenza (by letter): Mr. Behrend rightly points out that the reason for using high-tension generators is to limit their current capacity, as the distribution and conduction of large currents from the generators to the switchboards is cumbersome and expensive. I would add, that up to a certain point switching with high pressure is preferable to switching with very heavy current.

In his comparison the author refers very likely to central stations having such a switchboard scheme that the low-tension generator currents are collected on a set of bus-bars to which the low-tension circuits of the transformers are connected, and, as far as such scheme is considered, I quite agree with him in his conculsions. But there is an intermediate solution between this and the use of high-tension generators which is employed in some European plants. Low-tension generators are used, and each generator is connected to a set of transformers, with circuit-breakers; there are no switches, no fuses, nor instruments being used in this low-tension connection.

The generator and its transformers are considered as a high-tension generating unit, and all the switchboard is on the high-tension side of the transformers. Such a solution permits of all the advantages of low-tension generators, confines the high-tension in an apparatus much more fit to withstand it, and at the same time reduces the current capacity in the switchboards.

It has only one apparent drawback; that is, that a fault in a transformer will also put a generator out of service; but if the use of low-tension will have the effect of reducing the number of accidents in the generator, then there will still be an advantage, as the repairing of generator coils requires much more time than the time required to replace a faulty transformer with a spare one.

Philip Torchio (by letter): Referring to Mr. Behrend's question as to what part the ohmic resistance plays in the parallel operation of synchronous apparatus on long transmission lines, I wish to call the attention. of the parties interested in this subject to a paper contributed by Mr. G. Semenza to the Milan section of the Associazione Elettrotecnica Italiana, at their meeting of December 4, 1903.

The paper describes two series of tests: one upon two direct-current synchronous motor-generator sets, operated inverted from a large storage-battery and with the alternating-current machines connected through an adjustable resistance. The other series of tests was made on a synchronous motor fed from the main bus-bars of a large generating station through an adjustable rheostat. In both cases the load and power-factor and reactance and ohmic resistance of circuits were adjusted for different values so as to obtain curves showing the behavior of these machines. Pumping phenomena would appear in all instances under certain conditions of load, power-factor, and ohmic resistance of the circuit. The pumping had a frequency of from eighty to one hundred and twenty vibrations per minute, and beyond certain values the amplitude of the oscillation was so large that the machines were thrown out of step.

Mr. Semenza's analysis of the results gives lucid portrayals of the function of resistance and reactance in a circuit upon the parallel operation of synchronous motors, and possibly might be abstracted for the minutes of the Institute, or at least attention called to this contribution to the subject for the information of those who may care to look up the subject.

John Pearson (by letter): I agree that there are advantages in winding large alternators for 22,000 volts, especially when this is the potential required for distribution. As Mr. Behrend says, steam turbines will probably soon be built for 10,000 to 25,000 kilowatts. These large steam units will naturally be used in large cities where the distance of transmission is relatively short. Hydraulic turbines in the near future will possibly range in capacity, as at present, from 1,000 to 3,500 kilowatts. These turbines will, on the average, be used at a distance from the market or center of distribution, where the distance of transmission will be relatively long.

I believe it practicable to wind 22,000-volt alternators for use with large steam turbines where the distance of transmission is short. In this case, power stations using 22,000-volt alternators will need no step-up transformers, resulting, of course, in higher efficiency. The danger of generator coils being punctured directly by lightning will be small, as the average turbo-generator will be transmitting its power through underground cables.

The transmitting voltage of the future water-power station is likely to be from 60,000 to 100,000 volts, and one would not favor using, a 20,000-volt alternator where the transmitting potential was 60,000 or 100,000 volts, as transformers for raising the potential would also have to be used. Where step-up transformers have to be used, I believe it practicable to use generators wound for 2,200 volts, as there is very little danger of the generator coils giving way at this voltage.

A generator wound for 22,000 volts can, as far as insulation is concerned, be compared to an air-blast transformer. I know by experience that the oil-insulated transformer will stand more severe static strains than the air-blast transformer. Consequently, a 20,000-volt generator cannot be expected to stand up under severe static strains any better than can the air-blast transformer, on account of not having the benefit of oil for insulation. Oil simply for insulation is not all, as the oil fills all intermediate space between and around the coils and thereby keeps the dirt away from the coils, which is one good point.

Mr. Behrend states that the insulation of coils against ground is easier to obtain than against one another, and that the question of insulating the coils from one another is particularly difficult in turbo-generators on account of the crammed conditions of the winding space. From the above it is seen that no more insulation can be used than what is absolutely necessary; but it is comparatively easy to bring out leads and use cylinders and air-gaps, as shown in TRANSACTIONS A. I. E. E., 1904, Vol. 23, p. 570. Also TRANSACTIONS A. I. E. E., 1905, Vol. 24, pages 960-962-978.

I know by experience that when using spark-gaps across each coil, less insulation can be used, as abnormal strains are equalized over the whole winding. I do not consider it hard to insulate a generator for 22,000 volts under normal conditions, but such generators must stand up under abnormal static conditions as well.

It seems wise, therefore, to use spark-gaps across coils, the winding connected in star and the star and core grounded. By this arrangement the generator becomes to a certain extent a condenser, having capacity between coils; between coils and the frame, between coils and the ground, this capacity becomes more noticeable when any static strain can reach all parts of the winding at once, than if it only piled up on the first coil nearest the transmission line.

A paper presented at a meeting of the Chicago Branch of the American Institute of Electrical Engineers, Chicago, Ill., March 26, 1907.

HIGH-VOLTAGE DIRECT-CURRENT AND ALTERNATING-CURRENT SYSTEMS FOR INTERURBAN RAILWAYS.

BY W. J. DAVIS, JR.

The magnitude and direction of engineering development in apparatus for the electrical equipment of high-speed interurban railways is well illustrated by a study of the systems adopted by some of the more important lines recently built or now under construction. These systems may be divided into three classes, namely:

1. 600-volt, direct-current using either overhead trolley or third-rail.
2. 1200-volt, direct-current overhead trolley.
3. Single-phase, alternating current, 3300- or 6600-volt overhead trolley.

As apparatus for the operation of the 1200-volt, direct-current system is being manufactured in this country only by one company, the list of roads given below comprises only those using equipments manufactured by this company, and is limited to sales to new roads made during the last year.

The largest installation undertaken during the last year was that of the West Jersey & Seashore Railroad, comprising equipment for 145 miles of single track and 35600 h.p. in railway motors. On account of the limited time required for the completion of this installation (six months from date of selecting power-house site) it was impossible to furnish apparatus of special type, making the selection of the 600-volt, direct-current system obligatory. For this reason the equipment of this road is not included in the following statistics.

	Length of track	No. of Cars	Size Motors	Total motor h.p.
600 *volts, direct current*.				
Texas Traction Co.	63 miles	15	4 75 h.p.	4,500
Elmira, Corning & Waverly.	15 "	7	4 60 "	1,680
Buffalo, Lockport & Rochester.	70 "	19	4 75 "	5,700
Oregon Railway.	40 "	8	4 75 "	2,400
	188 "	49		14,280
1200 *volts, direct current*.				
Central California Trac. Co.	16 miles	6	4 75 h.p.	1,800
Pittsburg, Harmony, New Castle &Butler.	63 "	12	4 75 "	3,600
Indianapolis & Louisville.	41 "	10	4 75 "	3,000
Indianapolis, Columbus & Southern.		3	4 75 "	900
San Jose & Santa Clara.	9 "	8	4 75 "	2,400
	129	39		11,700
Single-phase, 3300 *or* 6600 *volts*.			4 125 }	
Washington, Baltimore & Annapolis.	52 miles	25	2 125 }	11,500
Central Illinois Constr. Co.	40 "	10	4 75	3,000
Anderson (S .C.) Railway.	35 "	3	4 75	900
Richmond & Chesapeake Bay.	15 "	4	4 125	2,000
	142	42		17,400

Total horse power in motors sold, 43,380 of which
600 volt, direct current has 33 per cent.
1200 " " " " 27 " "
Single phase alternating current has 40 per cent.

It is most interesting to note that two-thirds of the total motor capacity sold consists of 1200-volt, direct-current and single-phase alternating-current motors, indicating the eagerness of electric railway builders to take advantage of the reduced cost of construction and equipment, and economies in operation, resulting from the use of higher secondary distributing voltages. The magnitude of the possible savings will depend upon the local and service conditions and will vary over a wide range.

Generally speaking, increased voltage at the trolley will be attended with reduction in cost of copper and sub-station apparatus, and by increased cost of car equipments due to the inherently heavier and more expensive character of the motors and control systems. Where the car movement is especially frequent, as in case of rapid-transit suburban service in the vicinity of the larger cities, requiring from two to four tracks, the 600-volt, direct-current systems will generally prove the cheaper, a result largely due to the lower cost of the motors.

On account of the variable character of the conditions encountered, each problem requires a special investigation before the relative merits of the three systems can be reliably determined, but the following general limitations will be found to hold true.

1. Street railways and elevated roads in cities should unquestionably be equipped with standard 600-volt, direct-current apparatus.

2. Suburban lines 10 to 15 miles in length operating cars on frequent headway should be equipped with 600-volt, direct-current system.

3. For high-speed interurban railways operating cars 50 ft. or more over all at speeds of 40 miles per hour or more:

a. The 600-volt, direct-current system is the most reliable on account of being most fully developed.

b. The 1200-volt, direct-current system is somewhat cheaper in cost than the 600-volt system, but is as yet an untried system.

c. The single-phase, alternating-current system will in most cases show material saving in cost over the direct-current systems, and has been developed to a point where it may be considered commercially successful and capable of giving satisfaction in operation, if properly proportioned for the service to be performed.

There are certain conditions which render the alternating-current motor system unduly expensive or impracticable; namely, the enforced use of a frequency greater than 30 cycles, the presence of grades greater than 8 per cent., or the necessity of obtaining perfectly balanced three-phase load under all conditions. In such cases, the 1200-volt or the 600-volt direct-current system will prove the most economical, preference being given to the latter although the cost of installation will be greater.

The single-phase, alternating-current and 1200-volt, direct-current equipments may both be made to operate satisfactorily on standard 600-volt, direct-current systems, and assuming equal reliability, the question becomes one of first cost and economy in operation. The following table will show approximately the relative cost of a typical suburban road with the several systems.

It is of interest to compare the operating economy of the three systems, eliminating those items which are of equal value in each. The comparison given below is based on coal at $3.00 per ton; coal consumption 3.5 lb. per kilowatt-hour; sub-station attendance $1750 per annum; maintenance of car equipments, 0.4c. per car-mile for 600-volt direct current, 0.5c. for 1200-

volt direct current, and 0.6c. for alternating current, and fixed charges at 10.5%.

COMPARATIVE COST PER MILE, SINGLE TRACK.

	Direct current 600 volts	Direct current 1200 volts	Alternating current 6600 volts
Roadbed complete including grading, ballasting, etc....	$15,000	$15,000	$15,000
Trolley and feeder installed	3,800	3,000	2,100
Track bonding	600	530	480
Transmission line, installed	1,500	1,500	1,300
Sub-stations, installed	2,200	1,600	600
Power station, installed	2,450	2,450	2,570
Cars and equipment	1,800	1,970	2,300
Telephone	120	120	120
Total	$27,470	$26,170	$24,470
Saving over 600 volts, direct current		1,300	3,000

RELATIVE OPERATING COST PER MILE SINGLE TRACK PER ANNUM.

Per mile of track, one-hour headway	Direct current 600 volts	Direct current 1200 volts	Alternating current 6600 volts
Car-miles per day	64	64	64
Kilowatt-hours per day at power house	275	275	245
Cost of coal per annum	470	470	419
Cost of sub-station attendance	175	79	46
Maintenance of motors and control	94	117	140
Total	$739	$366	$605
Saving over 600-volt direct current exclusive of fixed charges		73	134
Saving in fixed charges		137	315
Total annual saving		$210	$449

Another method of comparison is to capitalize the annual saving exclusive of fixed charges. Assuming fifteen years as the average life of equipment and construction work, the present value of the annual saving in operating expenses per mile of track at 5% interest will be:

For the 1200-volt, direct-current system.........	$ 756
To which add saving in first cost...............	1300
Making the total capital value of...............	$2056 = 7.5%
And for the 6600-volt, single-phase system......	1390
To which add saving in first cost...............	3000
Making total capital value of...................	$4390 = 16%.

The above comparison is based on service and construction conditions applying to the typical high-speed interurban electric railway, the fundamental assumptions and principal data being as follows;

Length of road, 50 miles or more.

Cars 52 ft. over all, weighing 21 tons without equipment or load and seating 56 passengers.

Car equipment, four 75-h.p. motors.

Maximum speed on tangent level track, 45 miles per hr.

Schedule speed 24 miles per hr. including stops and slow running through towns.

Headway, maximum service, 0.5 hour.

Frequency of stops, one in two miles, interurban.

Average car energy, 85 watt-hours per ton-mile at car.

	Direct current 600 volts	Direct current 1200 volts	Alternating current 6600 volts
Cost of cars equipped	$10,800	$11,800	$13,800
Spacing of sub-stations	10 miles	22 miles	32 miles
Maximum voltage drop, trolley line	25%	25%	10%
Efficiency of system, generator bus-bars to cars	71%	71%	84%
Average efficiency car equipment	75%	75%	73%
Average power-factor of system	96%	96%	85%

As the 1200-volt, direct-current system is still in process of development, a brief description may prove of interest.

The roads which are now being equipped may be divided into three classes: 1. Those which are required to operate on 600-volt direct current at full maximum speed as on the 1200-volt sections; 2. Those which are required to operate on 600-volt direct current but at approximately half maximum speed; and 3, those which operate only on 1200-volt trolley.

The first class requires motors wound for 600-volts but designed to stand 1200 volts without danger of flashing or injury to the insulation. The motors are connected four in multiple when run on 600 volts and in two parallel groups of two motors in series when run on the 1200-volt sections.

In the second and third classes the motors may be wound for either 600 or 1200 volts, preference being given to the latter on account of improvement in tractive power at the slipping point of the wheels. In order to obtain satisfactory commutation qualities and to control the tendency to flash at the commutator at the high voltages encountered, all motors for the 1200-volt system are provided with a compensating winding in the shape of series wound auxiliary poles located midway between the magnetizing poles and so proportioned as to neutralize the armature reaction under all loads. The additional insulation required causes the motors to weigh 15% to 20% more for a given output than 600-volt motors. This additional weight is not due to the inter-pole construction, as on the basis of equal voltages the inter-pole motor will weigh about the same or a little less than the standard railway motor.

The control system is substantially the same as that used on the 600-volt system, with the exception of some slight changes in the insulation of the primary circuits. The secondary circuits are all energized at 600 volts, as are also the car heaters and lights, and for this purpose a small dynamotor is furnished for use when run on 1200 volts, the function being to change the voltage to 600. The capacity of this dynamotor as furnished with quadruple 75-h.p. equipment is 38 amperes, which provides for the lighting, heating, and air-pump circuits for one car, and secondary control circuit for a train of six cars.

DISCUSSION ON "HIGH-VOLTAGE DIRECT-CURRENT AND ALTERNATING-CURRENT SYSTEMS FOR INTERURBAN RAILWAYS," AT THE CHICAGO BRANCH, MARCH 26, 1907.

James Lyman: No branch of engineering is more active than that engaged in the electrification of transportation systems, so Mr. Davis' paper is as timely as it is interesting and instructive. The network of interurban railways in the middle West is one result of this activity. There is one system of electric railways centering in Indianapolis having 400 or 500 miles of road, and another in the central part of Illinois having about 300 miles of road, with 150 miles more now under construction.

Mr. Hesing: It has been pretty well demonstrated what the 600-volt, direct-current motor will do, but possibly it is not quite so well understood what the alternating-current motor will do. Just at present I have charge of a little alternating-current line, and maybe a short description of what we do will be of some interest. We operate at 3300 volts. The line is about 22 miles long, with no sub-stations whatever. We have a 00 trolley wire. In fact, we started out with two 00 trolley wires, and one was moved over to the pole and now acts as a feeder. The cars are not very large, about 35 tons, requiring 75-h.p. motors. To my mind, the operation has been very satisfactory. Our records show that the cars have run from 75,000 to 85,000 miles with only one furbishing of the commutators, and they run from 5,000 to 6,000 miles with one set of carbon brushes. We subject our cars to pretty severe treatment. They are geared for 42 miles an hour, and as the road is quite small and sometimes pushed beyond its capacity, a couple of ordinary flat cars are used for trailers, side boards are put around them and folding-chairs are provided. These are called "chair cars", and probably 600 or 800 people are hauled at a load. It doesn't look very nice, but it pays.

I am glad that the speaker says the alternating-current system is of so much value. I can hardly see how it can be improved upon, except in one particular—the acceleration of the motors is slow. Our stops are not frequent, but where, as in the city practice, stops are very frequent, I think the service would be a little bit slow. Paralleling the Alton, when we made a run for that, we had no trouble whatever to give the same service as the expensive red train. So I think that for a little road—really an experimental road—the alternating-current system is the thing to use.

Mr. Gould: Having had experience only with the standard 600-volt, direct-current system, I am more in the nature of a questioner. I would like to ask Mr. Davis as to the relative costs of maintenance of the line and trolley system of the two; that is, how much does the line maintenance of the alternating-current system exceed that of the 600-volt, direct current-system?

W. J. Davis, Jr.: The single-phase system has not been in operation sufficiently long to permit complete standardization of the line material. Such experience as we have had, however, indicates that a 6600-volt overhead trolley system using catenary construction may be made very reliable and durable, and should give a maintenance cost at least equal to the best 600-volt, direct-current construction.

Peter Junkersfeld: In making comparisons on the cost, I notice that Mr. Davis has used a figure of 10.5% fixed charges and he has applied that to all three systems. It seems to me from what I have heard and from what Mr. Davis has told us, that if 10.5% is fair for the 600-volt system it is liable to be somewhat low for the other two systems, for the reason that they are somewhat new and untried. It seems quite low to me even for the 600-volt system.

W. J. Davis, Jr.: That 10.5% does not represent maintenance. It simply represents interest, taxes, insurance, depreciation, and charges of that nature, with interest at 5%. These are independent of the kind of system used. The depreciation has been taken the same for each system; that is, life of buildings 40 years, copper and line equipment 20 years, rolling stock 15 years. These values are rather low than otherwise for a good system. It is possible to get more than 15 years out of modern car equipments, if well maintained.

Peter Junkersfeld: What I have in mind is, on the new and untried systems there would be quite a considerable "antiquation charge"; that is, the system will probably be perfected a great deal more in the next five or ten years, and part of the equipment will probably then be obsolete.

W. J. Davis, Jr.: That is true. Taking that into consideration the fixed charges should be somewhat higher.

Peter Junkersfeld: And that in time would make it a little more favorable to the 600-volt system. Another question: how does the maximum allowable drop compare in the two systems?

W. J. Davis, Jr.: The maximum momentary drop permissible in the 600-volt system should not, as a rule, exceed 50%; most systems are usually calculated for about 25%. The latter condition will give about 5% average energy drop, depending upon the frequency of the service, grades, and other conditions. In the 6600-volt, single-phase system the average allowable drop in the secondary distributing system is usually fixed at 5%, including that in the rail return, with swings approaching 10%. It must be remembered that in the alternating-current system the drop in the various sections between the car and the power station bus-bars is cumulative. In addition to the drop in the trolley line and track, there is an energy drop and reactive drop in the step-down transformers, transmission line, and step-up transformers. Finally, there is the regulation of the generators and the drop in speed of the engines when the car starts. These are all cumulative in their effect. In a direct-current system, on the other hand, we have only to consider the drop from the sub-station bus-bars to the car. For the above reasons it is necessary and desirable to allow a much smaller maximum drop in an alternating-current system than in a direct-current trolley system. A maximum voltage drop of 10% in trolley and track of a single-phase system will often correspond to 25 or 30% drop in the whole system.

W. A. Blanck: Mr. Davis makes a statement about 40% of these roads being single-phase roads. I must say I have enjoyed the statement very much, because we have tried in the middle West to find railways on which we could use the single-phase system. Most of those we have investigated found it almost prohibitive to use the single-phase system, because of exchanging rolling stock with other roads and running into the cities where direct current is used. Furthermore, we find it very difficult always to use high potential in the cities themselves. Is it possible to overcome these difficulties? Most of our systems run into cities where we can not use the alternating-current system to-day.

Mr. Davis proposes to put the sub-stations about 32 miles apart, which would give 16 miles on each side for one section. That is rather long and it makes the section dependent on any kind of breakdown in that long section, so that more subdivisions with feeders or more frequent sub-stations will be required. Have these questions been investigated, and has any difficulty been found in placing the sub-stations so far apart?

W. J. Davis, Jr.: I do not think it necessary to place sub-stations closer together, because of possible unreliability in the secondary distributing system. It might be well to have a switch on a pole suitably located so that a part of the line may be cut out for repairs. If the line is properly erected, a 30-mile section, where cars are operating normally on one-hour headway with a maximum of one half-hour headway, ought not to be considered excessive in the light of past experience. The time may come in the development of the alternating-current system when sub-stations will be omitted entirely and 11,000 volts will be fed direct into the trolley with power stations located 30 to 50 miles apart. If the load-factor is sufficiently good to warrant the use of this arrangement, the system is reduced to the basis of the ordinary city railway system so far as simplicity and reliability are concerned. Some of the 6600-volt, single-phase roads now being installed will feed out 15 or 16 miles from one sub-station.

W. A. Blanck: It is necessary to enter cities with interurban roads. If steam-road conditions prevailed, if there were isolated terminals, an alternating-current system would be practicable, but interurban roads generally terminate in a city, and must operate therein by the direct-current system. We are all convinced that the alternating-current system is a coming system—much less investment for same amount of traffic done—but present operating conditions almost make it prohibitive to put it in.

W. J. Davis, Jr.: So far as the motor is concerned, the alternating-current motor can be built to operate as well on direct current as the ordinary direct current motor. Several instances have come under my observation where a combination of the 600-volt, direct-current and 6,600-volt single-phase sytems has made it possible to secure an increased economy in operation and also a considerable saving in cost.

I have in mind the case of a road 65 to 70 miles long. On the first 15 miles the service will be extremely heavy, requiring the operation of two- or three-car trains on 15-minute headway with frequent stops. The rest of the road will require the service of single cars every hour. There will be required a rolling stock equipment of about 30 cars, of which 25 will operate on the 15-mile suburban section and the remaining five on the longer interurban section. A straight single-phase system will prove objectionable on account of the intrinsically higher cost of the car equipments, due to the frequent service. on the other hand, the straight direct-current system will prove expensive on account of the larger number of synchronous converter sub-stations required on the 40-mile interurban section. A combination of these two systems, the 15-mile suburban system being equipped for direct current and the 40 miles interurban section for alternating current, will prove cheaper in first cost and more economical to operate than either system considered separately. This combined system will require two alternating-current sub-stations on the 40-mile interurban section, two direct-current sub-stations on the 15-mile suburban section, twenty-five direct-current equipments, and five single-phase equipments. The objection from an operating standpoint of having two types of motors is more than counterbalanced by the possibility of securing the most desirable operating features of both systems with the objectionable features of each reduced to a minimum.

T. F. Clohesey: What is the relative efficiency of these motors while running? For instance, a 300-h.p. car at full load alternating current and then when it enters a city and has to operate on direct current? What is the efficiency of the same car provided there are no stops?

W. J. Davis, Jr.: It will be about 2% better on direct current than on alternating current.

W. A. Blanck: Have you overcome all the difficulties now in regard to interference with telephone lines? I have heard that in the East especially there are frequent complaints from telephone subscribers in the interurban districts—they have complained of interference with the service.

W. J. Davis, Jr.: There were complaints in the early days, because we had no operating experience with the actual conditions existing between the telephone lines and the single-phase lines, but within the last year we have found out how to cure all of the troubles. I do not know of a single case where, if proper consideration is given to the system when it is first put in, there should be any trouble with the telephones.

W. A. Blanck: There is another very interesting question to be settled—the bow versus the trolley. In the different tests mentioned, which arrangement has been used for collecting the current from the conductor?

W. J. Davis, Jr.: That question is probably the most vital of the whole alternating-current system. No overhead collecting device has yet been devised which experience has shown to be safe and reliable and to have a low maintenance at a speed exceeding 60 miles an hour. The third-rail is the only system which has been proved to be absolutely satisfactory. There have been several bow collectors designed, but none of these has been operated long enough to show exactly what maintenance could be expected from it. After a little more experience we may probably produce some form of collector which will have a longer life than the present form.

W. A. Blanck: What difficulty have you experienced in regard to the suspension of the trolley wire in the catenary form. Where the suspension points are less than three feet apart, do you find in running 60 miles an hour that each point gives a particular shock or kick to the bow, or do you overcome these difficulties? Have you been able so far to see what it will take to keep up the catenary construction work? Have you any data on these matters?

W. J. Davis, Jr.: No; we haven't any data to cover any period of time of sufficient length to be reliable. The suspension points in my opinion ought to be 15 to 18 ft. apart; this spacing giving the best results at high speeds where bow collectors are used. Where a wheel collector is used, the spacing between suspensions may be made 50 ft, or about three to the interval between poles.

W. A. Blanck: Have you found it necessary in your exerience to bond both tracks for single-phase service? or do you think it is sufficient to have only one track rail bonded, and in case of double track to have one cross-bond every half mile or so, or do you find it necessary to put a bond on each track?

W. J. Davis, Jr.: It 's usual to bond both tracks, because of greater safety, but I do not think there would be any great danger if only one track were bonded. In many high-tension systems a ground wire is carried on the poles as a lightning protection. If that ground wire were connected to the rail at suitable intervals trouble would be prevented.

W. A. Blanck: My special question with reference to that is whether one of the rails can not be used for signal service, and if it is what interference is there from having only one rail bonded and alternating current in one rail, while perhaps there is another frequency for single phase in the second rail, which I understand to a certain degree is used in the New York Central.

W. J. Davis, Jr.: I do not know of any case where that arrangement is used, but I can think of no objections to it. It would appear to be perfectly safe if a ground wire is run in connection with the track return.

L. M. Zapp: Mr. Davis, in his statement as to direct-current efficiency, said I think 71 per cent. from power station to the car on 600 volts. Is not that rather high?

W J. Davis, Jr.: The value given is based on 90% efficiency for the trolley system, 83% for sub-stations, including transformers and synchronous converters, and 95% for the transmission line.

L. M. Zapp: Of course that would depend on the load-factor and also on the magnitude of the system, whether it is only a 50-mile system operating from one power station, or a 300-mile system. The load-factor on an interurban line operating half-hour or even hour schedules will very seldom be greater than 35%, if storage-batteries are not used. May I ask Mr. Gould if he remembers just what his figures are?

Mr. Gould: They will not average 35%.

W. J. Davis, Jr.: Do you remember what your efficiency is?

Mr. Gould: About 75% from the sub-stations bus-bar.

L. M. Zapp: In a paper written by Mr. A. S. Richey, electrical engineer of the Indiana Union Traction Company, he said that the average efficiency of transmission from power station to the car motors on that system was a little better than 56%. That was on about a 300-mile, single-track system. I was connected with that road, and I remember that with 13 sub-stations we got an average efficiency from power station bus-bars to sub-station bus-bars of about 70%. The sub-stations would average about 15 miles apart. The feeder was nearly all 500,000 circular mils. Mr. Richey's later tests showed that the average efficiency to the car motor was only about 55 or 56%. That being the case, it would make the figures still more favorable to the alternating-current railway.

I. E. Brooke: In the alternating-current system with sub-stations 32 miles apart, what system of lightning protection is used for the catenary? Is there any other protection than that at the sub-stations themselves?

W. J. Davis, Jr: I think it would be well to have lightning-arresters more frequently than at the sub-stations. It is usual to place pole arresters about one mile apart.

I. E. Brook: It is a simple matter in a direct-current system to put up a lightning-arrester on a pole every 1000 ft. or so. ith 6000 volts it is a different proposition.

W. J. Davis, Jr.: Yes; they should be boxed in.

I. E. Brook: What are railway engineers doing at present with three-phase motors for heavy power work? Has that proposition been dropped or are they still considering it?

W. J. Davis, Jr.: There is quite a well defined field for the three-phase motor. That field, however, apparently does not exist in interurban railway work, but it has been found to be especially applicable to hauling trains on heavy mountain grades reaching 2% and 2.5% and covering sections of 10 to 30 miles. By the use of the three-phase motor, it is possible without material complication in the control system to return power to the line on descending grades. Power saved by such regeneration is of secondary importance, however, as the greatest gain is made by the saving in wear on wheels and brake-shoes.

The company with which I am connected has not yet built a locomotive of this type, but a large number of designs have been investigated, and there are no physical reasons why such locomotives cannot be built as powerful and as reliable as direct-current or single-phase locomotives.

H. R. King: What is the character of the station in a 1200-volt-direct-current equipment; that is, the character of the generator equipment?

W. J. Davis, Jr.: With one exception the roads now being built will use two synchronous converters connected in series. It is perfectly feasible to build reliable 1200-volt, direct-current generators or synchronous converters.

Mr. Hatch: In regard to the 1200-volt line now building from Seymour to Sellersburg. If I remember aright the current out of Indianapolis is 550 volts; then there is a stretch using 1200 volts, and on the other end of the line I believe it is 650 volts. Will they be able to run any car clear through on that line?

W. J. Davis, Jr.: Yes; the motors will be wound for 600 volts, and on the 550- and 650-volt sections they will run at full maximum speed with motors in multiple. For 1200 volts, the motors will be connected in groups, two series, two multiple.

Mr. Hatch: Would there have to be very much change in an ordinary direct-current car to do that?

W. J. Davis, Jr.: No; simply having a commutating switch which will change the grouping of the motors as the car passes from one section to the other.

Mr. Hatch: Practically the same speed?

W. J. Davis, Jr.: Yes. The volts per motor will be the same for 1200- as for 600-volt operation. There may be cases where it is desirable to run at half speed on the 600-volt section; namely, within city limits. Here it might be well to use a 1200-volt motor, although the same result can be obtained by connecting in series-multiple groups, using 600-volt motors.

E. N. Lake: What rate of acceleration have they been able to attain with the later single-phase equipments?

W. J. Davis, Jr.: That depends on the size of the motor and gear-reduction. Most interurban single-phase cars, geared for 40 to 45 miles an hour with four 75-h.p. motors, 42-ton car, will give about one mile per hour per second rate of acceleration. As a matter of fact, it is not essential to have a very high rate of acceleration for interurban work, because the stops are infrequent (averaging about one in two miles) and the difference between one mile per hour per second and a mile and a quarter per hour per second, would not materially affect the running time.

James Lyman: Mr. Junkersfeld has referred to the depreciation percentage. Mr. Davis' figures are, I think conservative. In the development of a new line of apparatus, like this alternating-current–direct-current car equipment, it is understood that there are some features that undoubtedly will become obsolete after a time and will have to be replaced. There is also a good deal of apparatus that can be depended upon as reliable and as slow in depreciation and good for many years. The question that confronts the railroad engineer is whether it is not better on new work where the conditions are favorable to get in line at the start for the alternating-current type of apparatus that will soon become standard practice and which will eventually, if not at once, show marked economy over the standard 600-volt, direct-current system.

A paper presented at the 217th meeting of the American Institute of Electrical Engineers, New York, March 29, 1907.

LIGHTNING PHENOMENA IN ELECTRIC CIRCUITS.

BY CHARLES P. STEINMETZ.

1. Originally lightning denoted electric discharges between clouds or between cloud and ground, and, when applied to an electric circuit, the results of such a discharge striking the line. Later it was found that during atmospheric disturbances, such as passing thunder storms, disturbances occurred in electric circuits even without the discharges striking the line. These disturbances, caused by induction, were also classed as "lightning," and applied to electric circuits, lightning then came to mean all the effects of atmospheric electricity.

With the introduction of electric circuits of higher voltage and larger electrostatic capacity, phenomena were observed in such circuits of the same character and effect, and requiring the same protective devices, as the disturbances caused by atmospheric electricity, even in cases where atmospheric effects were excluded, as in underground cable systems. The term lightning when applied to electric circuits, therefore, was extended to cover also these effects, which are due to internal circuit changes, as changes of load, discharges through weak places of the insulation, etc.

The damage done by lightning to telegraph and telephone circuits being relatively small compared with the disastrous effects occasionally occurring in high-potential systems of large power, it was acknowledged that frequently most of the damage is done by the power generated in the system; the atmospheric or other disturbance merely started the phenomenon. The term lightning was thus once more extended to include all the abnormal phenomena of the flow of generated power of the system which result from an atmospheric or other disturbance.

In its most general meaning, as understood now when dealing with electric circuits and their protection, ***lightning denotes all phenomena of abnormal voltage and abnormal frequency.***

The lightning phenomena in electric circuits then comprise:

External lightning, the disturbances due to atmospheric electricity.

Internal lightning, the disturbances due to defects of the circuit or its operation, etc., and

Surges, that is, disturbances in the flow of generated power, brought about by the external or internal lightning and depending for their energy on the power of the generator system, hence frequently destructive.

2. The phenomena of abnormal voltage and frequency in electric circuits are the same three classes of phenomena met with in the disturbances in any medium which is the seat of energy:

1. Steady stress or gradual electric charge.
2. Impulse or traveling wave.
3. Standing wave or oscillation and surge.

1. *Electric Charge.* The potential difference against ground, or pressure of the total electric circuit, may gradually rise by an electric charge accumulating in the circuit—just as in a body of water, a river, the height may gradually rise until the water breaks through the embankment—the electric charge discharges across the lightning-arresters, or punctures the insulation, whichever is the point of least resistance.

Some causes of such steady and gradual accumulation of electric charge, and of potential difference against ground, of an electric circuit, are:

a. Collection of static charge from rain, or snow-drift, or from fog, carried by the wind across the line. Illustrating this on a three-phase system with insulated neutral, it will be seen that the potential difference against ground, which normally is symmetrical, Fig. 1, Curve I, gradually, by the simultaneous static charge of all three lines, changes to Curves II, III and IV, until the maximum potential difference against ground is sufficient to discharge to ground. The system then returns to the condition Curve I, and then traverses the same cycle again. This electrostatic accumulation of charge, in the case of efficient lightning protection, may appear as a series of discharges over the lightning arresters, which periodically follow each other.

b. Electrostatic induction from a passing cloud.

Assuming, for instance, a positively charged cloud passing over a transmission line. The ground below the line then carries a negative electrostatic charge, corresponding to the positive charge of the cloud. The line should have a negative charge

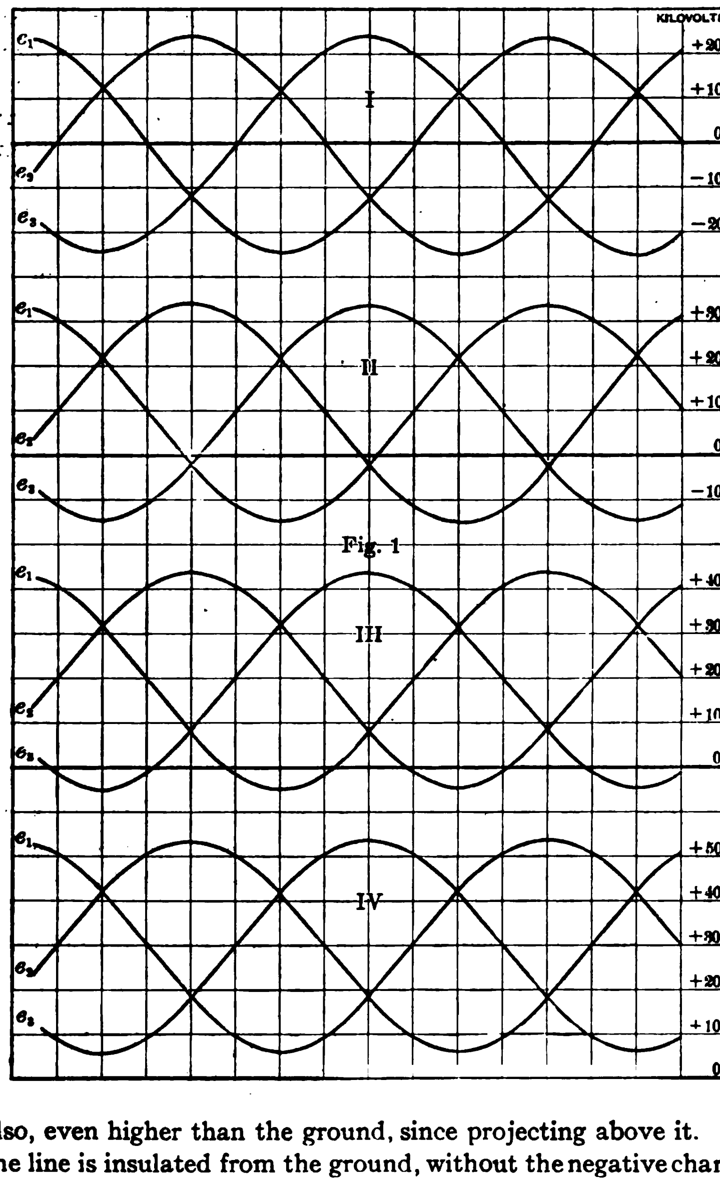


Fig. 1

also, even higher than the ground, since projecting above it. If the line is insulated from the ground, without the negative charge required for electrostatic equilibrium, it thus appears at a positive potential against ground; that is, at cloud potential. With the approach of a positively charged thunder cloud to the transmission line, the positive potential of the line against ground rises until a discharge takes place from the ground to the line, charging the line negatively. Inversely, with the cloud receding from the line, the line remains negatively charged; this charge not being bound any more by the positive charge of the cloud, discharges to ground. That is, during the approach and during the recession of a thunder cloud, discharges may occur between a transmission line and the ground; in the former case with the line of the same potential, in the latter case, with the line of opposite potential to ground, as the cloud, and due to a gradual accumulation of electrostatic potential difference, by induction from the cloud.

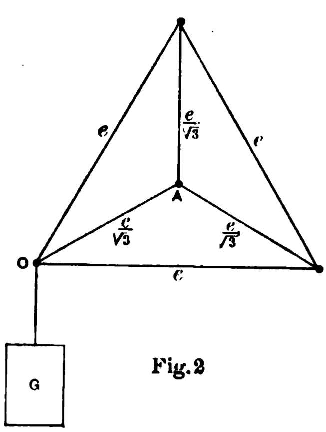


Fig. 2

This is the same phenomenon as, in the electrophorus of the physical laboratory, an equal charge appears on the inductor when approaching it to the resin plate; an opposite charge when withdrawing it.

c. Potential differences between line and ground due to differences of atmospheric potential in different regions traversed by the line, especially if the line passes through different altitudes as valleys and mountain ranges.

d. Accidental electrostatic charges entering the circuit, as friction electricity from the belt of belt-driven machines.

Somewhat similar phenomena result from:

e. Unsymmetrical conditions of the generator potential. For instance, if in a three-phase system one line is grounded, with the three-phase voltage e between the lines (Fig. 3) and $\frac{e}{\sqrt{3}}$ between lines and neutral, the mean potential of the total system is that of the neutral point A, hence, with a ground G at O, the total system as a whole has an alternating potential difference $O A = \frac{e}{\sqrt{3}}$ against ground, and induces electrostatically or causes other disturbances, with this potential difference.

f. Existence of higher harmonics in the electromotive force wave of a polyphase system, of such order that they coincide in the different phases; that is, the whole system rises and falls with their frequency. So in a three-phase system, the 3d, 9th, 15th, etc., harmonics coincide and may cause trouble, where

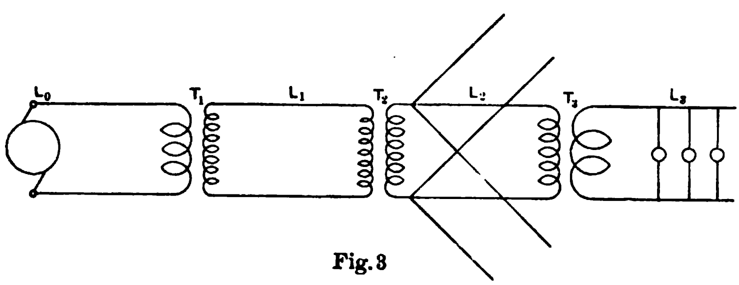


Fig. 3

they appear, as for instance, by star connection or primaries and secondaries of transformers with grounded neutral.*

The danger of such accumulations of potential lies:

a. In their liability to damage the insulation of the system by puncture, and

b. In their liability of producing, by their discharge, other and more serious disturbances.

In taking care of these by lightning-arresters arranged to discharge at a safe margin of voltage above the normal, the main problem is to arrange the discharge path so that the discharge passes harmlessly; that is, without producing other disturbances. It is the same problem as in the protection of a water-power station against freshets by dam and overflow, safely to discharge the water by means of the overflow.

*See A. I. E. E. Proceedings, November, 1906, Discussion.

3. The effects of steady electrostatic stress, whether unidirectional, a to d, or alternating as e and f, appear not only in its own circuit. but also in circuits in inductive relation thereto, and may even be more serious in secondary circuits. For instance, let Fig. 3 diagrammatically represent a transmission system, comprising generating station L_0, step-up transformers T_1, transmission line L_1, step-down transformers T_2, primary distribution circuits L_2, a local lighting transformer T_3, and house light circuit L_3.

All these circuits have capacity against ground, and the transformers also capacity between primary and secondary, and as regards the electrostatic capacity, the system can diagrammatically be represented by Fig. 4.

Let C_0, C_1, C_2, C_3, represent the capacities against ground respectively of the generating station L_0 and the circuits L_1, L_2, L_3 (including the capacities of the corresponding trans-

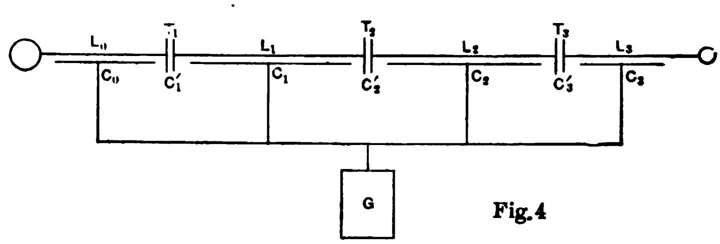


Fig. 4

former coils against ground) and, C_1', C_2', C_3', the capacities between primary and secondary of the transformers T_1, T_2, T_3.

An electrostatic charge of line L_1, giving the potential difference against ground e_1, also has an electrostatic path to ground, over the two capacities C_1', and C_0 in series, and so produces a potential difference against ground, e_0, in the generator circuit L_0, which is intermediate between e_1 and 0, in the proportion of the capacities C_1' and C_0; that is,

$$e_0 = \frac{C_1'}{C_1' + C_0} \tag{1}$$

e_0 is very much lower than e_1, but the circuit L_0 is of very much lower voltage than the circuit L_1, and while e_1 may be a safe voltage for the high-potential insulation of L_1, the lower voltage

e_0 may be beyond the safe limit of the insulation of the low-potential circuit L_0.

If L_0 is a generating station, or sub-station, its capacity against ground, C_0, is so large compared with the capacity C_1', that for steady stress the voltage e_0 is generally negligible, and this phenomenon is appreciable only when e_1 is an alternating potential, or the high frequency of an impulse or oscillation. Hence this phenomenon is of importance only where the capacity of the low potential circuit against ground is small. This may be the case in a house lighting circuit. An electrostatic, or alternating voltage (case e and f) e_2 in the primary distribution L_2, gives an induced voltage:

$$e_3 = \frac{C_3'}{C_3' + C_3} \tag{2}$$

in the circuit L_3, and with the short extent and low capacity C_3 of a local house-lighting circuit, and a voltage e_2 of several thousand volts, e_3 may be sufficient to involve under unfavorable conditions at least a fire-risk. The voltage e_3 is reduced by reducing the effective capacity C_3' by grounding the transformer core and case of T_3; but entirely eliminated only by grounding the circuit C_3.

2. *Impulse and Traveling Wave.* 4. The second class of phenomena is the impulse or traveling wave. A sudden local electrostatic charge of a transmission line, as by a lightning stroke, or inductively by a lightning flash suddenly discharging a cloud, or any other sudden local change, produces a wave of potential and of current which runs along the line, just as a water wave runs over the ocean surface.

Such a potential wave or impulse is very high and of steep wave-front at its starting point or point of impact, but gradually broadens and flattens out, and ultimately disappears, if the line is of unlimited length; just as the wave produced, for instance, by throwing a stone into a body of water is steepest at the point of impact and gradually flattens out and disappears. Successive stages of such a traveling electric wave are illustrated by Figs. 5 and 6.

Such a wave, when reaching the end of the line, is reflected and thrown back, thus returning again and so forming a system of nodes, and maxima, as shown diagrammatically in Figs. 7 and 8; that is, a standing wave.

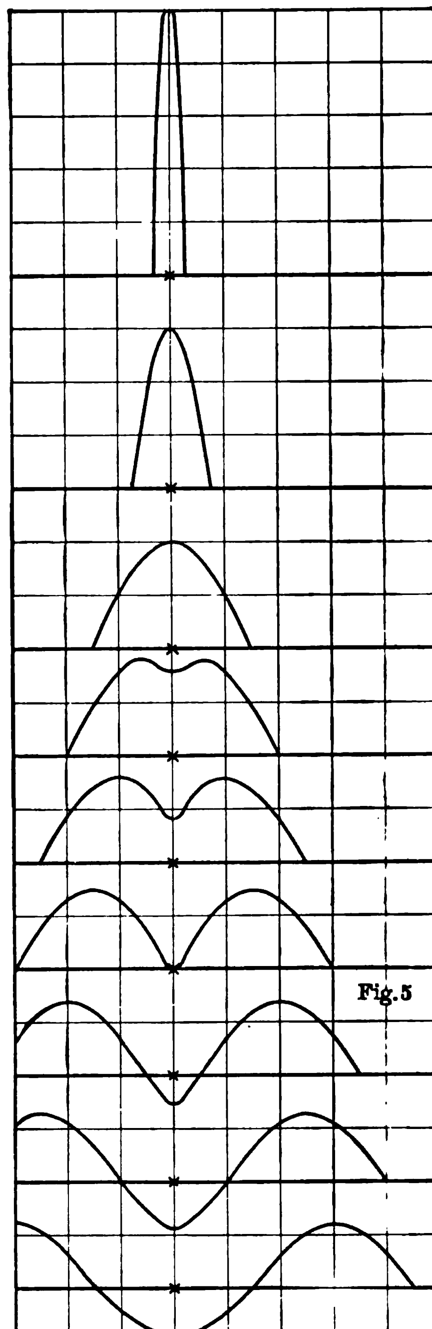
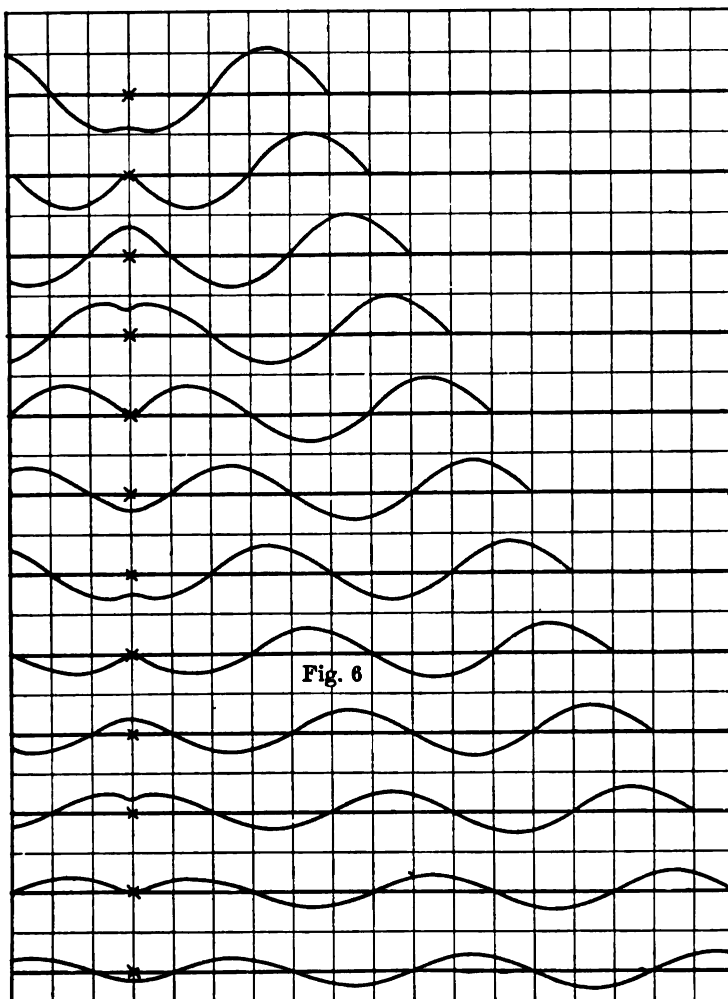


Fig. 5

When reaching the station—generating or sub-station—such a traveling wave is partly reflected by inductance of reactive coils, transformers, instruments, etc., and partly transmitted. The different reflected and transmitted waves so superpose upon



each other; that is, the impulse is broken up into a number of secondary impulses and local standing waves, which may reach voltages far higher than that of the traveling wave, just as an ocean wave when approaching the beach is broken up into the surf, with wave-crests far exceeding in height that of the un-broken wave.

The complex system of phenomena resulting from the ap-

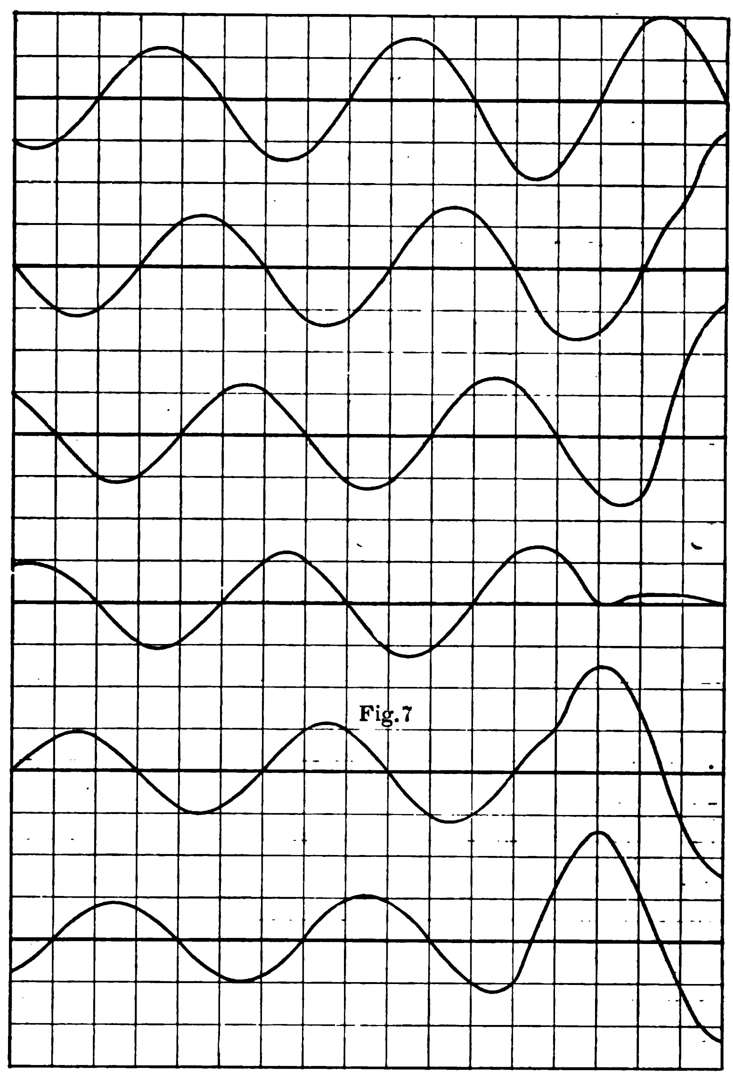


Fig. 7

proach of a traveling wave to a station is analogous to the breaking up of an ocean wave into surf, and may indeed be called "electrical surf." While individual effects; for example the formation of high-frequency standing waves or oscillations from an electrostatic impulse entering a circuit of inductance and capacity, the effect of an inductance in the path of an impulse, the phenomena occurring at a branching point between two circuits, etc., can be calculated, the complete predetermination of all the electrostatic and electromagnetic effects of an electric wave entering the complex system of circuits of a station is no more feasible than the exact calculation of the motion of the water particles of an ocean wave when it breaks as surf at the beach.

The breaking up of an impulse or a series of impulses or traveling waves in entering a station appears as electrostatic displays, sparks, streamers, and brush discharges at conductors, switchboards, etc., the so-called "static," which signals in the station the existence of a disturbance on the line.

The general equations of a traveling wave are of the form:

$$\left.\begin{aligned} e &= \sum_{1}^{\infty}{}_{k}\ \varepsilon^{a_k u - b_k t} A_k \cos\,(k\,c\,u - w_k)\,\cos\,(k\,g\,t - \phi_k) \\ i &= \sum_{1}^{\infty}{}_{k}\ \varepsilon^{a_k u - b_k t} B_k \cos\,(k\,c\,u - w_k')\,\cos\,(k\,g\,t - \phi_k') \end{aligned}\right\} \qquad 3$$

5. Some of the causes of such traveling waves are:

a. Direct or secondary lightning strokes entering the transmission line. This usually gives a single impulse, or very few impulses of extreme steepness of wave-front, but short extent, and capable of exerting very considerable power only locally, but not after traveling considerable distance; that is, a direct lightning stroke may shatter several poles, but do no damage to the station, if not very near to it.

b. Electrostatic induction by clouds. Corresponding to the electrostatic potential between cloud and ground an electrostatic charge exists on the line. Every lightning flash in the cloud, and between cloud and ground, represents an abrupt change of the electrostatic potential and requires a rearrangement of the electrostatic charge on the section of the line below the cloud, and thus gives an impulse of an intensity corresponding to the intensity of the flash, or rather the magnitude of the change of electrostatic potential of the terrestrial field. Thus during a thunder storm, or other atmospheric electric disturbances near a transmission line, a series of impulses travel along the line, increasing in severity and frequency with the approach, and decreasing again with the recession of the storm. While each of these impulses is rarely of sufficent power to do serious

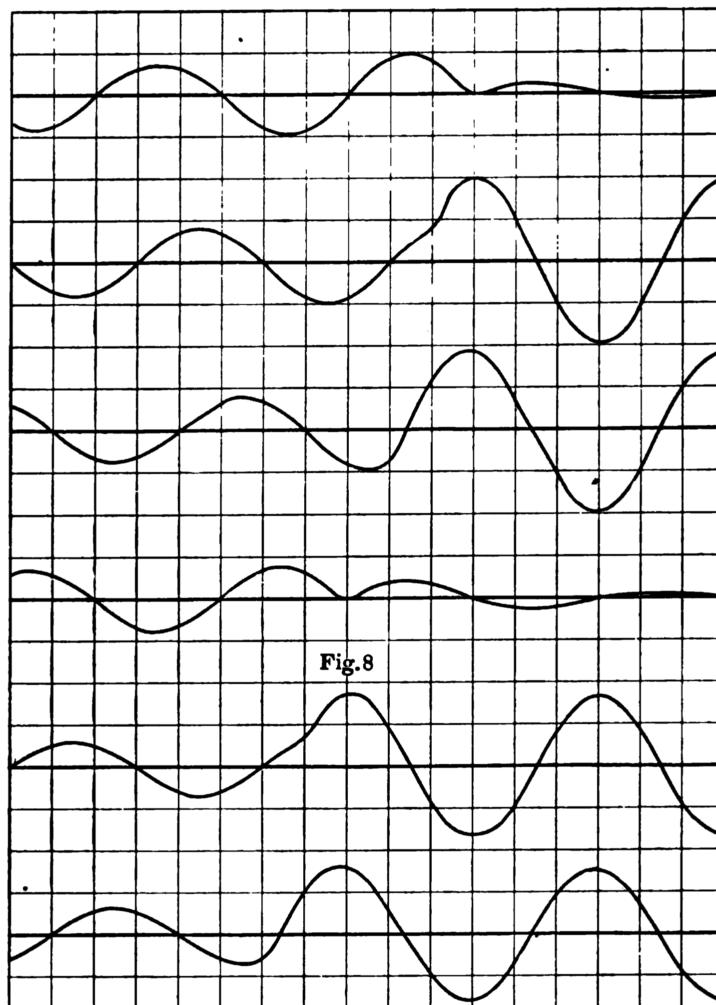


Fig.8

damage, due to their frequency of recurrence, they may lead to the production of destructive internal surges.

Traveling waves resulting from this electrostatic induction are usually of lesser voltage than direct lightning strokes, but their origin is of greater local extent; that is, they do not cause local destruction at the point of origin, but travel considerable distances, and their effect is therefore far more generally felt through the system. They probably are the most common manifestation of atmospheric electricity in electric circuits.

Through the electrostatic capacity between primary and secondary of transformers, these impulses frequently enter secondary circuits at an intensity increased by partial reflection at the transformer, and may even lead to sparks jumping from secondary wires to ground, as gas and water pipes, thus constituting a certain fire-risk, which can be completely eliminated by permanently grounding the secondary circuit.

c. Discharges of slowly accumulated potential, resulting in a series of successive impulses.

d. Any spark discharge from the line to another line or to the ground.

e. an arcing ground on one phase of an insulated system, or in general the existence of a " self-rupturing arc " in the system. As explained on former occasions, an arc, when shunted by capacity, as an arc between one conductor of an insulated transmission line and the ground, or between a conductor and the armor of an underground cable, is self-rupturing; that is, blows itself out explosively, due to the characteristics of the arc, and hence produces an impulse. An arcing ground thus sends out a series of impulses. Due to the very rapid succession and considerable power—the $\frac{e^2C}{2}$ of the system—these impulses are very serious electric disturbances of the system, and frequently lead to a low-frequency surge and result in extensive destruction. In their appearance in the station, they are very similar to *b* except of greater intensity and rapidity, and therefore are more dangerous.

f. Sudden changes of load, connection and disconnnection of apparatus, etc., also cause impulses. For instance, when connecting a dead transformer to the system an impulse traverses the transformer, and usually penetrates beyond the transformer into the circuit.

3. *Standing waves, oscillations, and surges.* 6. In water, standing waves are less frequent and prominent appearing in general only as stationary ripples in small pools. They form when a wave-train is reflected and thrown back by an obstruction, and the returning wave and the incoming wave

meet. Then at some places the waves neutralize each other and form a node; at others they add to a wave-crest of greater height than the traveling wave. Figs. 5 to 8 show the gradual change from an impulse to a traveling wave-train, and from the traveling wave to the standing wave or oscillation. Wave formation takes place only in large bodies of water, in which the wave-length is small compared with the total path of wave-travel, and the boundary usually too irregular to give good reflection and to allow standing waves to form. Standing waves, however, are the vibration of a tuning fork, or a violin string, or of the air in an organ pipe. Since the velocity of propagation of an electric wave is very high, 188,000 miles per second, even with very long transmission lines, oscillating as a single standing wave, or at fundamental frequency, the period of oscillation is relatively short, the frequency hundreds of cycles per second. In this respect, an electric circuit is rather more analogous to a violin string or the body of air in an organ pipe, and has the same tendency to form regular standing waves or oscillations. Just like a violin string, the electric circuit may oscillate either as single wave without nodes, or a number of nodes form, and the different sections oscillate separately, at higher frequencies.

This phenomenon of standing waves, or oscillations in transmission lines, has been investigated repeatedly. It is usually approached by considering the distribution of current and potential in a circuit of distributed capacity, inductance, and resistance.*

The standing wave is produced by the superposition of a wave and its reflected wave, and the general equations result from equation (3) by combining the impulse with the reflected impulse. Since the production of an oscillation or standing wave presupposes a slow decay of the wave-train; that is, b_k must be small, an approximate value is derived by suppressing the term $\varepsilon^{-b_k t}$. This means neglecting the gradual dying out of the wave; that is, considering it as alternating instead of oscillating. The trigonometric function of time can then be eliminated by the introduction of the complex quantity, and the equation of the standing wave, or oscillation, becomes:

*See Steinmetz, Alternating Current Phenomena, third edition, page 181.

$$E = \varepsilon^{-r\sqrt{\frac{\pi}{2}\frac{C}{L}}u} \sum_{1}^{\infty} {}_k A_k \left(\cos \frac{k\pi u}{2} + jk \sin \frac{k\pi u}{2} \right)$$

$$- \varepsilon^{+r\sqrt{\frac{\pi}{2}\frac{C}{L}}u} \sum_{1}^{\infty} {}_k B_k \left(\cos \frac{k\pi u}{2} - jk \sin \frac{k\pi u}{2} \right) \tag{4}$$

$$i = \sqrt{\frac{C}{L}} \left\{ \varepsilon^{-r\sqrt{\frac{\pi}{2}\frac{C}{L}}u} \sum_{1}^{\infty} {}_k A_k \left(\cos \frac{k\pi u}{2} + jk \sin \frac{k\pi u}{2} \right) \right.$$

$$\left. + \varepsilon^{+r\sqrt{\frac{\pi}{2}\frac{C}{L}}u} \sum_{1}^{\infty} {}_k B_k \left(\cos \frac{k\pi u}{2} - jk \sin \frac{k\pi u}{2} \right) \right.$$

where:

L = inductance,
C = capacity,
r = resistance,
per unit length of line, and
A_k and B_k are complex constants.

The lowest frequency of oscillation of a line is the frequency which makes the line a quarter wave-length. That is, if:

l = length of line,
v = velocity of light,
It is:

$$N_0 = \frac{v}{4\,l} \tag{5}$$

$$= \frac{47000}{l}$$

If l is given in miles.

From the line constants this fundamental frequency can be expressed, approximately, by:

$$N_0 = \frac{1}{4\sqrt{L_0\,C_0}} \tag{6}$$

where:

$L_0 = l\,L$ = total inductance,

$C_0 = l\,C$ = total capacity of the line.

In addition to the fundamental frequency L_0, all its odd higher harmonics, or any frequency:

$$N = (2\,k - 1)\,N_0 \tag{7}$$

may exist.

7. In general, an oscillation of a transmission line is a complex wave, containing fundamental and higher harmonics. The relative proportions of the different harmonics in the oscillating

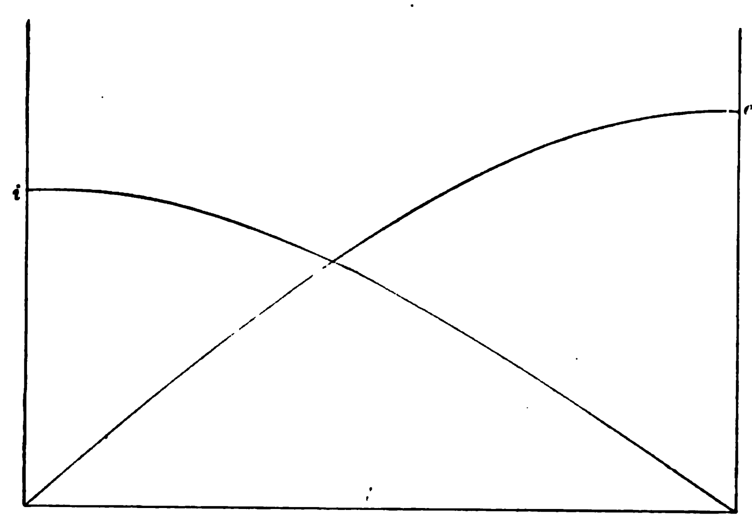


Fig. 9

wave depend upon the distribution of potential and of current at the moment of the start of the oscillation.

If the distribution of potential and of current at the start of the oscillation were perfectly sinusoidal, as shown by Fig. 9, only the fundamental wave would appear. The more irregular the distribution is, the more prominent are the higher harmonics; with a very irregular and abrupt distribution, the fundamental wave does not appear at all, but only higher harmonics.

A transmission line has, therefore, not only one frequency of oscillation, as a combination of condenser and separate inductance, but an infinite number of frequencies, of which one is the lowest or fundamental, the others its odd multiples or higher harmonics.

These frequencies depend on the resistance, inductance, and capacity of the line. None of these quantities is entirely constant. For instance, at high voltage the capacity increases by electrostatic glow, brush discharges, and streamers; inductance and resistance vary with the unequal current distribution throughout the section of the conductor, etc., so that at the very high harmonics, which are close together—for instance, the 199th and the 201st harmonics differ in frequency by 1% only—the gap between successive harmonics is bridged by the variability of the frequency, and a line for very high frequencies can thus oscillate at any frequency whatever. In other words, a transmission line can oscillate at a fundamental frequency, the lower higher harmonics thereof, and at any very high frequency whatever; that is, the line has definite frequencies of oscillation only at low and moderate frequencies, but not at very high frequencies. This is analogous to the formation of other standing waves.

8. The oscillation is the phenomenon by which in an electric circuit after a disturbance of the circuit conditions the flow of power restores its equilibrium. Any circuit disturbance may, and usually does, produce an oscillation which may be local only, that is, contain only the very high-frequency harmonics, if the disturbance is local; but it may become universal by including the fundamental and the lower harmonics. In the latter case it is usually called "surge."

In some respects, therefore, the oscillation is a result of a disturbance, as an impulse, and the power which oscillates is the generated power of the circuit; hence the possible destructiveness of the oscillation is limited only by the available power of the generating system, but does not directly depend upon the severity of the disturbance which caused the oscillation.

The power, which oscillates, is the energy stored by the flow of generated power in the electric field of the transmission line, as electromagnetic energy: $\frac{i^2 L}{2}$, and as electrostatic energy: $\frac{e^2 C}{2}$, and the shorter the section of line which oscillates the higher is the frequency of the oscillation. The smaller, however, is also the power and the destructiveness of the oscillation; considerable damage results, therefore only from low-frequency oscillations; that is, oscillations of the whole or a large part of the system. Local high-frequency oscillations are dangerous chiefly in their liability to destroy insulation by puncture, and to produce a low-frequency surge of higher power.

Since as a rule the maximum amount of energy which can be stored in the electric field of a circuit is the electromagnetic energy of the short-circuit current, $\frac{i_0^2 L}{2}$, the short-circuit surge is the most powerful and destructive.

Some typical forms of oscillations are:

a. Spark discharges to and from the line, as over some lightning-arresters; the breaking up of a traveling wave when entering the station, etc., result in the formation of very high frequency oscillations, millions of cycles per second.

b. Arcing grounds and other arc discharges to ground from

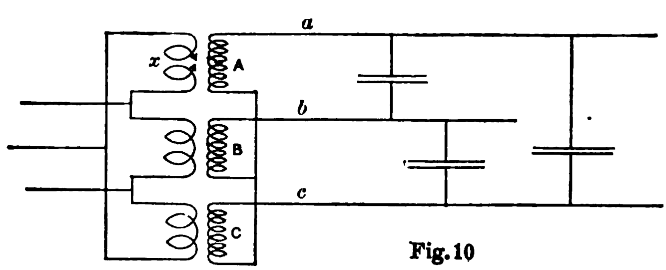


Fig. 10

a line of an insulated system; reflected traveling waves, etc., give oscillations which, while still of very high frequency, reach considerably further down in frequency than *a*, hundred thousands of cycles per second, and still lower.

c. Charge and discharge of the line, as when discharging an accumulated electric charge over a path of low resistance; connecting a dead transformer into the circuit, etc., results in high-frequency oscillations containing also an appreciable low-frequency component.

d. In general, changes of circuit conditions, as sudden changes of load; connecting or disconnecting a transmission line; opening a short circuit suddenly, etc., give oscillations in which the fundamental frequency predominates.

e. Low-frequency surges, consisting primarily of the fundamental wave, may be produced by certain transformer connections in polyphase systems, in which in case of an accident, an unequal distribution of load, or other causes, the open circuit inductance of a transformer coil is in series with the line capacity, in the circuit of a live transformer. Typical hereof is the case of a delta-star connected system without grounded neutral, if one of the sides of the delta is open circuited, as shown as X in Fig. 10. The high-tension coil A of this transformer is in series with the line capacity, $a-b$, in the circuit of transformer B, and in series with the line capacity, $a-c$, in the circuit of transformer C. In this case the voltage between a and the other two lines b and c is practically unlimited. A number of such transformer connections exist, and in their use this phenomenon should be guarded against.

9. Looking at the oscillation as surge of energy between the electromagnetically stored energy, $\frac{i^2 L}{2}$, and the electrostatically stored energy, $\frac{e^2 C}{2}$, it can well be seen, that the electrostatic energy is in general far more limited than the electromagnetic energy; and the maximum possible energy which can be stored in the electric field is the electromagnetic energy of the short-circuit current, as stated above. The most powerful oscillation is therefore the short-circuit surge of a system or oscillation produced by instantaneously rupturing a short circuit, as by a self-rupturing arc. In this surge the fundamental predominates, and the equations of the surge potential are:

$$e = i_0\sqrt{\frac{L}{C}} \left\{1.26 \cos\omega \sin\phi + 0.40 \cos 3\omega \sin 3\phi + 0.22 \cos 5\omega \sin 5\phi + 0.13 \cos 7\omega \sin 7\phi + 0.07 \cos 9\omega \sin 9\phi + 0.03 \cos 11\omega \sin 11\phi + \ldots \right\} \tag{8}$$

where:

i_0 = short-circuit current

L = inductance of line

C = capacity of line

$$\omega = \frac{\pi u}{2 l} \tag{9}$$

l = length of line,

u = distance along line, from point where the short circuit was ruptured, as zero point.

$$\phi = 2\pi N t \tag{10}$$

t = time

$$N = \frac{1}{4\sqrt{LC}} = \text{frequency of fundamental wave of oscillation.} \tag{11}$$

For instance, for a line of 50 miles, consisting of wire No. 0000, and transmitting 30,000 volts at 25 cycles, it is, approximately:

$L = .2\, h$, hence:
$x = 2\pi N_0 L = 31.4$ ohms
$C = 0.4$ mf., hence:

$$N = \frac{1}{4\sqrt{LC}} = 880 \text{ cycles.}$$

$$\sqrt{\frac{L}{C}} = 707$$

$r = 26$ ohms,
hence:

$$z = \sqrt{r^2 + x^2} = 40.8 \text{ ohms,}$$

and, assuming that the supply voltage, with a short circuit at the other end of the line, drops instantly to one third, or $e_0 = 10{,}000$ volts:

$$i_0 = \frac{e_0}{z} = 245 \text{ amperes.}$$

hence the surge voltage:

$e = 174{,}000 \left\{1.26 \cos\omega \sin\phi + 0.40 \cos 3\,\omega \sin 3\,\phi + 0.22 \cos 5\,\omega \sin 5\,\phi + \ldots\right\}$ volts.

At:

$$i_0 = 245 \text{ amperes,}$$

this gives the power of the oscillation:

$$e\, i_0 = 42{,}500 \text{ kilovolt-amperes.}$$

Standing waves or oscillations in electric circuits vary from the very low frequency of the fundamental surge of very long transmission lines, which approaches commercial alternating-current frequencies, especially when, as commonly is the case, the generating system participates in the oscillation, to frequencies of several hundred million cycles per second, in the discharge oscillation between the cylinders of a multi-gap lightning-arrester. Due to this enormous range of frequency, the physical effect of the oscillation also varies greatly. In very high frequency oscillations the power is very small; the electrostatic effects, as luminous glow, brush-discharge, streamers, and sparks, are prominent, but the direct damage is usually insignificant, and the effect local. Inductance opposes a fairly effective barrier. On the other extreme, low-frequency surges show little or no luminous display; inductance offers no obstruction, but due to their high power and wide extent, considerable damage may be done all over the system.

Oscillations, therefore, are frequently subdivided into high-frequency oscillations, in which the lower harmonics are absent, and low-frequency oscillations, in which the fundamental predominates, The name surge is frequently applied to denote the latter.

Between these two extremes, however, the low-frequency surge and the high-frequency oscillation, oscillations of intermediate frequency are found—against which inductances do not give sufficient protection—which have considerable power, and also give luminous displays, as streamers and brush discharges. Oscillations of this intermediate class are occasionally given by arcing grounds, spark discharges through defective joints in large cable systems, etc.

10. The four types of lightning disturbances here discussed—static charge, impulse, oscillation, and surge, may occur singly, in groups, or all occur together, or rather successively, the one preceding and causing the other. A static charge, for instance, rises, until it breaks through to ground and discharges, thus producing an impulse or traveling wave.

A traveling wave breaks at a station, and produces high-frequency oscillations.

A high frequency oscillation, puncturing the insulation, causes a short circuit, which ruptures itself, and thus produces a low-frequency surge.

A static charge, discharging over lightning-arresters with insufficient damping, causes a high-frequency oscillation.

A static charge, short circuiting the system by its discharge, causes a low-frequency surge.

Lightning-arresters, when discharging a high-frequency oscillation, may fail to hold back the machine current, and the short circuit resulting therefrom produces a low-frequency surge.

All four types of disturbances may occur successively:

An electrostatic charge rises until it breaks down to ground, thereby starting an impulse. This impulse at the entrance to a station breaks up in high-frequency oscillations. These oscillations puncture the insulation and produce a short-circuit surge.

The traveling wave produced by connecting a cable to the bus-bars may cause a spark discharge from conductor to cable armor at some defective joint. This spark develops into an oscillating arc, which sends out traveling waves along the cable. These, when entering the station, produce high-frequency oscillations, and systems of such oscillations follow each other with great rapidity, produced by the successive impulses caused by the oscillating arc, and produce a continuous "static" in the station, which ultimately produces somewhere a short circuit, and consequently a low-frequency surge.

In short, the number of combinations of such phenomena is unlimited.

11. The problem of lightning protection then is threefold.

1. Prophylactic; to guard against the entrance or origin of disturbances.

2. Restrictive; to guard against a disturbance leading to other disturbances.

3. Curative; to discharge a disturbance harmlessly:

As seen, the problem is a vast one, and comprises nearly every part of design, installation, and operation of the system.

1. Prophylactic; against entrance of atmospheric disturbances The location of the transmission line should be chosen so as to avoid exposed positions as far as possible. A grounded overhead wire of good conductivity offers considerable protection. Grounded side wires increase the protection and discharge side drift. The question of barbed wire against plain wire is still open to discussion. Emergency arresters in the lines or arresters at intermediate stations may shunt traveling waves toward ground.

Grounding the neutral of the high-potential circuit offers some protection against static charges and against arcing grounds, but increases the liability to short circuits and shutdowns due ot other causes.

A study of transformer connections and their operating conditions, of generator wave-shape and connections, of the possible origin of higher harmonics of the potential wave, the construction and location of underground cables, the protection of their joints, the desirability, size and location of reactive coils—all are subjects requiring careful consideration from the point of view of lightning protection. In short, the most important problems of lightning protection are met and should be solved before the question of lightning-arresters is approached.

The problems 2 and 3, to limit the disturbance, so that it does not cause other and possibly more severe disturbances, and to discharge it safely, are the problems which the designer of the lightning-arrester has to solve.

A paper presented at the 217th meeting of the American Institute of Electrical Engineers, New York, March 29, 1907.

PROTECTION AGAINST LIGHTNING, AND THE MULTI-GAP LIGHTNING ARRESTER

BY DAVID B. RUSHMORE AND D. DUBOIS

In this paper the term " lightning " is used in its comprehensive sense as defined by Dr. Steinmetz to include " All phenomena of abnormal voltage and abnormal frequency."

The object of this paper is to set forth the most recent developments in the multigap lightning arrester and to give recommendations concerning the protection of transmission lines and electrical apparatus from lightning disturbances. Reliable photographs of lightning are rare and difficult to obtain. A number of these, some of which have been published before, showing the varieties of lightning discharge, are included as a matter of general interest.

Fig. 1 is an instantaneous exposure of a stroke showing the peculiarly knotted path often taken. The best explanation of this is that the lightning at that point took a direction toward the camera, and, as is always the case, did not follow a straight line. We, of course, see the projection of its path in our direction.

Fig. 2 shows an instantaneous photograph of what is known as a meandering discharge. It is confined to the clouds and seems to be a general neutralizing of potentials.

Fig. 3 is an actual photograph of that riddle, " the thunderbolt." This phenomenon has been observed so often that we cannot deny its occurrence. There are at least three theories as to its nature.

1. That it is what it appears to be, a ball of globular lightning, which bounds about burning and destroying. This theory is backed up by no explanation.

2. That it is an optical illusion. That the eye is blinded by the light of a lightning flash and therefore sees the ball of fire

FIG. 1.

wherever it looks. This theory is rational except that it does not account for the damage done where the ball is last seen.

FIG 2.

3. That the eye sees a stroke coming directly toward it from the sky, as in the knot of Fig. 1. This would produce the effect

Fig. 3.

Fig. 4.

of a ball of fire, but the ball described usually moves slowly from place to place. To fit the theory, then, the lightning must be supposed to last for a considerable time and to shift its

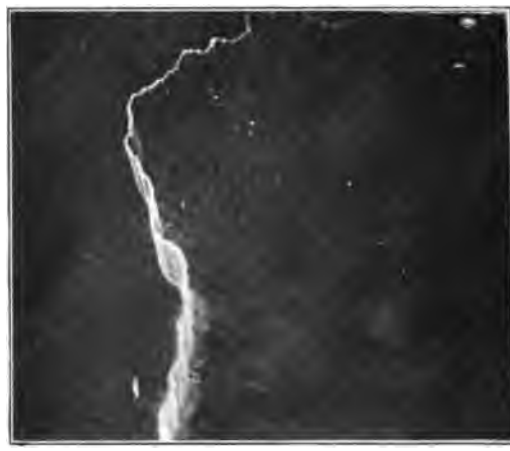


FIG. 5.

path, or to be made up of a number of strokes, each traveling by a slightly different path.

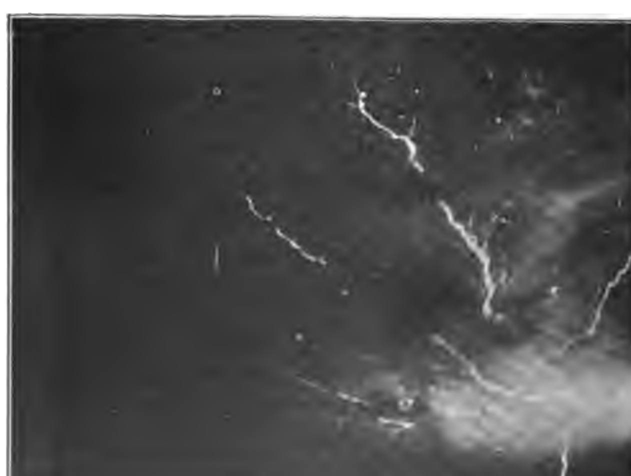


FIG. 6

The photograph here shown should discredit the second of these theories. The dotted character of a part of a stroke should be noted.

FIG. 7.

FIG. 8.

Fig. 4 shows in the lower corner another of these peculiar strokes.

Fig. 5 shows what is known as ribbon lightning. This photograph was taken from an express train on the prairie of North Dakota. This effect may not be due to the movement of a camera, as the telegraph pole shown shows no movement. It may be, however, that only the brightest part of a flash gave enough light to take the photograph of the pole. In the first case we would conclude that the stroke moves sideways. In the second case that the stroke lasted for some time. Possibly if viewed from near the point of striking this would have resembled the "thunderbolt" of Fig. 3.

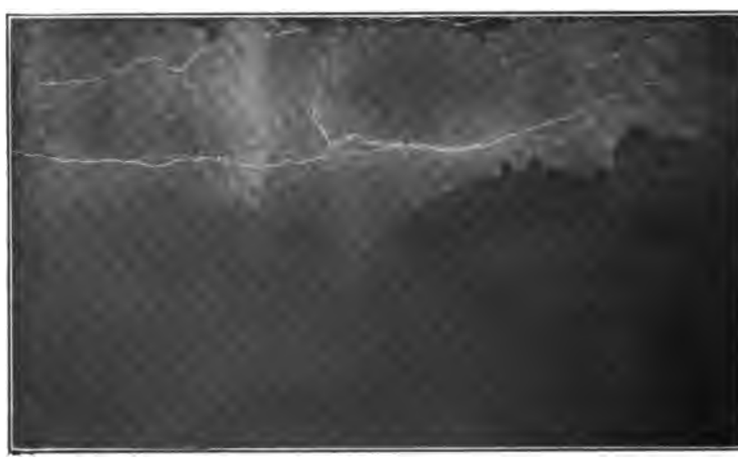


Fig. 9.

Fig. 6 shows a radial discharge among the clouds.

Fig. 7 shows a parallel discharge, most likely two discharges, one closely following the other.

Fig. 8 shows a horizontal discharge turning earthward. In this case a discharge must have started from cloud to cloud, but have come so near the earth that a second and stronger stroke took place from earth to one of the clouds. The second stroke would naturally follow the path ionized by the first.

Fig. 9 shows a horizontal discharge from cloud to cloud over Salt Lake City.

Fig. 10 is a remarkable photograph of lightning striking the tower of the City Hall in Philadelphia. This stroke knocked off one of the great iron rosettes of the tower but did no great damage.*

In considering lightning protection, the first step is naturally to study the apparatus to be protected, then the forces to which it will be subjected, and finally the protecting apparatus. The source of trouble "Lightning" is the subject of another of this evening's papers. For apparatus to be protected, we have insulators, transformers, switches and generators. The specifications for dielectric strength of generators is as provided

FIG. 10.

for by the American Institute of Electrical Engineers. The usual specification for high-tension transformers is that they shall stand from line to core twice the normal line voltage, independently of whether the transformers are star or delta connected. Switches are made to stand two and one-half times normal line voltage, and insulators should stand three times the line voltage dry, and one and one-half times the line voltage

*These photographs were obtained through the courtesy of Mr. W. F. Jennings, of Philadelphia, Pa. They are copyrighted.

with a precipitation of one-fourth inch per minute at 45°. The allowable rise of potential on the line is therefore less than 100%; about 60% of line voltage seems a desirable point at which the protective apparatus should operate.

Protecting apparatus consists briefly of lightning arresters, horn arresters, static discharges, choke-coils, and ground wires. Here lightning arresters are defined as apparatus that can relieve the line of high voltage without disturbing operating conditions.

Transformer Connections. From the standpoint of protection of the system from static disturbances, whether external or internal, the grounded star transformer connections with overhead ground wire offers the best conditions, and is in general recommended where other conditions do not decide. The causes of most frequent disturbances on transmission systems are short-circuits and grounds.

As regards short circuits between wires, there is but little to choose between the star and delta connections; but as regards grounds, and especially partial grounds, the grounded star system affords a great advantage in the reduced possibility of a disastrous increase in voltage.

When a ground is formed on one line of a high-tension transmission, that line should at once go out of operation, and with a properly designed system no interference with the delivery of power should result.

All of the considerations which enter into the question of transformer connections are not pertinent to the question of lightning protection, but from that standpoint the grounded star system with the overhead ground wire is most desirable.

The Horn Lightning Arrester. Due to its apparent simplicity, the horn lightning-arrester has of late received considerable attention. It is, however, not a piece of real protective apparatus in the sense of protecting the line without disturbing the conditions of operation. If it is used without resistance, it has the effect of a short-circuit; with resistance high enough to prevent it from causing a great drop in voltage, the protective features are largely eliminated. It is in reality an emergency device, a weak point in the system which is the first to rupture when the voltage rises to a dangerous value; if the system is without protective apparatus, it locates the point of breakdown when the condition is such that some failure must occur.

In general, the discharge of horn arresters without resistance will throw synchronous apparatus out of step, and necessitate starting up the system again. The voltage will drop to zero at a short circuit, and, as the arc may last from two to three seconds, the disturbance of the system is considerable. Where a fuse is used in series with a horn having no resistance, it can, of course, take but the one stroke and after this the system is unprotected. A flaming arc in air, such as occurs with the horn arrester, is a possible source of disturbance much worse than the original one, and under certain conditions can give rise to very high voltages, so that the possibility exists that the horn, instead of being a protective feature, may become a disturbing one.

The horn arrester with sufficient resistance to prevent short circuiting the system at time of discharge has some small protective value, which can easily be determined by the amount of resistance used. The real function of the horn arrester is its use to protect insulators along a transmission line, where the horns are so arranged that the current will jump to the horn before it will arc around the insulator. In this case the system would be disturbed either way. Where it is allowed to arc around the insulator, the latter would probably be destroyed and the time of disturbance of the system might be considerable—possibly until the insulator is replaced. With a horn protecting the insulator, the resulting short-circuit, while very undesirable in itself, is less disastrous than in the former case, and may only necessitate starting up the synchronous apparatus again.

Many disturbances caused by atmospheric lightning are of such high frequency that they will not travel along the line for any distance; but will jump to ground within a short distance of where the disturbance originates. To protect against this, the use of horns is recommended.

Care must be taken in the formation of the horns, and it must be remembered that the magnetic effect in putting out the arc is much greater than that of the heat causing the arc to rise. By improperly forming the horns, the arc will travel down instead of up, and will not clear itself. Horn lightning arresters have been installed on transmission lines in this country for a considerable number of years. In most places, however, where they have been used no careful record has been kept of their operation.

Protection for Wood Pole Transmission Lines. Practically complete protection for wood pole transmission lines can be effected against disturbances from atmospheric lightning. The best method of doing this is shown in Fig. 11. Here we have an overhead ground wire in connection with a lightning-rod and

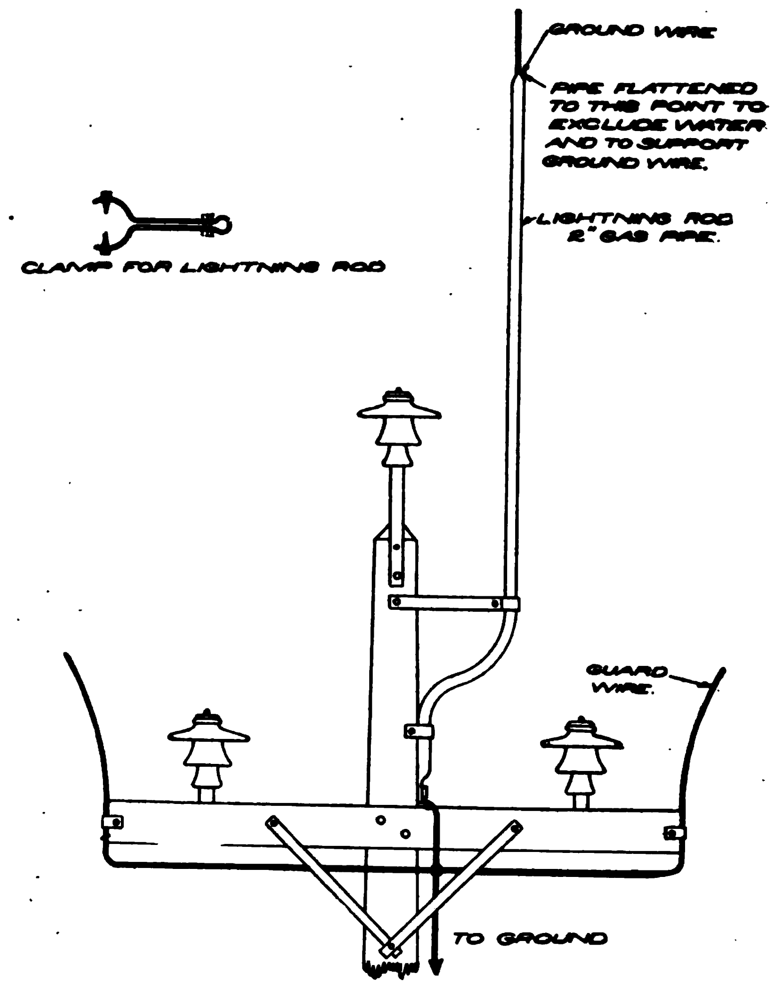


FIG. 11.

horns protecting the insulators. The overhead ground wire relieves the electrical stresses that would otherwise be thrown on the transmission line. The pipe supporting the ground wire acts as a lightning rod, and also as a horn to the top conductor, protecting its insulator. Side horns are attached to the cross-arm, protecting the two lower insulators, and these are all well grounded by a conductor attached to the side of the pole. This sketch is somewhat diagrammatic. The actual dimensions and construction as shown would not be used. The addition of the lightning rods has in some cases been found very efficacious.

Static Discharges. From the description of the new form of multigap arrester it will be seen that the arrester includes a static discharger consisting of the high resistance with the smallest possible number of gaps in series. This should offer sufficient protection against static wherever the arrester is used. There are cases, however, where the complete arrester is not thought necessary; such, for instance, as to protect underground cable systems having no exposure to lightning. In these cases the high resistance and series cylinders can be installed alone. Of course no protection against low-frequency surges of power is obtained, and if such are likely to occur the whole of the arrester should be used.

Water-Jet Arrester. What is known as the water-jet arrester has been used abroad to some extent, and in certain localities has apparently obtained a reputation which it is difficult to justify.

The equivalent needle-gap and the resistance of this arrangement are so great that it is evident that no real protection is obtained by its use. Its only function can be that of a high resistance connected permanently to the line, and in this case it has the advantage of being self-repairing if ruptured by discharge. It should to some extent prevent the slow accumulation of static charges on the line. It is, however, difficult to install, and it is questionable if the same results cannot better be obtained in other ways. Its use is not recommended.

Ground Wire. Without doubt an overhead ground wire affords protection to a transmission line. This protection is not complete, as a very few cases exist where insulators have been lost by lightning strokes even when a ground wire was used, but these instances are so very rare that the use of a ground wire is strongly recommended. It should, however, be installed in addition to other apparatus, and, while it will almost entirely protect the line, it does not protect the station apparatus completely. The use of a ground wire very greatly relieves the stress which can be thrown on the station apparatus, however, and much reduces the duty required of the station lightning arresters.

A $\frac{3}{8}$-in. stranded steel wire, grounded at least every 500 ft., should be installed above the highest transmission wire. Experience demonstrates that this is desirable, and that a ground wire below the transmission wires or in the center of a triangle is not as effective as one above. One ground wire is all that is necessary, although theoretically more are better; but, considering the great relief obtained from one wire and the small possible margin of protection from an additional wire, which would double the cost of installation, it is doubtful if commercial considerations would often allow the installation of more than one wire. The ground wire in connection with the earth forms a short circuited secondary which helps to dampen out disturbing oscillations.

Some early experience with ground wires were with those mechanically weak, and, at least in one case, the benefits which might have been derived from the electrical protection were more than cancelled for by the frequent breaking of the wire and the trouble caused by these disturbing the transmission system. With the wires specified above, no such trouble will result.

Where a ground wire is used in connection with the grounded neutral of a star-connected high-tension system, the best results will be obtained. In some cases the ground wire is mounted on insulators and is identical with the other conductors, in which case it is possible to use it as a spare conductor after removing the grounds. In all cases, both with wooden pole transmission lines and where steel towers are used, the use of a ground wire is recommended as a protective device against the effect of lightning.

Choke-Coils. The disturbances on a system in which protective apparatus is used come from various sources and are of various characteristics as regards voltage and frequency. If our object was to protect the station against disturbances which emanate from the transmission line, high reactance might be desirable except as it interferes with the regulation of the system. When, however, the disturbance is inside the choke-coil, high reactance is undesirable. In the case of a system with large capacity, an arcing ground in series with the high-reactance choke-coil may cause excessive rise of voltage. If one goes through the list of possible disturbances, it is seen that in some cases high reactance in a choke-coil is desirable; in others it is equally undesirable. It is, therefore, recommended that a choke-coil be used, but that it possess but moderate reactance, sufficient to reduce the pressure thrown on the station apparatus by an amount which will in general bring it within the safe value of the dielectric strength of such apparatus. Moreover, a choke-coil to be effective at high-frequency discharges should have very little capacity between turns; otherwise the discharge will merely pass through from turn to turn. The coils should, therefore, not be too close together and should be insulated by a substance having low specific

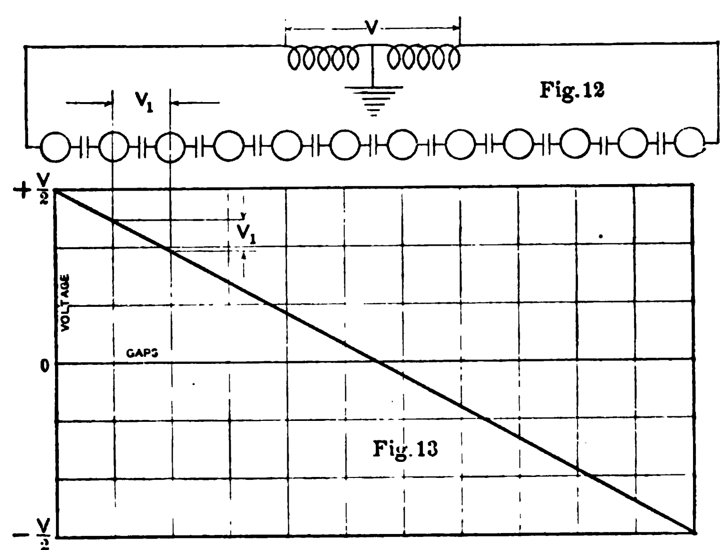
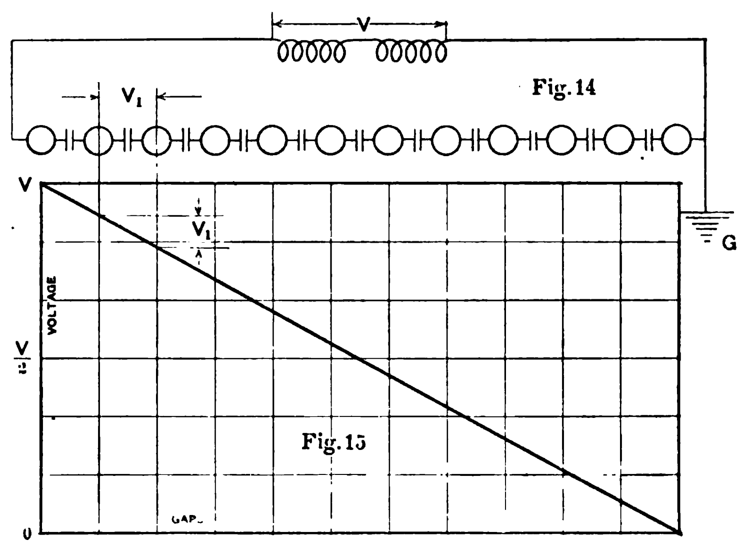


Fig. 12

Fig. 13

inductive capacity—air. Another advantage of air as an insulator for a choke-coil is that there is nò chance of permanent short circuit. Where ordinary insulation is used in a choke-coil there is no way to tell that the insulation has not been destroyed. Each stroke may break down a few turns until finally the coil is punctured from end to end. At the next stroke there is trouble.

Grounds. It is of the utmost importance to have lightning arresters well grounded. The ground wire, preferably flat copper strip, should lead directly to ground with as few bends as possible. It sometimes happens that a good ground cannot be conveniently made near the arrester, or that a better one can be made at a more distant point. In this case it is recommended that the principal ground be made at the more distant point, but that a ground of some sort, the best possible under the conditions, be made directly underneath the arrester. By the use of three grounds at a station the ground resistance of each can be determined. The two secondary grounds need not be complicated or expensive; iron pipes driven into the ground will answer. A record of the resistance of the grounds can thus be kept, and their good condition assured. All three should be used in parallel.



MULTIGAP LIGHTNING ARRESTER.

Theory. As is well known, the essential elements of the multigap lightning arrester consists of a number of cylinders between line and ground and line and line, these cylinders being spaced with a small air-gap between them.

The multigap arrester is distinguished from the single-gap arrester in that it can be made to discharge abnormal rises of potential without disturbing operating conditions. Under most conditions of operation, it discharges at a much lower voltage than does a single gap the length of which is equal to the sum of the small gaps, and the interrupting power is such that the disturbing charge passes off without allowing the dynamic current to follow for more than one-half cycle.

The following theory of the multigap arrangement is in part new, and is the result of very careful study of its characteristics.

As shown diagrammatically in Fig. 12, the cylinders of the multigap arrester act as plates of condensers in series. This condenser function of the multigap arrester is the essential feature in its operation.

Supposing capacity to exist between the cylinders, and no capacity between cylinders and ground; if a potential is applied across the arrester, the distribution of this potential will follow a straight-line law and the fall of potential will be the same between any two cylinders. This is shown in Fig. 13. If now we ground one end of this device, Fig. 14, the distribution of

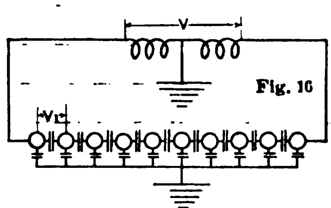


Fig. 16

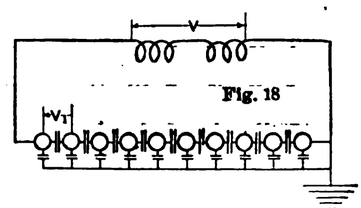


Fig. 18

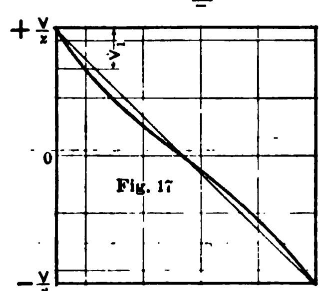


Fig. 17

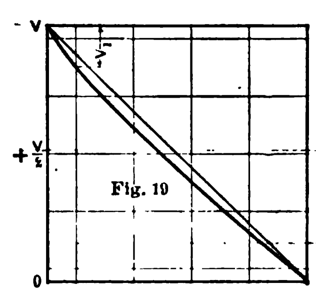
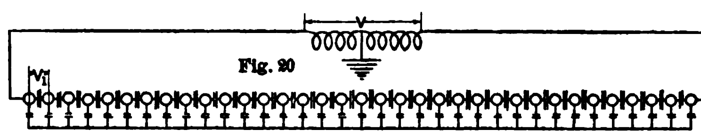


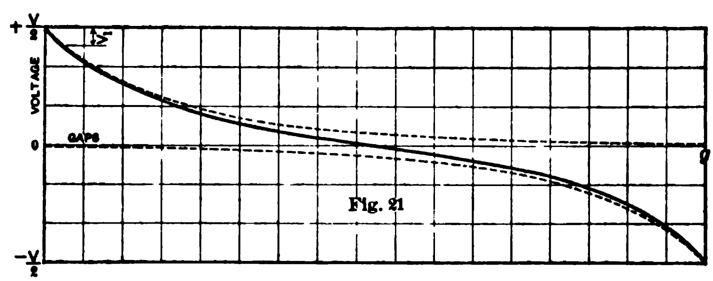
Fig. 19

potential over the cylinders remains the same in value, but the potential is all in one direction, or the whole device is raised above zero potential, as shown in Fig. 15. However, besides the capacity between cylinders, capacity also exists between each cylinder and ground. This is shown diagrammatically in Fig. 16. The function of this second capacity is to distort the gradient.

Where the number of cylinders is small, the curve showing the distribution of potential does not differ greatly from a straight line, as shown in Fig. 17. It will be noticed that this is a reversed curve, being symmetrical above and below the line of zero potential.

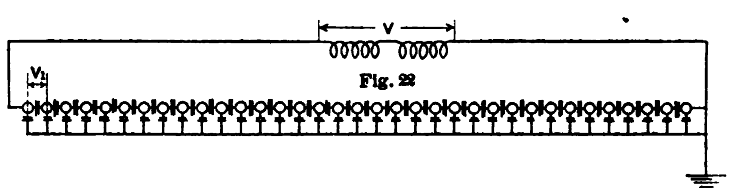
If instead of grounding the transformer in the middle, we now ground it at one end, (Fig. 18), the whole device is raised above zero potential and the distribution of potential over the

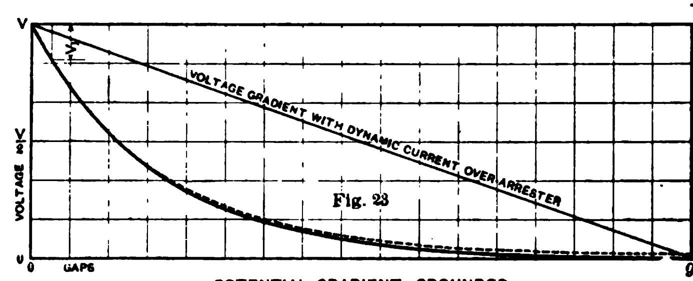




POTENTIAL GRADIENT, UNGROUNDED

cylinders is as shown in Fig. 19, where the curvature is in the same direction throughout but again not differing greatly from a straight line.





POTENTIAL GRADIENT, GROUNDED

Where we have a large number of cylinders, the conditions are somewhat changed. If we have a device as shown in Fig. 20, which is supposed to represent a large number of cylinders connected across a transformer with grounded neutral, the distribution over which is shown in Fig. 21, it will be noted that this curve differs considerably from a straight line. In this case there is a part of the apparatus in the middle where very small difference of potential exists between the cylinders, and the fall of potential at the end cylinders is much greater than that which exists between the cylinders nearer the middle. The distribution of potential over the device exhibits the general form of combination of an exponential function of opposite sign. If one end of the transformer is grounded instead of the middle, as shown in Fig. 22, we have the distribution of potential shown in Fig. 23. It will be noted that the drop of potential over the end cylinders, as shown in V_1, Fig. 23, is very much greater than that shown in V_1, Fig. 21, the voltages between lines being the same. If this potential drop reaches a certain value, a discharge across the cylinders takes place. With a large number of cylinders, therefore, a voltage which could not break through when the system was grounded in the middle may be high enough to break through when one end is grounded.

It will be seen that the potential between the first and second cylinders in Fig. 23 is much greater than between the second and third, etc., from which it is evident that this arrester breaks down in successive steps. At a certain voltage across the arrester the potential gradient between the first and second cylinders is sufficient to break down the dielectric between them. The potential of the second cylinder, then, being connected to the first by an arc, rises, and may rise to such a point that it breaks down to the third cylinder, and the third to the fourth, and so on till the arc has passed entirely across the arrester; then the line current starts flowing across and the distribution of potential is changed, following now a straight line as shown. The potential difference between all cylinders is then the same, and becomes much less than in the case before a breakdown. It is well known that to maintain an arc of alternating current across a gap, the voltage must be at least high enough to re-break down the dielectric each time after the arc goes out at the end of a half-cycle. The dielectric is greatly weakened by the heat produced by the passage of the arc, therefore the voltage to maintain the arc need not be as high as that which originally broke across. The weakening of the dielectric depends on the heat of the arc, and as this depends in turn upon the boiling temperature of the metal of the arc cathode, certain metals when used as electrodes require a higher voltage than others to maintain an alternating-current arc. The connection between the boiling point of the electrode metal and temperature of the arc is as follows: the current is carried across the gap by a stream of metal vapor coming from the cathode. If the metal vapor forms at a low temperature, the temperature of the arc will be low. Unfortunately, the low boiling temperature metals do not hold their form well under the electric arc. It is, therefore, necessary to use alloys rich in these metals. The metals of higher boiling point can not vaporize while those of lower boiling point are present, and so hold the cylinders in form without effecting the temperature of the arc. In the actual lightning arrester, much depends upon the choice of this alloy for the cylinders.

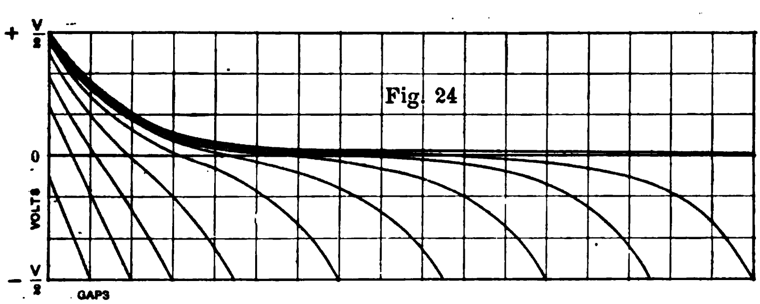
The arresters are, of course, designed so that the voltage gradient shown by the straight line in Fig. 23 is not steep enough to give a voltage across the gaps high enough to maintain an alternating-current arc. An arc following a discharge across the arrester would therefore go out at the end of the half-cycle in which it occurred.

In connection with the physical phenomena which takes place when the dielectric breaks down between cylinders, a note on the characteristics of air as a conductor of electricity is of interest.

Gases in general are such poor conductors of electricity that for long there was discussion pro and con regarding their possession of this property. A very small conductivity, however, exists under normal conditions, and this may be much increased in a number of ways, so that gases under certain conditions are good conductors of electricity. The gases conduct electricity when the temperature is raised above a certain point; when the gas is drawn from contact with incandescent metals or carbon, or is drawn from the vicinity of flames; when an electric charge has passed through the gas, or when röntgen, lenard, or cathode rays have passed through the gas; also when rays from radioactive substances or from uranium or thorium have passed through it; when gas has been exposed to rays from electric sparks; when the cathode is illuminated by ultra-violet light; also when air has passed over phosphorus or bubbled through water. Thus it is seen there are many means of imparting electric conductivity to gases, and not a few of these are concerned in the breakdown of the multigap arrester.

When gas has become ionized by an electric discharge or otherwise, it retains its conductivity for a period which may vary from five to eight minutes, more or less, a fact which has an important bearing on discharges which follow the first breakdown, and also a fact to be taken into consideration in the use of fuses and circuit-breakers.

The partial breakdown of a lightning arrester under normal conditions, when the static spark is playing across the first few gaps, generates rays which assist the breakdown of the gaps exposed to them; and as the breakdown of the arrester is a process of successive steps, the cumulative influence of this action may be considerable. The first discharge which passes across the dielectric or air is a true conduction of electricity



POTENTIAL GRADIENTS UNGROUNDED

by the gas. The succeeding strokes, however, are more or less in the nature of a minute arc stream, as shown by the spectroscope.

As before stated, when the voltage between any two cylinders becomes high enough, an arc takes place between them. Also voltage is highest between the cylinders nearest the line. Fig. 24 represents a series of potential gradient curves, with number of gaps and voltage just sufficient to start the discharge across the first gap. These curves are for the ungrounded case and follow the approximate equation:

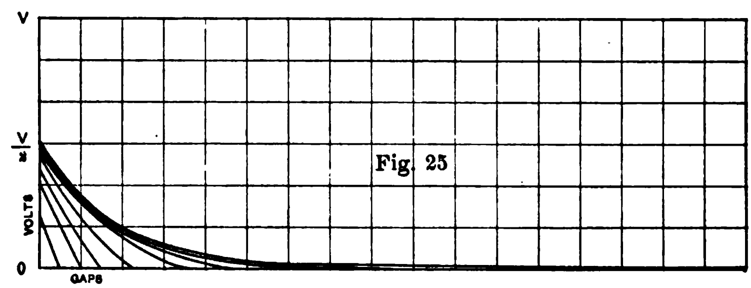
$$V_x = \frac{V}{2} (K^{-x} - K^{x-g})$$

where V_x is the voltage at any point x,

V is the voltage across any arrester,

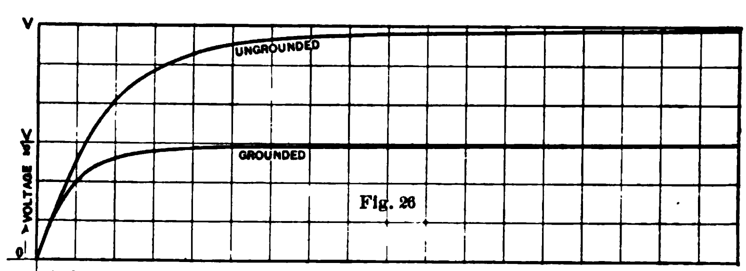
g the gaps of the arrester, and

K a constant depending on the ratio between the capacities of cylinder to cylinder, and cylinder to ground. In all these the potential gradient between the end cylinders is seen to be the same and is supposed to be steep enough to break down the dielectric. It is seen that the number of useful gaps



POTENTIAL GRADIENTS GROUNDED

is limited, that beyond a certain point it makes no difference how many gaps are added, the voltage of breakdown is not raised, and that there is a definite limiting voltage which would start a spark across the first of an infinite number of gaps. As has been often pointed out, a lightning stroke itself must be a phenomenon something of this nature, as the distances are so



great that we cannot conceive of voltage high enough simultaneously to rupture the entire dielectric. The lightning must either break from drop to drop or from dust particle to dust particle, working its way across to its destination.

Fig. 25 shows the condition with one line grounded. In this case the potential gradient between the first and second cylinders is the same as before. It is seen that both the number of useful gaps and the limiting voltage are half what they were before, for where the number of cylinders is such that the curve of distribution of potential becomes tangent to the axis of zero potential, any increase in the number of cylinders does not increase the voltage at which they break down, and this is just half the limiting curve for the ungrounded condition. In the design of the practical lightning arrester, however, we do not

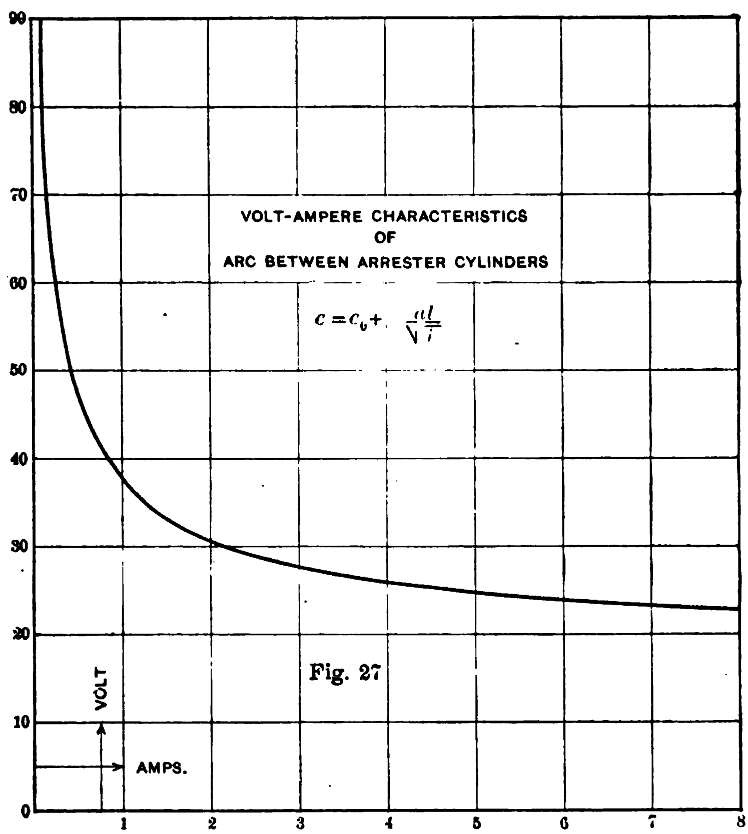


Fig. 27

work so high on the curves as is here shown, and the curves themselves are altered by the use of resistance. It is to be noted that for a low number of gaps there is little difference between the grounded and ungrounded curves.

Fig. 26 shows curves of voltage and number of gaps founded on the curves of Figs. 24 and 25. These curves are of the same shape as have actually been found by test.

Fig. 27 shows the volt-ampere characteristic of the arcs between cylinders, and indicates that the voltage between cylinders is equal to the counter electromotive force of the arc plus a factor which is approximately inversely proportional to the square of the current.

Fig. 28 shows the distribution of potential over the arrester with one line grounded, where breakdown occurs over a number of gaps without a complete discharge. This is one of the phenomena of multigaps. It will be noted that the potential gradient between the first two cylinders begins in this case at a point greater than the spark voltage, and that when this gap breaks down a new gradient is then established from cylinder No. 2, which, although not so steep as that from No. 1, still breaks down the gap to No. 3; thus the successive gaps break down until a gradient is reached less than the spark voltage. The reason for the decrease in gradient is as follows:

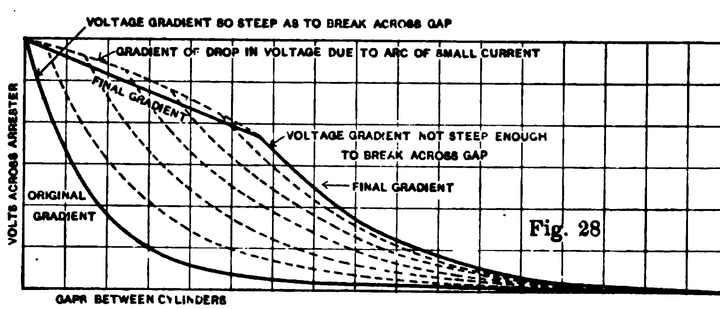
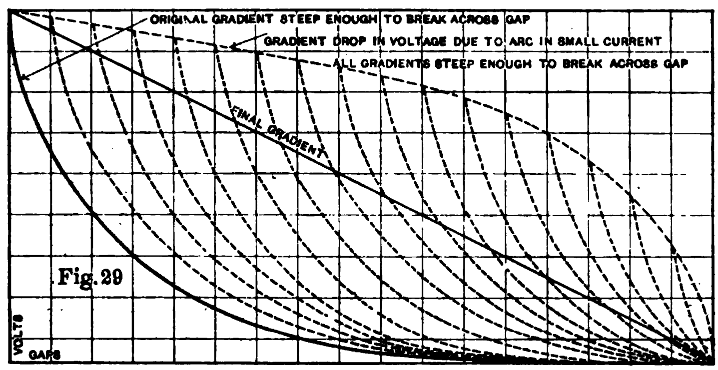


Fig. 28

when breakdown occurs from one cylinder to another, the second cylinder is charged to the potential of the first, less the drop in voltage due to the arc, which is shown in the arc characteristics, Fig. 27, to be very great at small currents. The current which flows across the gaps in this arc is, of course, small. It is made up at the normal frequency charging current and the charging current necessary to raise the gradient to its new position. On low frequency this last is most important. Due to the drop in voltage as the successive cylinders break down, the current through the arcing gaps also decreases, the gradient of drop in voltage following a curve. If the potential gradient as the arrester breaks down from one cylinder to another does not reach a value less than that of the spark voltage, the breakdown of the arrester is complete and discharge passes entirely across the apparatus. This means that either the voltage was higher at the start than in Fig. 28, or that the drop in voltage between the gaps was less. This is shown clearly in Figs. 29 and 30, which also indicate in the most interesting manner the difference due to the effect of frequency, which is a very important factor with the multigap lightning arrester.

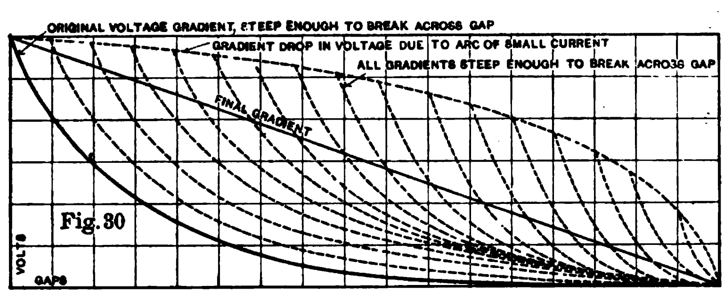
In Fig. 29 the voltage was higher than in Fig. 28 and the



COMPLETE BREAKDOWN LOW FREQUENCY

discharge was therefore complete. Fig. 30 with the same voltage as in Fig. 28 shows the effect of high frequency.

As stated above, when the breakdown occurs from the first to the second cylinders, the potential of the second cylinder depends upon the amount of current which passes. As this current



COMPLETE BREAKDOWN HIGH FREQUENCY

is that due to the capacities, which have been considered, it will be greater at high frequencies and the fall of potential between the first and second cylinders will therefore be less. As the arrester gaps break down successively, the fall of potential from one cylinder to another is less, and therefore such an arrester will discharge at a lower voltage for a higher frequency than for a low. At high frequency, due to the inductance of the cylinders themselves, the normal gradient is steepened; this also assists breakdown. In such cases (Figs. 29 and 30) where the arrester discharges completely, no point is reached where the potential gradient is less than that of the spark voltage.

As is well known, the multigap arrester without resistance discharges more easily at high frequencies than at low. By properly designing the resistance, this can in a large measure be overcome, so that the arrester will protect equally well at one frequency as at another. However, in the case under consideration, no resistance was assumed.

In the same way that high frequency lowers the breakdown of multigaps by increasing the current of the spark, high resistance, by absorbing voltage when this current flows, decreases breakdown. Resistance is more effective at high frequency in increasing breakdown voltage, as at high frequency the charging current is higher and therefore there is more voltage drop in the resistance.

Resistance. Resistance is one of the important factors of lightning-arrester construction. Its usual functions are, in general 1, to limit the current, 2, by shunting part of the arrester to give fewer gaps for low frequency to break across.

Series resistance limits the current under all conditions, but, although in this way protecting the arrester, it is dangerous in case of a surge. It has still another and perhaps worse effect. All resistance is more or less inductive, and in case of high-frequency stroke, serious resistance will prevent free discharge and tend to reflect the disturbing wave. With series resistance the arrester may have all the optical appearance of discharging freely and may puncture test papers, while its real value as a protecting device is not indicated in any way.

The discharge of any quantity of electricity from a good resistance during a time which must be at a maximum but a half-cycle is easily a matter of calculation, and it is apparent that, other things being equal, the protection afforded by an arrester is inversely as the amount of series resistance.

As will be described below, an arrester has been developed in which no series resistance has been used, but in which resistance nevertheless limits the current of discharge except in extreme cases of surge. Resistance also makes the arrester break down at uniform voltage at all frequencies and assists to discharge surges.

The desirable characteristics of resistance are as follows, it being impossible to obtain them all in any one known combination:

1. Sufficient heat-absorbing capacity.
2. Surface of such character that arc will not flash over.
3. Must be easily replaceable.
4. Non-absorptive as regards moisture.
5. Uniform conductivity over section.
6. Non-inductive and straight.
7. Should have no coherer action.
8. Sufficient mechanical strength to stand red heat without failing.
9. High specific resistance.
10. Resistance should not change with use.
11. Must not become incandescent under service conditions.
12. Must allow of good contacts.

Ideal Lightning Arrester. The ideal lightning arrester should prevent any rise of voltage dangerous to insulation. It should offer a free path of discharge from line to ground and from line to line, and should preform its functions without disturbing the operation of the system. It should put out the arc at the end of the half-cycle in which it starts, and should have no discrimination in its protective power as regards the frequency of the disturbance. That is, it should discharge at a certain voltage for any frequency. An arrangement of gaps and resistance as shown in Fig. 31 meets this last condition in this way; gaps alone break down more easily at high frequencies, but high frequencies will not readily break down through both resistance and gaps. Low frequency is not impeded as much by resistance, but can break through only a few gaps for the same voltage compared with high frequency. For a given voltage, then, the higher frequencies would break through the path with gaps only; frequencies somewhat lower, through the path with moderate resistance; and low frequency and accumulated static through the path with the high resistance. An arrester of this type, however, possesses the disadvantage that after a voltage of low frequency breaks across the gaps in series with the high resistance, the current which can follow cannot relieve the line. This can be overcome by an arrangement such as shown in Fig. 32. In this case the same paths of breakdown for the different frequencies are retained, but now if low-frequency breaks down the gaps in series with the high resistance, the entire voltage less that consumed in the arcing gaps is concentrated across the next highest division of gaps. These, if correctly designed, will at once break down, passing the strain still farther up the arrester, and so on, the arrester breaking down in sections until it is either completely broken down or the line voltage

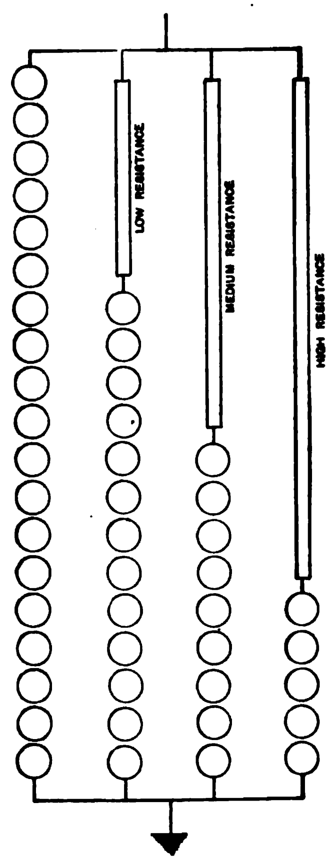


FIG. 31

has been lowered by the current flowing through the resistance. This idea has been worked out in the design of a new line of arresters described below.

THE GRADED RESISTANCE LIGHTNING ARRESTER

During the last year a very large amount of experimental work has been done to develop the multigap arrester, and it is felt that the results obtained will be, so far as can now be seen the maximum development of this type of apparatus.

The multigap lightning arrester has had the property of responding more readily to high frequencies than to low. In the new designs, however, by the use of resistance, as just described, this has been, so that a low frequency now discharges

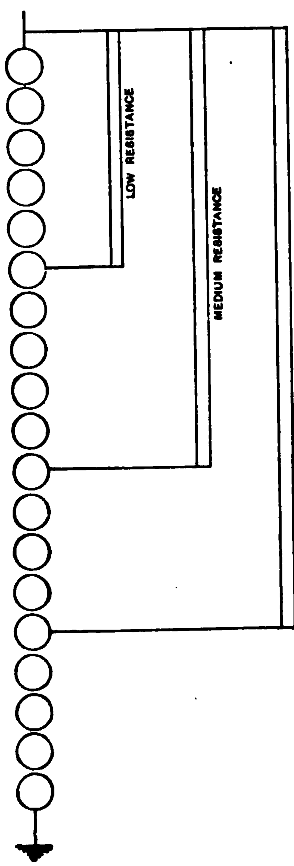


FIG. 32

with the same facility as high frequency, and the discrimination with regard to that condition is largely removed.

The arrangement for these arresters for 35,000 volts is shown in Fig. 33 for the delta and ungrounded star transformer connections, and Fig. 34 for grounded star systems. In each case we have three legs made up of *V* form multigap units, Fig.

35. Each leg is connected to one of the lines through a spark gap shunted by a fuse. Connected in just below the fuse

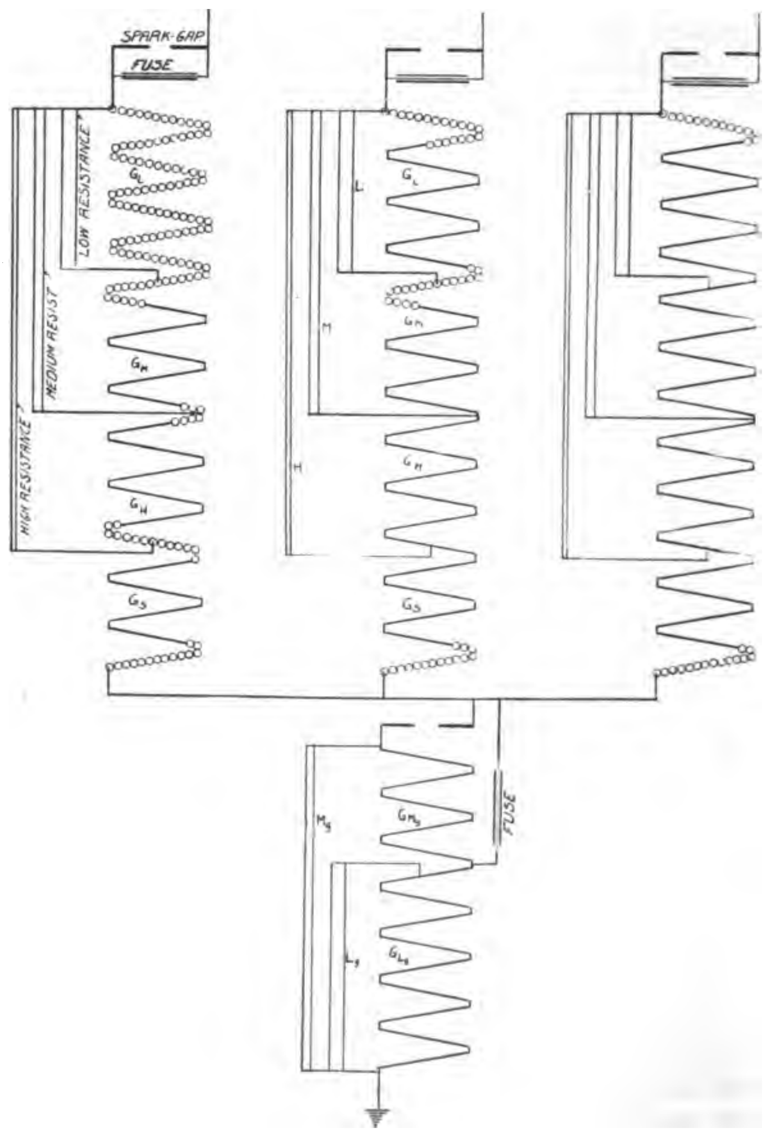


FIG. 33.

we have a novel device, in that we have the three resistances in parallel, tapping in to different parts of the leg as shown. These three line legs are joined at their lower ends by a common or multiplex connection, from which, for ungrounded systems, a fourth leg connects to the ground. In the arrester for grounded star systems no fourth leg is added, the multiplex connection being connected to ground.

Fuses. The use of a fuse in shunt with the spark-gap is for the condition of continuous high voltage on the lines from any cause, an arcing ground or otherwise. The fuse will then blow

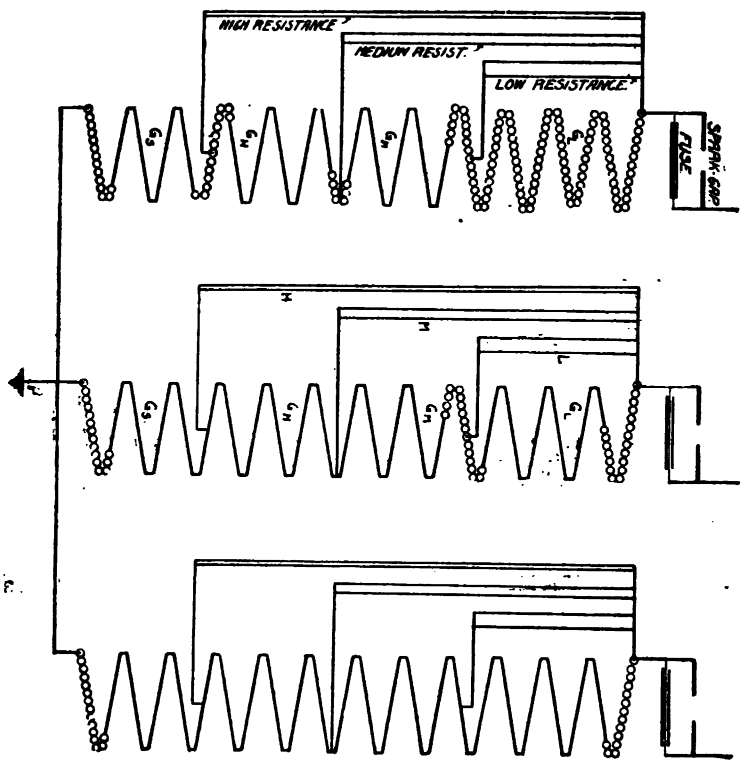


FIG. 34.

and it will throw the gap in series with the arrester and thus bring about an automatic adjustment of the gaps. This allows the arrester to be adjusted to discharge at but a small percentage above the line voltage, and thus to afford real protection. The introduction of the extra gap does not destroy the arrester as a protective device; it merely adds a factor of safety against the destruction of the arrester. If this fused gap were omitted, its equivalent would have to be introduced as additional multigaps. This fuse is so proportioned that it will not blow at an ordinary discharge. The small complication of the addition of this device is much more than offset by the close adjustment possible in the arrester, thus allowing the best protection to be had.

Resistances. The three resistances, designated respectively L, M, and H for low, medium, and high, represent a distinct advance in the art of lightning-arrester design.

The operation of these resistances has been partly described above. It has been shown how they force discharges of different frequencies to select different paths, giving breakdown at about the same voltage in each case; also how they assist in the breakdown of the arrester to give full discharge in case of surge. It

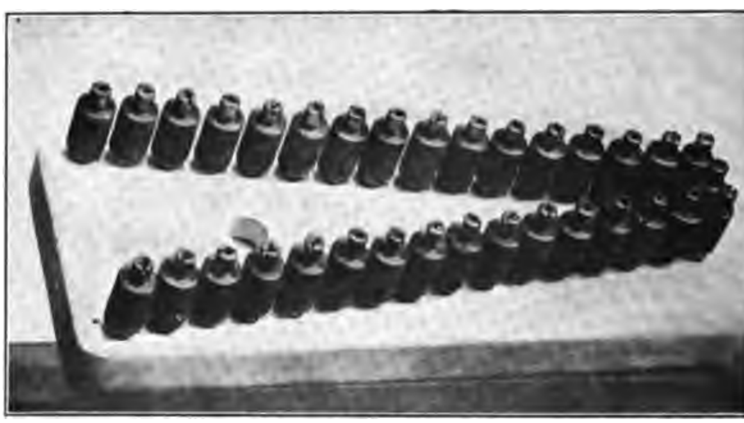


FIG. 35.

should be noticed that the gaps G_1, which would be the last to go down in this way, are of greater number than the other divisions, as it is not desirable that these gaps should breakdown except under extreme conditions. The low resistance, L, should be able to discharge the line sufficiently to relieve the voltage. It must be clearly understood that the use of the word "breakdown" means the discharge, not the failure of the arrester. It has been found that when gaps are shunted by resistance and the resistance is low enough, dynamic current will not follow a high frequency across those gaps, but will shunt at once to the resistance. Such a relation exists between the gaps G_1 and the resistance L. This being the case, it is seen that the resistance L is practically a series resistance so far as the safety of the arrester is concerned, but that it introduces neither of the objectionable features mentioned above. High frequency discharges do not have to pass through it, and the shunted gaps can arc over in case of necessity.

Another point to be brought out is that when gaps in series with resistance, such as L and G_m, are shunted by a second resistance such as M, a certain relation will bring about a condition such that a discharge of high frequency down the arrester will be followed by dynamic shunted through M instead of through L and G_m. M may be in this arrangement many times L in resistance, and in the arresters is high enough to limit the current which follows a stroke so as to give very little burning of the cylinders.

The resistance H, as has been explained, is used for assisting the breakdown of the arrester, and is also used as a static discharger, to allow small currents to leak to ground and thus prevent any accumulation of electricity on the line.

The arresters of this type are so designed that, should the arc pass across all of the gaps following the static discharge, the number of gaps is sufficient to extinguish the arc, and this holds with each resistance and with the gaps connected with it. That is, any current which might start across any of the resistances and the corresponding gaps would immediately be extinguished by that combination alone without the shunting effect of the other resistances, thus rendering the extinguishing of the arc doubly secure.

The breakdown of the gaps does not follow a straight-line law as regards voltage and number of gaps, the increase in voltage being less than proportional to the increase in the number of gaps. This is the reason why, with a grounded star system, no fourth leg is used in the arrester connection to ground, although we have in reality the multiplex connection between line and line. In this arrester the same margin for breakdown exists between line and line as between line and ground, but twice the number of gaps in series do not require twice the voltage to break over them, but with these proportions, approximately the voltage multiplied by $\sqrt{3}$.

With regard to the grounded leg, the fuse is so connected with the L_g resistance that but few gaps are in series, and we have a sensitive condition where the arrester will discharge easily at low as well as high frequencies. When, however, the fuse in the grounded leg blows, due to a ground on the line, we still have an arrester which will protect the line with one phase grounded, without suffering any injury to itself.

Lightning arresters of the form shown in Figs. 33 and 34 have been designed for the following voltages: 6,600, 10,000, 12,500, 15,000, 20,000, 25,000, 30,000, 35,000, 40,000, 45,000, 50,000, and 60,000 volts. Anything between these voltages is, of course, taken care of by the arrester on one side or the other, as is thought best. For lower voltages, down to 300 volts, the arresters are of slightly different design, having only two resistance rods. The 2300-volt arrester is shown in Fig. 36. For voltages below 300 volts no resistance is necessary, as the voltage is so low that the arc can never hold. These arresters, therefore, consist simply of single spark-gaps to be connected directly across the line.

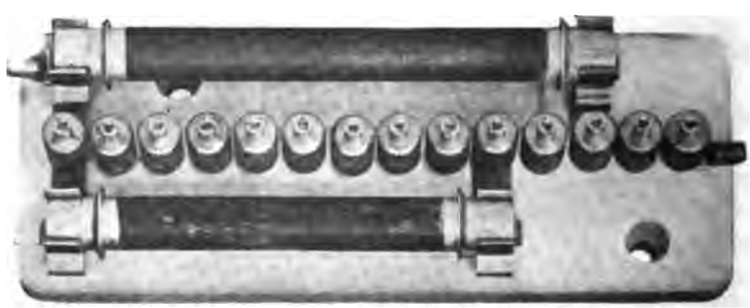


FIG. 36.

The 2300-volt arrester, Fig. 36, being intended for pole as well as station use, is necessarily simpler in design than the high-voltage arresters. It consists of 14 cylinders, 9 of which are shunted by a low resistance and 11 by a high resistance. As in the case of the higher voltage arresters, the grading of resistance makes this arrester discriminate between frequencies, giving each a path to break down that requires a voltage not too high or too low. Accumulated static passes off across the high resistance and two gaps in series. High-frequency discharges pass across the entire arrester; moderate high frequencies across the low resistance and four gaps. The low resistance is, as in the other arresters, proportioned with the number of shunted gaps so that the high-frequency discharge across these gaps is never followed by the dynamic current, the dynamic shunting at once to the low resistance. A photograph of this arrester discharging is shown in Fig. 37. Note that a discharge takes place over all the gaps, but that the arcs between the gaps shunted by the low resistances are very small compared with the bright arcs between the last four gaps. The static discharge is passing through all the gaps, while the half wave of dynamic current following the static is shunted part of the way by the resistance.

Fig. 38 shows an oscillogram of this phenomenon. It is seen that the only current in the shunted gaps is the current of static discharge. It should be noted that the current shown is not a measure of the true current, as the oscillograph can not respond to currents of such high frequency.

Fig. 39 shows an interesting oscillogram. Here both the total

Fig. 37.

number of gaps and the shunted gaps were reduced to a point considerably below the safe limit. The static discharge was at once followed by a half cycle of short-circuit current across all the gaps, voltage falling almost to zero. The following half-cycle, however, shows that the current left the shunted gaps and flowed through the resistance, extinguishing entirely after the end of this half-cycle. With the small number of gaps used, if it had not been for the resistance the arc would have undoubtedly and the arrester would have been destroyed. This merely held shows the protection offered by a shunt resistance a step below that designed. In a correct design, the dynamic could not have started across the shunted gap in this way, and the total number of gaps is sufficient to extinguish the arc of short circuit,

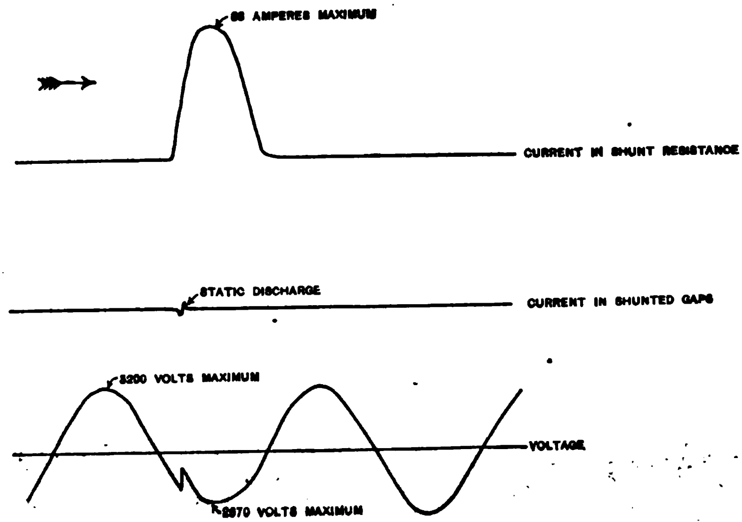

AMPERES MAXIMUM
CURRENT IN SHUNT RESISTANCE
STATIC DISCHARGE
CURRENT IN SHUNTED GAPS
3200 VOLTS MAXIMUM
VOLTAGE
2870 VOLTS MAXIMUM

FIG. 38

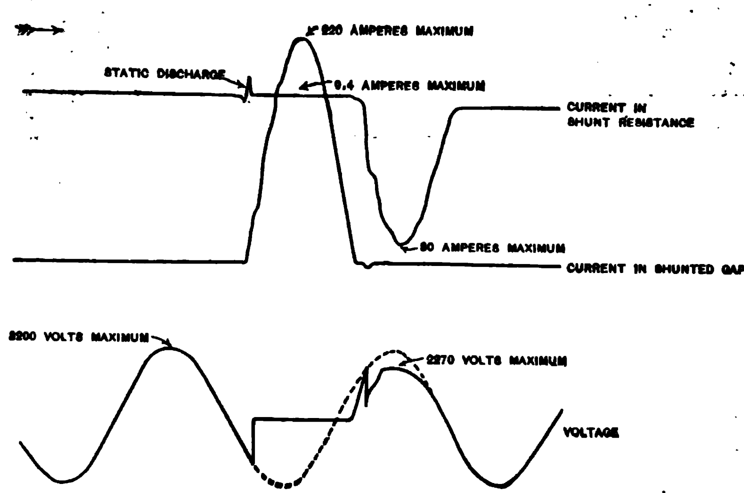

220 AMPERES MAXIMUM
STATIC DISCHARGE
9.4 AMPERES MAXIMUM
CURRENT IN
SHUNT RESISTANCE
80 AMPERES MAXIMUM
CURRENT IN SHUNTED GAPS
3200 VOLTS MAXIMUM
2870 VOLTS MAXIMUM
VOLTAGE

FIG. 39

even with no resistance. Returning to the low-frequency breakdown; as before stated, accumulating static merely discharges over the two end gaps. For a rise in generated voltage or a power surge, however, the current which could discharge through the high resistance would have no protecting effect. But with these two gaps broken down and arcing across, the high voltage would be concentrated across the next two gaps. As practically the same voltage broke through the first two, these will at once break down, allowing a discharge through the low resistance which should be able to take care of the system. To sum up, the effect of this use of resistance is as follows: the high resistance discharges static at low voltage and assists breakdown in case of surge. The low resistance allows low breakdown in case of surge, gives correct breakdown to medium high frequencies, reduces the burning of the cylinders and in that way gives the arrester longer life, and prevents any disturbance of the system which might result from a half-wave of short-circuit to ground.

This arrester is designed to operate across 2300 volts. It is used, however, from each line to ground, it giving in that way sufficient protection and being always able to handle a discharge when one line is grounded. It is built to be used single-pole, but by placing two or three in the same box, becomes double-pole or triple-pole.

On grounded systems this arrester can be used up to 4,000 volts between lines. On ungrounded systems by using two arresters line to line and one from the middle to the ground, this arrester can be used up to 4,000 volts.

The 1000-volt arrester is nearly the same in design but has only one series gap below the high-resistance rod.

A paper presented at the 217th Meeting of the American Institute of Electrical Engineers, New York, March 29, 1907.

NEW PRINCIPLES IN THE DESIGN OF LIGHTNING ARRESTERS*

BY E. E. F. CREIGHTON

The installation of lightning arresters is of the nature of an insurance. A certain percentage of the cost of the apparatus can reasonably be invested as a safeguard in protecting the apparatus. Furthermore, a percentage of the income can also be invested in protective apparatus as an insurance against interruption of service. The value of uninterrupted service depends upon the nature of the use of the current and will consequently vary in different plants. Plants which make contracts involving penalties for interrupted service naturally put a higher premium on good service. Protecting the insulation of the apparatus has been an easier matter than protecting the continuity of service. It has sometimes happened that the service has been interrupted by the action of the protective apparatus itself. This is especially true in the case of a grounded phase on an insulated delta or Y system.

It is the opinion of the writer that we have in view complete protection at the terminals of the lightning arrester apparatus against any high potential surge above 150% of the normal voltage of the system, regardless of the natural frequency of the surges and the duration of their application and also regardless of the cause of the surges. Direct strokes of lightning on a transmission line must of course be taken care of where they strike. Arresters at some distance away in the station can be expected to take care of only that part of the charge which reaches the station. How thoroughly a grounded overhead wire will pro-

* This is the first of two papers on this subject.

protect the line from direct strokes has not been fully determined, or otherwise put, how many and what conditions of overhead grounded wires are necessary to protect the line against direct strokes of lightning is not definitely known.

Arresters can be built to take care of high-frequency surges, low-frequency surges, grounded-phase surges during an hour or so, and standing waves. This leaves the causes of interruption of the electrical circuit limited to short-circuits. These short-circuits may be limited to accidental conditions, such as a wire thrown across the transmission line, overheated apparatus, etc.

On the Design of Multigap Arrester.

The novel features of a new multigap arrester consist first, of the discovery of a true nonarcing condition of shunted gaps; secondly, a combination in a cumulative manner of several shunt resistances, and thirdly, the design of ohmic resistance by the volume method rather than by the radiating surface.

First; Absolute Nonarcing Condition. The term "non-arcing" has long been misused in the sense of arcing during only the brief time of a half cycle or only a few cycles of the generator wave. This action is more correctly described by the term rectifying. By the term "non-arcing" in the present application it is meant that the condition of sparking exists without the formation of an arc. Transition of a spark, where the conducting medium is the heated air, to an arc where the passage of electricity is accomplished by means of convection in the arc stream of zinc vapor, involves the expenditure not only of energy but also of power.

The discharge of several hundred amperes for a brief period has been produced across a gap without bringing the difference of potential across the gap down to the normal value of 40 volts, corresponding to a current of one ampere. The power in this case was large as compared to the energy. In this connection brief periods approximating 1/100,000 second are considered. It seems to require an expenditure of power for a much longer time to bring the arc voltage down to even 100 volts. As the heating continues the voltage decreases. This effect is shown in Fig. 1. The voltage of any increasing value of current is higher than the voltage of the corresponding decreasing value, (see the two lower curves).

The difficulty in the initial transition from the condition of spark to the condition of arc is shown by another test on the same brass cylinders. Forty-five volts from a storage battery were applied to a 1/32-in. gap and a discharge of a Tesla coil was passed continuously across the gap for several minutes without causing an arc to form. In other words the battery gave out no energy. This is a case of a considerable energy at low power failing to cause an arc. It is seen from Fig. 1, however, if the impressed voltage of the battery is higher the arc will form and the arc voltage will drop far below 45 volts.

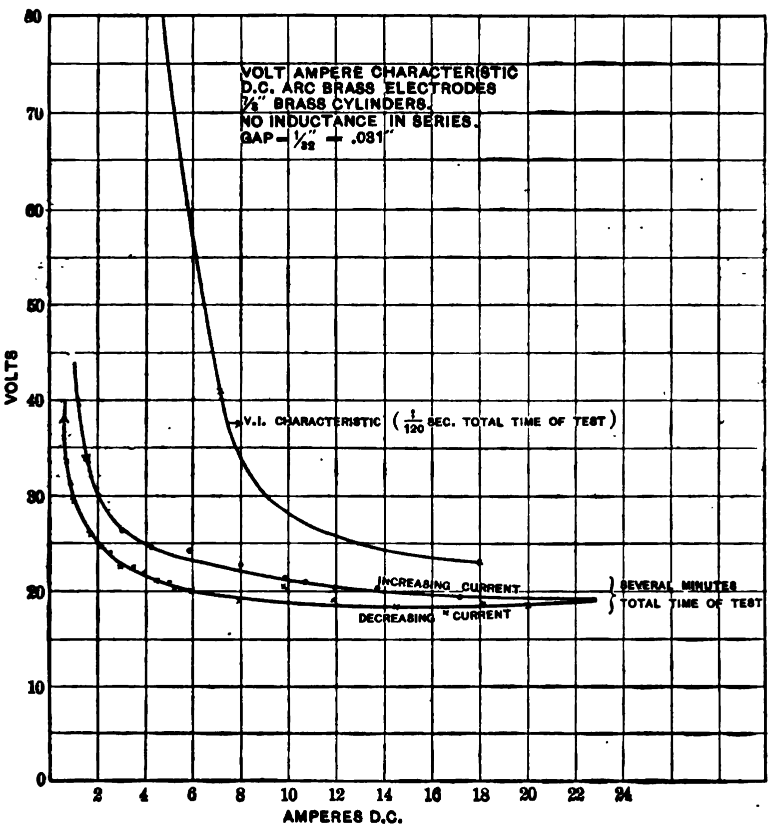


FIG. 1.

It is possible to discharge induced static electricity over multigaps directly to ground without the intervention of series resistance and still prevent the dynamic current of the generator from following the static spark, with the resultant short circuit. This condition requires an adjustment of the resistance in parallel with the gaps such that the current will be transferred to the resistance before the heat expended in the gaps is sufficient to bring the arc voltage to a low value. The problem is that of the instability of an arc (which is well known) under the unknown condition of volt-ampere characteristic of an initially established arc. The condition of instability of an arc and resistance in parallel will now be considered using the volt-ampere characteristic (middle curve) of Fig. 1. This curve shows that the arc is extinguished by any resistance in parallel which reduces the current of the arc to about four amperes. Below four ampere the rate of decrease of current is less than the rate of increase of voltage, therefore the current will increase continuously in the shunt resistance, stealing away all the current from the arc.

FIG. 2.—Combined non-arcing and rectifying arrester. The resistance on the near side of the gaps is of low value. It has cap contacts in the slips. The nine gaps in shunt with this low resistance are bridged by a static spark having an initial current value estimated at 1000 amperes. The spark has a clean cut outline and illuminates the cylinders near it. In the four remaining gaps to the left the dynamic current is established by the same static discharge. The blurred impression of the arc is due to the sudden expansion of the zinc vapor. The resistance back of the cylinders has a high value and plays no appreciable part in the dynamic discharge. The nine gaps show the new principle of the absolutely non-arcing condition.

The assumption is made that the total current is constant. This assumption is usually permissible. The value of resistance in parallel which causes the arc to become unstable depends on the value of total current; the higher the total current the less must be this value of resistance. For example, in the volt-ampere curve considered, if the total current is 10 amperes, it requires four ohms in parallel to make the arc go out. If the total current is 22 amperes, the shunt resistance must be reduced to 1.3 ohms to extinguish the arc. If the total current is 500 amperes the resistance is parallel must be reduced to 0.05 ohms.

This last mentioned value is too low to be of practical importance. Lightning discharges may easily reach 500 amperes, but it must be recalled that the volt-ampere-characteristic curve of the initial discharge lies far above the two curves given in Fig. 1, consequently a very useful value of a few ohms per gap will extinguish this spark before the dynamic arc can be established. The more favorable condition for the shunting of the gaps when the arc is just being started is shown in the upper curve of Fig. 1. The values of this curve were taken from an oscillogram of the voltage across one gap of an arrester during the brief period of a half cycle (1/120 sec).

Fig. 2 is a photograph of the combined discharge of static electricity and dynamic current. In the shunt gaps there is nothing but the spark, whereas in the series gaps both the spark and arc bridge the gaps. The arc is shown in the photograph by its greater size and explosive stream of zinc vapor.

Fig. 3 is an oscillogram of the currents of the two shunt circuits and the potential across the arrester when the factor of safety is diminshed by having only six gaps in the parallel path. The potential across the arrester drops from 3,200 volts maximum to 2670 volts maximum due to the line drop and the regulation of the generator.

In order to avoid confusing the above described phenomenon with the usual familiar conditions of shunted multigap, a distinction is herewith pointed out. The unstable condition of a shunted arc has been known for a long time; but this instability has to do principally with alternating current, whereas in this case only half a cycle of the generator potential is considered; in other words, we are treating the instability of a shunted direct current arc during the initially brief period of formation.

Fig. 4 shows the phenomenon of extinction of arc in the shunt gaps by shunt resistance at the end of the first half-cycle. The arc in the series gaps was extinguished at the end of the second half-cycle. This is the effect previously obtained in shunt resistances where heavy currents were used. In this test the ohms per shunted gap were too great to suppress the initial arc.

There is still much research to be done to determine the exact nature of the phenomenon at the instant of establishing and extinguishing an arc. Most of the results are of academic interest only. Here are some queries. In the extinction of the arc in the series gap at the end of the half cycle in which the discharge takes place, how much effect is due to rectification of the zinc vapor and how much to the cooling of the arc during the brief period of zero current? The answer is not simple, we know. For small currents, the effect is almost entirely due to cooling; for large currents, rectification by the zinc vapor is more prominent. The distinction is liable to be obscured by

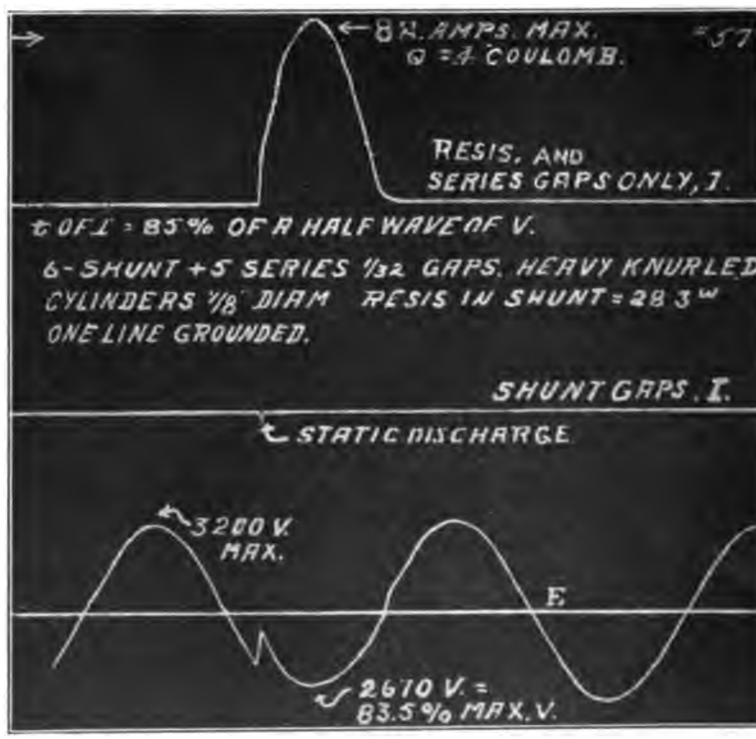


Fig. 3.—Oscillogram 57. Dynamic discharge when gaps are shunted to the absolute non-arcing condition. The upper curve is the current wave through the series gaps and low resistance. The middle curve shows the static discharge (and what little dynamic follows) in the shunted gaps. The lower curve shows the potential across the arrester inside the lightning arrester choke coils. The sudden drop in the voltage wave when the spark takes place is due to the regulation of the circuit. There is a 16% drop. The actual maximum voltage across the arrester is 2670 max. This is divided thus: 2590 volts across the resistance and 80 volts across the series gaps.

the two auxiliary accompanying conditions—first, the ionization of the air around the zinc arc and, second, by the splashing across the gap of the superfluous molten metal in the crater of the arc. Some years ago Mr. Thomas stated that it was necessary to limit the current in a multigap arrester in order to get successful operation and also that the extinction of the arc was accomplished with greater difficulty if the circuit was inductive. The explanation of these facts have a practical bearing on the matter given further on in this paper.

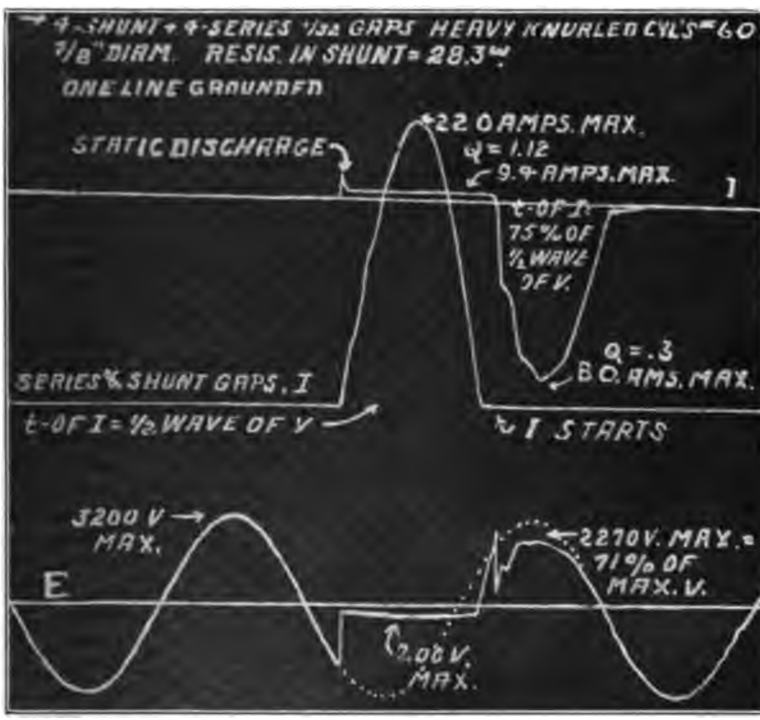


FIG. 4.—Oscillogram 60. Failure of shunt resistance. Former "non-arcing" condition. There are only 4 gaps in shunt with 28 ohms. The upper curve is the current through the resistance. Note the point marked "static discharge," the current in the resistance starts at a value greater than can be maintained. The current in the resistance is equal to the voltage across the shunt gaps divided by the resistance. This peak value bears out the statement that both energy and time are necessary to form a stable arc of normally low voltage value. The middle curve shows nearly short-circuit condition of the circuit. Note that this current lags the potential while the current in the wave above with resistance in series is in phase. The lower curve, the potential wave shows the condiion of sensibly short-circuit in the first half-cycle and the recovery in the second half-cycle. Note in the second half-cycle that the voltage jumps to about 2500 volts before the current is reversed in the series gaps.

Current Effect.—The extinction of an established arc in a multigap arrester cannot take place until the potential reduces to zero at the end of the half cycle in which the discharge takes place. Incidentally it may be remarked that if the arrester functions properly the arc should not extend over the second half cycle. (Assuming no high potential surge reestablishes the arc). If the rectifying power is not sufficient to extinguish the arc at the end of the first half cycle, it surely will be unable to do so at any instant later on account of the heated metal in the arc crater. (See Fig. 9). Consequently such an arc can be extinguished only by the flashing out of the multiarcs in one long arc in front of the arrester unit, the opening of the circuit elsewhere by a fuse or switch, or by the decrease in the generator electromotive force. This decrease in potential will be due to the reaction of the armature current on the field winding. Assume then that the arrester functions properly, and furthermore that the spark takes place on the rising point of the electromotive force wave, this gives the greatest possible discharge of dynamic electricity. The energy loss in each arc will be equal to 16 volts multiplied by the current. In other words, as the current increases there is a concentration of energy at the arc crater which melts more zinc than is necessary to supply the arc vapor. This molten zinc is splashed across the gaps and destroys the rectifying qualities of its vapor.

In consequence of the necessity of limiting the dynamic urrent, some designers have chosen between two evils and introduced series resistance into the arrester circuit. Other designers choose the evil of a possible short circuit. One improvement in design for this year is the use of a shunt resistance so proportioned as to prevent the dynamic current flowing in its parallel gaps, yet allowing a high-potential, high-frequency discharge to pass freely across the shunt gaps to ground, if the resistance offers an objectionable impedance. There is resistance for the dynamic but no resistance for heavy static discharges.

Inductive Circuit Effect.—Oscillograms show that if the arrester circuit is inductive the arc is not extinguished until the potential has passed through zero and is well along in the second half-cycle. Since the arc voltage is only 16 volts per gap for heavy currents the condition is nearly equivalent to a short circuit. When the current dies out the voltage across the gaps suddenly jumps to the value generated. (See Fig. 5). The arc has no time to cool and presumably the ionized air around the arc starts the current in the opposite direction. This condition is to be compared later to the condition of arc extinction in the liquid electrode arrester, where the current reduces to zero before the potential.

2. Cumulative shunt resistance. Referring to tne diagrammatic condition of Fig. 6, gaps No. 8, 9, and 10 are protected from dynamic current by the relation of the shunt resistance (r). The resistance (r) is small and requires, seven series gaps, Nos. 1, 2, 3, 4, 5, 6, and 7 to extinguish the dynamic

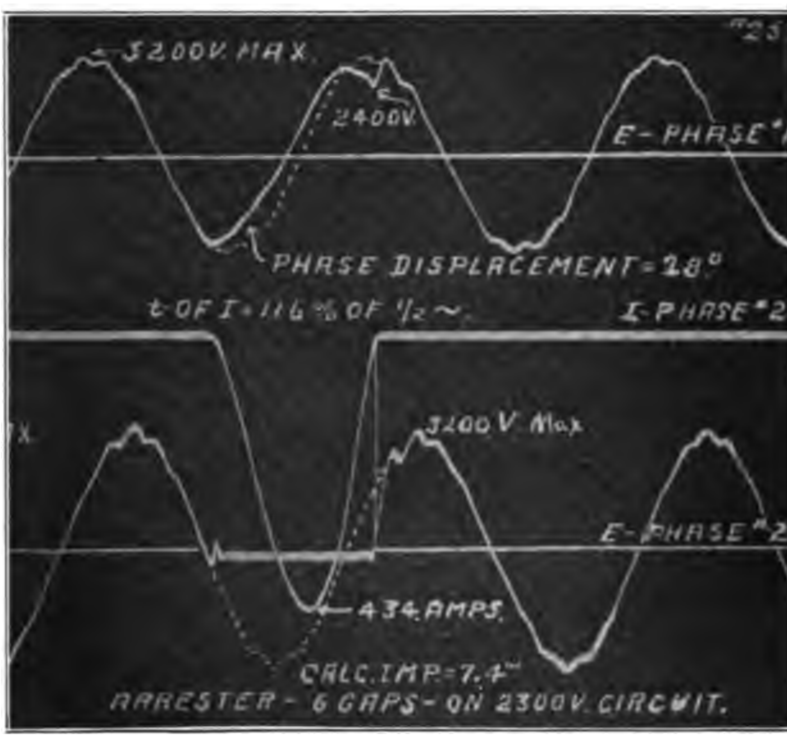


FIG. 5.—Oscillogram 253. Showing current lag, sudden recovery of potential, and displacement of another phase of the system. In the lower curve note the potential recovery when the current is extinguished. The dotted curve shows the original form of the wave. The middle curve shows 434 amperes short-circuit current. There were 3 miles of line wire to the generating station. The upper curve shows the phase displacement in phase 1 due to the reaction of the armature current in phase 2. It is noteworthy that the voltage wave of phase 1 did not have a peak value above normal maximum of 3200 volts during this interval.

arc. Under certain low-frequency conditions of discharge this number of series gaps is objectionably great. Consequently this number is cut down to, say, three gaps, No. 1, 2, and 3, and in order to extinguish the dynamic arc at the end of the first half-cycle the current must be less than that through the small resistance (r); the relation of the larger resistance (R) to the gaps numbered 4 to 10 inclusive is not such as to obtain the arcless condition of the gaps. The arcless condition of the gaps 4, 5, 6, and 7 is obtained through the presence of the small resistance (r) in shunt with the large resistance (R). So far as the large resistance R is concerned, gaps 8, 9, and 10 cannot be considered

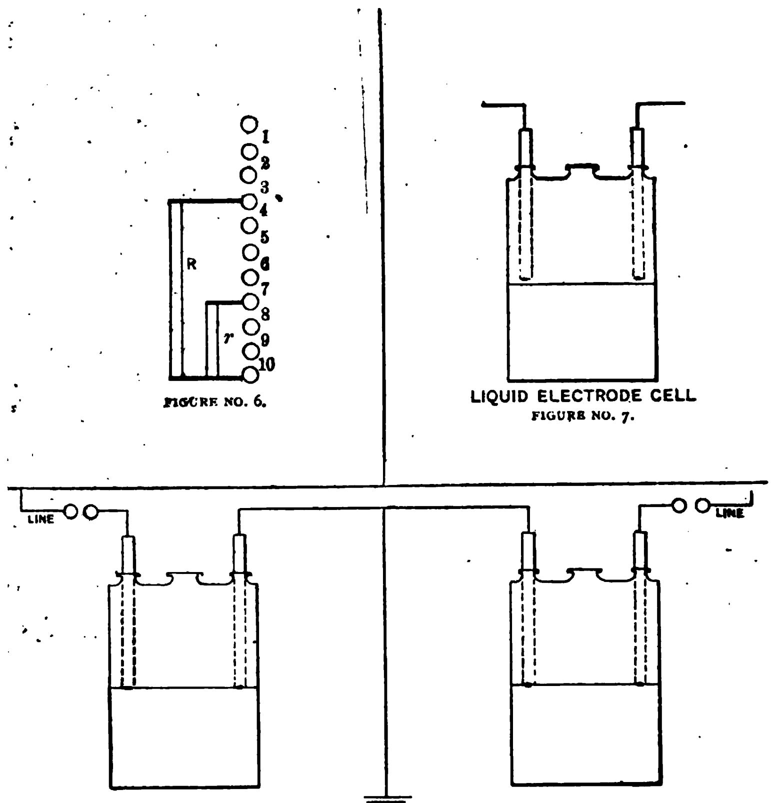


FIGURE NO. 6.

LIQUID ELECTRODE CELL
FIGURE NO. 7.

LIQUID ELECTRODE ARRESTER
FIGURE NO. 8.

FIGS. 6, 7, AND 8.

in the shunted circuit. In this cumulative manner of installing the resistance, the series gaps may be reduced to as near the spark potential of the normal circuit voltage as desired. Each time the series gaps are reduced, the resistance must be increased to such a value as to maintain the arc extinguishing effect.

Design of Lightning Arrester Resistance. Except in the case of recurring high potential surges the multigap arrester should extinguish the dynamic arc within the time of a cycle of the generator wave. This period of time is so brief that radiation of heat need not be considered in the design of the resistance. The basis of design is the utilization of the specific heat or the heat capacity of the resistor. In the lower resistances of the lightning arrester it would be impracticably expensive to design the resistance

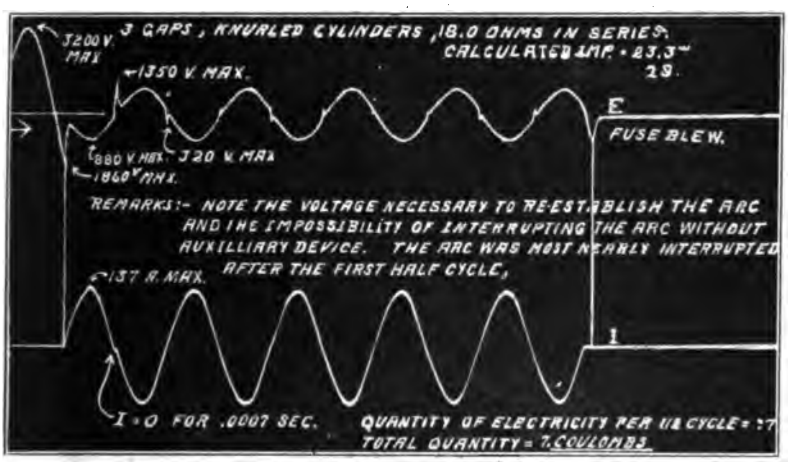


FIG. 9.—Oscillogram 29. Three gaps and 18 ohms on a 2300 V. (effective) circuit. Arrester fails to interrupt the current of 137 amp. maximum. If the arc is not extinguished at the end of the first half-cycle, the rectifying effect is lost. The spark takes place at 1860 volts increasing potential. The voltage then drops due to line resistance, etc., and reaches 880 volts max. instead of 3200. At the end of the first half-cycle the potential rises to 1350 before the current is reversed. At the end of the second half-cycle it requires only 320 volts to reverse the current. At the end of the first half-cycle on the current wave, the current remains zero for a brief period. This effect does not reoccur at the end of any subsequent half-cycle. If the current had been less three gaps would have extinguished the arc at the end of the first half-cycle.

to radiate the energy that would be lost therein if the current were applied even for several seconds.

E^2 over R multiplied by the time of a half cycle gives the energy to be absorbed. This value of energy must equal the product of the specific heat times the weight of material times the temperature times 4.2.

Assuming a safe temperature and factory of safety the weight of the material can thus be determined.

The specific resistance of the material must be chosen so as to give a length of rod great enough at least to prevent the formation of an arc along the surface. In the matter of selection of material for the resistance, notable improvements have been made.

Fig. 10.—Oscillogram 156. Voltage and current of one gap of a multigap arrester. The oscillogram shows an initial voltage of 93 volts. The drop from spark voltage to 93 volts was too rapid to be registered by the oscillograph vibrator. This sudden drop in potential was due to the heavy discharge from Leyden jars at a frequency estimated at 3,000,000 cycles. The decrease in voltage from 93 to 23 volts is very gradual with this value of current density. The upper volt-ampere characteristic curve of Fig. 1 was taken from this oscillogram.

LIQUID ELECTRODE ARRESTER.

The name "liquid electrode" is herewith given to a new form of electrolytic type of arrester, to distinguish it from the other cell types of arresters, such, for example, as the aluminum-cell type which the writer has been working on during several years. The liquid electrode is the distinguishing feature of this electrolytic type, whereas the hydroxide film of aluminum on the aluminum plate is the characteristic feature of the aluminum-

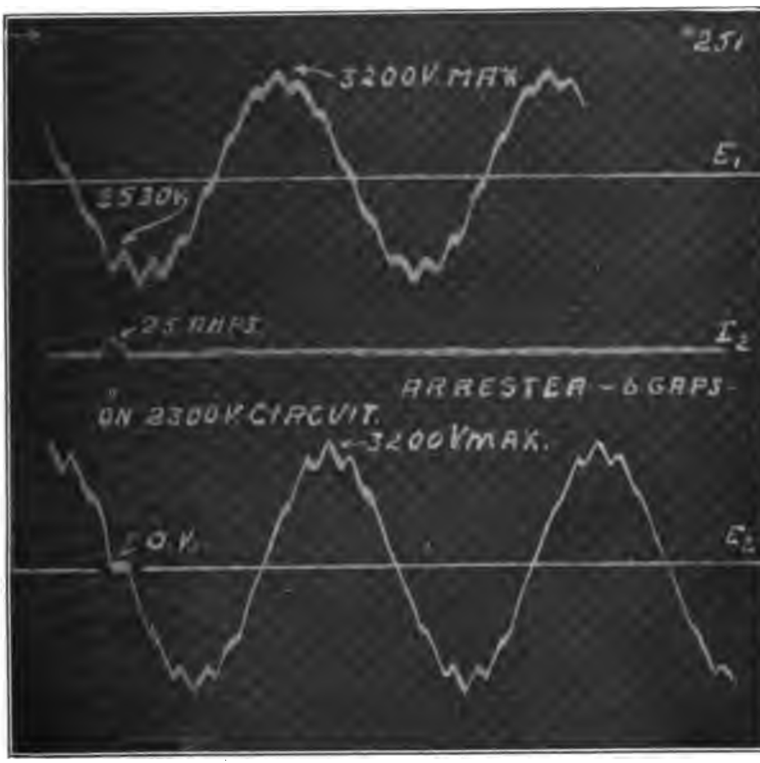


FIG. 11.—Oscillogram 251. Six gaps and no series resistance on a 3-phase circuit of 2300 volts effective. The middle and lower curves are of the same phase. These show a discharge of dynamic current where the spark takes place on the descending part of the potential wave. In spite of the short-circuit of the gaps the dynamic current rises only to 25 amperes. In practice the spark may of course take place at any point of the potential waves. In a poorly designed arrester if by chance the spark should happen when the potential is approaching zero the arrester will extinguish the arc satisfactorily; if, on the other hand, the spark takes place on the rising potential the effect may be that shown in Fig. 9. This oscillogram shows the futility of testing arresters without a synchronous switch to control time of spark discharge.

cell type. The phenomena which can be produced by the discharge of electric currents through electrolytes are of such a nature as to make valuable the employment of an electrolyte in protective apparatus. The main effect obtained in each case may be designated as a *critical limiting voltage.* The employment of a *critical limiting voltage* in lightning arresters permits the design of an arrester which will limit or suppress entirely the dynamic current at normal potentials, without the use of series resistance. Abnormal potentials above the *critical limiting voltage* of the arrester discharge current through the arrester freely without obstruction of either counter electromotive force or appreciable ohmic resistance. The characteristic action of the electrolytic types can be summed up in one

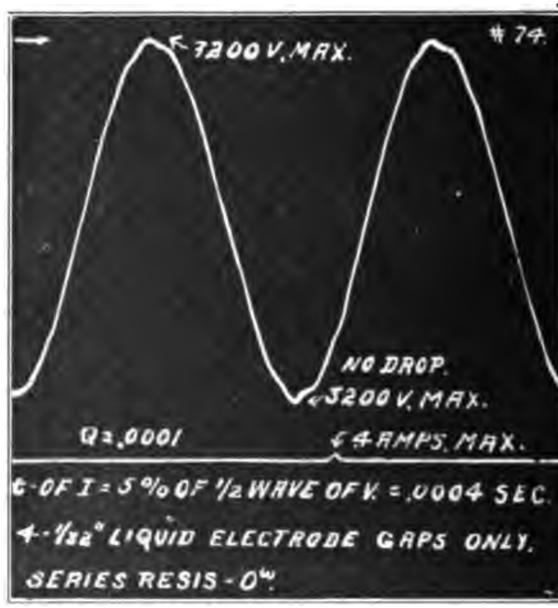


FIG. 12.—Oscillogram 74. Liquid electrode arrester using gaps at the surface of the electrolyte. Two cells in series. The current rises only to 0.4 amperes and there is no disturbance in the potential wave.

sentence: obstructed discharge of electricity at normal potentials of the circuit and free discharge of electricity at abnormal potentials. The electrolytic types give great promise.

The liquid electrode arrester may have any one of several forms all involving the same principal. One form is shown in Fig. 7. Two metallic electrodes extend into a vessel containing an electrolyte of high conductivity. The electrodes may be dipped into the electrolyte or there may be a small gap left between the electrode and the electrolyte If current is passed from one electrode to the other in either direction, the liquid must become negative at one or the other electrode. It requires about 1500 volts to maintain the current through the cell in spite of the fact that the resistance of the cell is extremely low. The current is limited by the so-called counter electromotive force of the arc.

Electrodes not in Contact. The difference in effect produced by

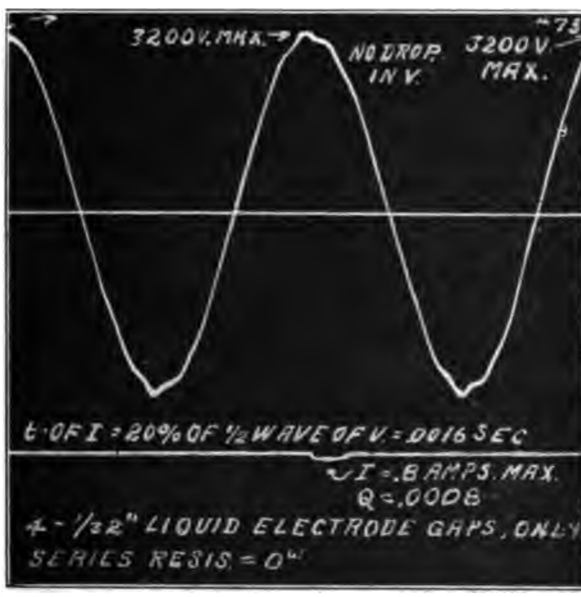


FIG. 13.—Oscillogram 73. Liquid electrode arrester using gaps at the surface of the electrolyte. Although the spark takes place at peak voltage only 0.8 ampere of dynamic current follows. Comparing the current discharge to Fig. 12, the current is twice as great and persists for a longer time. This is due to the fact that the discharge takes place at a higher point on the potential wave. The counter e.m.f. of the cells is approximately equal to the peak voltage (3200 volts) of the circuit. There is no disturbance of the potential wave.

the conditions of contact between the electrodes as compared to the air-gap setting is marked. For example, three of these cells were placed in series across a circuit having an impressed voltage of 2300 volts effective. Each electrode was set with a small gap. The equivalent needle-gap was the same as for four $\frac{1}{32}$-in. gaps between standard brass cylinders without series resistance. With this arrangement several hundred static discharges having an initial value estimated at 1000 amperes were passed through the cell, but no dynamic current followed the discharges. The novel relation of counter electromotive force practically as great as the spark voltage of the cell is obtained. The sum of the counter electromotive forces per cell is greater than the impressed voltage of the circuit, consequently a spark passes without causing the formation of an arc.

Under similar conditions in the multigap arrester using four $\frac{1}{32}$-in. gaps the spark voltage of a single gap may

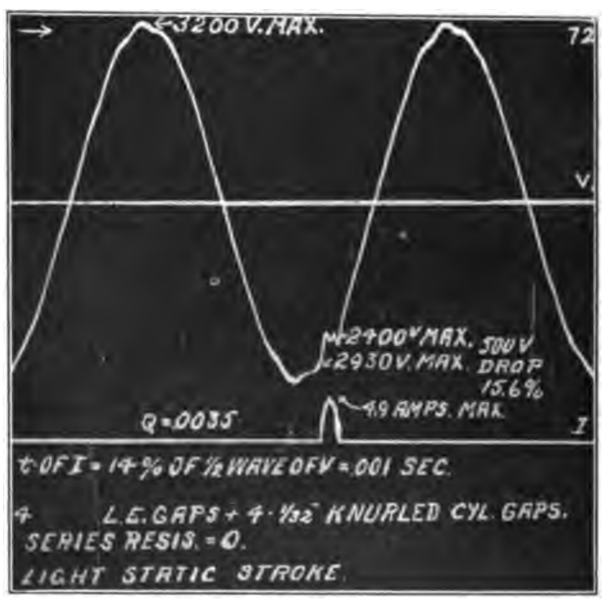


FIG. 14.—Oscillogram 72. Liquid electrode arrester using series gaps in conjunction with the small gaps above the electrolyte. There were two large lightning arrester choke coils of the pancake type in series. These choke coils give the exaggerated drop of potential (500 volts) at the instant of discharge.

be in the neighborhood of 2000 volts and the spark voltage of the four gaps in series may lie between 5000 and 6000 volts. The electromotive force absorbed by a single arc in practice will be scarcely greater than 16 volts per gap or 70 volts total for the four gaps. The spark voltage is about 125 times as great as the arc voltage for a single gap or about 80 times as great for the total of the four gaps.

Herefrom it follows that the multigap arrester does not work on the principal of counter electromotive force but upon the principal of rectification. The arrester is therefore suitable for alternating-current circuits but not at all adapted to direct-current circuits. When the currents attempt to reverse at the beginning of the second half-cycle, several hundred or even thousand volts may be required to cause the reversal. During the first half-cycle there is little obstruction to the current flow-

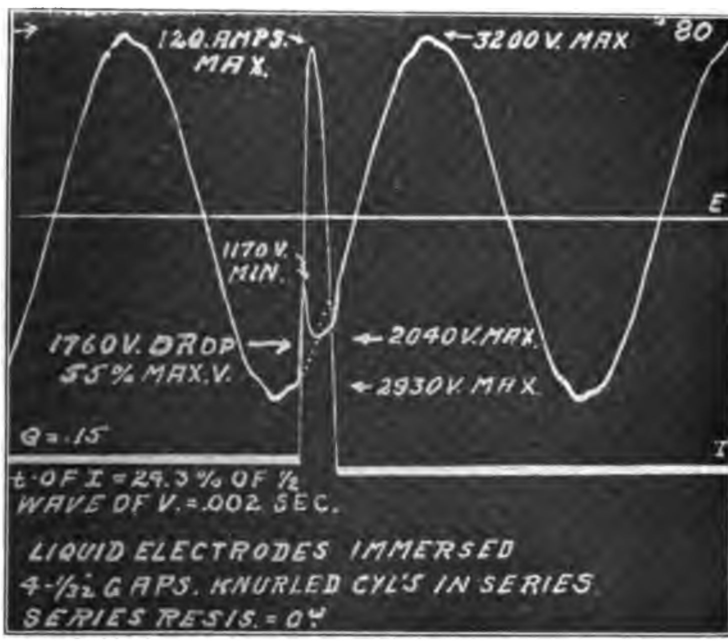


FIG. 15.—Oscillogram 80. Liquid electrode arrester with immersed terminals. The heavy lightning arrester choke coils are in series. These reactance coils add to the line drop of potential. This oscillogram shows a method of obtaining any desired quantity of dynamic discharge before the interruption of the current. The current has increased from 0.4 ampere (Fig. 12) to 120 amp. maximum due to the immersion of the metal terminals. In spite of this heavy current discharge the current decreases to zero before the potential reaches zero. Compare this to the results in Fig. 5 where the potential reaches zero and reverses before the arc is extinguished.

ing in the arcs of the gaps, and therefore it is necessary to have an artificial resistance in series to limit the dynamic current.

A liquid electrode arrester set with four gaps of equal value to the above mentioned case will have a spark voltage of 1⅓ times as great as the electromotive force absorbed by the arc, considering a single element only; or about 1.8 times as great considering both cells. On a 2300 (effective) circuit the maximum voltage is about 3200 volts. The maximum arc voltage of the two cells containing a particular electrolyte is about 3000 volts. A spark can form into an arc only at the peak value and is extinguished long before the generator voltages reaches zero. Any voltage above 1500 volts per cell produces a rush of current in proportion to the pres-

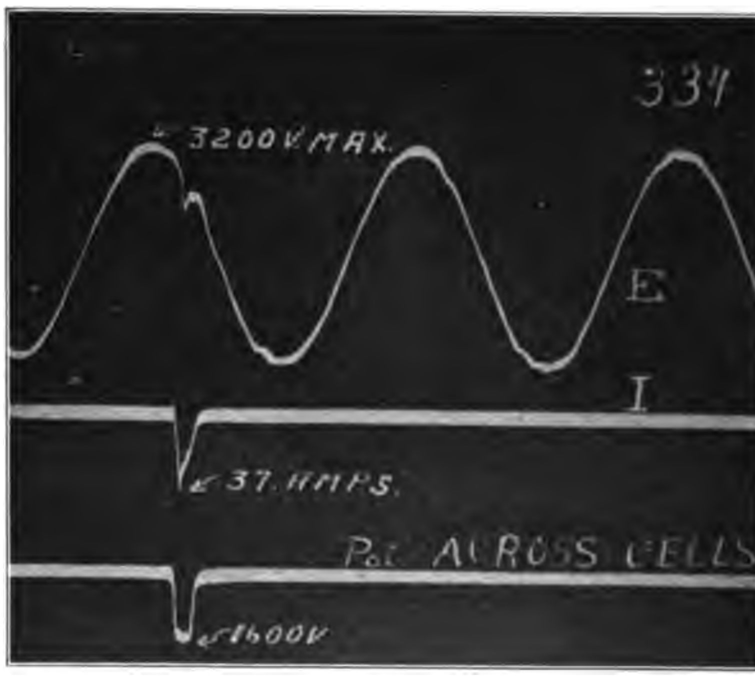


Fig. 16.—Oscillogram 334. Liquid electrode arrester with the metallic electrodes slightly in contact. The upper curve, the potential wave, is only slightly distorted. The middle curve, the current wave, rises rapidly to 37 amperes and diminishes gradually to zero. The lower curve, the potential across the cell, rises with the same abruptness as the current wave, maintains a constant value while the electromagnetic energy of the circuit is discharging and then drops quickly to zero when no longer required to oppose the current discharge.

sure above 1500 volts. In other words, the cell has a critical voltage above which there is a free discharge of electricity without the intervention of anything more than a slight ohmic resistance. In the foregoing explanation only general considerations have been held in view. Some of the experimental data from which the conclusions were drawn are given later in the form of oscillograms.

Electrodes in Contact.—When the metallic electrodes touch the liquid it is necessary to introduce a single gap in series to hold back the line potential. Since the counter electromotive force of arcs in the arrester limit the current, this single gap suffices even at the high potentials used on long-distance

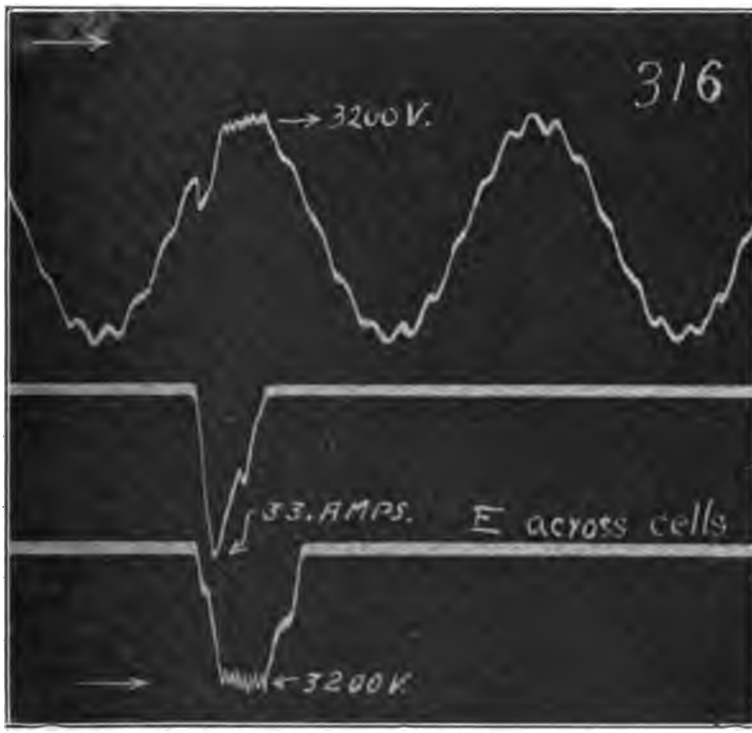


FIG. 17.—Oscillogram 316. Liquid electrode arrester with the metallic electrodes in contact with the electrolyte. The static discharge takes place on the rising part of the potential wave. The drop in the upper potential wave is due to the inductance of the circuit. The potential wave quickly recovers its normal form. The current reduces to zero in advance of the potential. The potential across the cell reduces to zero with the potential of the generator wave. The maximum counter electromotive force of the cells is equal to the impressed voltage of the circuit.

transmission circuits. A simple arrester circuit is shown in Fig. 8. The series gaps may be set at any value above line potential. When the potential breaks across the gaps the current begins to discharge at short-circuit rate. The current density at the electrodes is such as to start an arc which throws the electrolyte away from the electrode and automatically lengthens the arc. The arc voltage is greater than the impressed voltage and consequently the current dies out. The series gaps hold back the line voltage and the electrolyte assumes again its level in contact with the electrode. The current starts on short circuit but decreases so gradually that no surges have been detected either by the oscillograph or by parallel needle gaps. Extensive experimental tests have been made on a commercial

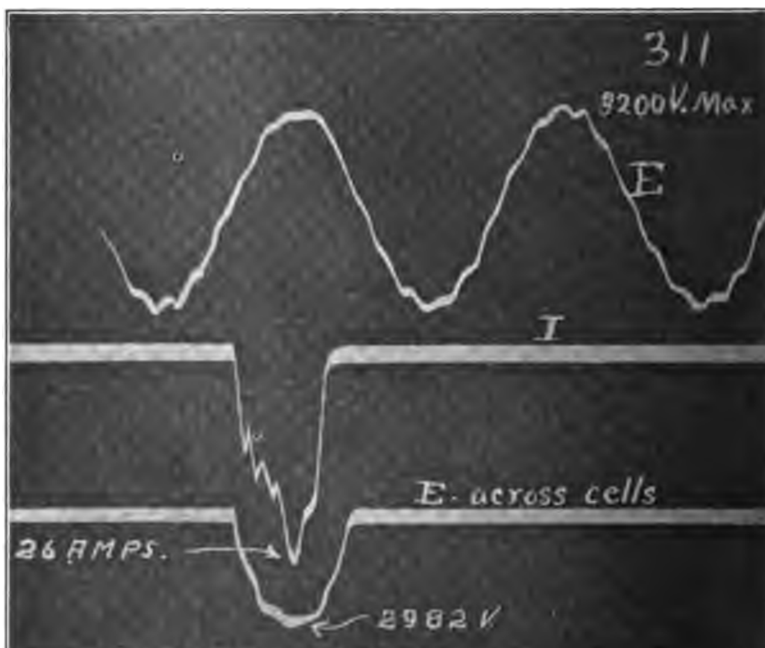


FIG. 18.—Oscillogram 311. Liquid electrode arrester with the metallic electrodes in contact with the electrolyte. The spark takes place near the zero value of rising potential, consequently the rise in current and potential across the cells is more gradual than in the previous oscillograms.

circuit of 2300 volts, 13,000 volts, and 33,000 volts normal voltage. The last mentioned circuit consisted of 30 miles of three phase line and was subjected to surges due to numerous arcs drawn out between a phase and ground. These arcs to ground attained maximum lengths of five feet.

The arc voltage of the liquid electrode depends somewhat upon the length of the arc. Since it is the current which depresses the surface of the electrolyte, the length of arc depends greatly upon the value of the current. As the current decreases the electrolyte rises toward the metallic electrode. After the first instant the phenomena are of the nature of cushion effects.

The quantity of electricity which passes through the arrester before the electromotive forces absorbed by the arcs becomes active depends upon the amount of surface of metallic electrode

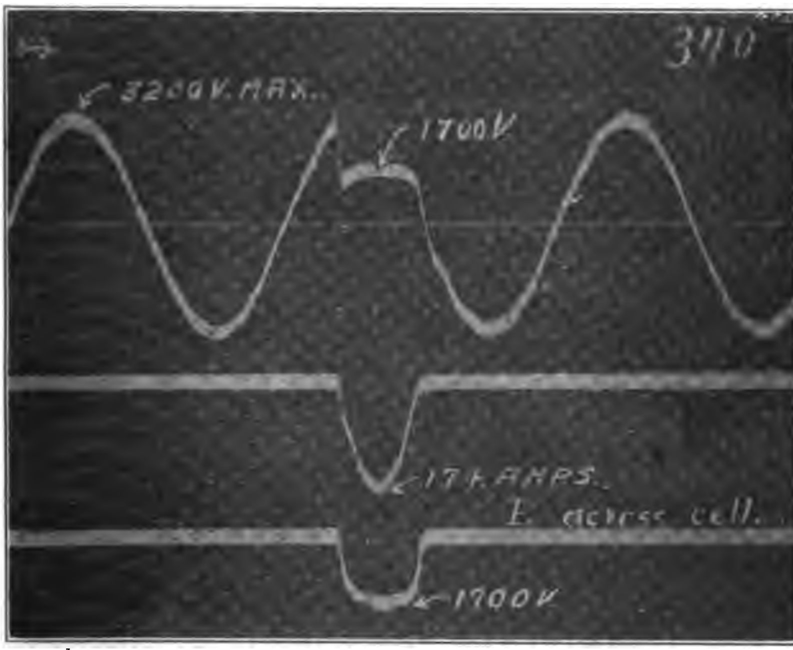


FIG. 19.—Oscillogram 340. Illustrating the critical limiting value of cell voltage. There is but one cell on a 3200 volts (max.) circuit. The spark takes place at about 3000 volts and the potential drops to 1700 volts and remains sensibly constant during the rest of the half-cycle in spite of the capacity of the generator to which it is connected. The current rises to 174 amp. maximum. This cell acts as a short-circuit for pressure above 1700 volts, but is active in opposing the current flow as soon as the pressure falls again to 1700 volts.

exposed to the liquid. This value can be increased by immersing the metal to a greater depth.

The ohmic resistance of the arrester is located initially in the liquid only but gradually divides between the series arc and the electrolyte. The electrolyte is a large body of large cross-section and low specific resistance, and therefore the resistance is very low.

The electromotive force absorbed by the arc at the electrolyte varies somewhat with the nature of the electrolyte.

Although the initial current may be considerable, the total current in continuous operation is not. To determine the en-

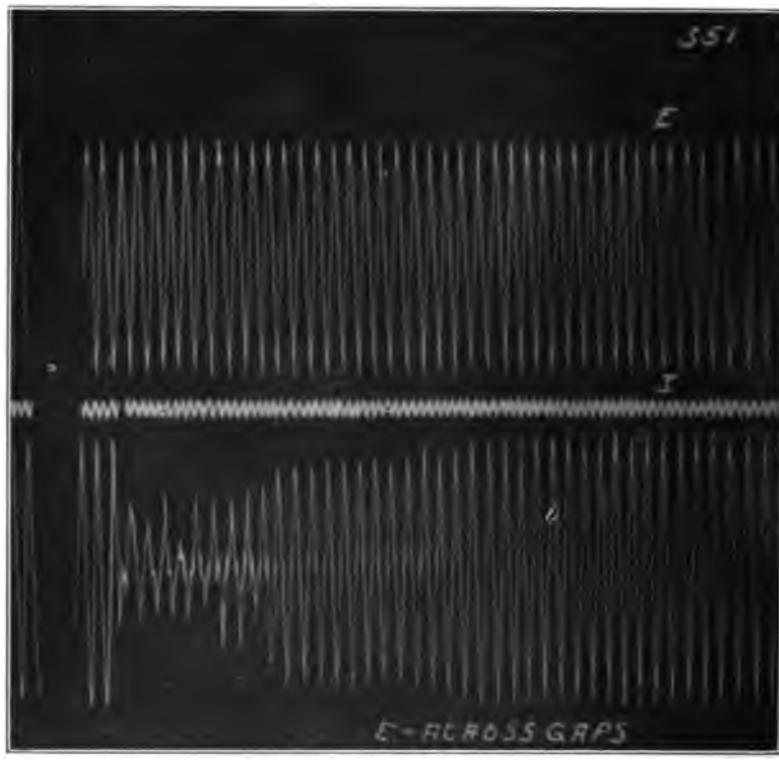


Fig. 20.—Oscillogram 351. The recovery of a liquid electrode arrester after a lightning discharge. The upper wave is the potential across the entire arrester. The lower curve is the potential across the series gaps alone. The middle wave is that of the current of discharge. The actual wave is not visible on account of poor illumination of the mirror of the vibrator, but the duration is shown by the open space in the zero line of current during the third cycle after the opening of the shutter. The potential curve across the gaps shows a drop to zero, then a gradual recovery to full line potential. During this interval the arrester is ready for a second discharge.

durance of the arrester, a 13,000-volt unit was connected to one phase of a circuit without any series gap or resistance. This circuit consisted of a 2000-kw. generator connected to nearly a mile of cable and seven miles of overhead line. The other two phases were protected by gaps set at 150% of line voltage. The potential of these phases did not jump the gaps during the severest tests. It should be noted that the arrester was in action

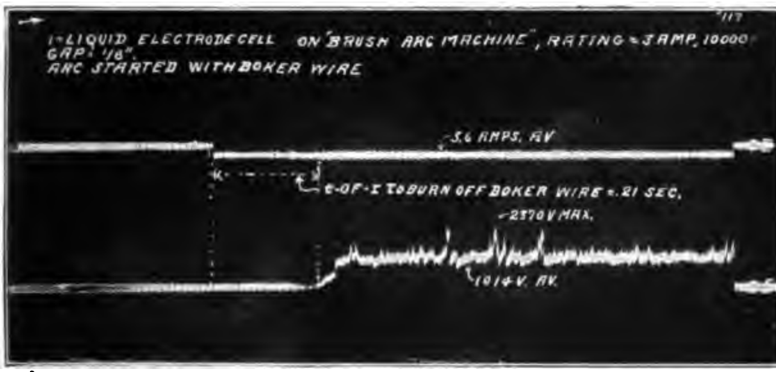


FIG. 21.—Oscillogram 117. Liquid electrode cell on 3.6 amperes constant current. The voltage varies considerably due to the splashing of the electrolyte. The small lumps in the current wave are due to the irregular intensity of the oscillograph arc. The average voltage for this electrolyte and current is approximately 1000 volts. The arc was started by means of a 5 mil Boher wire. It required 0.2 sec. to burn off this fuse with the current at 3.6 amperes.

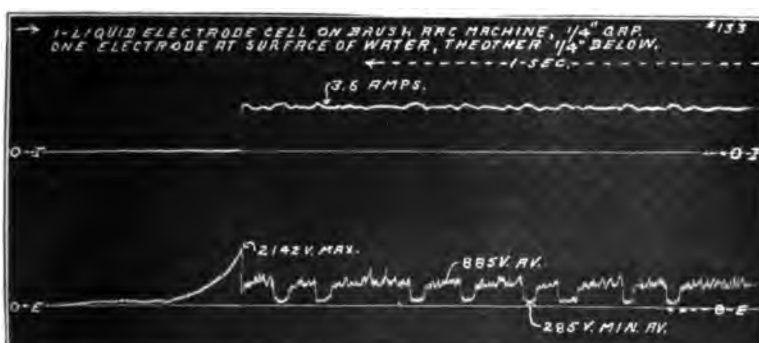


FIG. 22.—Oscillogram 133. Liquid electrode cell on direct current showing the time required for the arc to bore ¼ inch below the surface of the electrolyte. The average potential with the liquid as the negative electrode in 885 volts, but when the arc reaches the metal electrode in the liquid the voltage drops to 285 volts or less. Shortly after the liquid again sweeps over the lower metal electrode and raises the voltage again.

under the abnormal condition of no series gaps. The action of the arcs gradually lowered the level of the liquid until 13,000 volts would no longer maintain the arcs. The time required to do this depends on the construction of the cells. In the small cells it is about five minutes and in the large cells somewhere between ten and twenty minutes. This time can be increased if found advisable. This sustained operation should make the liquid electrode arrester suitable to take care of the recurring surges on an isolated delta or Y system, when one phase is grounded through more or less of an arc, during a time amply sufficient to disconnect the faulty line. In the foregoing experiment a 20-ampere fuse in series with the arrester was unaffected. Apparently the possibility of an interruption in practice due to the short circuit of the arrester can be eliminated as it was in this test.

In practice the number of cells would be chosen to give a

FIG. 23.—Oscillogram 136. Potential of a horn gap discharging 36 amperes constant current. The arc rose up the horns with considerable difficulty. The arc would flame to a peak and the potential would strike across below the peak and thus shorten the total length of the arc. The shortening of the arc would drop the potential. This effect is shown in the lower curve of the oscillogram by the repeated drops in the potential. The arc held in the narrow gap for about a second. This is shown by the low voltage of the curve. The total time the arc held was two seconds.

critical limiting voltage of 125% to 140% of the impressed voltage. The gap length may be set to give any desired protection. Since the arrester has but a single gap, the spark potential is as near independent of the natural frequency of the lightning surge as possible. It should discharge with facility low-frequency surges. It has a small dielectric spark lag.

The characteristics of the liquid arrester have been studied in detail with the aid of an oscillograph. A few oscillograms have been chosen which show the effect of a cell on the current and potential of a commercial 2300-volt circuit. Among other things shown in these oscillograms are:

The effect of discharge at different points of the potential wave.

The effect of more or less immersion of the metallic electrode on the current and potential.

The critical limiting voltage of an electrolyte.

The critical limiting voltage of the arc in the standard multi-gap arrester (this is given for comparison).

The initial short-circuit effect and subsequent cushion effect.

The recovery of the cell after the discharge.

The reduction of current to zero before the potential wave reaches zero.

The writer pays his grateful homage to the originator of the

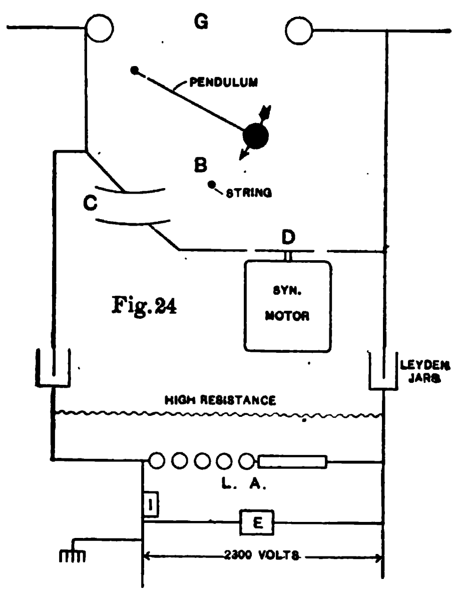


Fig. 24

oscillograph M. André Blondel. The value of the oscillograph in this work will be evident from an inspection of the oscillograms. The auxiliary apparatus necessary to get initial effects of discharges is quite essential. The problem is to place on a revolving photographic film with a total time of exposure of about 1/10 second, a static spark which will start the dynamic current flowing at any chosen point of the potential wave not varying in location by more than about 1/1000 second. In the following described combination of switches the operations are entirely automatic. It requires only the release of a latch. The oscillograph is so constructed that a lever operates the shutter. The shutter is opened by the lever and closed by a complete revolution of the drum carrying the photographic film. Fig. 24 shows the connections and locations of the apparatus. When the pendulum is released it strikes a string at *B* which opens the kodak shutter; it then closes the circuit between the two parallel strips during an interval depending on the velocity of the pendulum and the length of the strips. Meanwhile the synchronous motor carrying the synchronous switch at *D* closes the circuit of the static machine located at *G*. This release of the potential on the inner coatings of the Leyden jars throws the potential on to the lightning arrester *L A*, thus producing a spark across the gaps. An arc follows from the dynamic potential which is also impressed on the terminals of the lightning arrester. The vibrators of the oscillograph are shown at *E*, and *I*. The static machine is kept running at such speed that it will not spark across the gap at *C*. The potential of the static machine is also easily controlled by the application of more or less needles. These needles can be regulated to discharge the current of the static machine as rapidly as it is generated. The potential can thereby be limited to any desired value.

Discussion on "Lightning Phenomena in Electric Circuits", "Protection Against Lightning, and the Multigap Lightning-Arrester", and "New Principles in the Design of Lightning-Arresters", at New York, March 29, 1907.

F. A. C. Perrine: Dr. Steinmetz gives a clear description and classification of the lightning phenomena that aid us greatly in understanding the problems and the methods proposed for meeting them. They are, however, the simple problems; there is yet to discuss what occurs when two sets of waves started from different points on a long transmission line eventually come together. Aside from the increased constants (capacity and self-induction) I think there will be additional difficulties, due to the fact that in a long-distance transmission line traversing a great area there may be a storm at a certain part of the line and clear weather at another part; or there may be two independent storms in different parts of the line, giving lightning effects which induce waves that meet and combine, and increase the effects. Otherwise there would not be so much difficulty in protecting fairly well a long and extensive low-potential distribution system.

I am inclined to disagree with Messrs. Rushmore and Dubois in regard to the horn arrester. The real theory adopted by those who have used the horn arrester is largely left out of this paper. The horn arrester, where used successfully, has been used on the principle that the wave trains which Dr. Steinmetz has been explaining do not in themselves produce potentials that will break down the insulation of high-potential lines. The principle is that money would be better spent in erecting lines so as not to make the insulation subject to breakdown by wave trains of relatively low potential, such as would have to be guarded against in lower potential lines. The horn arrester is introduced with the idea of saving the apparatus from destruction where any other form of arrester would not itself be destroyed, and even if protected, the machinery would lie open for damage in the further continuance of the storm. This is a condition frequently met with in the introduction of the multigap arrester even of the best form. With extreme cases, which Dr. Steinmetz has described, of the short-circuiting potential and discharge across the arresters of extraordinarily high energy, the multigap arresters generally fail and the line is then left unprotected even if the machinery is safe.

At a recent meeting of the Institute, in referring to the lightning-arrester problem, if I remember correctly, Mr. Mershon said he used three sets of horn arresters each of a different value of resistance in series. That system has had, say, a year of operation at Niagara Falls. While it has demonstrated that the system of protection is not complete—requiring for certain types of discharge that come from the line a set of multigap arresters in connection with the horn arresters situated probably inside the station—yet the horn arresters will discharge over the multigap arresters, and these high-frequency discharges are discharged over the multigap arresters harmlessly. At the same time the horn arresters discharge the low periodicity surges which are usually destructive to the multigap arrester.

I do not agree with Mr. Rushmore and Mr. Dubois that the horn arrester is better adapted for discharging high-frequency discharges. As a matter of fact the opposite is true. As stated by Mr. Creighton, the higher the frequency of the discharge the more rapidly is it carried over the multigap arrester. The low-frequency discharges are not so well taken over the multigap arrester, whereas with the horn arrester the low-frequency discharge is more rapidly taken over than with the multigap arrester.

In the present state of the art, excluding the electrolytic arrester described in one form to-night and in another form by Mr. Jackson a few months ago, I think the best protection is a combination of the horn and multigap arrester; the multigap arrester to take charge of the relatively high-frequency discharges, and the horn arrester to take charge of the low-frequency discharges.

I think that the construction of a polehead to take care of the overhead ground wire is open to criticism. In the first place, the pipe is an extremely bad piece of engineering. The connection to the pole is not good, for the amount of leverage shown is excessive; and I confess that for the present I cannot see how a workman is going to attach a ground wire, ⅜-in. in diameter to the top of the pipe, unless there is some means provided for hauling up the wire to prevent the dead-end from being pulled over.

As regards the guard-wire put on the arm, as a horn arrester to protect the insulator, I cannot see how that particular form of arrester will do other than hold the arc. If an opposite horn were brought out from the line, and a horn arrester made there, it would discharge and protect the insulator In the same connection the authors speak of the specification for this overhead wire. I have always believed that a barbed wire, if made properly, is a better means of line protection than a smooth wire; at the same time I question very much whether a satisfactory barbed wire arrester can be made. I prefer a three-wire ¼-in strand of high grade steel to a ⅜-in. stranded steel.

The treatment of the multigap arrester adds to our knowledge of the manner of action of this bit of apparatus. Mr. Creighton explains particularly the influence of the rectifying effect of the non-arcing metal (to refer to Wurts' term). The capacity effects described in the paper by Messrs. Rushmore and Dubois are simply in addition to the effect of the series resistance or shunt resistance, and in addition also to the rectifying effect of the metal in the gaps--and metal which will rectify is absolutely necessary for the success of the multigap arrester. Mr. Creighton explains in an interesting way the function of the resistance in connection with the multigap arrester. He calls attention to the fact that there is really no radiation from the resistor in such an arrester; and in forming such resistor there must be taken into account the specific heat of the material and the extent of the metal, so that it may absorb the energy. At this time, and I believe for the first time, our attention is called to the fact that the radiation of the resistor is relatively unimportant

We seem to have here an entirely new form of electrolytic arrester. The principle Mr. Creighton describes is of actually striking an arc in the electrolyte, and so obtaining the benefit, as a resistance, of the counter electromotive force of the arc is very important indeed. We all know what Edison said of his storage-battery: "The damned thing is wet." This apparatus is not only wet, but it relies for its action on the formation of an arc within the arrester, which I should suppose would very rapidly evaporate the electrolyte, and the cells would require considerable watching in order to keep the electrolyte at a certain level.

As Dr. Steinmetz has aptly said, lightning-arrester problems cannot be efficiently studied in the laboratory. At the same time our somewhat restricted methods of work in the laboratory can better be explained and extended to practical use by means of the oscillograph than by any other means. The laboratory work on the electrolytic arrester of Mr. Creighton is of great importance, particularly because he shows his arrester as a single-gap arrester; in other words, a horn. At the same time he shows how the horns can be set close enough together so that they will take care of the high-frequency, low-potential discharges as well as the low-frequency, high-potential discharges; this gives practically a single horn arrester with a variable resistance in series, which is all that the horn arrester needs in order to become the best arrester that can be made. Furthermore, the electrolytic arrester puts what amounts to practically a variable fuse in the circuit, as well as a variable resistance, and it gives also a replaceable fuse. In my mind the need of the fuse is the greatest criticism that can be made of the arresters shown by Mr. Rushmore. All these arresters have fuses in them. If they are meant to blow, I feel quite sure that all operating men will agree that in a serious thunderstorm, such as occurs in the South or in the Colorado region, they will never be replaced after they have once blown during that storm. I do not know of any man with nerve enough to go near an arrester to put in a new fuse.

This substitution of a variable resistance, counter electromotive force, and a replaceable fuse and single gap arrester which is described by Mr. Creighton, is, in my mind, the practical solution of the lightning-arrester problem. I believe if this is worked out commercially we will be much nearer the complete solution of this problem than we have ever been before.

Farley Osgood: I will not attempt to discuss the papers individually, but will endeavor to contribute some corroborative evidence concerning the problem as a whole. Experience seems to show that lightning protection is an individual study for each individual plant, and for each individual locality. In talking with other operating engineers, I find that they use quite different methods of protection from the ones we use and they are equally successful or unsuccessful. Each man seems to have his own ideas about it, so I think that the lightning-arrester problem, like some of our other problems, is going to be a rather difficult one to standardize. I do not think the difficulties of atmospheric conditions are so very serious, generally speaking. Dense fog causes most of the trouble to our outside system; during other times we seem to get along without difficulty.

I will now relate some actual experiences occurring in a 33,000-volt transmission system, of 60 miles, carrying three substations, with power and lighting load, and 60-cycle synchronous converters. The multigap arrester with the resistance in series with the gaps, was used in 1904 and 1905, and was finally given up because the series resistance sticks broke and the protection was lost. The next year we took up the multigap arrester without the resistance sticks in series. This arrester, as can be seen from the photographs here, was very easy to adjust by changing the units to be shunted and changing the resistance of the shunt. We started with 14 units of 24 gaps each, shunting three units with 14 sticks, 250 ohms per stick. This equipment was gradually reduced until we used 10 units, to the multiple connection between the phases, and ten units below the multiplex, shunting 5 units with seven 250-ohm resistance sticks. We found by the tell-tale papers that with seven 250-ohm resistance sticks the current would seldom pass through the shunt resistance. We reduced them to five and then found that we got at least half the discharges through the shunt, sometimes more. This arrester, adjusted in this way, has been successful. It takes light discharges without the slightest difficulty; it takes moderate discharges with but very little difficulty; it takes very severe discharges at times, but these severe discharges are apt to cause the cylinders of the arrester to weld together, which of course puts the arrester out of service.

Another thing that has been noticed is that the discharge is more frequently line to line than line to ground. The 1906 record shows that we have taken in some storms twenty discharges without an interruption to service, our time-limit breakers being set at six and a half seconds. We have taken 17 discharges without interruption, the eighteenth discharge opening the breaker. I could cite case after case of storm in the surrounding country, but not directly on the system, where there were intermittent discharges between the phases to the extent of fifteen, or even as many as twenty-five in the course of two or three hours, without the slightest indication of interruption. This is the best record we have been able to obtain with protective devices.

Mr. Rushmore and Mr. Dubois speak of choke-coils. We have found them very effective, and consider that they are a great protection to the high-tension bus-bar insulators. A 20-turn coil 6 in. in diameter made of 00 copper seems to answer our purpose fairly well.

Dr. Perrine objects to the electrolytic arrester on account of its being wet, but I see no reason why it should not be made water-tight.

I do not wish to talk very much about Mr. Creighton's tests, although it was my pleasure to be present at the time they were made. I can simply corroborate what he says, that some 40 arcs, five feet in length, were drawn by grounding one phase wire just ahead of the liquid arrester. The multigap arresters just described, the record of which just given shows that they are very sensitive, were in parallel with the liquid arrester. Not once was there any apparent discharge on any of the units of the multigap arrester. These tests were made with 30 miles of circuit cut in.

Dr. Perrine speaks of the length of the transmission line having a great deal to do with the matter of protection. That seems to be true. In our experience we found wave peaks developed between stations, which do much damage before the arresters at the ends of the line begin to help out. We installed what we call our midway arrester, a multigap installation about 10 to 12 miles from the power station. Immediately after this was put into service the constant static discharge on the power station arresters and the sub-station arresters was cut down nearly one-half, and the constant static discharge at the midway arrester was greater than at the generating station or at any of the sub-stations. That seems to be fairly good proof that arresters on the line are a good thing. For the benefit of other operating engineers, I might state that this arrester equipment is very near the patrolman's house, so that it is easily controlled.

One great trouble in following the study of arresters is to get definite information concerning the action of the arresters. We do our best with tell-tale papers, but it is very often impossible to replace a tell-tale paper after a discharge comes, for another discharge comes so soon and operators have other things to do besides watching the arresters. Our tell-tale papers burn up during severe storms, and this destroys our records completely. I would suggest that a tell-tale paper which would not take fire but which could be prepared to show a puncture, would help us to obtain better records. It is a difficult matter to get the operators to realize the importance of following every lightning storm, to the extent of counting the number of discharges, but if proper forms are made for this purpose I see no reason why the study cannot be carried on without great difficulty.

The worst operating condition we have to meet is that due to grounding. More damage is done when a phase grounds than at any other time. I am not prepared to say that grounds only are responsible for the destruction of apparatus, but more apparatus is destroyed when there are grounds than at any other time. Mr. Creighton's liquid arrester, which was connected for the protection of grounds on the system, apparently solved the problem completely. The development of the liquid arrester brings out the fact that at least for grounds it may be necessary to have arresters only at the generating end of the system, or at least at the extreme ends, with no equipment in between. The power of self-restoration of the electrolytic arrester is one of its most beneficial qualities.

P. H. Thomas: It is interesting to note that most engineers are in agreement in the matter of protecting apparatus from damage by lightning. The multigap arrester with shunt resistance, ignoring the electrolytic arrester for the present, seems to be the most promising direction in which to work. The differences in commercial designs now are comparatively small.

In general I agree with nearly all that is said in these papers, but there are some things still open to an honest difference of opinion. Unfortunately, it is necessary to emphasize the things we do not agree with, even if they are not so important as some things we may approve of.

I do not know that I agree with Dr. Steinmetz's new definition of lightning. We must of course recognize the fact that an arrester is not only effective, if it is effective at all, against lightning, but also against the other sorts of static disturbances; but if we want a general term, rather than change the time-honored significance of "lightning," I would suggest the word "static," which has been pretty generally used. Another thing which does not appeal to me is the analogy that Dr. Steinmetz makes between electrical wave phenomena and the surf of the ocean. The reference to surf presumably means the dashing of spray which results from the pounding of the water against a surface, either the horizontal surface of the beach, or the overhanging surface of a rock. As we all know, in the electric circuit capacity is analogous to the spring or to elasticity; that is, the freedom of the water of the ocean to move upward in the analogy. Self-induction is analogous to inertia. The analogy of the splashing of water, where it strikes *against* an opposing surface, is the breaking, or instantaneous stoppage of the flow of current; it is in the nature of the Wehnelt interrupter, or the low-tension break in a Rhumkoff coil. The phenomenon in a transmission line, when a wave meets a reflecting point, is truly analogous to the wave in the water reaching a perpendicular smooth wall; the wave will rise to double the height, but there will be no splashing—a plain, simple vertical rise. If the wave be in a trough of water, and the trough tapered off to a point, and the taper commensurate with the length of the wave, there will be a rise of potential, but not a splash; a normal, straightforward rise. There is evidently no break in the continuity of a transmission circuit on the reflection of the electric wave.

I am more inclined to agree with Mr. Rushmore than with Dr. Perrine in connection with the horn type of arrester. I think we are far enough advanced to protect our apparatus without the very annoying disturbances of shutting down the plant. The grounded wire is certainly some protection, but, as Mr. Rushmore says, not complete protection. One of the difficulties, even if the wire is placed directly overhead is that the discharge which strikes the line is more apt to come from the side. Coming thus, it approaches one of the side wires before it does the grounded wire, and there is frequently recurring on these lines alternately positive and negative potential, which will tend to draw the discharge to one of these wires from the ground wire. It is often suggested that a grounded wire, if it be grounded frequently, will act effectively in reducing the severity of discharges, on account of the short-circuiting secondary action. It does not seem to me probable that the effectiveness of this action will be at all considerable, and for this reason—to produce any corrective effect the reaction of the induced current on the primary circuit must be considerable. Take an ordinary static transformer, where the reaction of the secondary on the primary is virtually perfect. To accomplish this result it is necessary to have an iron core and the closest relationship between the primary and secondary windings. In the constant-current regulating transformer, where there is provision to separate the windings, if the coils are close together, there will be a nearly perfect relationship between the primaries and secondaries, and a nearly perfect reaction of the secondary on the primary. But if the secondary is separated from the primary, the effect of the secondary on the primary is almost negligible.

In his admirable discussion of the principles covering the discharge through a series of gaps, there was one thing Mr. Rushmore did not take into account, and that is the fact of the leakage of current over the surface of the insulator between the cylinders. This will tend to distort numerically the conclusions reached. If this phenomenon gives trouble in designing arresters, it is easily controlled by placing a considerable gap in series with the arrester, between the lines and the first cylinder. or by using a shield connected to line. A great deal of stress has been laid on the fact that in virtue of the resistance adjustments the arrester Mr. Rushmore has designed will not break down on lower voltages at high frequency, than at a low frequency. Offhand, I do not see why if a high-frequency disturbance will go to ground more readily than a low-frequency disturbance, it should not be permitted to do so. If this resulted in a too frequent discharge of the arrester, it would be harmful, but our experience does not appear to indicate that such is the case.

The term "rectification of vapor" has been used several times to-night to explain the non-arcing property of a multigap arrester. The significance of this term I cannot quite understand. Vapor consists presumably of an aggregation of atoms or molecules, and since the atoms or molecules move freely in an entirely accidental manner, I cannot understand how this vapor of itself can have any directive effect. I think the action can perhaps be explained in the following manner: it is pretty well agreed that an arc starts by the ionization, through potential strain, of the gases between the electrodes, by which ions are liberated. They are then forced to move extremely rapidly by the high potential and produce other ions, until finally there is such an increase of temperature and such an increased ratio of ionization, that the quantity produced is sufficient to carry the normal arc current at a low voltage.

It is now easy to imagine in these narrow gaps between large cylinders in the multigap arresters that when the discharge comes along, ions are produced in this way, but that the instant the discharge and normal current ceases at the end of an alternation, in view of the close neighborhood of the conducting cylinders, the ions which would otherwise hold over until the return of the voltage are freely absorbed by the metal. The fact that an easily vaporized material is used in the composition of the cylinders will keep down the temperature; and since ionization is very closely related to temperature, the high temperature very much increasing the ionization, this effect will account for the properties of different materials. The current is of course carried by the movement of the positive ions to the negative pole, and the negative ions to the positive pole.

I would like to ask Mr. Creighton whether in his tests the results are based on anything more than the work with the 2300-volt outfit described here? that is, whether higher voltages or larger powers were used?

E. E. F. Creighton: We have taken some measurements at higher voltages, but we have not made as complete a study of them as in the case of the 2300-volt machine.

P. H. Thomas: The question of power behind the tests is absolutely of importance in this sort of work, and inherently the higher the voltage the more difficult to handle. Personally I should be very skeptical of the general non-arcing quality of this arrester without series resistance, and unless there are other data than what appears here, I should not suppose it would be safe to infer anything as to its general non-arcing quality. We find in one of the oscillographs, Fig. 4, that 200 amperes absolutely cuts the generator voltage down from 2,000 to a few per cent. of this value, showing a very limited capacity of power behind the arc. Similarly with Fig. 5.

V. G. Converse: Having installed at the plant with which I am now associated a considerable equipment of horn-gap arresters, I may perhaps be expected to take exception to the comments made in Mr. Rushmore's paper regarding this arrester; on the contrary, I quite agree with him. However, Mr. Rushmore states:

> Where a fuse is used in series with a horn having no resistance, it can, of course, take but the one stroke, and after this the system is unprotected.

This objection can be overcome by the use of repeating fuses arranged so that if one fuse blows, a switch drops, connecting in a second fuse; if the second fuse blows, a third is connected by a switch, and so on. If the fuse is of a proper enclosed form, it in itself very nearly meets Mr. Rushmore's requirement for the ideal arrester; but such a device may not be termed a horn arrester as the horns are no longer necessary.

Mr. Rushmore further says:

> The real function of the horn arrester is its use to protect insulators along a transmission line, where the horns are so arranged that the current will jump to the horn before it will arc around the insulator. In this case the system would be disturbed either way. Where it is allowed to arc around the insulator, the latter would probably be destroyed and the time of disturbance of the system might be considerable —possibly until the insulator is replaced. With a horn protecting the insulator, the resulting short-circuit, while very undesirable in itself, is less disastrous than in the former case, and may only necessitate starting up the synchronous apparatus again.

From my experience, and I believe that it will be found to be the experience of others, the principal lightning troubles on a high-tension system are stated in those few sentences. The Ontario Power Company during the whole of the last season had only one discharge of consequence over its arresters at the generating station, but had a considerable number of discharges along the lines, which caused interruptions of service.

The lightning-arresters described in these papers are essentially station arresters, and while it is gratifying to learn that satisfactory results are promised for this purpose, it should not be overlooked that for continuous operation, line lightning protection is also of great importance, for which other arresters are required.

D. Dubois: In regard to the breakdown of the high-voltage arresters at a low-frequency power surge, a little more should be added. As the voltage rises, and before it reaches a dangerous value, the gaps G_3, Fig. 3, arc over. As explained, the voltage to break down these gaps must be higher than if no resistance were used in series. With these gaps broken down, the current of the arc across them is limited by the high resistance to about $\frac{1}{16}$ ampere, which gives about 80 volts drop per gap. The remainder of the voltage is consumed in drop across the resistance rods and is thus applied across the gaps G_h. Although this voltage is less than that which broke across G_s, the series resistance is less, and approximately the same number of gaps will therefore break across at this lower voltage. With G_s and G_h broken down, the increased current gives a smaller drop in the gaps, but twice the number of arcing gaps are now in series. Therefore the number of gaps in G_m is made the same as in G_s and G_h. These three sections should all arc over in succession at very nearly the same voltage.

In this arrester the different kinds of lightning will follow different paths through the arrester, and test papers should be more useful than ever before in determining the nature of the discharge. Test papers should be placed in all four divisions of each line leg, and in the three divisions of the ground leg. Designating the different divisions as in Fig. 33, G_s, G_h, G_m, etc., the different kinds of lightning should produce punctures and burning as follows:

Static charge of the line relieved or a very light discharge—G_s small slightly burned pin-hole, others not touched.

Low-frequency surge of small power, or discharge of medium frequency—G_s and G_h small burned holes, others not touched.

Low-frequency power surge, or abnormal rise of power voltage—G_s, G_h and G_m well burned holes, G_1 not touched.

High-frequency discharge of the arrester—G_s and G_h small burned holes—G_m and G_1 punctured, but not burned.

The test papers of the ground leg can show whether the discharge took place from line to line or from line to ground, and whether the line became grounded during the discharge.

Wm. McClellan: While deciding on the lightning protection for a sub-station which takes current at 60,000 volts and delivers it at 11,000 volts to a trolley line, we were impressed with the well-known fact that the selection of lightning protective apparatus depends on the amount of power back of the stroke and the voltage of the line to be protected. For the 11,000-volt circuit a form of multigap arrester was used. Perhaps some of these multigap arresters are better than others, but any well-designed one will answer for low voltages. The small amount of lightning that we have had this year has burned the gaps somewhat; this we know is the chief difficulty in connection with the multigap arrester. For the 60,000-volt lines, outdoor arresters of the horn type were used. There are three horns on each leg of the three-phase circuit. In series to ground with one of these horns is an enclosed indicating fuse 6 ft. long; this fuse works very definitely and positively, although it has not yet operated in connection with lightning discharges. A second horn has in series to ground a resistance made up of concrete blocks. The third horn has in series to ground one of the electrolytic arresters described by Mr. Jackson several months ago. It is hoped to show that the electrolytic arrester will take care of all discharges through the lightning season. If this proves to be true, increasing experience will warrant us in discarding all other types and depending solely on this type of arrester.

Such an arrester is in the nature of a safety-valve. As soon as the pressure rises to a certain critical point, it provides a free path of very low conductivity to ground; and when the accidental pressure on the line is relieved, the arrester comes back to its normal resistance. Such an arrester will be operated with a gap in series just large enough to prevent the normal voltage from breaking over. A horn in this case is entirely unnecessary, since the arc is opened by the small arrester current after the accidental high voltage is relieved.

I agree in general with everything that is said in the paper in regard to the horn arrester, but I do not believe in an arrester consisting of various horns with graded resistances. When extra turns are put on the transformers and powerful insulators on the line, all designed to take care of the certain rises in voltage, there seems little use in applying horn gaps with high resistances in order to relieve the line of rises in voltage slightly above normal. I think the horn arrester has been found useful only in those places where there is sufficient power back of it, so that the current passing over the horn is not large enough to shut down the station. In other words the horn type is successful in those few places where one can wait for the horn to open the circuit. It should be remembered, however, that under certain wind conditions, and also if the horn is not correctly shaped, it may be an excessively long time in opening the discharge circuit.

My faith in the electrolytic arrester has grown, so that for circuits of approximately 11,000 volts I would be inclined to use this arrester indoors; for circuits of approximately 60,000 volts I would use the electrolytic arrester also, with or without a horn, supported, however, as a last resort by a sturdy gap with enclosed fuse in series to ground. Such an enclosed fuse containing a No. 30 copper wire will open the discharge circuit in less than one cycle, whereas from 30 to 60 cycles is the usual time for the horn type under the best conditions. With either, on all circuits, choke-coils should be used beyond the arresters.

R. P. Jackson: Regarding the non-arcing quality of the so-called non-arcing metal: Mr. Rushmore, I believe, ascribed it to the boiling point of certain elements in the alloy. I think one thing has been lost sight of. Years ago, when Mr. Wurts first made the discovery of non-arcing metal, he found that there were certain metals belonging to one group that had that quality to a large degree, and other metals did not have that quality to any considerable degree or to any degree at all. These metals were cadmium, mercury, and zinc. They are all monatomic; that is, their gases are formed of molecules of one atom. This has a very important relation to the non-arcing quality, in that the gases have twice the volume that gases from other metals have. Also it is highly probable that a comparatively small number of ions will exist in the gases. Therefore, there would be much less chance for the arc to establish or maintain itself, and possibly a much greater local pressure when the spark occurs in the gap; that is, when the spark passes there will be between the surfaces of the metal a momentary great rise of pressure.

In regard to the "ideal" arrester, I think that it must be considered as a reasonable development from previous arresters used. The original non-arcing metal consisted of a single row of gaps. It was found several years ago that double the number of gaps, with half of them shunted, would form an arrester of the same equivalent as the original gaps. This can be extended, adding more resistances and more gaps, gaps being shunted by the resistance; but the equivalent begins to rise, and if another step is added, it rises somewhat more, and soon gets to a point where nothing is gained. There is not very much to be gained from more than the one step; but the equivalent will not rise quite so rapidly as the number of gaps themselves. The explanation seems to be that there is a time-period in the breakdown of the gaps; that is to say, they are not simultaneous, but consecutive.

Fuses are very good devices where they are properly arranged. In several places I have tried a fuse in parallel with the series resistance of an arrester. Such fuses will perhaps blow once or twice in a season; but when they do blow, they are badly needed.

Regarding the horn arrester, I am not sure that the rising of the arc is due to magnetic effect. Experimentally I have not found that true. I understand that at the Ontario Power Company's station the horns were arranged with coils to increase the magnetic effect, without much gain being found. I think the virtues of the horn arrester lie chiefly in its mechanical characteristics; it is comparatively simple and cheap. It has some non-arcing or arc-suppressing quality, but it has no such arc-suppressing quality as the multigap arrester. If something can be put in series with it that does not offer great impedance to the discharge of lightning or other energy, it may become useful.

The electrolytic arrester, so far as I have been able to learn, has just the characteristics that Mr. McClellan describes. It has a certain equivalent that is controlled largely by Ohm's law. If the area of the plates or the electrolyte is increased, the equivalent is decreased. If the length of the electrolyte is increased the equivalent is increased, and that equivalent seems to have comparatively little relation to the volume of discharge through it, so that it seems possible to predetermine the voltage which could escape through the arrester and simply short-circuit everything above that. In the type of electrolytic arrester which I have used, however, I do not consider it to be the counter electromotive force that limits the power current; there seems to be a dielectric film, and that film is capable of puncture and also capable of resealing when the voltage drops below a certain point. It acts like a valve with a spring behind it. When the film is punctured, if the excessive static voltage exists long enough, there will be a very large power current flowing through, but of course the high voltage due to lightning or surges exists for a very short interval, so the power that follows is insignificant.

C. P. Steinmetz: Omitting the fuse shunting the gaps requires that the gaps be always left in circuit, so that after the fuse blows there is still the same protection to the system as there would be when no fuse is used. The fuse gives a far better protection for most of the time and under most of the conditions than would be permissible without it. This use of a fuse, therefore, is not analogous to the fuse in series with the horn arrester.

Some of the questions raised refer merely to matters of terminology and would be very interesting discussions to fill the volumes of a purely scientific body. They are of comparatively little interest to an engineering society; for instance, whether the effect of some metal cylinders discovered by Mr. Wurts, and published in his classical paper fourteen years ago, might be called rectifying, or might be due to some mysterious action of some mysterious bodies, ions, jolting around in some manner—all this is quite immaterial to me. Mr. Wurts called the phenomenon "non-arcing". Mr. Creighton finds two conditions: first, if the shunt resistance is low the disruptive discharge across the cylinder is not followed at all by the generator current; secondly, the disrupted discharge is followed by the generator current during one-half wave, but no further; that is, no reversal of the generator current can take place. Mr. Creighton adopted Mr. Wurts' term for the first condition; that is, called the case "non-arcing", where no generator current follows, and he gave the name "rectifying" to the case where the current can follow in one direction only, but cannot reverse.

Whether the non-arcing character of these metals is explained as being in one group—which, incidentally, is not quite right—does not seem to be a matter of very great importance. If I recollect aright, Mr. Wurts mentioned bismuth and antimony as non-arcing; these do not belong to the zinc group, though other metals which do belong in the zinc group are not generally recognized as non-arcing. The order of the non-arcing character of the metals as given by Mr. Wurts is the order of their boiling points. All this might be an interesting subject for a purely scientific or metaphysical paper, but does not seem to be of any particular value to us.

D. B. Rushmore (by letter): Many of the points brought out by the first speaker in the discussion are answered by a more careful reading of the paper or by the other speakers.

It is agreeable to find that the statements made concerning the horn arrester are in agreement with opinions held by men of such experience as Mr. Thomas and Mr. Converse.

It is stated somewhere in the paper that the illustrations showing the scheme for protection of wood pole lines are simply diagrammatic. Attention should, however, be called to the fact that the multigap arrester described in the paper is entirely new in design, and a careful reading of the action of the discharge over the multigaps will explain the difference in principle between these and former multigap arresters.

E. E. F. Creighton (by letter): Some one has observed that the liquid electrode arrester is wet. That is true: it is the condition sought for. After having gone over a number of different methods of preventing or extinguishing an arc, I have come to the conclusion that with but one possible exception, not yet published, the liquid gives the most valuable property to the lightning-arrester.

The objection to the liquid, as suggested by Dr. Perrine, lies in the necessity of maintaining a certain level, and it might be added to keep the liquid from splashing. This is a simple engineering problem which seems to offer no difficulty in its solution. There are several solutions being tried out at the present time, any one of which seems to be practicable.

The loss of liquid through the operation of the arrester by lightning is too slight to take into account. For example, one of these arresters was put into operation three hundred times, which would easily cover a whole season's storms even in the worst locality, and at the end of the test the level of the liquid had not been lowered to any measurable extent. The energy given out by the electric current in the arc is absorbed, first in raising the liquid to boiling temperature; secondly, in the latent energy of changing the liquid to a gas; and thirdly, in the chemical energy of dissociation of the gas. To carry through this process requires a relatively great amount of energy for a small amount of electrolyte. The amount of electric energy given off from the generator is comparatively small because the current is limited by the voltage absorbed in the arc at the surface of the electrolyte. In case of continuous discharges over the lightning-arrester due to a grounded phase on an insulated Δ or Y system, the electrolyte is gradually used up until the arc distance is too great to be bridged by the surges on the line. This, as already stated in the paper, will require a number of minutes, and it will be necessary after such an operation to refill the jars with water to the original level. It should be noted that the arrester is not damaged by this continuous operation.

In considering the operation of the liquid electrode arrester, the brief and convenient term, "variable resistance" was used but it is important to distinguish carefully between the effect obtained from a counter electromotive force and the effect from a variable resistance. Although the counter electromotive force gives the same effect as an increase in resistance in reducing the current, yet it differs materially in that it reaches a limiting critical value above which it offers no further obstruction to the current flow. From zero up to the critical voltage the ohmic resistance of the cell has probably diminished although the effect of the arc is that of an increase of resistance.

Dr. Perrine's kind expression of appreciation of the work on this new cell type arrester reminds me that it was he that first recognized the value of the aluminum cell-type arrester and aided most in its development when I began working on it some six or seven years ago.

In regard to the leakage of current between cylinder and cylinder of the multigap arrester. The experience we had some years ago will corroborate Mr. Thomas's statement. Instead of using individual units of porcelain, Mr. Wurts decided to use one slab of marble with the cylinders arranged in zigzag form, but it was found that the spark voltage or equivalent-needle-gap of the same number of gaps as used previously with the porcelain units was very greatly increased. The leakage of current though the marble was sufficient to prevent the separation of the positive and negative charge on each cylinder, and the consequent resultant static induction to the next adjacent cylinder. The ten-pin or card-house effect was lost. The drop of potential across the marble was uniform, the high frequency between cylinders was lost, and many of the gaps were in a condition of partial short-circuit due to the concentration of the leakage current in the marble in the shortest distance between terminals. I still have in my laboratory an expensive board made up in this way which is entirely inoperative as a multigap arrester.

Mr. Thomas calls attention to the short-circuit current shown in one oscillogram as only 200 amperes. This I might state was under a particular condition where only one small machine was on the circuit, and the short-circuit current shown in some of the other oscillograms is more than double the value stated. By considering the condition of discharge of the new type multigap arrester it will be seen that the generator capacity is amply sufficient to give the effect that might be obtained from a machine of any capacity. When the spark takes place across the shunt gaps, the generator is producing full potential across the arrester and the voltage is not decreased by the discharge of the dynamic; consequently if the spark is going to form into an arc there is every reason for it to do so regardless of the generator capacity. Stated otherwise, if the potential of the generator does not decrease, the experimental conditions of test are correct and nothing further could be obtained by using a generator of greater kilowatt capacity. This statement is general and applies also to the tests of the liquid electrode arrester. I admit of course that if the spark does form into an arc the damage caused will increase directly with the capacity of the generator.

C. P. Steinmetz (by letter): It seems to me that the disagreement on the horn arrester is more apparent than real: it depends upon what is expected of an arrester. Mr. Rushmore defines a lightning-arrester as an apparatus capable of discharging any abnormal voltage or abnormal frequency without interfering with the normal flow of current. This the horn arrester does not do. With series resistance it is limited in discharge capacity; without series resistance it may protect the system; but it short-circuits it, so shuts it down temporarily.

Mr. Thomas' criticism of the definition of "lightning" seems justified. It is rather strange to speak of "lightning-arresters" in underground cable systems. I have not introduced this definition; but it has gradually introduced itself in practice, and so will probably stay. The proposed name "static", however, I do not approve at all. The term "static" has been used to a considerable extent, and mostly abused. Occasionally one hears of such anomalies as "static transformers," instead of "stationary transformers". If "static" means anything, it can only mean electric phenomena of such limited power as not sufficient to produce an appreciable current; that is, phenomena in which the electromagnetic component of the field is negligible compared with the elctrostatic component. A short-circuit surge which bends heavy copper bars can then hardly be called static, but the lightning-arrester should protect against it.

In my paper I have drawn analogies between electric waves, and waves in a body of water. It is obvious that such an analogy, though elucidating the phenomena, is not complete. For instance, in an electric circuit the tendency to form stationary waves or oscillations from travelling waves or impulses is very pronounced; but in a body of water this tendency exists to a very limited extent only, since in the latter case the wave length is usually only a very small part of the total wave travel. I believe that Mr. Thomas misunderstands my comparison of the breaking of a wave train at the station with the ocean surf. Where complete reflection occurs, as at the open end of a line, a standing wave is formed from the travelling wave of the same frequency. An ocean wave, rolling on to a sloping beach, is, however, not completely reflected; it is only partly reflected, while partly it rushes up on the beach. Now at the entrance to a station an electric wave train is partly reflected, partly enters, and "surf" is the result of the interference of the various reflected and transmitted wave trains. This results in the formation of local standing waves. The surf is therefore not a complete reflection, but a breaking up of the wave. In this way an ocean wave on a sloping beach, is comparable with an electric travelling wave at the entrance to a station.

As regards the damping effect of a grounded overhead wire, it appears to be obvious that a current induced in the ground wire by a wave train in a transmission line consumes energy, and thus reduces the energy of the wave train. The energy dissipated by this induced current in the effective resistance of the ground wire is taken from the energy of the wave train in the main wire, and causes the latter to decrease more rapidly. The imperfect inductive relation between transmission wires and ground wires applies only indirectly in considering this effect. Of the total magnetic flux produced by the wave train in the main wire, and surrounding the main wire, only a part interlinks with the ground wire as mutual inductive flux; probably most of it passes between the conductors as self-inductive flux. This self-induction does not consume energy, and therefore does not dampen; but mutual induction consumes energy and so causes the wave train to decrease more rapidly.

In a lightning-arrester it is of fundamental importance not merely to discharge abnormal voltages or frequencies, but to discharge them with the least possible disturbance. This means to discharge over the highest resistance, which does not yet appreciably back up the voltage by its *Ir* drop. Sometimes the volume of discharge is such as to permit no resistance whatever. The lightning-arrester must therefore have a path of no resistance to ground. A half-wave discharge without any resistance is quite a severe shock, and should be avoided. For this purpose a medium high resistance in shunt is used to take care of most of the discharges; of the discharges that are too heavy for this resistance, most are still deflected over the "low resistance" of the arrester, so as to limit the dead short-circuit discharges to a minimum. Very many discharges, however, are of such small power that a resistance very much higher than the "medium resistance" can take care of them; and it is therefore undesirable to cause a fairly large dynamic discharge over the medium resistance every time one of these very small discharges occurs. For this purpose the high resitance has been added.

Mr. J. P. Jackson explains that the non-arcing character of mercury, cadmium, and zinc is due to these metal vapors being monatomic. It is unfortunate that helium and argon are also monatomic, but are by no means non-arcing; on the contrary, they are known to have abnormally low disruptive strength; that is, they require only a low voltage to maintain a discharge.

Wm. McClellan (by letter): It has always been difficult to get a physical conception of the action of the film used on aluminum electrodes, either of the type proposed by Mr. Creighton or the one proposed by Mr. Jackson some time ago. No physical conception can be had until a great deal more is known about this phenomenon.

The writer has always conceived of the film as being electrically porous so that up to a definite pressure it held the current, but beyond this pressure the pores, so to speak, opened, allowing the discharge to pass through freely. This conception seems reasonable when one views the formation of the film and sees the gradual decrease in the number of spark discharges all over the face of it, until finally upon the complete formation these discharges cease at pressures below the critical point. This conception is suggested by the old physical experiment of the hollow gold sphere which will hold a liquid until the pressure is raised to a particular point when the liquid squirts out all over the surface.

The writer has never been able to find or hear of more than two objections to the electrolytic arresters with the large surface as proposed by Mr. Jackson. The first of these objections is the possibility of the arrester being exploded or burst by a heavy discharge, the same as a telegraph pole or tree is frequently rent. In such cases the explosion or shattering is due to the fact that the conducting path is very circuitous and narrow and that there is a great concentration of energy in this path. In the case of the large surface lightning-arrester proposed no such condition can exist, as at the time of a heavy discharge there is a uniform path of high conductivity.

The other objection is the possibility of freezing the electrolyte. This objection, of course, would hold only in the case of high-voltage insulations where it would be necessary to put the arrester outside the station. The writer thinks that in case of this trouble with a three-phase installation of these arresters, it would be a comparatively simple matter to put the three sets of arresters either in a pit below the frost line or in a cabinet above the surface, according to drainage conditions. This would act to shield the arresters from wind and shaking. It is well known that a liquid if kept absolutely still will not freeze when brought to a temperature far below its freezing point. It would probably be found that the temperature would never get sufficiently low to cause freezing solid. Experiments show that it is only when the electrolyte is frozen solid that it ceases to have its peculiar resistance characteristics.

P. H. Thomas (by letter): Mr. Creighton speaks of the "discovery of the true non-arcing conditions of shunted gaps" which he distinguishes from "the unstable condition of a shunted arc" that "has been known for a long time", by considering the latter as a phenomenon having to do with alternaing current whereas the former is really a shunted direct current operating for a part of a cycle. This distinction does not appear to me to be well founded. If we have a number of gaps shunted by a resistance, and pass a static discharge through these gaps while they are connected to a source of alternating potential, there will be of course current flow through the resistance and there will be a tendency for current to flow through the gaps following the static discharge. Whether a sensible current will appear in gaps depends, obviously, upon the voltage maintained across the gaps regardless of whether there may be resistance in shunt or not; whether the current continues in the shunted gaps or not depends also on this voltage and not directly upon presence, absence, or value of the shunt resistances. If the source of current is able to supply a smaller amount of current through the resistance than will maintain an arcing voltage upon the gaps, manifestly no current will follow the static discharge in the gaps. If, on the other hand, a sufficient current can be supplied by the source of electromotive force to maintain a sufficiently high voltage upon the gaps, current must inevitably follow the static spark therein. The shunt resisance has not a direct effect upon the arc in the gaps; it merely effects the potential of the terminals of the gap.

If now the static discharge occurs at one portion of an alternation, the voltage at that moment impressed upon the gaps will have one value; if at another part of an alternation, another value. There must be a portion of each alternation during which the generator voltage is so low as not to allow current to flow in the gaps following a discharge. On the other hand, if the current capacity of the source be sufficient there will be times within the alternation when the voltage impressed on the gaps will be sufficient to cause a following of current in the gaps. The most favorable condition for such following is obviously that the static shall occur approximately at the maximum of the waves. It appears from Figs. 3 and 4 of Mr. Creighton's paper that the static discharge which he times with a synchronous motor occurs early in the cycle, at an instance when the generator electromotive force is far from its maximum. This condition is manifestly an unfavorable one for the following of current in the gaps. If Mr. Creighton has always passed the static through the shunted gaps at this part of the cycle, it would not be safe to draw any inferences as to the non-arcing quality of the arrangement under the conditions of actual service where the discharge is sometimes likely to come at the maximum of the wave.

The arc suppressing power of the shunt resistance depends entirely upon the current that is to pass through this resistance following the static discharge. The shunted lightning-arresters heretofore used have exactly the same electrical arrangement as Mr. Creighton's. When the current tending to flow in the resistance after a discharge is small, or when the discharge occurs at a low-voltage point of the cycle, no current whatever will appear in the shunted gaps. When, however, more current flows through the resistance there will be some current flow in the gaps this current will cease at the first alternation if it be not too heavy, or so much current may be forced into the gaps that they will continue the arc. There is no difference between the apparatus of Mr. Creighton and the previously shunted gaps; he has simply subjected them to milder conditions.

I would call attention to the curious form of the current curves in Fig. 1, which I believe to be generally correct. The first time it is met with, the high voltage at low currents is quite a surprising feature.

A paper presented at a Special Meeting of the American Institute of Electrical Engineers, New York, April 15, 1907.

THE ROWLAND TELEGRAPHIC SYSTEM

BY LOUIS M. POTTS

Since the invention of the Morse system more than fifty years ago, telegraphy has grown by law of natural evolution to meet the demands of an increasing business. The Morse system has been the measure of the potential of the telegraph wires and of the operator. To handle a continuously increasing business, telegraph managements have been compelled to stretch annually new copper wires and to employ new operators, because the present wire systems have been worked continuously to their capacity and operators to their highest efficiency under the conditions imposed by Morse methods. It is evident that this indefinite extension of wire systems and the force of operators involves the consequent investment of enormous capital and increases indefinitely annual maintenance charges.

In all other fields of modern industrialism when manual methods have thus shown themselves to have reached the limit of their development, and to be capable only of clumsy augmentation without radical resulting advantages, necessity has found the apparatus to meet the demand, and the introduction of machines and machine methods has inaugurated a new era of increased capacity and economy. For some years, telegraph managers have realized that the manual Morse system has about reached its limit of development and they recognize that further progress must result from the use of machine telegraph methods. They have understood that the machine to be valuable must despatch a greater volume of traffic on existing wires and give greater efficiency to the operator than can be done with the now highly developed Morse methods. The field of machine telegraphy thus determined has proved to be a most fascinating one to inventors and has enlisted the constant attention and efforts of a large number of able and ingenious men. As a consequence, various telegraphic devices and machines have been brought forward at different times to meet the demand of the situation, but since none has heretofore remained predominant in the field, it is clear that none has been able to meet the exacting requirements attending commercial operation.

The purpose of this paper is to describe a system of telegraphy which meets the requirements of the telegraphic service of to-day by providing for an enlarged wire capacity, combined with greater efficiency of the operator and adaptability to the requirements than any system previously described. In practical operation, it has continuously demonstrated its efficiency in despatching an enormous volume of business with regularity and accuracy on a single wire, while the operators employed have been not necessarily skilled in the use of the Morse code.

General Description

The Rowland Telegraphic System is a sytem in which the two features of multiplexing and printing are combined. The multiplex feature is accomplished by the synchronous operation of the instruments at the terminal stations. By this means, in an octoplex installation each of the four operators is given the use of a telegraph wire one-fourteenth of a second, at intervals recurring 3.5 times a second.* In addition, the wire is duplexed by the polar duplex method, so that four transmissions in each direction, or eight in all, are obtained. In a quadruplex installation, each of the two operators is given the use of the wire for one-seventh of a second at intervals recurring 3.5 times a second; and the duplexing of the wire provides for two transmissions in each direction, or four in all.

The printing is accomplished by a perfectly direct method; that is, no punched or otherwise prepared tape is used at either the sending or receiving station, but the printing is controlled directly from a keyboard, practically identical with that of a typewriter. The total duration of the operation, from the

*The normal operating speed is fixed at 210 revolutions of the line unit per minute, or three and one-half revolutions per second, or one revolution in one divided by three and one-half, or two-sevenths of a second. This interval of two-sevenths of a second being divided among four operators, gives each one the use of the wire for two sevenths divided by four, or one-fourteenth of a second.

depression of the key at the sending station until the character is printed at the receiving station, is less than one-quarter of a second.

All the operations at the receiving station are controlled from the keyboard at the sending station. This keyboard is identical with a typewriter keyboard, except for three additional keys, the so-called "lining," "backing," and "blanking" keys. The lining key is for the purpose of enabling the sending operator to move the paper from line to line on the printer at the distant station, the paper being moved the distance between two consecutive lines each time this key is depressed. The backing key is used for the purpose of returning the carriage at the distant station to the beginning of a new line. The blanking key is used for the purpose of shifting a telegraph blank on the printer at the distant station to the proper position for a new message. By the use of these keys in conjunction with the other keys, the operator has perfect control over the receiving printer at the distant station. All the operations performed on a typewriter, such as paragraphing, tabulating, etc., can be performed equally well with this keyboard.

At the sending station, in addition to the keyboard there is a home-recorder and a signal light for the guidance of the operator. The home-recorder consists of a tape-printing arrangement. A narrow paper band passes directly over the keyboard, and (directly) in front of the operator. On this tape is recorded the character corresponding to each key depressed. When the lining, backing, and blanking keys are depressed, in place of performing these operations on the home-recorder, characters are printed on the tape, indicating that these keys have been operated properly. When the backing key is depressed, an arrow is printed on the tape. This arrow, as the tape moves, travels with the tape along a properly graduated scale and indicates to the operator the position of the character last printed on the page printer at the receiving station.

In addition to the home-recorder, there is placed beside the keyboard a small red signal-lamp for the guidance of the sending operator. When the carriage at the receiving station has approached within a certain number of characters of the end of the line, this signal lamp automatically lights, thus performing the same function as the bell on the type-writer and preventing the sending operator from piling letters at the end of the line. When the operator depresses the backing key, this light goes out as soon as the carriage at the distant station has returned to the beginning of a new line.

At the receiving station the messages are automatically printed in page form on a long band about eight inches wide, (See Fig. 1 for facsimile of message) which may be prepared

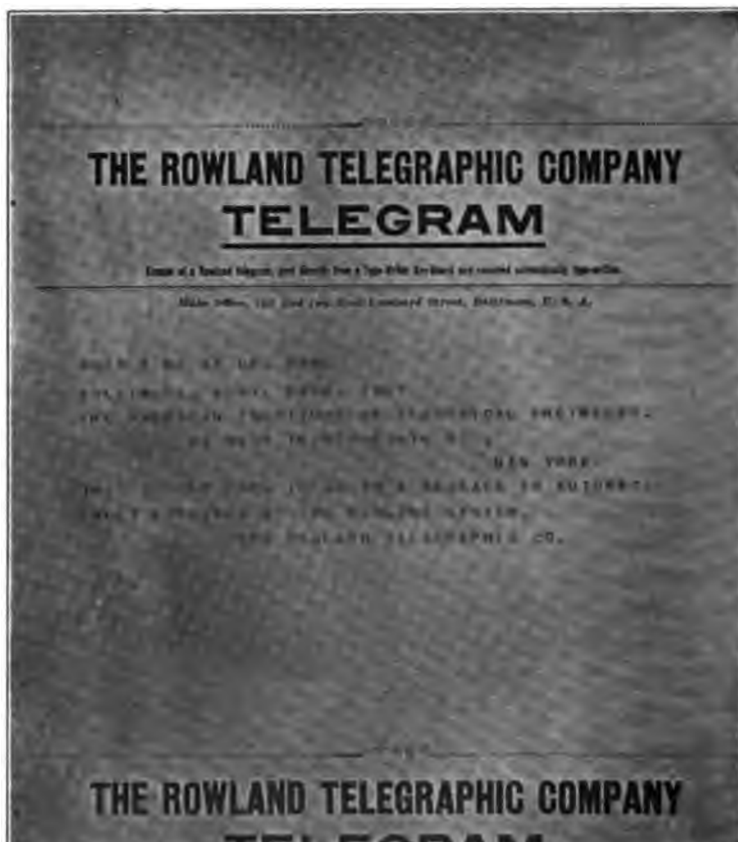


Fig. 1—Facsimile of Rowland Telegram

with the regular telegraph blank, or any other blank which may be desired. On these blanks the messages may be printed in any desired form, there being the same flexibility as can be obtained by the use of a typewriter. The page printer consists of a light carriage which carries the paper and is capable of being moved in a horizontal direction for purposes of spacing.

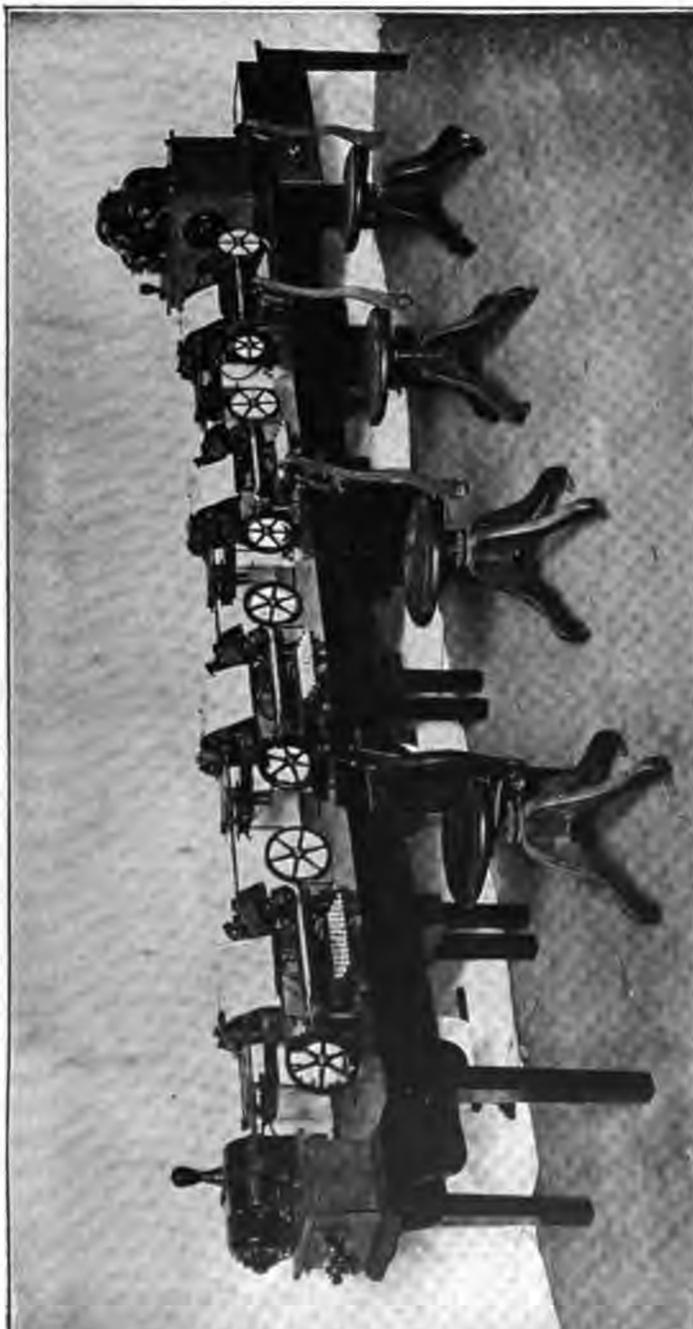


FIG. 2—Rowland Octoplex, sending side

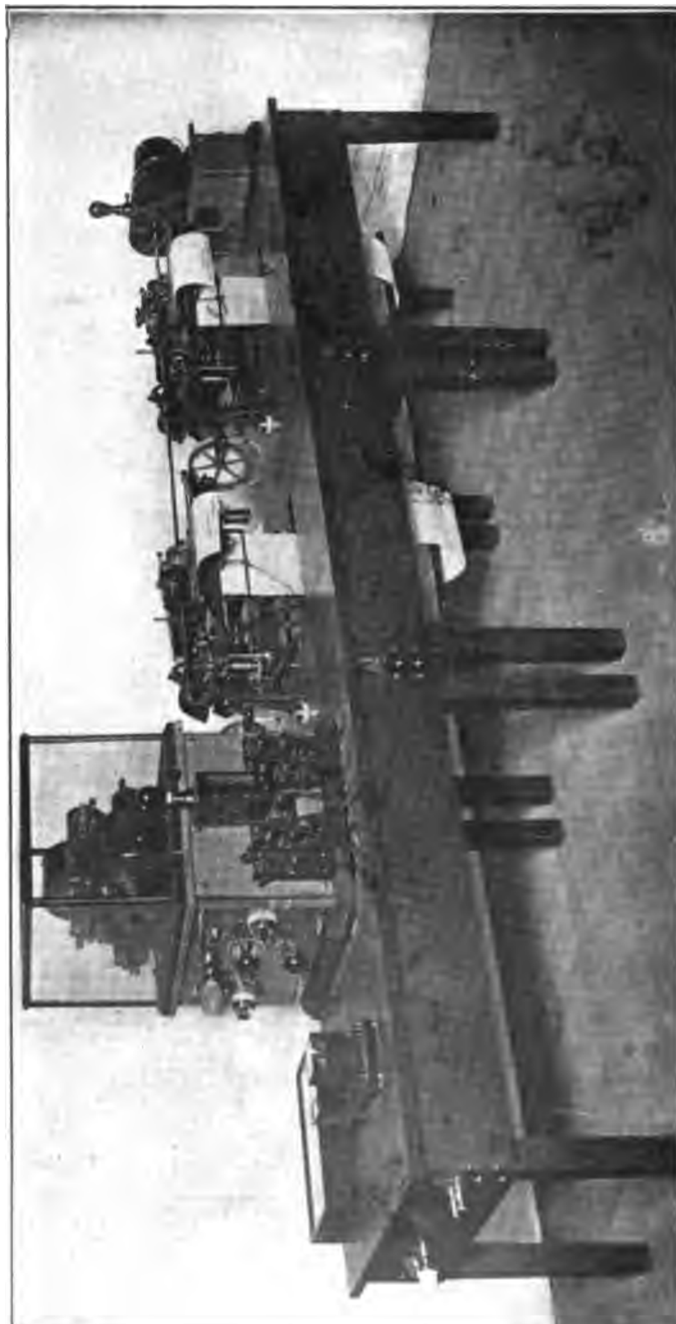


Fig. 3—Rowland Quadruplex, receiving side

The paper is carried around a roll, which by rotating places the paper in position for a new line. The paper is carried between a platen and a constantly rotating steel wheel, having the various characters engraved on its rim. When a character to be printed is directly over the platen, the platen throws the paper against the type-wheel, which is continually inked by a small felt ink-wheel. All the above motions and the operation of the platen are produced by electromagnets under the perfect control of the sending operator.

Speed of Operation

The speed of each operator is limited by the number of times per minute the keys are unlocked. The normal operating speed being 210 revolutions of the driving mechanism per minute, the keys are unlocked 3½ times each second, or 210 times per minute. One key can be depressed each time the keys are unlocked. The theoretical maximum speed is about 40 words per minute. On account of the time required for returning the carriage to the beginning of the line, and also because of the fact that the operator does not always take advantage of the unlocking of the keys, when operating for long periods, the speed in actual practice is about 35 words per minute. However, except on the longest lines the speed of the operation of the machine may be very materially augmented. Upon the basis of 30 words per message, which is generally accepted as a fair average, this speed is equivalent to a rate of about 75* messages per hour, per operator, or 300 in each direction per hour, per wire, or 600 per hour, per wire for the full octoplex.

Telegraphic Current

In the Rowland system of telegraphy, the basis of the telegraphic current is an alternating current.

In an octoplex installation the current, at the normal speed of operation, has a period of 98 cycles per second. The same current is used for signalling and synchronizing. This alternating current is sent over the line continuously. The signals consist in reversing certain combinations of waves, as will be described later.

Fig. 4, Curve I, quadrant *C* is an oscillogram of a block of 14 of the half waves of the basic alternating current. The half waves are numbered from 1 to 56, after 56 another block

*A rate of 71 messages per hour has been maintained in commercial practice for all-day operation. A rate of 50 to 60 messages per hour is maintained with ease.

begins with No. 1, and so on. This block of 56, which lasts two-sevenths of a second, is divided into four blocks each, *A*, *B*, *C*, and *D*, each of which is assigned to a different operator, making four transmissions each way if duplexed as mentioned. Each block recurs 3.5 times each second.

For the purpose of sending the actual printing signals, only 11 impulses are used in each block. One of the remaining three in each block is used for operating the lamp signals between the stations, and one other, in the *D* block, is used for the letter finder impulse as is described later. The sending of a signal for the printing of a character at the distant end consists in the reversal of two of the 11 impulses. By variously combining two at a time of the 11 impulses, a sufficient number of signals is obtained for telegraphic purposes, that is, 55 possible different signals, 51 of which are actually used, any one of which may be transmitted during a time in which 11 impulses pass over the line.

Fig. 5 shows how the 11 half-waves are combined to obtain the 51 signals used.

Fig. 4, Curve 1, is an oscillogram of the current received and which vibrates the main-line relay. At the particular time of the oscillogram the *A* operator is transmitting the signal period (.) The *B* operator is transmitting the signal for lining and the *C* operator is transmitting no signal and the *D* operator is transmi ting the letter *A*. The letter-finder wave is also shown reversed, as this is always reversed. The carriage on the *D* receiving printer is at the end of a line and the lamp signal in the *A* quadrant is reversed.

In a quadruplex installation the current has a period of just one-half that of the octoplex, or 49 per second; and the waves shown in the *C* and *D* blocks in Fig. 4 are omitted, the waves being numbered from 1 to 28 and after 28 the start being again made with No. 1. Each block recurs, as in the octoplex, 3.5 times a second and thus the time for each wave is twice as great as in the octoplex and the frequency is therefore one-half.

Generating the Alternating Current

The alternating current used for the Rowland system is generated directly by the machine itself, this being necessary because the frequency of the current must correspond exactly with the speed of the machine. The current is generated by a dynamo or by a transformer and a commutator together with

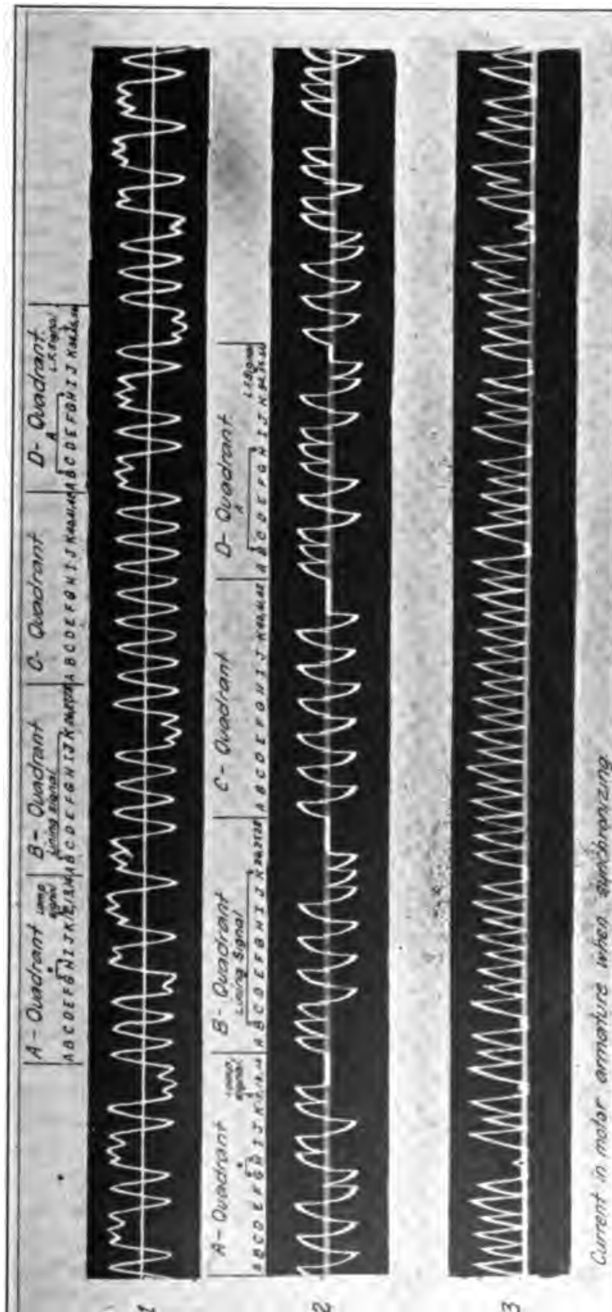


FIG. 4, Part I—Oscillogram

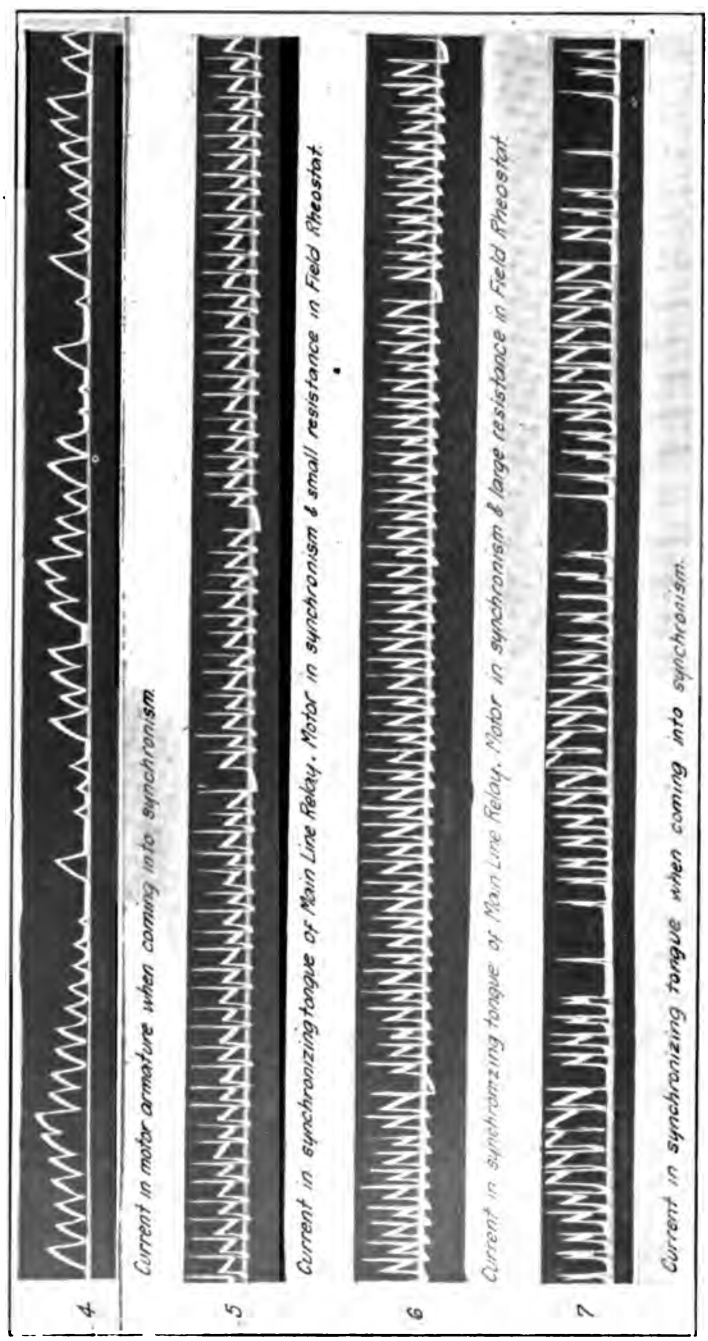


Fig. 4, Part II—Oscillogram

Curves 5, 6, and 7 above are printed in the reverse direction to that of the previous curves, and the lapse of time is from right to left, in place of left to right.

a combination of resistances and condensers which serve no other purpose than to reduce sparking on the commutator.

The transformer consists of two primary and two secondary coils with an iron core. The commutator used in connection with the current generator has eight rings, one being a solid collecting ring and the other seven being crown sections having in the octoplex 56 segments and in the quadruplex 28 segments every alternate segment being electrically connected.

One terminal of each of the two primary coils of the transformer is connected directly to negative. The other terminals

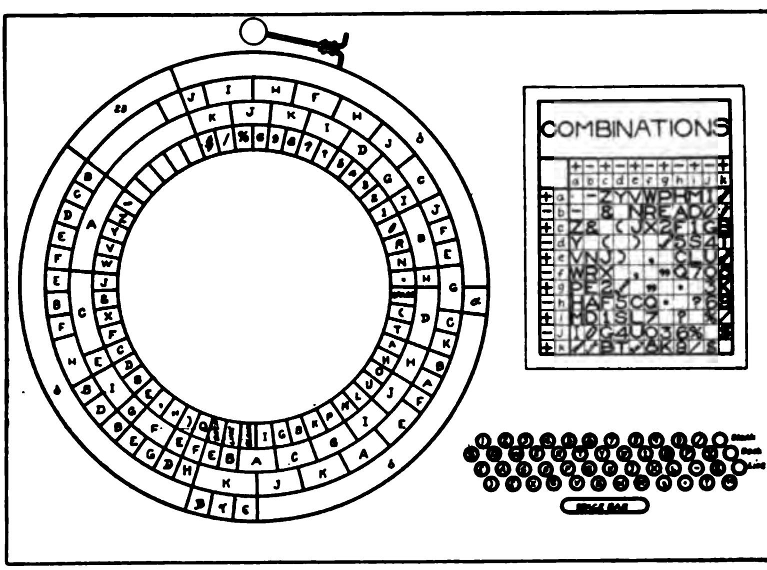


FIG. 5—Combination diagram

are connected to the alternate segments of the first crown section, the coils being so connected that the current flows through them in such a manner as to magnetize the iron in opposite directions. The theory of the operation of this current generating apparatus should first be considered with regard only to the solid collecting ring and the first crown section (see Fig. 6), the other crown sections simply serving the purpose of stopping the spark and preventing wear of the commutator and brushes. By taking into consideration only these parts, it will be seen that the brushes (which are all in metallic connection) alternately connect the two open terminals of the two primary transformer coils to the positive of the direct-current voltage, thus continually reversing the magnetism of the iron core of the transformer as the brushes pass from one segment to the next. These reversals of the magnetism of the iron core induce in the secondaries of the transformer an alternating current, the further operation of which will be explained later.

The remaining six crown sections of the commutator have their alternate sections connected to the two primaries in a similar manner to the first crown section, except that in place of being connected directly they are connected through resistances shunting condensers, these resistances increasing in value from the

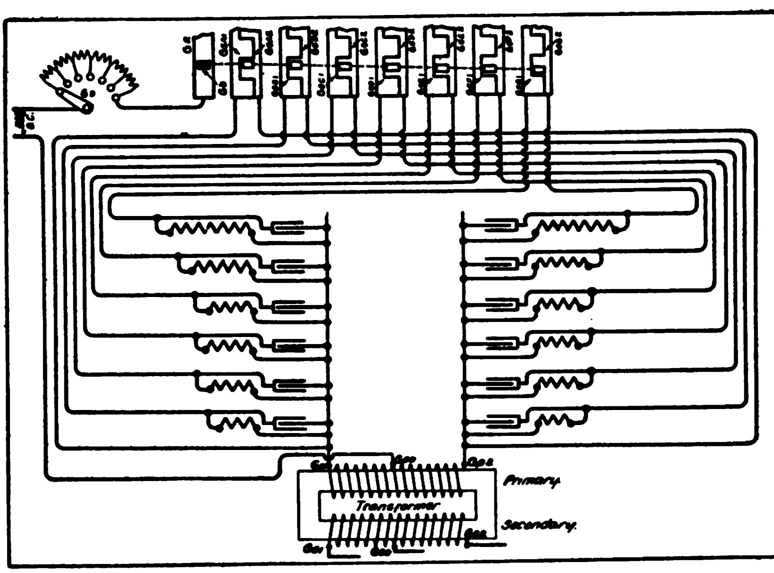


FIG. 6—Current generating connections

second crown section to the last. The brushes are so arranged on the trailer arm that the brushes leave corresponding segments of different rings in the order of increasing resistance. By this arrangement the spark which would otherwise occur when the brush leaves the segments is prevented.

On the end of the brush arm opposite to that carrying the contact brushes are mounted two carriers, the first one of which carries a piece of dry felt, the second one a piece of felt slightly oiled. These two carriers are operated by springs so that the felt is pressed against the surface of the commutator in such a way that the dry piece of felt cleans the commutator while the second piece of felt furnishes the commutator with fresh lubricant. The action of these pieces of felt is to diminish the spark on the commutator and also to prevent mechanical wear on both the brushes and commutator.

Amount of Current Required

In the Morse system of telegraphy, and in fact in most systems of telegraphy, it is customary to measure the currrent by applying direct voltage to the line so that the same amount of current flows at both stations. When the signalling current is reversed in direction at comparatively regular intervals there is quite a different phenomenon. In this case a greater current flows at the beginning of the line than at the end. This fact is readily understood by considering the action of the line. Each time that the current is reversed not only does a certain amount of current flow from the beginning to the end of the line, but there is also a large amount of current at the beginning of the line necessary to charge and discharge it. When the line has any considerable length, that is, a considerable capacity, the current which reaches the far end of the line will be only a small part of that which enters it. An example will illustrate: A particular line has a capacity of 8.4 mf. and a resistance of 2070 ohms, when operated in octoplex (period of current 100) 240 milliamperes were sent out at the beginning of the line and about 35 milliamperes received at the end of the line; that is, about six times as much current was required to charge and discharge the line as reached the far end of the line and actually vibrated the main-line relay. Of course, a similar state of affairs is present when a line is operated by any reverse-current system, such as the Morse duplex or quadruplex; but the phenomenon is not often observed as the steady state of the current is measured and alternating-current measuring instruments are not ordinarily required in a telegraph office.

For the proper operation of the relays used with the Rowland system, it is necessary to have at least 25 milliamperes at the receiving station. A very good practical working value for this relay is about 35 milliamperes, and when line conditions are very bad it may be found necessary to use 45 milliamperes. These values of current are required, not because the apparatus will not operate with less, but the signalling current must be sufficiently large to overbalance the effect of leakage and induction currents.

Duplexing

The duplex feature of the Rowland system is obtained as in many other systems of telegraphy by the use of a differentially wound relay and an artificial line, which represents as nearly as possible the real line as regards its resistance and capacity.

In order that the main-line relay may not be affected by the outgoing current, it is necessary that the currents in the two sides of the relay should be identical. In order that one may know when such is the case, a large resistance (about 5,000 ohms) is connected from one side of the relay to the other. Across a small part of this resistance (about 50 ohms) a telephone is connected.* When the currents flowing through the two sides of the relay are identical, no current will flow through this shunt and consequently there will be no sound in the telephone. By means of plugs it is possible readily to change the resistance of the artificial line, and also to move the condensers to any part of this resistance and thus to adjust the currents in the two sides of the relay until they are equal in phase and value. In the Rowland system the alternating characteristic of the current causes the balance to depend more directly on the capacity of the line than on its resistance. The balance used in its operation, therefore, is much more stable under varying conditions of the weather than in such a system as the Morse quadruplex, in which the resistance must be kept adjusted to the varying conditions, since the weather has much greater effect on the equivalent resistance of the line than on its capacity.

Synchronism

In most of the systems of multiplex telegraphy that have ever been tried the principle of synchronism has been used; that is, the apparatus at either end of the line has been operated in unison with that at the other end. In most synchronous systems of telegraphy, synchronism is obtained by adjusting the apparatus at each station so that it rotates very closely to some predetermined speed and in some way, at definite intervals, a correcting impulse is sent over the line; by this means the position of the apparatus is changed by the amount it has de-

* Recently a double-needle indicating instrument has been devised for use in connection with the Rowland system; one needle indicates when the resistance referred to has been properly adjusted, and the two needles by both giving zero readings indicate when the capacity has been adjusted and located.

viated from the other machine since the last correction. All methods of synchronism based on this principle have proved that they require extremely delicate adjustment, and even under the best conditions are subject to frequent disturbances.

The synchronism as used in the Rowland system of telegraphy is of a continuous and stable character. The synchronism is maintained by the use of every impulse which comes over the line, (of which there are in the octoplex 196 per second) and not a small fraction of the total number, as in the case of the systems referred to above. These impulses come at such a rapid rate that on account of the large inertia of the moving parts no effect is observed due to each impulse separately; but the regulation is entirely due to the integral effect of a large number of impulses, so that any variation of even a comparatively large number of the impulses will produce no sudden disturbance of the synchronism.

Potts' Synchronizer

This synchronizer (which is the form now used on the Rowland machines) consists of a small direct-current shunt motor, (See Fig. 7). On a shaft driven by this motor is mounted a trailer Z_b which passes over a crown commutator having alternate segments electrically connected. This crown commutator has such a number of segments that each segment corresponds to a half wave of the alternating current used for signalling. It will be seen that the effect of this brush arm and commutator is identical with that of the vibrating tongue of a relay. The alternate segments of this crown commutator are connected to the two contacts of the synchronizing end of the main-line relay. In series with the armature of the motor above referred to is a resistance Z_r. One side of this resistance is connected to the synchronizing tongue M_{st} of the main-line relay. The other terminal of this resistance is connected to the trailer Z_b.

The tongue of the main-line relay is kept in continuous vibration by the alternating current from the distant station, and the trailer Z_b is kept in continuous rotation by the motor. If the tongue of the relay is on the side contact which is connected to the set of segments of the crown commutator which the trailer is touching at the same time, it will be seen that the resistance Z_r is short-circuited; while if the tongue of the main line relay is on the side contact of the relay which is not connected to the set of segments of the crown commutator which the brush Z_b is touching at the same time, the resistance Z_r will be in series with the armature of the motor. In one case the armature will receive a much greater current than in the other.

Consider, first, the case when the vibrations of the tongue of the main line relay and the rotation of the brush arm bear such a relation to one another, that as long as the tongue M_{st} is against the contact M_{sc1} the brush Z_b is in contact with the segments Z_{s1}. If this condition is maintained it will be seen that the resistance Z_r is continuously shunted.

Secondly, consider the case when the vibrations of the tongue of the main line relay bear such a relation to the rotation of

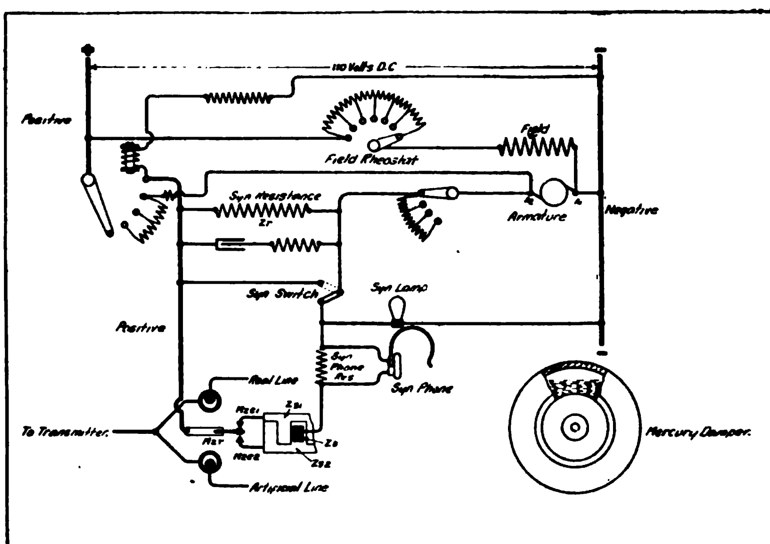


FIG. 7—Synchronizing connections

the brush arm, that when the tongue M_{st} is on the contact M_{sc1} the brush is on segments Z_{s_2} and when the tongue is on the contact M_{sc_2} the brush is on the segments Z_{s_1}. If this condition is continuously maintained it will be seen that the resistance Z_r is continuously in circuit with the armature.

Thirdly, consider any case in which the vibrations of the relay tongue and rotation of the brush arm have some relation between the above two. If any relation between the first two mentioned is continuously maintained, it will be readily seen that at rapidly recurring intervals the resistance Z_r will be in circuit and out of circuit. Depending upon the relation between the vibration of the tongue and the rotation of the brush arm, the intervals during which the resistance is in circuit and out of circuit will vary in length: and in addition to the regular current flowing through the armature, there will be a pulsating current flowing through the same and the strength of these impulses will depend upon the relation existing between the vibrations of the tongue and the rotation of the brush arm. Consequently, while the relay tongue is vibrating in unison with the rotation of the brush arm, there can be various amounts of current flowing through the armature of the motor, depending upon the relation of the relay tongue and the brush arm. (This relation is spoken of as the phase difference).

Let us assume that the relay tongue and the brush arm have such a relation that the current allowed to flow through the armature is of the correct value to maintain the speed of the motor at the same value continuously. If the rate of vibration of the relay tongue increases, the relation between the vibration of the relay tongue and the rotation of the brush arm will change, but in such a manner as to strengthen the impulses flowing through the armature; and consequently the speed of the motor will be increased, but only until this speed corresponds to the rate of vibration of the tongue. If the armature of the motor attempts to go faster than the vibrations of the relay tongue, the impulses through the armature are weakened and the speed is kept normal. If the motor attemps to go slower the impulses are strengthened and the speed of the motor is still kept normal. Consequently the speed of the motor follows any changes in the vibrations of the tongue and any tendency for the motor to change its speed, as, for instance, a change in the voltage in the power circuit, is immediately compensated for by a slight shift in the phase difference above mentioned. In starting the machine, synchronism is obtained by the use of a rheostat in series with the motor field.

The operation of the synchronizing device will be better understood by referring to Fig. 4 which gives several oscillograms of the synchronizing current under different conditions. Curve No. 3 is the current through the motor armature when in synchronism, and Curve No. 4 is same when the motor is coming into synchronism. Curve No. 5 shows the current furnished to the motor by way of the vibrating relay and not the total current in the armature of the motor and for a high value of current in the field of the motor. Curve No. 6 is the same as No. 5

except that a much smaller value of current is flowing in the fields of the motor. In both Curve No. 5 and No. 6 the motor was in synchronism. The difference in length and value of the impulses in the two cases is to be noted. Curve No. 7 shows the same current as No. 5 except for the condition when the motor is coming into synchronism. The rheostat is regulated until synchronism is obtained.

If the above arrangement is used alone, it will be found that the synchronism will not be steady, but will oscillate; that is at rapid intervals the speed of the motor will increase and decrease between certain limits. These oscillations are prevented by mounting on the high-speed shaft of the motor a so-called viscous damper. In one form this damper consists of a steel fly-wheel having a hollow rim which is nearly filled with mercury. The friction between the rotating mercury and the rotating rim of the fly wheel rapidly dampens any vibrations which tend to take place and makes the synchronism almost, if not quite, dead-beat. This effect of the mercury damper is identical with the effect produced on the vibrations of a pendulum by immersing it in molasses or mercury.

In regard to the practical operation of the above method of synchronism, it may be stated that the synchronism is often maintained for a whole day continuously without a single failure. Line swings of short duration do not cause it to loosen the letter, but cause an oscillation for an instant. All the variations of voltage, etc., under commercial conditions are automatically taken care of. To illustrate, in a test of this point changes in the conditions, which would cause the motor to change its speeds 50% if the synchronizing device were cut out, have been made without loss of svnchronism.

Synchronous Indicator

In addition to being able to produce synchronism, it is necessary to have some means of knowing when synchronism has been obtained. There are many methods of doing this. Two methods are usually provided.

First. The synchronizing telephone.

This is a telephone in parallel with a small resistance, through which flows a small part of the pulsating current which flows through the armature of the motor. If synchronism has not been obtained, sounds of two different pitches will be heard in the telephone. If the speed is sufficiently near synchronism beats will be heard, similar to those produced when two keys of nearly the same pitch on an organ are sounded at the same time. As the speed more nearly approaches synchronism these beats will follow each other at greater intervals; and finally, when synchronism has been obtained, there will be a smooth sound of a definite pitch.

Second. The synchronizing lamp.

An incandescent lamp is connected so that it receives a pulsating current similar to that passing through the armature of the motor and the telephone. When synchronism has not been obtained the light of the lamp will pulsate; when synchronism has been obtained the light of the lamp will be steady.

Finding the Letter

It will be noted from the description of the synchronizer that every alternate segment of the synchronizing commutator is in electrical connection, and that consequently when synchronism is obtained the brushes may be on any one of 28 segments in the octoplex, or on any one of 14 segments in the quadruplex. Before the signals can be received properly, it is necessary that the trailers of the sending and receiving stations shall be on corresponding segments.

The operation of shifting the brushes so that they are on corresponding segments is the so-called "finding the letter." For this purpose, at the sending station the impulse corresponding to the fifty-fifth segment (in the quadruplex it is the twenty-seventh segement) is reversed every revolution. At the receiving station the fifty-fifth segment in the octoplex, or the twenty-seventh in the quadruplex, operates the "letter finder" relay, identical in connections with a selecting relay. This relay is so connected, that when it receives a normal unreversed impulse it is against its rear contact; but when it receives a reversed impulse it is against its front contact.

A gear driven by the motor pinion on the line unit, at a speed of 3.5 revolutions per second—the normal operating speed—carries a pawl which engages with a 28 toothed ratchet; in the quadruplex the ratchet has 14 teeth. This ratchet is fixed rigidly on the gear which drives the commutator brushes. The motor pinion, then, drives the gear carrying the pawl, and the pawl engaging the ratchet drives the train of gears carrying the brushes on the commutator. An electromagnet attached to the frame of the machine operates a plunger which causes a pin to trip the pawl on the ratchet, dropping it back one tooth each time the magnet is operated. The circuit of the magnet is completed through a resistance, a push button, and the back contact of the letter finder relay.

If synchronism has been obtained and the brushes are not on corresponding segments at the sending and receiving stations, the letter finder relay will be back, and when the push button is depressed the letter finder magnet will operate and the pawl will drop back one tooth in the ratchet each revolution until the brushes are on corresponding segments, when the reversed fifty-fifth impulse will fall on the letter finder relay, and the circuit of the letter finder magnet will be broken. An incandescent lamp is connected from the positive terminal through the back contact and tongue of the letter finder relay to negative. As long as the brushes are not on corresponding segments this lamp will be lighted. When the brushes are on corresponding segments, and the relay tongue is therefore on its front contact, the lamp will go out indicating that the letter has been found.

Transmission of the Signals

The transmitting apparatus proper consists of a keyboard, a sending commutator, and a transmitting relay. (See Fig. 8.) The keyboard consists of a number of levers, one for each character, pivoted in the middle and each carrying a heavy contact strip which, when the key is depressed, makes contact with two pins. On one end of this lever is a small lip S_2 which engages a steel bar S_1, passing above the keys. By means of a cam S_4 and a lever S_3 this bar is given a reciprocating motion. In one position it permits the keys to be depressed at will, and in the other position it holds the keys down or up, as the case may be. At the usual speed of operation this bar is made to oscillate three and one-half times per second.

The sending commutator consists of a ring dvided into 56 segments in the octoplex, or 28 in the quadruplex. Each of these segments corresponds to a half-wave. Eleven segments being connected to each keyboard, each key when depressed connects two of these segments to the negative.

The transmitting relay consists of a polar relay of ordinary form, one coil of which is connected through a high resistance in such a way as to receive current continuously, giving the transmitter tongue a bias which holds it normally against one contact. The other coil when energized by current through the sending commutator, keyboard contact pins and key lever, and a resistance, attracts the transmitter tongue to the other contact. This disconnects the line from one secondary of the transformer and connects it to the other, thus sending an impulse the reverse of the normal. When the brush passes over such segments as are made negative by a depressed key on the keyboard, the magnet S_M is energized, and the impulses corresponding to these segments are reversed. The cam S_4 is so geared to the brush S_6 that the keys are always locked when the brushes pass over the segments corresponding to that particular keyboard.

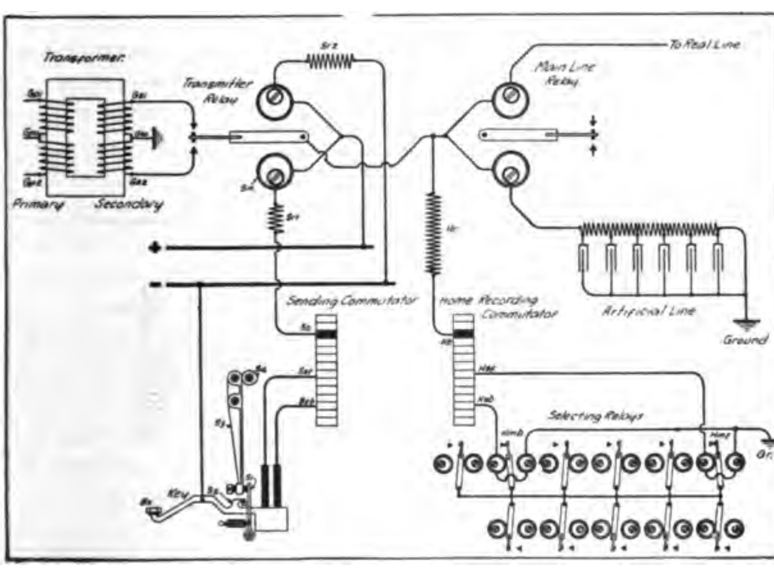


FIG. 8—Transmitting and home-recording connections

HOME RECORDER

In addition to printing the message at the distant station, a record is also obtained at the sending station for the guidance of the operator and for record purposes. This record is produced by the outgoing signals, in a manner similar to that used at the receiving station. For this purpose each sending position is supplied with a bank of home-recording selecting relays identical with those supplied at the receiving position. These relays, instead of being operated by a current from the contacts of the main-line relay, are operated by a current shunted off from the main signalling current just before it enters the main-line relay. This signalling current is distributed to the various home-recording selecting relays by a commutator of 56 segments (or of 28 segments in the quadruplex) identical in construction with the receiving commutator.

The home-recording printer, in the present form, is a tape printer. The operation of this tape printer is perfectly identical with that of the page printer, except that the mechanism for lining, blanking, and backing is omitted. (See description of page printer). Corresponding to the back contact signal on the page printer at the distant end, there is placed on the sending tape printer a small incandescent lamp which lights whenever

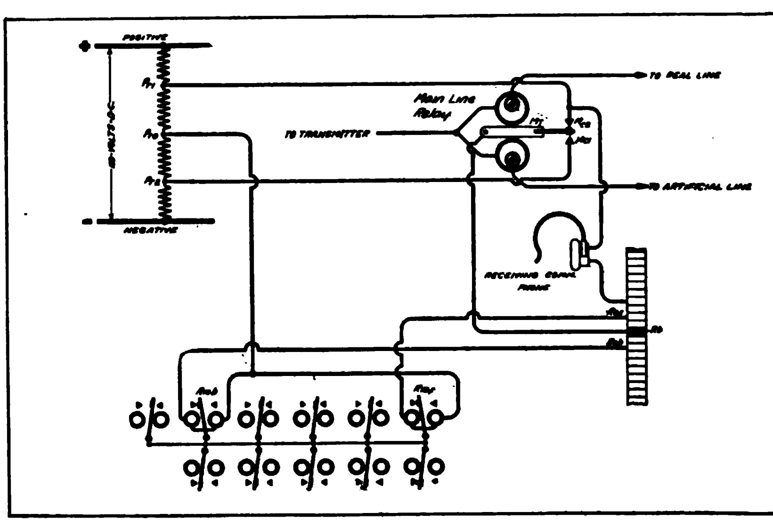


FIG. 9—Receiving connections

the receiving lamp relay is against its front contact; that is, whenever the carriage on the page printer is within a certain number of letters of the end of a line, notifying the sending operator of this fact.

RECEIVING THE SIGNALS

On account of the fact that the signals are produced by a combination of two out of eleven, it is necessary that the first of the two signals received be stored up in some way until the second signal is received, before the corresponding character can be printed. This is accomplished by the use of polarized relays, one corresponding to each of the eleven impulses. Each printer is furnished with a bank of 11 receiving selecting relays. (See Fig. 9.) For receiving the signals there is employed a vibrating tongue of the same line relay which is used for synchronizing, the relay having two independent tongues and pairs of contacts, one for synchronizing and one for printing.

The receiving, like the sending commutator, consists of a ring divided into 56 segments in the octoplex, or 28 segments in the quadruplex, one segment corresponding to each of the 56 or 28 impulses. One terminal of the winding of each relay is connected to a common point, and the other terminal to the corresponding segment of the receiving commutator, so that each relay represents one of the 56 or of the 28 impulses. Every alternate relay is connected in reverse, so that as the alternating current is distributed among the relays, each one is against its back stop, except in the case when the corresponding impulse is reversed, when the relay tongue will be against its front stop.

A resistance of 600 ohms is shunted across the 110-volt direct-current mains. The middle of this resistance is connected to the common terminal of the receiving selecting relays. The print contacts of the main-line relay are connected to points about 100 ohms from the terminals of the 600-ohm resistance. As the tongue of the main-line relay vibrates from one contact to the other, the current furnished the selecting relays changes its direction, and reproduces locally the signalling current received from the other station. As the brush R_b rotates in synchronism with the vibrations of the tongue M_T, each of the selecting relays will receive an impulse which will draw the tongue against its back or front stop, depending upon whether the impulse has been normal or reversed at the sending station.

Fig. 4, Curve 2, shows the impulses flowing through the selecting relays. The impulses shown correspond to those for the received current shown in Curve 1.

A telephone will be noted on Fig. 9. This is for the purpose of indicating the proper adjustment of the receiving commutator. When the commutator is not properly adjusted it is indicated by a loud rap in the telephone.

Automatic Translation of Received Signals into Printed Characters

The page printer, by means of which 51 different operations may be performed from the keyboard controlled by the operator at the distant station, involves the following features:

First. A solid steel type-wheel about 2.5 inches in diameter, on the circumference of which the characters to be printed are engraved. This type-wheel revolves continuously at the end of a horizontal shaft, and in synchronism with the trailers on the various commutators.

Second. A light paper carriage, carrying the paper which is fed from a roll underneath the type-wheel when new lines are to be made.

Third. A device to thrust the paper forward to make a new line.

Fourth. A device to move the paper carriage sideways to produce the space between letters and between words.

Fifth. A device to return the carriage to the beginning of a new line.

Sixth. A small printing magnet, which operates a hammer or platen which throws the paper against the lower side of the rim of the type-wheel, at the moment when the character to be printed has turned to its proper position above the line.

Seventh. A set of five polarized relays called the distributing relays, connected to the page printer by a cable, which serves the purpose of making contacts at proper moments for sending current to the print magnet to print; to a lining magnet to line; to a spacing magnet to move the paper sideways; to a backing magnet, which allows the carriage to return for the beginning of a new line; and to a blanking mechanism which rapidly feeds out the paper until a new blank is in the proper position for the beginning of a new message. Each of these operations is completely controlled by a key on the keyboard at the distant station.

Eighth. A combination commutator, the function of which will appear from the following description. Fig 10 shows such a commutator developed. This commutator consists of three rings being divided into a number of segments, one fifty-sixth of a circumference corresponding to each operation. The rings 1 and 2 are divided into various segments lettered from A to K. The arrangement of these segments are so chosen that at one point, and only one point, any two segments corresponding to a given character will be in line. The thiid ring is divided into various segments, and according as the combination at any particular point of the commutator is to print, space, etc., this segment of the third ring is connected to the corresponding distributing relay. All of the segments in rings 1 and 2 bearing the same letter are connected to the contact of the corresponding receiving selecting relay, in the bank of eleven selecting relays belonging to that page printer.

The operation of the page-printer will be readily understood by reference to Fig. 10, where the connections of the page-printer are shown. The incoming signal, which consists of two reversed waves, is first received, as elsewhere described, by throwing forward the tongue of the two corresponding selecting relays against their front contacts. By so doing, the segments of the combination commutator having the same letters as these relays will be connected to the frame of the bank of selecting relays, since the eleven tongues of this bank of relays are electrically connected to the frame. The brush bearing on ring No. 2 of the combination commutator is connected directly to negative, the frame of the machine, while the brushes on rings No. 1 and No. 3 are insulated from the frame, but connected to each other.

When the trailer brushes on the combination commutator, being in continuous rotation on the three rings Nos. 1, 2, and 3, rest at the same time upon segments of the commutator which are connected together, through the contacts and tongues of the two selecting relays which are against their front stops, an impulse will be sent through the wire *P* 12 and the front spool of the print relay. This will throw the tongue of the print relay forward and close the circuit of the print magnet, operating the hammer and throwing the paper against the type-wheel at the proper time to print the letter corresponding to the signal sent.

When the print magnet operates, a contact on the hammer will ground the contact 5, and thus send a current through the back spool 13, of the print relay, and also through the front spool of the space relay. This will open the circuit of the print magnet, thus releasing it, and at the same time will close the circuit of the space magnet. When the space magnet has operated the spacing mechanism of the printer, a contact attached to this mechanism connects the contact 7 to the negative, thus sending an impulse through the back spool *P* 7 of the space relay, and pulling the tongue of the space relay against its back contact, thus opening the circuit of the space magnet.

The electrical operation of the backing mechanism is similar to that of the printing and the spacing, except that the operation of the release contact is somewhat different. In order to throw the backing relay against its back stop, it is necessary to make two contacts. One of these contacts, 9, is made when the paper carriage has returned to the beginning of a new line, so that current continues to flow through the back magnet until the carriage is returned to the beginning of a new line. The other contact, through wire, No. 23, is made by the trailer brush passing over a short segment on the combination commutator. The " buffer " magnet is energized by current through wire No. 14 and a contact on the plunger of the backing magnet, as soon as the backing magnet is operated. When the carriage returns to the beginning of a line it is held by the buffer magnet, which prevents the carriage rebounding, until, at the next revolution of the trailers, contact is made on the short segment of the commutator, and current through wire No 23 and contact No. 9 and the back spool of the backing relay opens this relay and releases the backing and the buffer magnets.

The electrical operation of the lining mechanism is identical with that of the printing and the spacing. When the operator has finished a telegraphic message and desires to start a new one, the blank key is depressed. This throws forward the blanking relay against its front contact. This connects the front spool of the lining relay to negative by way of contact 16 and the blanking relay. The contact of the lining mechanism normally rests against the contact 16, and if the blanking relay is front the lining relay will be thrown front, and the lining magnet will operate and in so doing will ground the back spool of the lining relay through the contact 11, thus opening the circuit of the lining magnet, which will allow the negative contact of the lining mechanism again to throw front the lining relay. This process will continue and the paper will be fed out as long as the blanking relay remains forward. However, at definite intervals the paper is perforated, and as soon as the blank has advanced to the proper position the holes allow the brushes 17 to make contact through the paper with a negative connection on the frame. This sends an impulse through the back spool of the blanking relay, thus pulling the tongue of the blanking relay against its back contact and thus stopping the operation of the lining mechanism.

When the carriage is within a certain number of characters of the end of the line, a contact is made by the action of a strip on the carriage frame, thus grounding the segment on the sending commutator which corresponds to the back signal. This continues to send the backing signal to the operator at the distant

ınd
ing
nal
hat
the

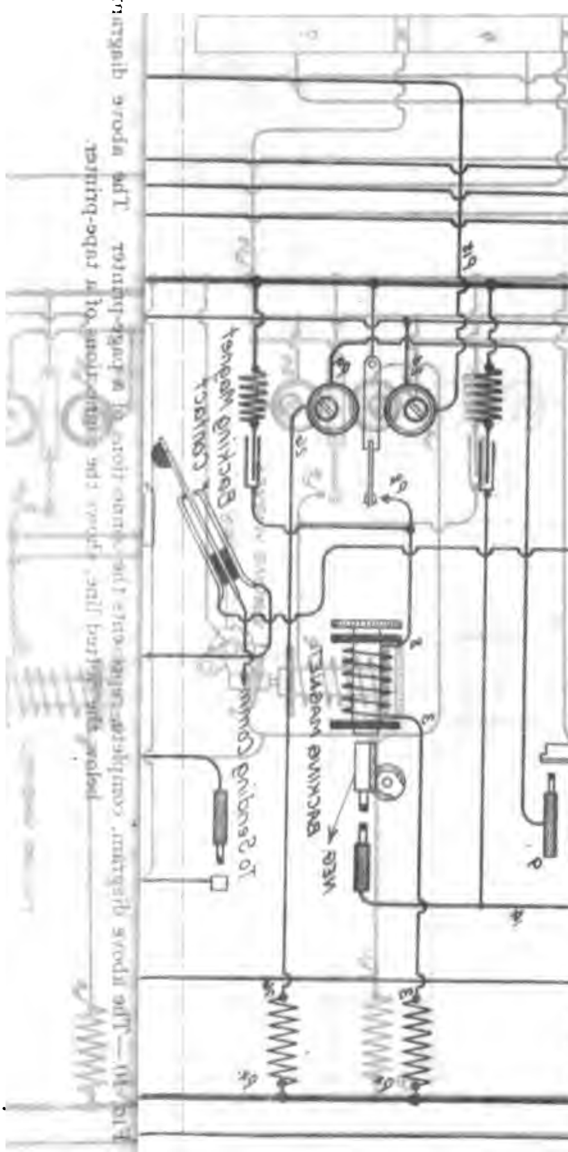


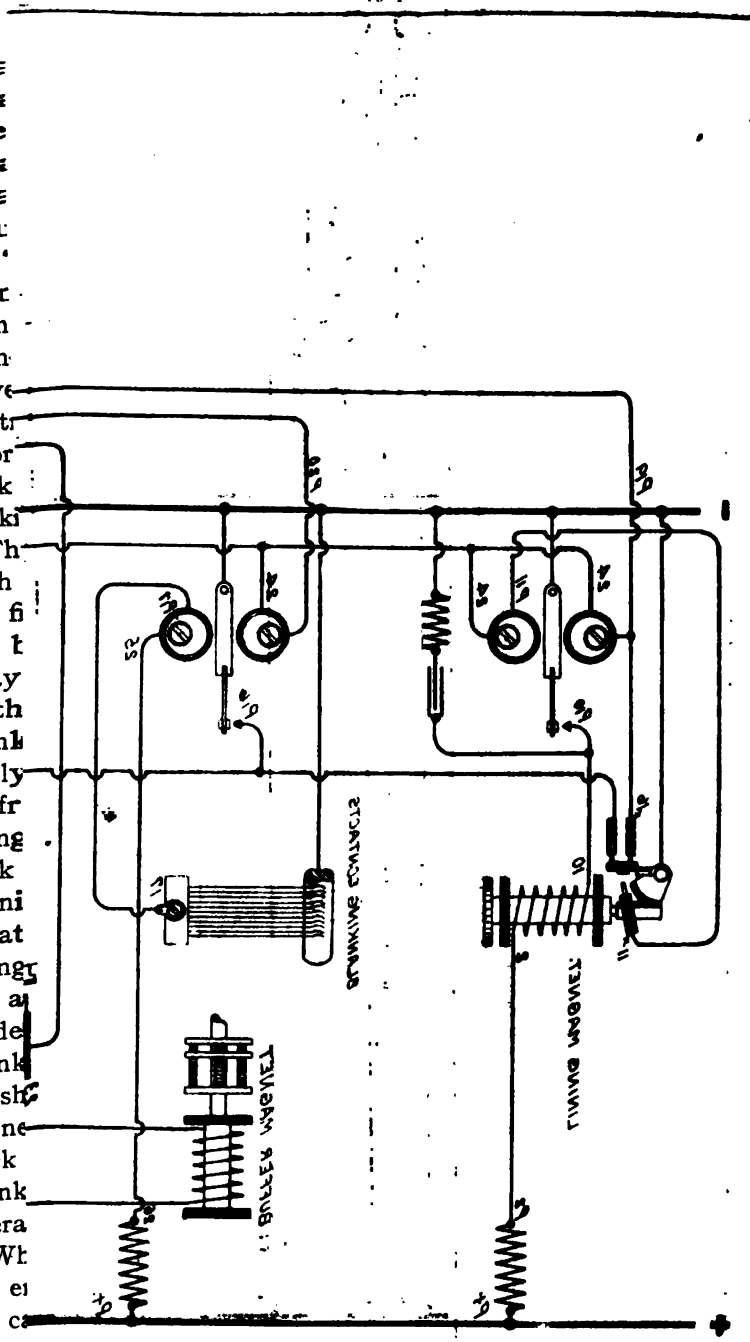
FIG. 10.—The above diagram, complete, represents the connections of a page-printer. The above diagram, including only that below the dotted line, shows the connections of a tape-printer.

rus
lses
ors
als,
ble,
in
ıich
ınly
yn-
tion
ıan-
ıtus
uta-

ple-
the
ers,
ison
two
the
rush
son-
ox—
erm-
l of
the
ıshes
-unit

the
king
ıding
ance
-unit
ıshes

conte
carria
curre
carria
conte
passi
The
14 ar
as th
to th
preve
the tr
tator
back
backi
Th
with
has fi
the t
relay
of th
blank
mally
is fr
lining
back
openi
negat
lining
out a
at de
blank
brush
conne
back
blank
opera
Wh
the e
the ca
comm
tinues



end as long as the carriage is within a certain distance of the end of the line. This is also so arranged that when the blanking relay is front and the paper is feeding out, it sends the signal to light the red lamp at the sending station, thus insuring that the sending operator does not begin a new message before the paper has stopped moving.

MECHANISM FOR PRODUCING THE UNISON OF LOCAL APPARATUS

In order that the motor which is synchronized by the impulses over the line, and which drives the brushes on the commutators directly concerned with the sending and the reception of signals, have as little and as constant an amount of work to do as possible, the printers and home-recorders are sometimes (particularly in large installations) driven by a separate motor, Fig. 13, which is kept in unison with the motor on the line unit. It is not only necessary that these two pieces of apparatus be kept in synchronism, but also that their commutators bear a definite relation to one another. In order that this may be the case, the mechanism which maintains the unison of these two pieces of apparatus is so arranged that this unison is possible only when the commutators bear a correct relation, the one to the other.

On the line unit is a commutator, known as the multiple-unison commutator, divided into twelve segments; and on the unison unit, which is the driving mechanism of the local printers, is a similar commutator of 12 segments, known as the unison unit commutator. The corresponding segments on these two commutators are electrically connected. The brush on the multiple-unison commutator is connected to negative. The brush on the unison-unit commutator is connected—after the unison-unit motor is brought up to speed by means of the starting box—to one terminal of the motor armature, and also to one terminal of the synchronizing resistance. The other terminal of the synchronizing resistance is connected to negative: and the other terminal of the motor armature to positive. The brushes on the unison-unit commutator are driven by the unison-unit motor.

When the line-unit and unison-unit motors are running at the proper speed the brushes on each commutator will be making 210 revolutions per minute. If the brushes are on corresponding segments of the two commutators, the synchronizing resistance will be short-circuited, and the armature of the unison-unit motor will be directly across the power mains. If the brushes are not on corresponding segments of the two commutators, the synchronizing resistance will be inserted in the armature circuit, reducing the speed of the unison-unit motor, which will run slowly until it has dropped back to a point where the brushes are again on corresponding segments on the two commutators, when the armature will again receive its full current. By adjusting the resistance in series with the shunt field of the motors, the speed can be regulated to such a point that the action of the brushes on the commutators, in short circuiting the synchronizing resistance, will keep the unison-unit motor in syn-

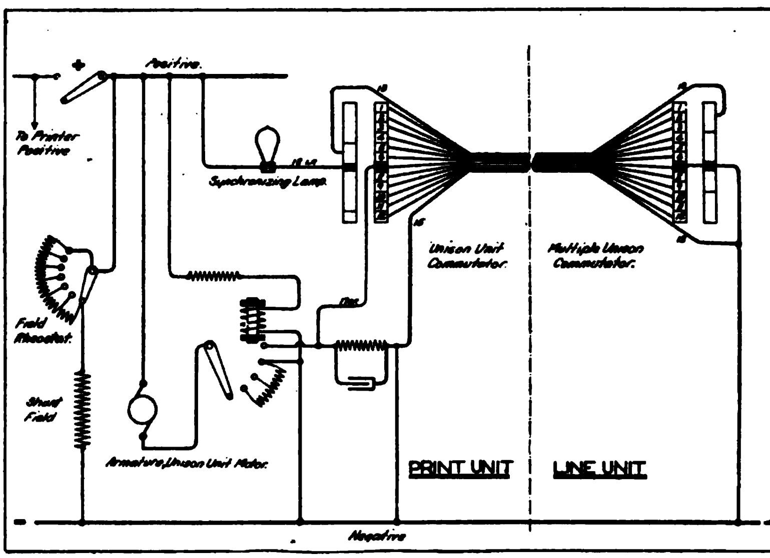


FIG. 11—Unison-unit connections

chronism with the line-unit motor. It is of course not necessary to adjust this resistance every time the motor is started. This resistance is set for any speed of operation once for all, and the motor is then started just the same as any motor; *i.e.* by the use of a starting lever. The synchronism takes care of itself.

For the purpose of indicating when the two pieces of apparatus are in unison a unison lamp is provided. The circuit of this lamp is completed through extra rings on each commutator. It will be noted by reference to Fig. 13, that this lamp receives no current when the two brushes are rotating in synchronism; but if the synchronism moves the distance of more than one segment, this lamp will receive an intermittent current and will thus indicate that the two pieces of apparatus are not in unison.

To secure a uniform rotation of the print-unit driving shafts, a mercury damper similar in action to that on the line-unit motor, is provided for the unison-unit motor. To assist further in obtaining as nearly as possible an absolutely uniform rotation of the type-wheel on the individual printers, so that the type-wheel will travel at all points in its revolution a fixed, definite distance between the time when the impulse is received by the print relay and the time when the platen strikes the paper against the type-wheel, and thus give uniform spacing between the letters, each type-wheel shaft is provided with a fly-wheel; and the driving dog on the end of the shaft, through which the motion is transmitted to the shaft, is made up by winding a flat steel spring into a spiral, one end of which is fastened rigidly to the shaft, and the other end of which engages the driving dog. The spring has a strip of heavy, non-elastic material wound with it, the action of which prevents rapid oscillations of the spring.

Method of Construction of Apparatus

The Rowland apparatus is divided into a number of units for convenience of manufacture and operation. Any unit can be quickly removed and replaced by another unit. In general any machine is divided into three units, the line unit, the correspondence unit, and the unison-unit. (See Figs. 2, 3, 12, and 13.) The line unit comprises the current generator, sending, receiving, and home-recording commutators, synchronizing device, transmitter and main-line relay and all the parts directly concerned with the line, in other words the purely telegraphic parts of the apparatus The correspondence unit comprises the keyboard, home recording printer, and receiving printer; in other words, a duplex electrical type-writer. The unison unit simply serves to supply power to operate the correspondence units; it may be dispensed with in case of small installations, as they can be operated directly by the line, or a separate one may be provided for each correspondence unit if so desired.

Conclusion

From the foregoing discussion of the telegraphic situation and the description of the Rowland system, it has probably been understood already that the latter is constructed essentially to meet the demands of the former. A brief examination of the adaptability of the machine to the situation, however, is necessary in order to appreciate thoroughly its practical utility and efficiency.

The most important practical requirements of the telegraphic service are accuracy and promptness. These factors, in a great measure, determine for the telegraph its peculiar field. In the Morse system the presence of the human element in every operation necessarily introduces corresponding inaccuracies. In the Rowland system the human element is reduced to a minimum by keyboard transmission and automatic reception. The

FIG. 12.—Correspondence unit, sending side showing keyboard and Home recorder.

printed local record before the Rowland operator, too, shows what has been transmitted, and furnishes the operator an immediate method of checking the message sent. The octoplex wire capacity of the Rowland and direct transmission from typewriter keyboards with direct reception in printed characters on regular telegraphic blanks ready for immediate delivery constitute the best possible combination to insure promptness. With the Morse system, particularly in wet weather when the wire capacity is reduced, serious delays in transmitting telegrams often occur through a sudden or abnormal accumulation of business. The octoplex wire capacity of the Rowland system in all weather conditions provides a greatly increased margin for reducing and avoiding such delays.

As already explained, the machine demanded by the telegraphic field must give greater efficiency to the operator and the wire than can be done with Morse methods.

The efficiency of a Rowland operator is practically double that of a Morse operator. To transmit a Morse message, two skilled operators are necessary, while to transmit a Rowland message one typist is necessary. The sole requirement that the operator shall be a typist and able to transmit a message in-

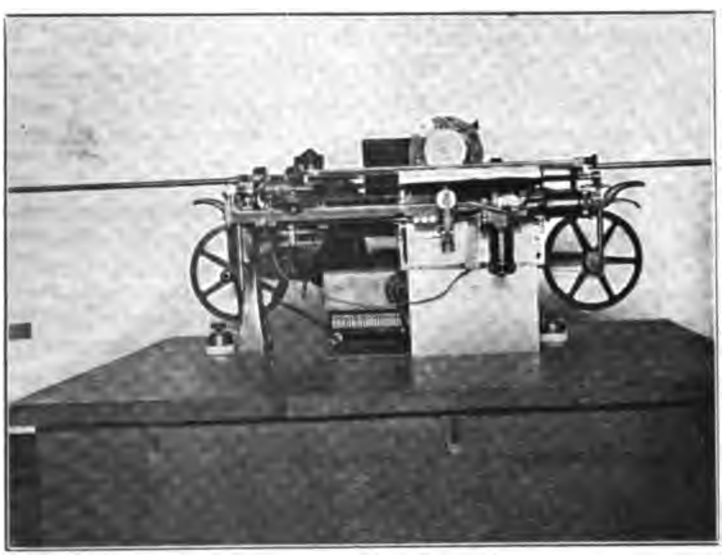


Fig. 13.—Correspondence unit, receiving side showing page-printer.

telligently greatly broadens the labor field and permits the economies incident to such an increased supply.

The more complete utilization of the wire operated by the Rowland, as compared with the Morse, has already been suggested. Under weather conditions most favorable to the Morse, the Rowland wire capacity is double that of the Morse, while in weather unfavorable to the Morse, the Rowland wire capacity is triple or quadruple that of the Morse.

As features of the Rowland system which lend themselves to further expansion and development in the telegraphic field, it is interesting to note that the method of dividing the use of a telegraph wire among a number of operators provides the fundamental and ideal requisite for the development of new and improved distributing methods for the general service and for facilitating and expanding the private use of the telegraph. Machine methods of relaying, more accurate and efficient in their operation than Morse methods offer further promising fields for greater efficiency.

In conclusion, having indicated the field and the demand for a machine telegraph and how the machine under consideration meets the conditions imposed, it only remains to suggest that with the application of machines, which provide for the more efficient transmission of a greatly increased business on present wire systems, and the further developments of the possibilities outlined, it is not unreasonable to expect that the telegraphic service directed by a broad policy will become in the near future hardly second in its unrestricted use and importance to the post office itself.

NOTE.--The above article has been written with special reference to American practice and in particular the highly developed American Morse methods and the highly skilled American operator. Many points of difference present themselves in foreign practice. It is possible elsewhere to use much smaller values of received current than here. The saving in wires becomes much greater when considered with reference to countries making use of other methods of transmission.

Discussion on "The Rowland Telegraphic System," at New York, April 15, 1907.

Ralph W. Pope: First I wish you to join with me in an expression of our appreciation of the esteemed privilege of having with us to-night our first honorary member, and I may say one of our oldest members, Sir William Preece, who has awarded to us the distinguished honor of presiding this evening.

When undertaking to open the discussion on the paper this evening, it was not my intention to go into the technical details of this very remarkable instrument which has been described in the paper before you. My first opportunity of examining this system was at the Paris Exposition in 1900, where it was on exhibition only, as we may say. On Saturday last I had an opportunity to examine the system in actual commercial operation between New York and Boston, and upon one of the worst days, so far as weather is concerned, that could be conceived, which tended to reduce the speed, not only of this system, but of any other system of telegraphy with which we are familiar.

In approaching the discussion of a system of this kind I wish to say we should first divest ourselves of the prejudice against the Morse telegraph, which exists in the case of those who are not practical operators and familiar with the code. To those who have practised Morse telegraphy, some of those things, which appear to be a mystery to others, are like an open book before us. I may say in explanation of my position on this subject that I learned telegraphy on the Hughes printing telegraph forty-nine years ago. I might make it fifty years, but I would not lie for one year. I learned the Morse telegraph as a side issue, simply as a man might pick up the art of playing the violin, without any idea that the Morse system would eventually prevail. The Hughes printer, which was new at that time, was invented by David E. Hughes, a musician in Kentucky, and one of the pair which I first operated was the second then in use, the first. I think, being between New York and Philadelphia, and the second, on which I learned, was between Great Barrington and Pittsfield, Mass., which at that time was an unimportant line. The contempt for the Morse and Bain systems which were in operation at that time may be well expressed by the terms applied to them by the printing operators. The Morse was called the "woodpecker," and the Bain system the "dyetubs"; and any message transmitted by either of these systems, *via* Springfield, was supposed to be "bulled", as the only system which was known to be "accurate and reliable" was the House printer, on which the Hughes was afterwards grafted. In those days, when an inventor brought out a new system a company was organized to exploit it. Consequently we had in the old times the magnetic, the House, and the Bain telegraphs. The House printing telegraph, the invention of Royal E. House, was a triumph of electromechanical skill. It is true that between New York and Boston it could not be worked through, on account of the rapidity of the vibrations, and consequently the Hughes printer, requiring but one pulsation to each letter was preferred to the House and eventually superseded it I am giving these instances of the situation at that time.

Now, there is no doubt about the speed of the Morse, the House, or the Hughes, so far as a single wire was concerned. The House was perhaps the fastest, the Hughes next, and the Morse last. Eventually there came about a consolidation, and the House printer was displaced, the Hughes system was transformed by the late George M. Phelps into the "combination" printer, and subsequently into the "motor" printer and was in actual operation up to within a few years ago. It was duplexed, and I might say, although I will come to it later, that the expert operators on the Phelps printer. between New York and Boston, and New York, Philadelphia, and Washington, were the highest paid in the telegraphic operating department, so that we may cast aside for the moment the idea that because the letters are on the keys, any fool can be an expert operator.

The telegraph is the oldest, and I will also say the most important development of the modern applications of electricity. The electric light has its rival in gas, the electric railway has its rival in steam, and the telephone is applicable only to comparatively short-distance transmission; but, for world-wide communication, for the general distribution of intelligence, and that application of electricity which would be the last we would part with, telegraphy stands at the head

The Morse system, as it is known to those who operate it, may be used under the most adverse conditions. Prior to the expiration of the Morse patents, which covered the application of the local circuit and the sounder, the opposition companies were obliged to use simply the relay without the sounder, so that we had to read from very faint sounds. On one occasion I was visited in Exchange Place by an operator from the old American office it was a wet day, and I had my relay screwed down so that the sound of it was like the ticking of a watch. The office was about one-quarter the size of this stage, and the relay began to tick, and I said, "I am busy." He asked, "What are you doing?" I replied, "I am receiving from Boston." That was a fact: I was receiving on that relay without the local sounder and he although only four feet away could not hear a sound It might be assumed I was guessing at it, but I was actually reading it.

I am rather wandering over the subject. but I am bringing up the conditions that existed in regard to the Morse telegraph and why it prevails to-day In 1868 I was quartered in the Gold Room at the time of the "Black Friday" panic. The correspondent at the Boston or Philadelphia exchange was right at the counter. Assuming this platform as the exchange, the operator, if he had a message, would call out for the man for whom the message was intended, and he would come to the counter for his telegram. I have sent a message to Boston, and received a reply and delivered it to the original sender of the message, before the ink on the original was dry, probably in the course of a minute. Now, leading up to the instrument which we have under discussion this evening, I made a similar test with Dr. Sheldon, who was with me last Saturday; I sent a telegram to Boston, to be repeated back to New York and delivered to Dr. Sheldon, who was at my side. I handed him the following message in the course of regular business: "Samuel Sheldon, Boston—I will arrange Monday morning for payment suggested, and will adjust the matter with Mr. Carty as soon as possible. R. W. Pope." The message was delivered back into my hands, in printed form, having been sent from New York to Boston and returned from Boston to New York, in five minutes. As a practical demonstration, I am quite satisfied with that, for the reason that my reply was sandwiched in with other commercial messages received in the ordinary course of business, and I wish to say, as the result of our investigation, that four operators were sending to Boston over one wire, and the messages were coming in over the same wire on the four instruments from the Boston end. I consider this a very satisfactory showing.

There is a weaker point in the telegraph service than the simple transmission of messages, and that is the question of delivery after the message is received. In my earlier days, when I received a message, I used to close the office for a half hour, during which time I went out to deliver it. I have also known of cases when one messenger was in the office, when two messages were received, one message to go a mile in one direction, the other a mile in the opposite direction, and the question was which of the two messages should be delivered first. That leads up to another point, and that is the classification of service.

We have heard from the advocates of the telegraphic system, that all messages should be sent and delivered in the order of their reception, which is well known to be practically impossible. In the first place, the ordinary customer hands in his message over the counter, and it may go to a distant point over one out of perhaps ten or a dozen wires. If he happens to be a broker at the exchange, it may go over a special wire and be delivered in the course of a few minutes, while, if it goes in the ordinary course of business over a busy wire, the sender will be lucky if it is delivered in an hour. So that there are some things to be considered in regard to telegraphing outside of the transmission of messages.

Reverting to the system we have under discussion, we must understand that it applies in the main, as most of these systems do, that is, the machine or automatic systems, to the trunk line business, or business between any two large cities, where the volume of business is such that apparatus of this kind can be installed and kept in continuous operation. It appears to me that the general use of the Morse telegraph is due to its simplicity, low cost of operation, and its application to all conditions.

As I was saying in regard to my learning the Morse system as a side issue; after learning to read by sound, if the Hughes printer broke down we could send or receive a telegram through the bell on the side, using the Morse code. The Hughes printer was based on synchronism. The instruments at each end of the wire were required to be in almost absolute synchronism. If they varied, one of them "threw out," as we called it, and had to be put in unison and started up again. There was a very peculiar instance of the necessity of that unison that occurred to me at the time I learned the business, and that was on the occasion of the first message over the original Atlantic cable in 1858. My brother, who was my superior, had gone away for a day. I was on duty, and the station twenty-five miles north had been endeavoring for two hours to send me a communication which I could not receive on the Hughes printer. When the train arrived the newsboy on board set off a pack of fire crackers. I inquired what was up, and was told that the Atlantic cable was a success. My brother was on the train. He came into the office, and I told him what I had been doing; that the office twenty-five miles away had been trying to send something to me for nearly two hours, and that the printer continually "threw out." He looked at the machine, and took a hammer and knocked along the brake governor on the shaft about $\frac{1}{16}$ of an inch. The brake had shifted about $\frac{1}{16}$ of an inch on the shaft and did not strike in the center of the wheel; that was all the trouble. The machine was not quite fool-proof.

In closing, I call attention to the author's statement that: "In practical operation it has continuously demonstrated its efficiency in dispatching an enormous volume of business with regularity and accuracy on a single wire, while the operators employed have been not necessarily skilled in the use of the Morse code." That is quite true. They do not need to know how to fiddle or to play a snare drum, but all the same it is a fact that the Morse operator who is trained and familiar with the business, if he or she has learned the Morse code, they are adapted to telegraph work. So I find as a matter of fact, that the best operators, even the best operators to work a keyboard, are those who are trained in the telegraph service and have that intuition or familiarity with the business which makes them valuable employees. Consequently, while it is quite proper that they should be trained to do special work, in the ordinary office it is better to have the force interchangeable, and if there are Morse operators who are capable of operating the printer system, and operators of the printer system who are capable of operating the Morse system, the interchangeability of that force becomes a rather substantial consideration in the office organization; and I might go further and say that, while it is no doubt advantageous and economical to install a system which will convey a larger number of messages over a wire, it is still desirable that the systems should be interchangeable, that the simplicity of the Morse will persist, and, while it is true that the Morse telegraph has not been improved for many years so far as the operator is concerned and so far as the public is concerned, it has been improved so far as the company is concerned in regard to the greater earning capacity and by the use of the typewriter which has enabled the telegraph operator to receive at a higher rate than the sending operator can send the messages.

The speed of the Rowland system, and in fact all the claims set forth in this paper so far as the speed is concerned and in comparison with the Morse, I consider well substantiated. The speed of forty words a minute can be attained by a Morse operator, but it still remains to be seen whether we can develop a system which will send messages four in each direction at that rate ready for delivery, which is 320 words a minute over a single wire. The advantage of the delivery of messages in page form over the old tape printing system I consider is very desirable, and I am glad to know that the Rowland printer has reached its present state of perfection. I can hardly believe that the distinguished inventor would have asked that any better monument to his memory could be erected than the establishment and the continuation of a system bearing his name, and it is my hope that it may be continued and in the future be on an equality with the Morse telegraph of to-day.

A. E. Kennelly: It is remarkable that, although electrical applications have developed so rapidly and assumed so important a position in this and other countries, the electric telegraph has almost stood still. In fact, some say that it has not even marked time. A few years ago, in New York City one could pass through the main telegraph office and see a few printing telegraphs. One might have seen a number of automatic Wheatstone instruments, very likely a number of quadruplex sets. I think I am correct in saying there are now no printing telegraphs remaining except the recent ones of the system described here and one other new system; that there are no Wheatstone automatic sets, and that there are fewer quadruplex sets than there used to be. We are struck by the contrast between this apparent want of progress in telegraphy and the progress which has made itself felt in other lines of electrical advancement. It is, however, much easier to criticize destructively than constructively, and there are a number of influences which have been active in this country and elsewhere to account, in part at least, for this apparent want of progress.

First of all, the telegraph is the only apparatus which has maintained its original ground and kept on the earth. Everything else electrical has been driven off the earth. Telephones have been driven off the earth, to take shelter in metallic circuits. Even so huge a machine as the railroad motor has been virtually driven off the earth. The telegraph has stood, and at considerable disadvantage to itself, because it not only suffers from its own internal disturbances, but also from vagrant disturbances due to other systems in its neighborhood.

I think I am correct in saying that each man, woman, and child in the United States does not send more than about one telegram a year on the average. On the other hand, there are about five million telephones in the country, and the number of conversations by telephone of each man, woman, and child is something like two-thirds of a telephone message a day; this means a difference of, roughly, a message a year, and a message a day, in the two systems, respectively. It is the convenience and growth of telephony which has tended to keep progress in telegraphy in abeyance. The rate of growth of telegraph messages has been slower than the rate of increase of population, according to recent published reports. We seem to have reached rock bottom in the matter of economies. It does not seem possible to get a more economical operation of the system, and consequently anything which will enable us to rob the mails more than we do now, in the use of the telegraph, must be effected by some entirely new method. At the present time, there is not only the fixed charge upon lines and apparatus, but the cost of the operator's time at the originating station, at the intermediate stations, and at the receiving station. These costs seem to be impossible of elimination on the Morse system.

We cannot flatter ourselves that any system such as that which has been described to-night will eliminate the Morse system everywhere. The Morse system is admirably adapted not only for way traffic, but also for through traffic of not great pressure. We can only hope for something to take the place of hand telegraphy where the telegraph traffic is great and the pressure keen. If traffic is to increase, there can be but two ways of handling it. One is to duplicate the Morse circuits, to duplex and quadruplex them, if possible. The other is to have something entirely different. Here is a system which offers something entirely different. We must have something which will eliminate the telegraph operator on high-pressure trunk circuits. The hand Morse must be eliminated. The Wheatstone system did that in part, because it enabled a number of sending operators to work together on one wire, and the same number of receiving operators to work together on the same wire; but here is an apparatus which will enable the Morse code to be completely eliminated; a simple mechanism to be operated from both ends of the line, keyboard to keyboard, typewriter to typewriter. That is an ideal system, if the inertia of the removing parts can be reduced so as to make the speed of the same order as that which can be secured by instruments of the Bain type. I am sure we hope that this apparatus, and ot..ers of similar type, may so far develop as to bring progress once more to the neglected art of telegraphy, and let us have a chance to relieve the hands of the operators without reducing the demand upon their skill and intelligence.

William Maver, Jr.: It is true that telegraph engineers and managers admit that the ideal system of telegraphy is one in which the messages may be transmitted, without previous preparation, at a high rate of speed and be received accurately at a distant station on page form in printed Roman letters. There have been many difficulties in the way of producing this ideal system, and therefore the degree of success which has been reached by the Rowland system, and I might also say by the Buckingham, Barclay, and Murray systems, is most encouraging. I have long pondered on what set Professor Rowland's mind in the direction of multiplex telegraphy. I do not think it could have been the idea of making money, because we all know it requires the purse of a millionaire to bring into practical operation or even into fairly practical operation, a multiplex telegraph system. I have heard of one inventor who has spent more than $150,000 in the attempt to do so, and recently I saw a statement to the effect that $9,000,000 has been expended in the last decade in the attempt to perfect printing telegraph systems. I do not know that these figures are strictly accurate, but even if cut in half they would suffice to illustrate the point.

I had the pleasure of seeing Professor Rowland's original apparatus some years ago, and it certainly was somewhat crude. At that time if I remember rightly it was a tape printer. Before Professor Rowland passed away—too early I think—the system had undergone two complete changes, and since then I believe it has undergone four more radical changes. To-day it is in a very fair state of practical operation. I saw the system in operation, as Mr. Pope saw it, last Saturday, working between Boston and New York, on the lines of the Postal Telegraph Company. It worked very nicely. I think, however, that it is necessary to make some qualification or amplification of Mr. Potts' statement, with reference to the efficiency of this system in meeting the requirements of commercial telegraphy. In fact this system is in operation on one wire, about 280 miles in length, as an octoplex; that is to say, eight messages are transmitted by this system simultaneously at a certain rate of transmission. To apply this system to a circuit between New York and Chicago will most likely entail some modifications; as, for instance, the reduction of the capacity of the system from that of an octoplex to that of a quadruplex. It will also require the introduction of an automatic repeater midway of the circuit, the practicability of which has not as yet been tested out. As Mr. Pope has pointed out, the system is not applicable readily to way wires and certain other circuits. The capacity of the system is given as 600 messages per hour; this, it should be noted, is the maximum capacity of the system when operated as an octoplex on comparatively short overhead wires. On long circuits this capacity will be, it is probable, materially reduced.

There seems to be no question as to the utility of the Rowland system on the comparatively short circuits to which it has thus far been applied. The matter of general reliability, accuracy, and cost of operation of the system are probably yet to be determined. I believe Mr. Murray has intimated that he considers his system better adapted to long circuits than to short circuits, presumably because of the necessity for preparing the messages in advance for transmission, etc. On the other hand, it is possible that the Rowland system may find its best field on comparatively short lines.

The author states that the basis of the telegraph current used in this system is an alternating current. This is of course true. but it is a somewhat singular fact that the actual signaling currents are made up of pulsations of continuous or one-direction currents. This is evident from the oscillograms. The accuracy of this remark will also be apparent from the fact that if, for example, a signal is to be made by normally negative impulses Nos. 2 and 4, and if we assume that the impulse before impulse No. 2 was a normal positive impulse, then impulse No. 2, when it is reversed, will also be positive, which gives the desired reversal, so called. Similarly, impulse No. 4 will be preceded by a normal positive impulse. Consequently, when impulse No. 4 is reversed it will be followed by a normal positive impulse. Therefore in this and numerous other combinations for signals, there will be five successive positive or negative impulses. Hence the "clearing out" effects of alternating currents are not fully obtained. The currents used in signaling in this system are indeed virtually akin to those employed in submarine cable signaling.

The author states that the current strength necessary for the operation of the relays of the Rowland system is about 35 milliamperes. It is interesting to note that this is about the current strength required in the operation of the ordinary Morse duplex and quadruplex relays.

The author implies that the presence of the human element in the Morse system introduces corresponding inaccuracies. I have the honor to differ somewhat with him in what he implies in that statement. It has long been an axiom among telegraph managers and engineers that the receiving operator of the Morse system is a continual check upon the sending operator. In many cases in actual practice the receiving operator instantly detects and corrects or prevents errors of the sending operator, as well as the errors or omissions that would be frequently caused by momentary line trouble, and which no mere machine at the receiving end could do.

At first sight, this highly ingenious telegraph system may appear somewhat complicated. This impression, however, wears off with a clearer knowledge of the apparatus; for it is apparent that the seeming complexity is due more to the necessary multiplication of the parts than to the intricacy of the system as a whole. The engineers of the Rowland system are to be congratulated on the success they have thus far achieved. They are fortunate in now having the system in operation under practical conditions, where its defects, if any remain, will become apparent and when opportunities for further development and improvement of the system will doubtless be found.

Henry G. Stott: In reading over this paper, it occurred to me with a great deal of pleasure that to-night I was to take part in a meeting at which Sir William Preece was to preside. I experience this pleasure largely because over twenty years ago, when I studied electricity under Professor Andrew Jamison, our text-book on telegraphy was one by Preece and Sieveright. Now we come to the fountain-head for more information on the subject of telegraphy. I think if we had the book here to-night it would be found that very little has been written into the progress of the art since that volume first became a text-book.

Several of the public-service corporations have recently been forced to increase their rates. No board of directors deliberately sits down and increases the rates for its service just for the pleasure of doing so; the only thing that prompts them to do this is in the realization of a grave duty to the stockholders. True, the cost of copper has gone up 100 per cent., and the cost of labor 50 per cent., in the last ten years. But why is it that telegraph rates have had to be increased, while electric-light rates, power rates, and telephone rates have all gone down?

Some time ago Mr. Pope called to my attention a letter which he received from a telegraph engineer in the West. The letter was in the nature of a complaint against the Papers Committee, of which I am a member, and said: "Why do you have so many papers on lightning arresters, electric railway motors, and things of that kind, and you never give us a paper on telegraphy?" I shall try to answer that letter here.

Why do the other gentlemen, who present elaborate papers on lightning-arresters, railway problems, features connected with transmission lines, etc.—why do they come here with these papers? Simply to get the benefit of the criticism and comment of their co-workers in these fields. How many papers have we had presented on telegraph subjects in the last ten years? I think this is the first one that I can recall; but I trust that it is only the precursor of many equally important papers, that the period of stagnation in the development of telegraphy is at last at an end, and that the rapid development by our members of automatic apparatus, such as that described in to-day's paper, will enable our telegraphic companies to progress as rapidly as the other electrical industries.

E. F. Northrup: I have in hand a small piece of paper which speaks of the human side of the development of this system of telegraphy. I am reminded that it will be six years to-morrow morning since Professor Rowland died. Mr. Maver said this evening that he wondered why Professor Rowland turned his attention to telegraphy. I think I can answer that question, for I was with Professor Rowland at the time that he began to be interested in this telegraph. I acted as his assistant in its development for three years previous to his death and I had the exceptional pleasure of spending two weeks with him at his cottage at Seal Harbor, Maine, and there heard from him why he devoted himself to the development of his telegraph system. He had a disease which he knew would probably be fatal and he could not get a life insurance. He told me he had many problems in physics of the highest importance that he would love to work out, but that he felt that it was his duty to try to leave his family a heritage that would have a monetary value. He was the most courageous man that I ever have known. He worked on his telegraph almost to the day before his death, as this paper will attest. Three days before his death I received this note written by him on his sick bed:

> Put in patent condenser, also coils; duplex of many lines so as not to interfere with each other. You do not know this; come and learn. H. A. R.

I went to his house and got his instructions while he was on his sick bed.

I worked on the telegraph for a year after his death, but I cannot take time to speak at length regarding the technical features of this system with which, at one time, I was very familiar. I may say, however, that the system is peculiar in this respect, that it is a kinetic system as distinguished from a static system. I mean by this that normally current is passing over the line at all times and not at a time only when a signal is being sent. The system presents, however, this paradox: that when a signal is being sent at the same instant from opposite ends of a duplexed line, there is at that instant no current on the line. The signal is made by stopping the vibrating tongue of a relay, while in most other systems a signal causes a relay tongue to move.

One feature, not spoken of to-night, is the immense flexibility of the system in the matter of the distribution of the lines and messages. Professor Rowland laid the foundations of innumerable methods for the distribution of the messages which the flexibility of the alternating current admits.

Gano Dunn: It is some years since I used to pound a key, but I love it still and trust I may be pardoned a tribute of affection to the telegraph business, because the telegraph business opened to me the door of a college education and an electrical career. It took me from a dingy office haunted by messenger boys to this glorious building which speaks a development of the electrical industry far beyond the dreams of the early telegrapher. The old Morse systems had in their ranks nearly all the men who later started this electrical development and I feel proud that I am, as it were, a member of the old union. It is fitting that this first evening of the week of dedicatory exercises should be devoted to a telegraph meeting.

If the paper presented to-night were read by the general public, especially the paragraph which rates the capacity of the new system at 600 messages per hour, the public would be inclined immediately to ask Mr. Clowry, who in the newspapers a few days ago explained the increase in rates of our large telegraph companies, how long it will be before these rates shall be again reduced to a very small amount, in view of the enormous difference between 600 messages per hour per wire and 17 messages per hour which he referred to. If not qualified, this paper would give the public a false impression. It is not the capacity for transmission that limits the telegraph business to-day, for actual transmission is the least part of all the business involved in the receipt and delivery of messages. The Rowland system, beautiful as it is, a system which I believe will come into large use, is, after all, applicable only to trunk lines between large cities, to places where there are experts to watch it and places where its use will be justified by the volume of business.

I doubt if the Rowland system will ever drive out the old instruments. Their simplicity and reliability have won for them their present place. The fact that we still have them testifies eloquently to their fitness. It does not testify to stagnation in the technical development of telegraph systems.

In the Rowland system the typist takes the place of the operator, but the typist is seldom qualified to rearrange damaged or displaced parts; and these things happen sometimes in a telegraph office when the manager's back is turned, for boys occasionally throw ink-wells that put the apparatus out of business. I have seen 150-ohm relays and the rest of the accompanying Morse outfit unmindful for years of everything that was thrown at them.

The grounds for the statements I made of the limited field to which the Rowland system may look forward are in the proportion already existing between quadruplexes and single lines. Roughly speaking, there are 30,000 offices in this country. Notwithstanding the fact that the quadruplex is cheap and yet increases the wire capacity nearly four times, I doubt if there are 3000 quadruplexes in use. If there were the great demand for increased wire capacity, which the advocates of the machine-telegraph and multiplex systems generally take as their starting point, we should see more quadruplexes. The proportion mentioned indicates the balance between the advantages gained by their introduction and the accompanying disadvantages of inflexibility and complications.

Although the Rowland system increases the wire capacity eight times that of a single wire, and claims an increase in operator capacity about three times, and makes further claim to increase in operator capacity by not requiring a receiving operator (although making no allowance for the skilled mechanician that would be needed) I believe that these great advantages will be almost counterbalanced by the enormous complication of the apparatus. If Mr. Kipling should write up the telegraph business, the Rowland system is what he would call an eight-day clock.

I think the success of the Rowland system must be looked for in large offices where there are trained experts, and a high degree of organization. It is my opinion that for many years to come ninety per cent. of the clicks we shall hear over the length and breadth of the land will be good old "Morse."

Sir William Preece: I think the hour has arrived when we had better close this discussion, but it will afford me an opportunity to play the same role that Mr. Pope has played and to refer to my early years and the memories of the past. My career commenced in the year 1852, so that I have had 55 years' experience, while he said 49; he was afraid to say 50, like the man who shot 999 ducks and would not admit that he had shot the thousandth. Fifty-five years' experience in all branches of practical telegraphy gives me the privilege and honor of saying that I have had something to do, directly or indirectly, with every single practical application of electricity. I commenced first with the telegraph, and my heart still goes out to the telegraph. In my early days I was brought into contact with Faraday—I believe I am to-day the only living pupil of Mr. Faraday. My early acquaintance with Dr. Kennelly was in poring over Faraday's Researches. In 1853 we laid down underground wires between London, Liverpool, and Manchester, 212 miles long, and we had serious effects due to static induction. We did not understand it. We called in Faraday and Sir George Wren, who was then the Astronomer Royal, and I worked with these two great philosophers for many months and carried out all the experiments Faraday wished to have carried out. I still have some of the records.

The first automatic system of telegraphing was that invented by Bain. The currents were transmitted through punched paper, and marks made on strips of paper saturated with prussiate of potash. They were blue marks, and I have many of the records made in those days to show the influence of static induction in retarding and in elongating the currents that came out at the distant end when a mere dot was introduced at the sending end. Many years after this, my first acquaintance with Edison arose from his coming over to England with an automatic system based on this chemical recorder. He had placed at his disposal a cable coiled in one of the tanks in the cable makers' works. He asked me what I thought would be the length of a dot through a thousand miles of cable. I had in my mind a thousand miles of cable laid out straight, and I told him

I thought a dot would come out about six inches long. He said, " What do you think it would be in the case of a cable coiled in a tank?" I said, " I really cannot tell." " Why," he said, " I wanted to know what the length of that dot would be; and when that dot came out, what do you think it was? It was 28 feet long!" That was Edison's experience with the effects of static induction. It was an experience of great service to those who are transmitting currents through long underground cables. That led to a very extensive system of underground cables, and no doubt we shall learn a good deal of the influence of the alternating current in working to great distances. I commenced with an automatic system that transmitted 1500 words a minute. It was competent and capable of transmitting 3000 words a minute. Why didn't we use it? Because there was no business for it. This question of automatic versus manual telegraphy is, after all, a question of business, a question of the number of words one wants to transmit, not the number of words one can transmit. In the last fifty years I have been engaged in developing automatic systems of all kinds, but the one in which I am peculiarly interested is the Wheatstone system. When I left the post office service in 1889 we had worked up the Wheatstone system so that it would give 650 words a minute on our longest circuit. We did not want 650 words, for the simple reason we did not have 650 words a minute coming in. It is a question of the messages to transmit, and those having practical knowledge of the working of the telegraph system know this: that in the telegraph business of a country there is a curve precisely similar to the curve we know so well, the load curve of the generating station, for whatever purpose it is used. Messages come pouring in according to the business hours of the day. In England we have a peak load every morning between 11 and 12 o'clock. It subsides during luncheon hour, and comes up again in the afternoon. In England there is only one time over the country, here in America there are four times, Eastern, Central, Mountain, and Western, and consequently there are peaks at different times of the day. There is three hours difference between San Francisco and New York; the result is the load curve for business in this country is different from the load curve in England, and therefore no fair comparison can be drawn between the rate at which the messages are transmitted per day or per wire, between the two countries. In the last analysis what is wanted is the very best system that will carry the work through to the best advantage of those who use the telegraph.

I discussed this question some years ago with Dr. Green when he was president of the Western Union Telegraph Company. This is my fourth visit to the United States, and whenever I come, my first object has always been to visit the two telegraph companies and learn what progress they are making. I come here to learn, and, if I see things done in a manner that is contrary to my judgment, I do not hesitate to criticise them; on the other hand, if I find things meritorious and worthy of commendation, I adopt them on the other side and give full credit to those who have produced them on this side of the water. In discussing these things with Dr. Green, he said to me, in the decisive manner he had, " In this country time is our only competitor." What he meant was, that the time elapsing between the moment the message was written and the moment it was delivered, was the time they wanted to control, that was the only thing he feared.

In England I think we have the automatic system in a state of perfection. I do not think there is any system that will beat the Wheatstone for business as it is. It may be that if we increase our load-curve and get a load-factor for the whole day of 50 or 60 or 70 per cent., then we will want automatic systems. At the present time there is no real need in our part of the world—I do not know what it may be here—for any automatic system which will send more than 200 or 300 words a minute, and that we have. It may be that the business will increase and necessitate such a thing. Automatic work is essensential and absolutely imperative on submarine cables, but submarine cables are different from the aerial wires we use. There is a great distinction between telegrams which are always short, and news work which is very considerable at times. In England it is enormous. In England our news business is much greater than in this country. We are all in a compact little island. There is not a single country town of any magnitude that does not issue an evening paper full of news sent by automatic telegraph, and there we find that 400 words a minute is ample to supply all the newspapers with what they want. It won't come in any quicker. A man making a speech, who wants it to appear in the next morning's paper, does not speak over 110 to 120 words a minute. I am not speaking to you now at a rate of more than 110 words a minute, and if there were a shorthand writer here who was reporting my remarks for the purpose of sending them to Chicago, for instance, it would not require an instrument that could work 1500 words a minute to send 110 words a minute. I want to point out that however new and perfect an automatic system may be—and I must say this is a beautiful instrument—there will always be some features concerning it which may not be entirely satisfactory. I had a good deal of correspondence with Dr. Rowland on this very subject, as he was anxious to make a start in England. We lost him too early, as he was one of the most brilliant scientific men of the age. His work will live for many years.

I take it the effect of the discussion to-night has really been, not to bring out very strongly the relative merits of manual telegraphy and automatic telegraphy; but it has raised this one question, and a very important question, and that is the value of labor in the telegraph service. In our younger days, Mr. Pope and I, when we used the key, thought ourselves howling swells because we could not only send messages, but we could absolutely and instinctively see a fault or error. When you are at your instrument, you know it like you know your child or wife. The instinctiveness with which an experienced telegraphist can trace a fault is quite wonderful. We take a great deal of pride in our knowledge, but it has this great defect in our country—it has caused our telegraphists to suffer from that complaint which is generally called " swelled head." There has been a good deal of trouble over there. The tendency has been to develop as much as we possibly can these automatic systems rather than to bring down the gentleman whose size of hat increases rather too frequently. It is rather a misfortune, but the development of the brain, in the great growth of business, is one of those things which cannot be helped. I think Mr. Dunn referred to the complication of these systems. That of Dr. Rowland is a combination of others. The synchronism was invented by Hughes; the breaking up of a circle into several divisions transmitted by switch systems was invented by Bain. It was tried a good deal and made practicable by Baudot in Paris, and it is working over submarine cables between Paris and London with a considerable amount of success. You have the alternating current introduced by Crehore and Bedell. There is really little novelty in the principles used, but there is considerable ingenuity shown in the mechanical arrangements. One likes to see a good thing worked up and put into practice. I have done a great deal in introducing automatic apparatus. It seems that we all want to meet the views of Dr. Green. We want to lick time. We can only do that by having means to transmit a message as rapidly as possible from the sending end to the receiving end. The conception of using a wire for many circuits, octuple, as in the Rowland system, is certainly a very great advantage. The reason why the quadruplex has not grown much in England—and I do not think it has grown much in this country—is because of the fault that it " throws out," and you lose the advantage of quadruplexing with four circuits, or octuplexing with eight circuits. Therefore, a fault on the line with these systems is very serious. That is the reason why there is a tendency to fall back on the duplex method. The tendency was to use copper very much for speed, but the price of copper has gone up so much it has rendered that practically impossible.

I am sorry to have kept you so long. I have been exceedingly interested to-night in taking part in this discussion. It has been one of the principal studies of my life, as I have told you, and it is like renewing one's childhood almost, to come back here and take part in a discussion of something that I studied over fifty years ago. I can only repeat what I said, that my coming to-night has been a source of great pleasure to me. I come here and meet familiar faces, some of whom I meet on the other side, and many more, perhaps, that I meet only when I come here. I find that marine architecture has done much to make the journey across the Atlantic a matter of luxury. Brittania is said to rule the waves, but marine architecture to-day rules the spirit of the waves. We passed through three very severe gales. We never had the fiddles on the table, and I never saw a sick person on the ship. One is in a beautiful palace for five or six days,—it will soon be four and a half days—from Liverpool to New York. I imagine in the future it will be a simple thing for a man to come from England, attend one of your meetings, and the next day take a steamer back home. There is one thing in which you fellows beat us horribly, and that is in your delightful hospitality. It is not mere hospitality, it is not the fact of the hospitality, but it is the way you do it. I do not know why it is, cannot tell you, but I assure you every time I cross the Atlantic and come here I find the gentlemen treat me in such a pleasant way that if I am spared I will come over again as soon as I can get away. I again thank you most heartily for all the courtesies which have been extended to me by your members.

A paper read at a meeting of the Schenectady Branch of the American Institute of Electrical Engineers, April 25, 1907.

CONSTANTS OF CABLES AND MAGNETIC CONDUCTORS

BY ERNST J. BERG

In the paper on "Line Constants, Etc.,"* equations were given for the inductance and capacity of the parallel conductors used in transmission lines. The formulas given were sufficiently accurate for any transmission line calculations where the distance between wires is large compared with their diameters; where, however, the diameters are comparable with the distance, as is often the case with cable transmissions, it is necessary to use the strictly theoretical expression.

In looking up the available literature on this subject, one is surprised at the great number of different formulas given. This is particularly the case in reference to the inductance formula which generally consists of two terms, one of which is constant and is usually given as 0.5, 0.75, or 1; the other a logarithmic function, also variously expressed.

Frequently the constant term is left out altogether, especially in formulas pertaining directly to standard line constructions.

To clear up the situation the following deductions are made. and a discussion added to show when the approximate formulas can properly be used.

A and *B* in Fig. 1 represent a couple of parallel cylinders of radius r and distance between centres D. For convenience in reasoning it is assumed that they are made up of a large number of strands or elements.

A current I flowing through conductor *A* will set up magnetic fields inside of the conductor and in the surrounding space. Consider at first the flux inside of the conductor.

* PROCEEDINGS, A. I. E. E., September, 1907, p. 1409.

The flux per unit length of line in section $d\,x_1$ is due to the current flowing inside of zone $d\,x_1$, which current is $\frac{x_1^2}{r^2}I$.

Thus the magnetomotive force per unit is $\dfrac{\frac{x_1^2}{r^2}I.}{2\,\pi\,x_1}$

The field intensity is $4\,\pi \times$ magnetomotive force $= \dfrac{2\,x_1\,I}{r^2}$

Therefore the flux $= \dfrac{2\,x_1\,I\,d\,x}{r^2}$

The electromotive force corresponding to this flux $= k \times$ flux in each section $= \int_0^r k \times \frac{2\,x_1\,I\,d\,x_1}{r^2} \times \frac{x_1^2}{r^2} = k\,\frac{I}{2}$. The equivalent flux corresponding to this electromotive force is $\frac{k\,I}{2k}$ $= \frac{I}{2}$, and therefore the equivalent inductance, which is $\frac{\text{flux}}{\text{current}} = \frac{1}{2}$.

The flux outside of the conductor is found in a similar way. In that case the magnetomotive force per unit length is $\frac{I}{2\,\pi\,x}$ the field intensity $4\,\pi\,\frac{I}{2\,\pi\,x} = \frac{2\,I}{x}$ and the flux

$$M_0 = \int_r^{D-r} \frac{2\,I}{x}\,d\,x = 2\,I\,({}^n lg\;(D-r) - {}^n lg\,r) \;= 2\,I\,{}^n lg\,\frac{D-r}{r}$$

The total flux expressed in centimeter-gramme-second units is therefore $M = I\left(2\,{}^n l\,g\;\frac{D-r}{r} + \frac{1}{2}\right)$ and the inductance

$$L = \frac{M}{I} = 2\,{}^n l\,g\,\frac{D-r}{r} + \frac{1}{2}$$

Transforming this equation to practical units and expressing L in millihenrys per mile of conductor we get:

$$L = \frac{161}{10^3}\left(2\,{}^n l\,g\,\frac{D-r}{r} + \frac{1}{2}\right)$$

In transmission lines D is usually large compared with r, so that the equation may be written:

$$L = \frac{161}{10^3}\left(2\,{}^{n}lg\,\frac{2D}{d} + \frac{1}{2}\right)$$

where D is the distance between centers of wires and d their diameter.

Determination of capacity between two parallel cylindrical conductors. Let A and B in Fig. 2 represent two conductors charged

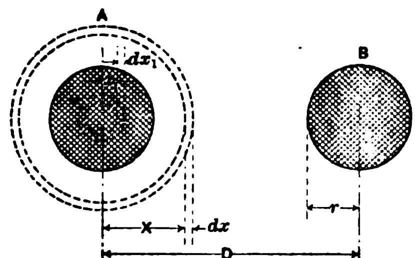


Fig. 1

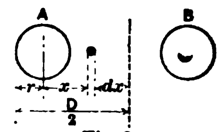


Fig. 2

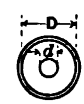


Fig. 3

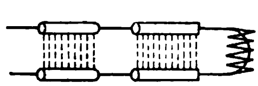


Fig. 4

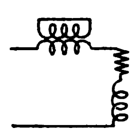


Fig. 5

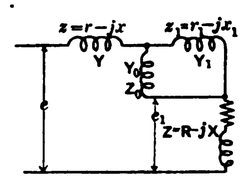


Fig. 6

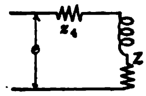


Fig. 7

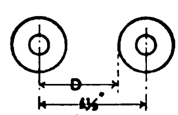


Fig. 8

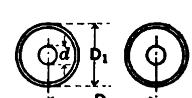


Fig. 9

with a certain amount of electricity Q, A being positive $+Q$ and B negative $-Q$.

Around each of these conductors is a field of stress, gradually decreasing towards zero potential plane.

The total field emanating from A is $4\pi Q$, thus the field intensity of an element at any distance x from A is $\frac{4\pi Q}{2\pi x}$ or $\frac{2Q}{x}$.

The corresponding field intensity due to the charge in B is—
$\frac{4\pi\, Q}{2\pi\,(D-x)} = -\frac{2\,Q}{D-x}$, so that the resultant static field intensity or static potential is:

$$\frac{2\,Q}{x} - \frac{-2\,Q}{D-x} = 2\,Q\left(\frac{1}{x} + \frac{1}{D-x}\right)$$

Consequently, in moving the element from the plane of zero potential to the surface of the conductor its potential rises to $\int_r^{\frac{D}{2}} 2\,Q\,d\,x\left(\frac{1}{x} + \frac{1}{D-x}\right)$ which integrated is $2\,Q\,{}^{n}l\,g\,\frac{D-r}{r}$

The capacity, which is the ratio of charge to potential causing the charge, is therefore

$$C = \frac{Q}{2Q\,{}^{n}l\,g\,\frac{D-r}{r}} = \frac{1}{2\,{}^{n}l\,g\,\frac{D-r}{r}}$$

which in practical units is:

$$C = \frac{890\,k}{10^4\,{}^{n}l\,g\,2\,\frac{D-d}{d}}$$

where C is microfarads per mile of conductor
k specific inductive capacity,
D distance between centers of wires,
d their diameter.

In transmission lines where $K = 1$, and $2D$ is large compared with d, the formula can sufficiently accurately be written as:

$$C = \frac{890}{10^4\,{}^{n}l\,g\,\frac{2D}{d}}$$

Cables. With the present state of the art it would not be conservative to use a cable at more than 25,000 volts between conductors, although it is to be expected that at least with rubber-covered cables, or cables with insulation of gradually decreasing specific inductive capacity, a higher voltage can finally be used.

At present time essentially, or almost entirely, two kinds of cables are used, one having paper insulation and the other rubber insulation, both being covered with lead.

Although the dielectric strength of paper is considerably less than that of rubber and therefore more insulation is needed due to the lesser cost, it is almost entirely used, and no doubt will remain so until cables for higher voltages are required.

It is almost impossible to give a general rule for the safe current capacity of a cable, since it depends largely upon what kind of conduit is used, the relative amount of insulation, etc. Perhaps 0.025 watts per square inch radiating surface (outside) is as fair approximation as can be made. When, however, the cable is laid directly in soil, 50% more current can be carried, and when placed in water 100% more current seems safe. This last case corresponding to 0.1 watt per square inch. The actual rise in temperature in the conductor is then about 30° cent.

On account of skin effect it is not desirable to use a conductor larger than about 1 in. in diameter in 60-cycle circuits, and one of 1.5 in. diameter in 25-cycle circuits, in which case the effective resistance is about 10% greater than the ohmic resistance. The fact that the conductor is made up of a number of small wires does not materially lessen the skin effect, since the individual strands are not thoroughly intermixed, but each remains at the same distance from the center at all times.

There is, however, for given outside diameter of the cable as compared with the outside diameter of the solid conductor, a slightly lesser skin effect in the case of the cable, due to the higher specific resistance of the cable, when considering the total cross-section.

In other words, there is less conductivity for a given area of cable than in the same area of solid conductor, and since the skin effect depends upon the resistance per given area the skin effect must be reduced. The theoretical equations governing this phenomena are extremely complicated and are therefore omitted.

The inductance and capacity equations deduced apply directly as long as all conductors belonging to the same circuit are in the same conduit or cable. If, however, that is not the case, but as in a single-conductor cable independent cables are used for the outgoing and incoming conductors "effective" values have to be calculated.

In the preceding were given the inductance and capacity formula for two parallel cylindrical conductors. In dealing with cables we require to consider the inductance and capacity between concentric conductors, such as single conductor in lead-covered cable where current is permitted to flow in the lead or concentric conductors in general. In that case the equations become

$$L_{m\,h} = \frac{370}{10^3}\ {}^{10}\log \frac{D}{d}$$

$$C_{m\,f} = \frac{770\ k}{10^4\ {}^{10}\log \frac{D}{d}}$$

Where L and C are respectively inductance in millihenrys and capacity in microfarads per mile of conductor. Thus in a concentric single-phase cable in 0.5 mile of length of cable or in a three-phase cable in 1 mile of length.

Effect of grounded lead covering of single-conductor cables. The lead covering obviously acts as a short-circuited secondary to the electromotive force induced by the reactance of the line. It consumes some of the electromotive force, therefore reduces the inductive drop but increases the ohmic loss due to the currents in the lead.

In calculating the phenomenon we will substitute for the line the primary of a transformer of same resistance as the line and with a magnetizing current the same as the line current at the voltage corresponding to the reactance electromotive force.

The reactance of the primary in this equivalent transformer is caused by the flux between lead covering and the conductor and is therefore as a rule quite small.

The secondary resistance corresponds to the resistance of the lead (which for given cross section is 14 times that of copper). the reactance is the same as that of the primary.

We can therefore diagramatically show these circuits as in Fig. 4.

The lead covering being grounded acts as a sheet of metal surrounding the conductor in inductive relation to the primary.

Or as in Fig. 5, where the line resistance and reactance are assumed as concentrated in a transformer.

Or finally as in Fig. 6, as a combination of inductive circuits with the proper transformer constants.

Let e = line voltage.

$Z = R - j\,X$ = load impedance.

$z = r - j\,x$ = primary impedance.

where r = line resistance.

x = reactance between conductor and lead.

$z_1 = r_1 - j\,x_1$ = secondary impedance.

where r_1 = resistance of lead covering (For the same cross-section 14 times that of copper.)

Y_0 = primary admittance = $j\,b$ where

$$b \text{ is } \frac{I}{E_x} = \frac{1}{x_0} \text{ or } Y_0 = \frac{j}{x_0}$$

x_0 = line reactance if no lead covering existed and a conductor of the same outside diameter as that of the lead covering were used in the calculations.

$$z_0 = \frac{1}{Y^0} = -\frac{j}{b} = -j\,x_0$$

Joint admittance of the two parallel circuits of impedance z_0 and z_1 is $Y_0 + Y_1 = Y_2$. The corresponding impedance z_2 =

$$\frac{1}{Y_0 + Y_1} = \frac{1}{\dfrac{j}{x_0} + \dfrac{1}{r_1}}, \text{ since } x_1 \text{ is small}$$

$$\text{we have } z_2 = \frac{r_1\,x_0}{j\,r_1 + x_0} = \frac{r_1\,x_0\,(x_0 - j\,r_1)}{r_1^2 + x_0^2}$$

Total impedance is $= z_2 + z + Z$

$$\text{Current therefore} = \frac{e}{z_2 + z + Z}$$

$$\text{Voltage across load } e_1 = \frac{e\,Z}{z_2 + z + Z}$$

$$E_1{}^1 = \text{drop in line } e - \frac{e\,Z}{z_2 + z + Z} = \frac{e\,(z + z_2)}{Z + z + z_2}$$

Let $z + z_2 = z_3$

We have then $E_1^1 = \dfrac{e\, z_3}{Z+z_3}$ .....A

In an ordinary line we have

current $= \dfrac{e}{Z+z_4}$. Drop in line $E_1^1 = \dfrac{e\, z_4}{Z+z_4}$ ..B.

Comparing these two equations, A and B, we see that if the values of line impedance obtained by writing $z_4 = z_3$ are inserted we can use the ordinary line equations

$$Z_4 = r_4 - j\, x_4.$$

From above we have—

$$Z_4 = z_3 = z + z_2 = r + \frac{r_1\, x_0^2}{r_1^2 + x_0^2} - j\left(x + \frac{r_1^2 x_0}{r_1^2 + x_0^2}\right)$$

or neglecting x, which is small, we can write the effective resistance as—$r + \dfrac{r_1\, x_0^2}{r_1^2 + x_0^2}$

and the effective reactance $= \dfrac{r_1^2\, x_0}{r_1^2 + x_0^2}$

As a rule x_0 is small compared with r_1 and we can write

$$\text{effective resistance} = r + \frac{x_0^2}{r_1}$$

$$\text{" reactance} = x_0$$

When estimating the reactance and effective resistance of a grounded single-conductor lead-covered cable—calculate the ohmic resistance r of the conductor, the ohmic resistance r_1 of the lead covering, (specific resistance 14 times that of copper) determine the reactance x_0 as between two parallel conductors of same diameter as the outside diameter of the lead, and substitute the values so obtained in the equations given above.

Instance. Two cables of 1000 ft. total length placed on 4.5 in. center, each cable contains a 0000 B. & S. conductor. Outside diameter of lead 1 in., inside diameter 0.75 in. What is the effective resistance and reactance of 25 and 60 cycles?

$r = 0.049$, area of lead $\frac{1}{8}\pi\frac{7}{8} = 0.343$ sq. in. corresponding to copper section $= \frac{0.343}{14} = 0.0245$ sq. in.

Therefore $r_1 = 0.332$.

At 25 cycles reactance outside of lead is $\frac{2\pi 25}{10^9} \times \frac{161}{10^3}$

$$\left(2\,\pi l\,g\,\frac{8}{1}+\frac{1}{2}\right)\frac{1}{5.28} = 0.0223 \text{ ohms.}$$

Therefore effective resistance

$$= 0.049 + \frac{0.0223^2}{0.332} = 0.0505 \text{ ohms.}$$

At 60 cycles the reactance is 0.0535.

Therefore effective resistance = 0.0572.

The resistance is increased 3% in the first case, 16% in the latter.

To illustrate the increased loss in a single conductor lead-covered cable, table *A* has been prepared. It applies to a single-conductor cable No. 0000 B. & S. having a lead covering $\frac{1}{16}$ in. thick, the outside diameter of the lead covering is 1 in. Losses are given for various distances to return conductor and at various frequencies.

It shows that in general the losses introduced are small and need only be considered in 60-cycle systems when the cables are a considerable distance apart. This table refers to one mile of conductor.

Cycles				12.5
Distance inches	2.13	4	12	24
r	0.264	0.264	0.264	0.264
$x_0 = x_e$	0.0249	0.0458	0.0772	0.0952
x_2^0	0.0006	0.0021	0.0059	0.009
r_e	0.2642	0.2649	0.2665	0.2678
Increase	0.1%	0.34%	0.98%	1.4%

Cycles		25		
Distance inches	2.13	4	12	24
r	0.264	0.264	0.264	0.264
$x_0 = x_e$	0.0497	0.0916	0.1544	0.1904
x_0^2	0.0025	0.0084	0.0238	0.0362
r_e	0.2651	0.2676	0.2743	0.2796
Increase	0.42%	1.37%	3.9%	5.9%

Cycles		60		
Distance inches	2.13	4	12	24
r	0.264	0.264	0.264	0.264
$x_0 = x_e$	0.1193	0.220	0.3706	0.4570
x_0^2	0.0142	0.048	0.137	0.208
r_e	0.2701	0.2848	0.3233	0.3536
Increase	2.3%	7.9%	22.5%	33.9%

Effect of a non-grounded lead covering in single-conductor lead cable. Since there is a difference in flux between the inside and the outside half of the lead covering, currents must flow alongside the covering in one direction in the inside half, in the other direction in the outside half.

The average distance between center of one conductor and the nearer half of the lead covering of the other conductor is

$$D - \frac{D_1}{4}$$

The average distance to the outer half is

$$= D + \frac{D_1}{4}$$

The difference in inductance is therefore

$$l_d = \frac{742}{10^3}\left({}^{10}\log\frac{D+\frac{D_1}{4}}{d} - {}^{10}\log\frac{D-\frac{D_1}{4}}{d}\right)$$

$$= \frac{742}{10^3}\,{}^{10}\log\frac{D+\frac{D_1}{4}}{D-\frac{D_1}{4}}$$

Where l_d is expressed in millihenrys per mile of conductor.

With I current flowing in the conductor and the resistance of the lead covering calculated as above, that is a conductor of same length, as the conductor proper, and with the actual cross-section of the lead, we get:

$$\text{Reactance electromotive force} = \frac{2\,\pi\, n\, l_d\, I}{10^3}$$

$$\text{and eddy currents in lead} = \frac{2\,\pi\, n\, l_d\, I}{4\, r_1\, 10^3}$$

$$\text{Thus the loss in the lead} = \frac{4\,\pi^2\, n^2\, l_d^2\, I^2}{4\, r_1\, 10^6}$$

Therefore the effective resistance

$$= r + \frac{n^2\, l_d^2}{r_1\, 10^5}$$

Where n = frequency
l_d = inductance in milhenrys
r_1 = lead resistance—as defined above.
r = resistance of conductor proper.

With 4 in. distance between centers and one inch conductor, we get:

$$D + \frac{D_1}{4} = 4.25$$

$$D - \frac{D^1}{4} = 3.75$$

$$l_d = \frac{742}{10^3}\ {}^{10}\log 1.13 = \frac{40}{10^3}\ \text{mh.}$$

Therefore effective resistance

$$= 0.049 + \frac{25^2 \times 40^2}{0.33 \times 10^6 \times 10^5} = 0.04903.$$

We see from this that the eddies in a single conductor lead covered cable are negligible if the lead is not grounded.

Effect of iron-armored single-conductor cable. If the cable instead of being covered with lead, were covered with a magnetic material such as iron, the problem would be more complicated on account of the increased flux due to the iron. Such conduit is indeed quite out of the question on account of the increased reactance and eddy losses.

From the saturation curve of the iron it is possible to determine the magnetic density and therefrom the flux in the iron for a given current in the conductor.

Assume this flux to be M

E, the electromotive force corresponding to this flux is

$$\frac{4.44 \times M \times n}{10^8}$$

The corresponding reactance is $\frac{E}{I}$

which reactance should be added to the normal reactance as obtained in a non-magnetic system.

The hysteresis loss corresponding to this density is found from the hysteresis curves of the iron, and this loss divided by I^2 gives an equivalent resistance which should be added to the resistance as obtained in case of a non-magnetic conduit.

As an instance. Assume the cable described above covered by iron instead of lead, and that 150 amperes are flowing in the main conductor.

Assume further that the iron is $\frac{1}{8}$ in. thick and that the total loss due to eddies and hysteresis is five times as great as the hysteresis loss proper.

The magnetomotive force available is $150 \sqrt{2} = 212$ ampere-turns.

The magnetic length is $\frac{7}{8} \pi = 2.75$

Magnetomotive force per inch $= \frac{212}{2.75} = 77$

This corresponds to a density of 100,000 lines per sq. in.

The magnetic cross-section $= 1000 \times 12 \times \frac{1}{8} = 1500$ sq. in.

Therefore the total flux $M = 150{,}000{,}000$ and $E = 166$ volts, the reactance due to iron is thus $\frac{166}{150} = 1.1$ ohm.

From hysteresis curve we find the loss per cubic inch per cycle $= 0.028$ watts.

Therefore the loss is $0.028 \times 5 \times 1500 \times \frac{1}{8} \times \pi \times 25 = 14{,}500$ watts.

Whereas the $I^2 R$ proper is but $150^2 \times 0.049 = 1100$ watts.

It can readily be proved that even the thinnest iron covering is prohibitive in single-conductor cables for alternating currents.

In concluding the discussion of the effect of armor we may add that where two or more conductors involving a complete circuit are carried in the same conduit, it matters not whether the covering is of iron or lead, grounded or not grounded. The effect of the covering on the resistance or the reactance is negligible.

Iron wire and cables used as electrical conductors. Since the ohmic resistance and permeability of iron changes very considerably in different grades and since the permeability varies with the current, it is evident that it is very difficult to lay down any definite rules regarding the effective resistance and reactance. So that in order to get accurate determinations it is necessary to test samples of the conductor intended to be used.

With the present price of copper wire, it is evident however that wherever small power is carried relatively short distances at high voltages, iron wire, or at least iron cables, could be used, and calculations must be made before the actual wire has been secured.

With direct current the matter is fairly simple, since the permeability does not enter and wires of definite resistance could be ordered. This resistance in iron wire varies from say four times that of copper to seven or eight times that of copper.

With alternating current the skin effect causes additional resistance, which, at least in large conductors, is considerable, often several times that of the true ohmic resistance. This effect is however small in small wires, say wires of number 8 to 12 B. & S. gauge, but with large wires it is considerable. Such small wires can not, however, well be used for transmission lines for mechanical reasons. Therefore, it seems probable that stranded cables only need to be considered.

From a number of deductions it would seem as if the effective resistance of such stranded cable (7-strand cable) could be expressed by the following formula:

$$R = r + \frac{K\ N\ B^2\ D^2}{r\ 10^5}$$

In which K depends upon the permeability and may average 2.

R = effective resistance per mile of cable.
r = ohmic resistance.
N = frequency.
B = current density in amperes per square inch superficial area
D = external diameter of the cable.

The reactance can be approximated as:

$$X = x + 0.01\,N + \frac{K\,N\,B^2\,D^2}{r\,x\,10^5}$$

Where X = effective reactance per mile of wire.
x = reactance as obtained if the cable were made of copper.

These formulas apply fairly well, at least to cables of from ⅛ in. to ½ in. external diameter. It is unlikely that larger cables will be used, since the skin effect is very considerable with ½ in. cables, and it is unlikely that smaller cables will be used, on account of mechanical reasons.

It is to be noted in connection with these formulas that the reactance as a rule is not prohibitive with the use of iron cables. It has often been thought that the reactance was the limiting feature, but this is not the case—the effective resistance is of more importance.

When using very large iron or steel conductors, such as rails in the case of single-phase railroading, the effective resistance can be estimated from the degree of penetration of current, and this has been approximated by Steinmetz and others to be

$$\delta = \frac{2000}{\sqrt{g\,\mu\,N}}$$

Where δ, the penetration, is expressed in inches.

g = electrical conductivity, which with soft iron is about 110,000, μ is the permeability and might be about 500 and N is the frequency.

Consequently, the resistance of such large iron and steel conductors does not depend upon the actual cross-section, but upon the perimeter. It is furthermore proportional to the square root of the frequency.

[For additional discussion on this paper see page 926].

A paper presented at the 218th Meeting of the American Institute of Electrical Engineers, New. York., April 26, 1907.

THE TELEPHONE WIRE PLANT

BY SERGIUS P. GRACE

Telephone engineering has been looked upon by many engineers as principally a switchboard problem. The switchboard problem was undoubtedly deserving of the great amount of attention given to it by telephone engineers, and the results are everywhere evident to-day in the perfect working mechanisms of the modern, central battery switchboard. An analysis of the construction costs of the telephone plant will, however, show that from two-thirds to three-fourths of the total expenditure is required for the outside plant; that is, for conduits, poles, cables, and wire. Because of the very large proportional expenditures for the outside plant, it becomes evident that the systems of line distribution should be most carefully studied in order that the best service may be given at the lowest cost.

In considering a telephone plant for a community, the first thing to be done is to decide upon a proper development plan for the growth of the business for a reasonable number of years. In view of the rapid advances in the telephone art and the possibilities of the introduction of new systems of transportation and communication, it would seem that fifteen to twenty years is as far ahead as we are justified in planning telephone development. If the plant is to care for service offered during this period, it must be originally so laid out and designed that the additional subscribers can be taken on without the redesign and reconstruction of the plant From time to time the development plan can be revised so as always to keep it from fifteen to twenty years ahead of the plant. In laying out a telephone development plan for a city, there are many things to be considered. The growth in population for the last ten years must be carefully considered; from all possible sources of information a prediction should be made of the population for the next ten to twenty years. It next becomes necessary to determine upon the percentage of development which may reasonably be expected; that is, the ratio of telephones in use to the population. This will vary considerably with the prosperity of he community and whether there are large manufacturing districts employing low grades of labor. It seems certain that this development in the ultimate will lie between 15 and 30 per cent. of the total population. A careful estimate must also be made of the ratio of line to stations. Thus if a very high party-line development is expected, the ratio of lines to stations will be low. To-day the telephone line really mean, more to us from the wire plant standpoint than the number of telephones. Formerly we used to consider the number of telephones as affecting the wire plant; now it is the number of lines. Because of the introduction of private branch exchanges two or three trunk lines may care for fifteen or twenty telephones, or there may be a number of telephones on one line, so it is the line in which we are interested.

After having looked over the city in a general way and obtained the best available data regarding the industries and the growth of the population in various parts of the city, the next thing to do is to resort to a detailed count of all the buildings, and block by block make an estimate of the number of telephones expected at the end of various periods during the next twenty years. In addition to the count of the present buildings, an estimate should be made of the probable ultimate number of the various classes of structures in each built up block of the exchange area. In providing for the number of lines to be installed at once, which at the same time should provide for two or three years' growth, the present number of lines in each block should be determined and to this number about one-third more lines should be added. This will vary in different cities and must be the subject of a special study in each case.

After having made a study of each block in the exchange area and determined the probable number of lines and stations at the end of each five year period during the next twenty years, the entire number of lines and stations as shown by the block map should be summed up and carefully compared with the ultimate figures deduced from the general development plan which is based upon the character of the city and the probable growth in population. If the estimates arrived at by the general development scheme and the detailed block scheme do not compare favorably, both estimates should be gone into again most carefully to determine the possible

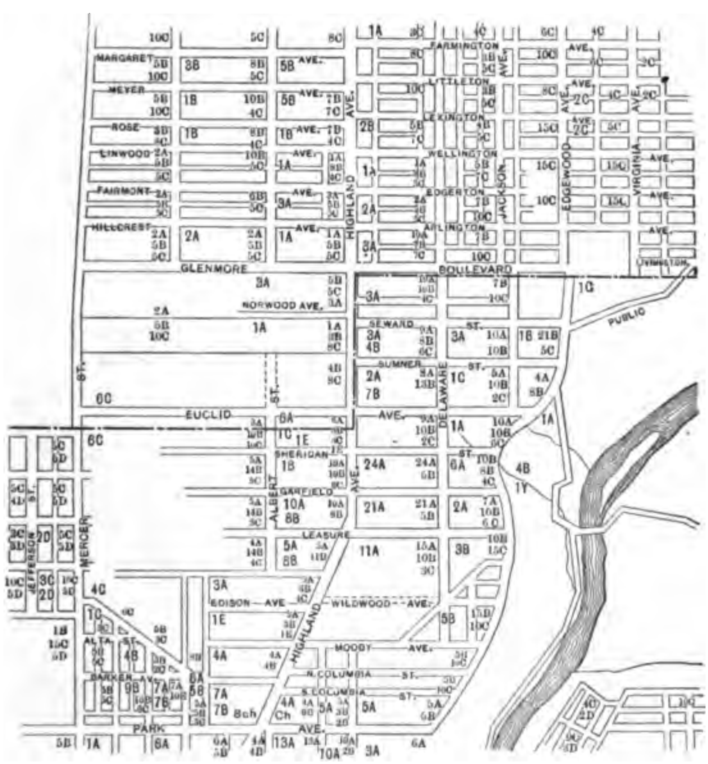


FIG. 1—Development plan. Present ultimate number and classes of houses in each block

errors. In Fig. 1 is shown a section of a city of about 40,000 inhabitants. On this map are marked the numbers of the various classes of houses. At the left of the block in circles are shown present number and at right are shown ultimate number of houses. In Fig. 2 are shown the number in five years and ultimate number of lines in each block.

When the number of telephones in each block for the twenty year study has been decided upon, it remains to determine the most economical grouping of these telephone lines into exchanges. In small cities where the number of telephone lines in the ultimate will not exceed 8,000 to 10,000, it is reasonably certain to assume that one exchange will prove the most economical. If the district is very much scattered or very much elongated this is not true, and the proper number of exchanges

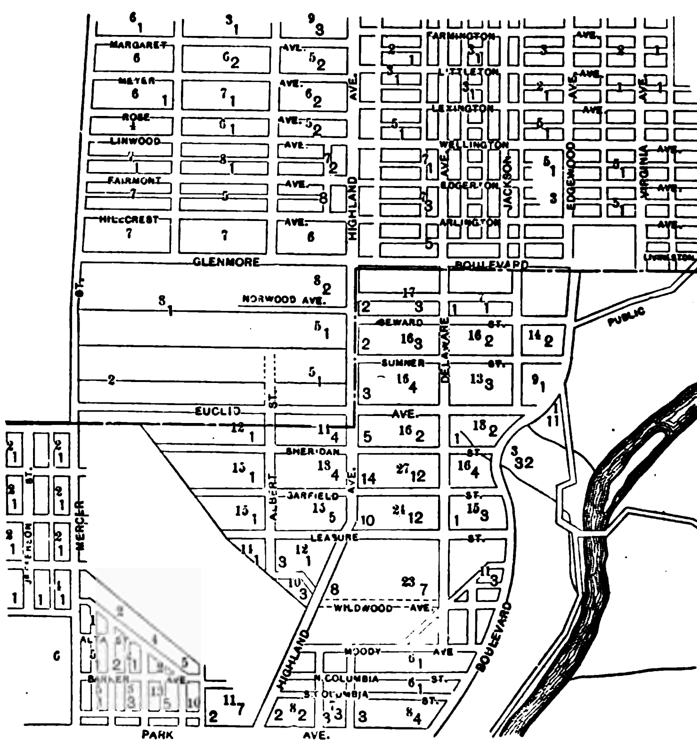


FIG. 2—Development plan Number of lines in five years and ultimate number of lines in each block

should be determined in a manner to be described later. If one exchange is decided upon, a location for this exchange must be determined which will make the subscribers' line wire mileage a minimum. The determination of this centre with extreme precision is a problem for the calculus. The most simple case is when the streets are all rectangular, in which case the mathematical centre of distribution is found by drawing lines at right angles through the exchange area, so that the number of telephones in the ultimate on each side of the lines is the same. If the present centre is a considerable distance from the ultimate centre, a mean centre between the two should be decided upon.

When the centre is determined, a complete conduit system should be laid out, touching at least one side of every block in the exchange area. It will never be necessary to construct all this conduit at once, and perhaps even in the ultimate, much of it will not be installed, but if a definite plan is prepared the conduit extensions from time to time will be of correct dimensions and in the right direction. This conduit must, of course, feed to the exchange centre by the most direct routes possible, and the lines should be concentrated in the smallest number of subways which will not affect the efficiency of the distributing system. Since it is known from the development plans the number of lines in each block at the present and the ultimate periods, a skeleton feeder plan carrying these pairs back to the exchange centre can readily be prepared, and from this it is easy to determine the number of ducts and sizes of manholes in the various parts of the subway. In Fig. 3 is shown a typical conduit plan. In general, the terminal cables feeding into the block should be of the ultimate size, while the feeder cables back to the exchange centre should be so proportioned as to care for the growth in business for from two to five years. Fig. 4 shows a cable plan for a five-year growth. In the districts where conduit is not constructed, pole lines may be used for distribution and feeder purposes.

In the case of a large city where it is evident that a number of offices will be required to furnish the service, it is a very complex and complicated problem to determine how many exchange districts there should be. The cheapest number of districts will vary as follows:

1. With the grade of talking transmission.
2. With the subscribers mileage—varies directly as the number of offices.
3. With the *A* and *B* position equipment—varies directly as the number of switchboards.
4. With the multiple jacks—varies inversely as the number of switchboards.
5. With the rent—varies directly as the number of offices.
6. With the office constant—varies directly as the number

of offices. This office constant takes care of the equipment which is common to all offices, such as the charging dynamos, storage-batteries and power boards.

7. With the central-office labor—varies directly as the number of offices.

8. With the trunk mileage—varies directly as the number of offices; also on number of calls per line and per cent. of trunking.

Fig. 3—Development plan. Typical underground conduit layout

Good telephone service is fundamentally based upon good talking efficiency. The means for transmitting the talk is what the telephone company really furnishes to the subscriber. In very large city districts, because of the distances between the central offices, the cost per message is materially increased on account of the high-grade trunk plant required to give the subscribers good transmission. The central battery system of subscribers lines has proved very efficient and economical from service and maintenance standpoints. There is, however, a considerable loss introduced into each line by the ohmic resistance which operates to cut down the flow of current through the transmitter. In addition, then, to the attenuation loss present in all cases we have added to this in the transmitting loop, a loss due to the reduction of the current through the transmitter.

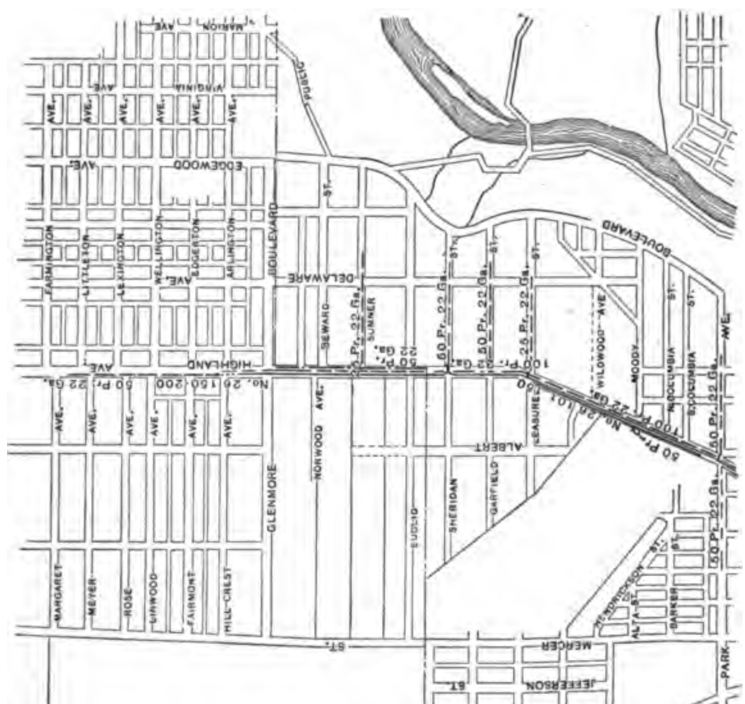


FIG. 4—Development plan. Cable plan for five years' growth

In designing the subscribers lines, 22-gauge cable should be used as much as possible. In the case of a large city with a number of central offices there is a limiting resistance for the subscribers' lines which can not be exceeded without making the trunking plant very expensive. This limiting resistance of the subscribers' lines will vary in different cities because of the varying distances between central offices which affects the trunk line mileage. In general the subscribers' and trunk line plant must be so designed that, while there will always be good talking transmission between the subscribers, the annual charges on both the subscribers' and trunk line plant will be a minimum.

To lay out a city in the correct number of districts all the items above mentioned must be given careful consideration. From past experience it is generally possible to predict approximately the number of districts which will be found most economical. A number of districts above and below this value should be decided upon, and the costs and annual charges for each of these three groupings should be carefully calculated. The first cost and annual charges of all the variables given on preceding pages must be known in order to make these comparisons. Our past experience indicates that the following is about the best theoretical number of districts for cities of various sizes.

	Offices.
For an ultimate of 10,000 lines or less	1
For 10,000 to 15,000 lines	2–4
For 15,000 to 25,000 lines	5–8
For 25,000 to 35,000 lines	6–10
For 35,000 to 50,000 lines	8–12
For 50,000 to 100,000 lines	10–16

After the number of offices has been decided upon, and the conduit study following the general development plan is made, it yet remains to construct the outside plant so as efficiently and economically to connect the subscribers by means of the wire plant to the central offices. Conduits should be built in the congested districts and along what may be considered as main feeder routes. In general it is economical to construct at once a conduit if 400 to 800 pairs of wires are expected within five years. In the vicinity of the underground conduit system every effort should be made to connect the subscribers without resorting to aerial construction. Where the buildings are large and permanent and an average of ten telephones per building may be expected, the best method of construction is a cable directly into each building from the nearest manhole in the main conduit system. In the case of large office buildings one or more building cables should be run vertically in the wire or pipe shafts and terminal boxes provided at each floor, to which can be connected the individual wires for each telephone. The scheme

FIG. 5—Standard cable terminal

for distributing these individual wires most to be preferred is the hall molding scheme. These hall molding troughs should connect to the terminal box on each floor so that the wires to each telephone may be run from time to time as needed. This system is cheaper to install and easier to maintain than the conduit system following electric light practice. In many cities there are large area ways under the sidewalks, and a cable run through these area ways from one building to another

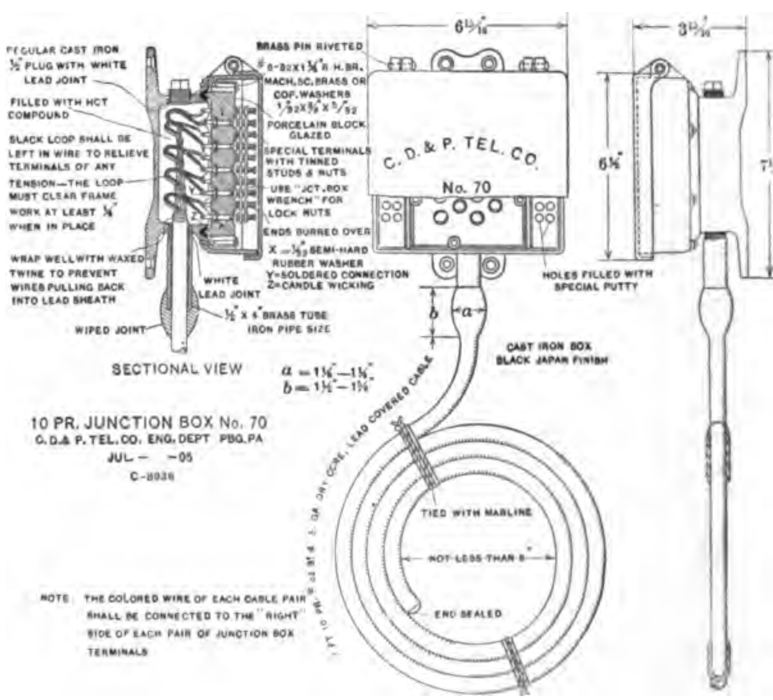


FIG. 6—Details of standard cable terminal

and provided with a tapping terminal on each property makes a very good form of distribution.

Where the blocks in the vicinity of underground conduit are well built up, but where none of the buildings is large enough or important enough to warrant direct connection the interior block system may be used to great advantage. In this system one or more underground laterals from the main subway system are run into the interior of the block and terminated on the

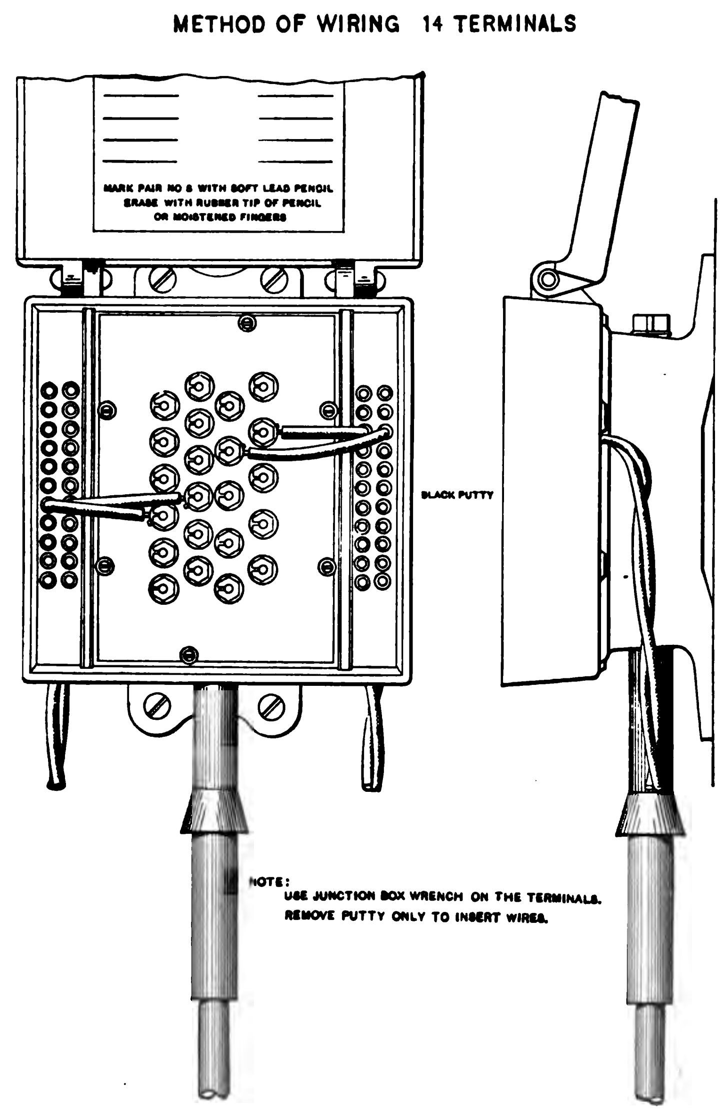


FIG. 7—Wiring diagram of cable terminal

rear walls of the most substantial buildings. Around the interior walls at a height preferably not over ten feet from the ground are cleated lead-covered dry-core cables. At intervals of 100 to 200 feet a multiple tap is taken to terminal boxes. From these terminal boxes No. 18 B & S. gauge rubber-covered and braided-bridling wire is carried through bridling rings spaced about four feet apart to the various entrances to the subscribers' premises. This distributing cable is of course connected to an underground cable from the main subway. In case the number of telephones within the block is small, a terminal box at the end of the underground cable may be sufficient, and nothing but bridling wires through rings used for distribution purposes. Since no protection is needed between the distributing lines and the underground cable, a very neat form of terminal box may be used. The type of box which is being largely used for this service at the present time is shown in Figs No. 5, 6, and 7. In this box the wire terminals are mounted on hard-burned porcelain. A five-foot length of dry-core lead-covered cable is connected to the terminals on the porcelain blocks, after which the blocks are firmly seated on a gasket of wicking saturated in compound. The cast-iron retaining case is then filled with compound, the cable wiped to a brass nipple, and an air-tight plug inserted in the top. This hermetically seals the terminal. On account of the durable nature of the materials employed in the construction of this terminal; namely, porcelain, cast iron and brass, the depreciation and maintenance should be very low.

In Figs. 8, 9, 10, 11 are shown examples of interior block distribution This type of construction is so inconspicuous as to be rarely objectionable, and in consequence its use should be adopted wherever possible. In certain districts in the neighborhood of underground subways, the buildings may be very old or may be very widely scattered. In these cases an interior block system could not be installed to advantage, and a low ring-top distributing pole should be used, pending the time the block will be sufficiently built up to permit of direct connection or interior block wiring. Figs. 12 and 13 show examples of this type of construction. Distributing poles are useful for furnishing connection between the underground system and the subscribers' premises during a period when direct connection or interior block wiring is not warranted. Ultimately, it seems certain that the distributing pole is bound to go.

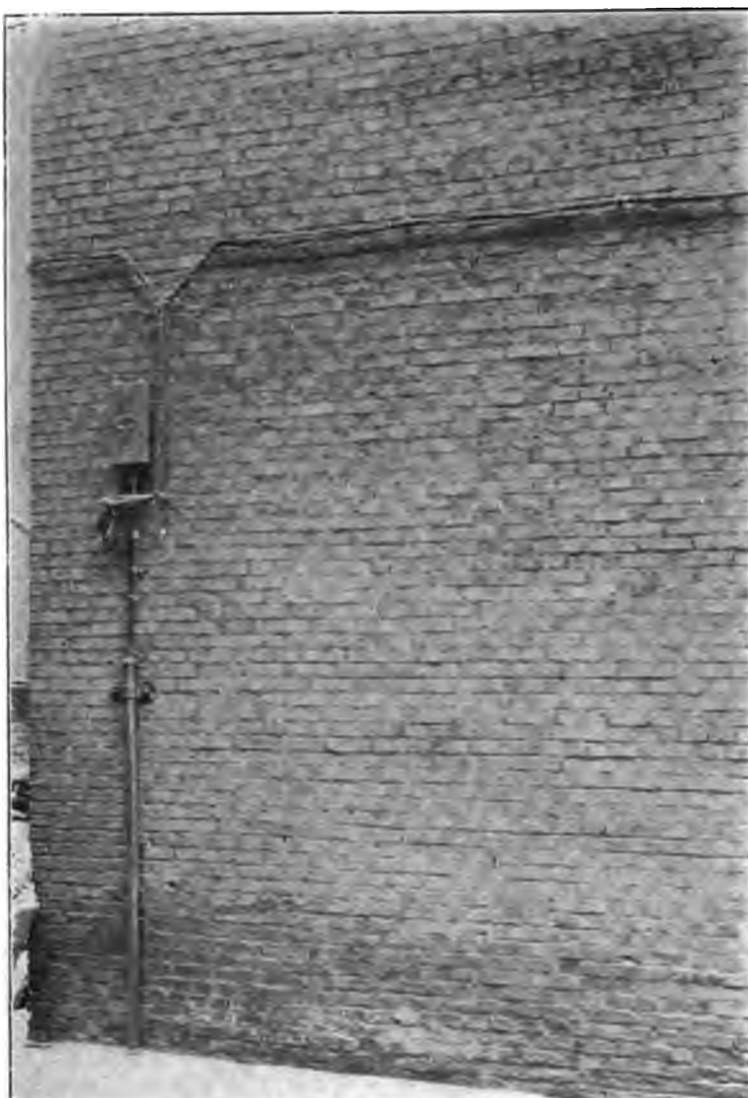


FIG. 8—Interior block distribution Sub-duct cable terminal and wiring runs

FIG. 9—Interior block distribution Example of wiring run to upper floors of building

A very large proportion of telephone service must be given in scattered residence districts where the number of circuits is so small as not to justify conduit construction. If conduits were installed at once, the construction plant costs would be very materially increased and consequently the cost of service to the subscribers would have to be increased. It is therefore necessary to determine what is the most economical, efficient, and sightly form of aerial distribution. In the early days of the telephone it was but natural that the distribution of the telephone wires should follow the same practice adopted by the telegraph companies. Very soon it was found that the number of telephone wires multiplied very rapidly, which required towering poles, equipped sometimes with as many as twenty cross-arms. The invention of the dry-core, lead-covered cable furnished relief for these lines, although for many years it was the custom to use as much open wire and as little cable as possible.

In the territory about Pittsburg the topography of the ground is exceedingly rough. This results in winding streets and almost an entire absence of alleys. To construct very large open wire lines in these winding streets was early seen to be impracticable, and when the great expansion of the telephone business began in 1897 it became imperative to design other methods for aerially distributing telephone lines. The system which was finally worked out and decided upon is that known as the aerial cable or all-cable system which was adopted in 1897 and has been our standard type of aerial construction ever since. In this system, very low poles are used, rarely exceeding 30 to 35 feet in height. These distributing lines are placed in alleys if they are available. A cable is strung near the tops of the poles and on alternate poles are placed 10- or 15-pair terminals. Each pair in the distributing cable appears in from two to four terminals, and common pairs are so laid out in adjacent terminals that it is easy to provide for party lines. The multiplying is so arranged that when the cable becomes crowded it may be cut into two or four parts, all pairs appearing in each part, and relieved by feeder cables. No cross-arms or bare wires are used for distribution along the lead, but from the binding-posts in the cable terminal a twisted pair, rubber-covered, and braided wire is strung directly to a point within the subscriber's premises. The use of this well insulated twisted pair wire very materially reduces the maintenance. An aerial cable system of

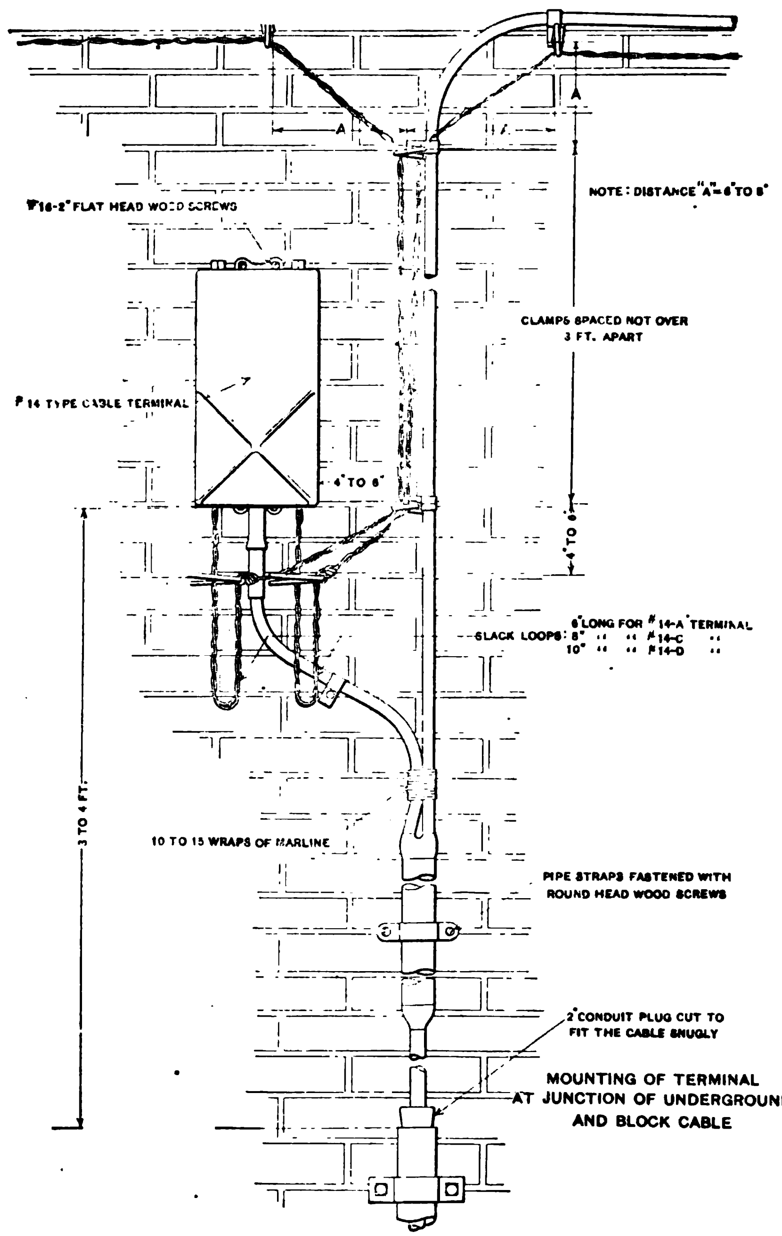


FIG. 10—Interior block distribution. Details of cable terminal-connections on wall of building

this kind with twisted pair wires leading directly to the subscribers' houses is undoubtedly the most sightly form of aerial distribution, since all the cumbersome and troublesome open wires are done away with. In Figs. 14, 15, 16, 17, and 18 are shown methods and materials used in aerial cable construction. Attention is called to the grooved insulators used for supporting the twist wires. Each wire of the pair occupies a separate groove, thus preventing a crossing of the wires, which sometimes injures the insulation when there is a heavy strain on the wires.

FIG. 11—Interior block distribution Suspending wires from building to ærial cable terminal on pole

There has been considerable discussion among engineers regarding the life of twisted-pair, rubber-covered distributing wire. Rubber and paint are somewhat alike, in that all kinds of mixtures are sold under their names. From the very beginning we have been careful to specify a reasonably high grade of rubber and to insist on making tests of all wire submitted to us, to be sure that our specifications have been complied with. Very good wire was thus obtained, and samples which we now take down after having been in use for seven to nine years still show an insulation resistance of 200 to 400 megohms per mile when submerged in water. If the ordinary type of market wire, which is mainly intended for inside wiring, is used, the life will be much shorter. A good quality of rubber distributing wire well protected with a heavy braid should prove serviceable for ten or fifteen years.

Until recently the type of distributing wire most generally used was made of No. 14 B. & S. gauge copper. This size of wire was not necessary for conductivity, for as a rule it was

FIG. 12—Distribution of subscribers' lines from circle top distributing pole

connected to a 22- or 19-gauge cable pair. This size of wire was required for mechanical strength, because the wire was strung in spans and had to be self-supporting. During the past year there has been put on the market a copper-clad steel wire which is made by a new method. Copper is welded to a steel ingot and the copper and steel drawn out uniformly together. From all the examinations we have been able to make it seems that there is a perfect union between the copper and the steel. A No. 17 B. & S. gauge copper-clad wire having

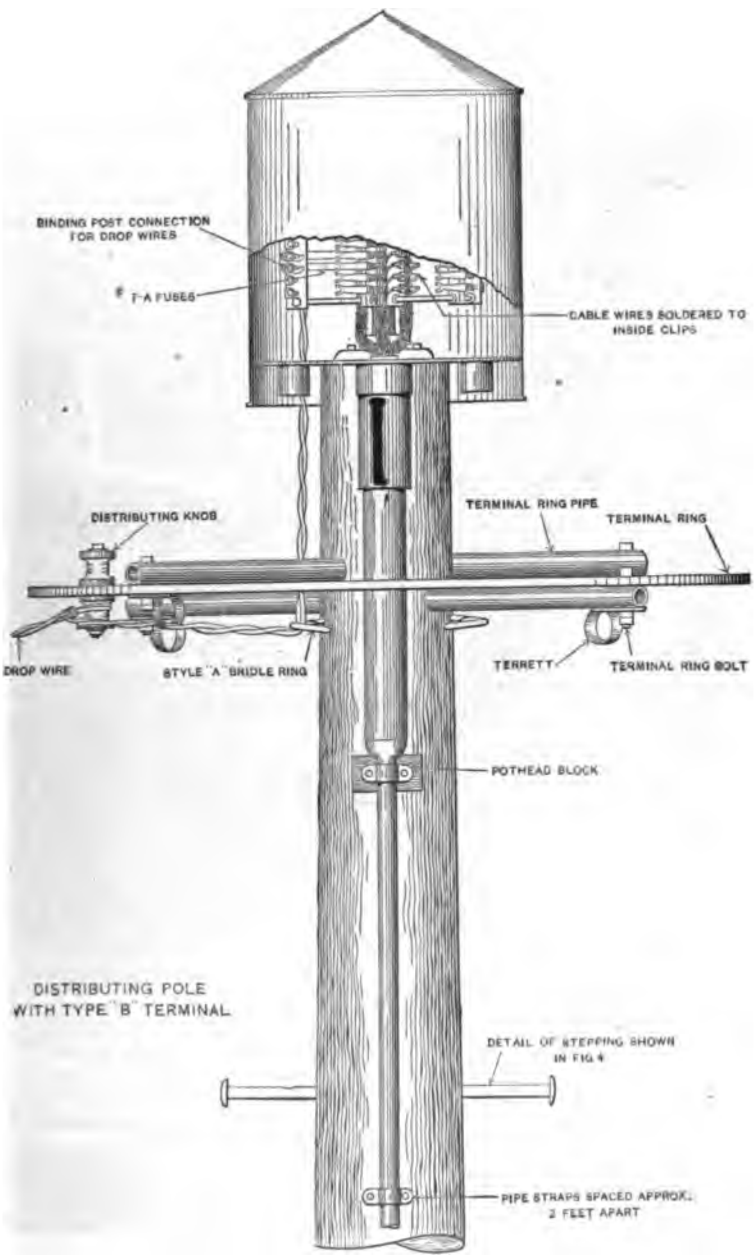


FIG. 13—Details of circle top distributing pole

30% conductivity of copper has the same tensile strength as a No. 14 B. & S. hard-drawn copper wire. This reduces the amount of material in the distributing wire one-half, and what

FIG. 14—Aerial cable distribution Cable top and drop wires to residences

is still more important, on account of the reduced area, decreases the amount of expensive rubber compound required to surround the wire. The amount of braided covering is also materially reduced. The finished wire is very light and easy to handle and costs approximately 30% less than the No. 14 B. & S. type of wire.

At first sight it seems that a terminal on alternate poles must be expensive, and that terminals farther apart and with intervening distribution made by bare wire, would be cheaper. In order to determine this point clearly, a study was made some time ago showing a comparison between aerial cable distribution with taps on alternate poles and with twisted pair direct to the houses, as compared with aerial cable supplemented

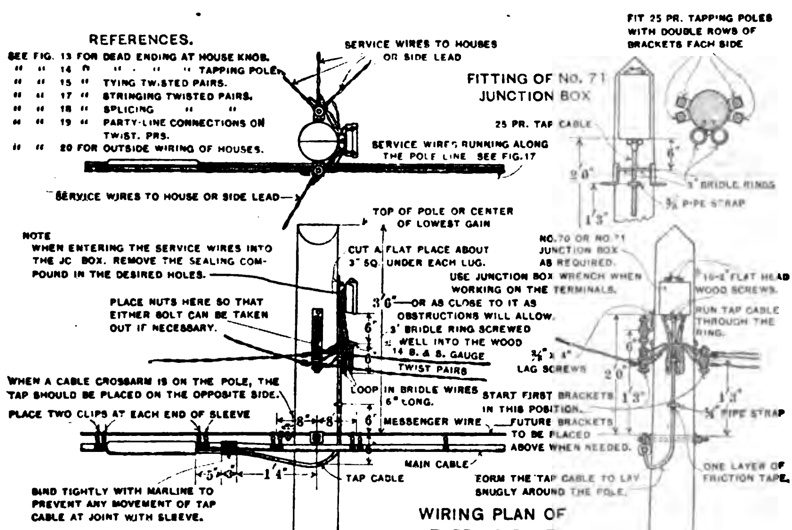


FIG. 15—Details of construction at branch terminal pole

with bare-wire distribution. Various densities of telephone distribution were assumed, and it was found that in nearly all cases the system with taps on alternate poles was not only cheapest in first cost but also in annual charges. Where the distribution was very dense it was found that a tap on every pole was the most economical. As a general principle it would seem that we should carry the telephone circuits just as far as possible in cable and make the subscriber's drop of minimum length.

There will, of course, be many streets and districts where for the present time aerial cable is not warranted. If these districts are in the neighborhood of an aerial cable base line, and the subscribers are not located more than 1000 feet away from the cable line, it is economy to connect them with twisted-pair wire strung on distributing brackets rather than to resort to the use of bare wire and cross-arms, where perhaps a large part of the arm capacity will lie idle for several years. This method

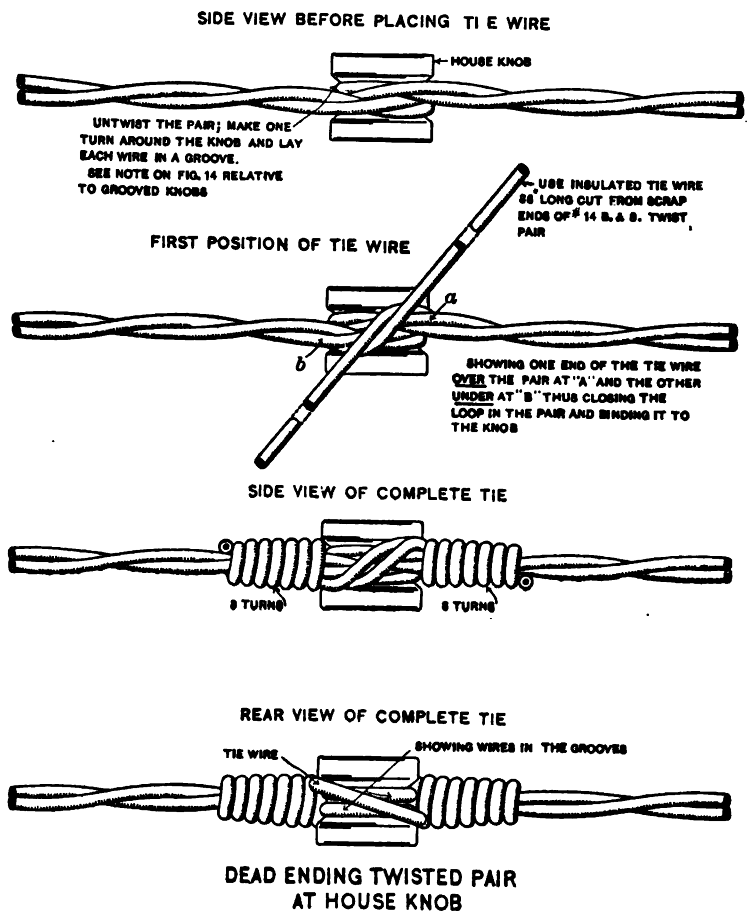


FIG. 16—Method of tying twisted-pair insulated wires to porcelain knobs

of wiring is shown in Fig. 19. If the side streets are clear of trees and it appears probable that many of the circuits will be more than 1000 feet long, the distribution should be made by means of bare wire on cross-arms, as shown in Fig. 20. Generally speaking, the bare wire on these side lines should be of copper, for at the present time with so much sulphurous smoke in the atmosphere of our cities and towns, the life of iron wire is too short to warrant serious consideration. Copper wire smaller than No. 14 N. B. S or No.

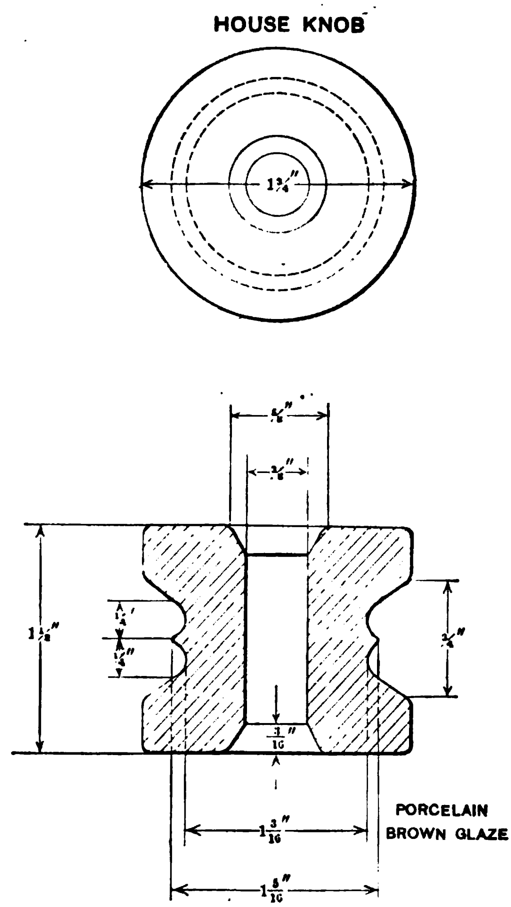


Fig. 17—Porcelain knob used for attaching twisted pair drop wires to houses

12 B. & S. gauge cannot safely be used in spans because of of its low tensile strength. This size of wire is not required for conductivity, since in the places where this wire is usually strung we would be satisfied with a cable conductor of 19 or 22 gauge. Here again it also seems possible to make considerable

saving by the use of copper-clad steel wire. A No. 14 B. & S. or No. 16 N. B. S. copper-clad wire is sufficiently strong mechanically and has a conductivity equivalent to a 19-gauge cable pair. This will reduce the first cost of line wire about one-

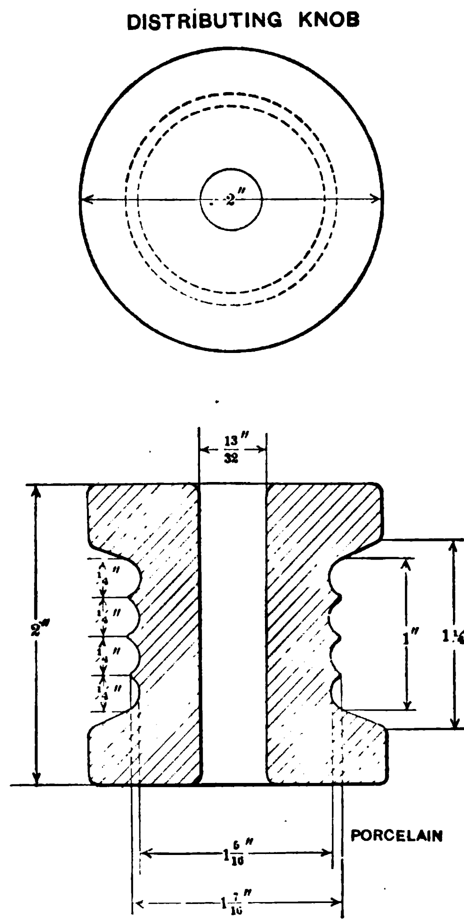


FIG. 18—Porcelain knob used for attaching twisted pair drop wires to poles

half. The copper-clad wire will be just as durable as copper, and since its strength lies on the inside rather than in the hardened outside shell, it will be subject to a lesser number of breaks, and besides it can be taken down and used in other places. It is usually necessary to scrap copper wire when taken down, for as a rule it will not stand re-stringing in another location without causing much trouble from breaking, due to nicked and scratched spots.

When the open-wire subscribers' circuits fill several cross-arms, it is generally economical to replace them with a cable. From studies which we have made, it has been found that when a cable is placed on a lead of this character, it is economy to remove the open wires and cross-arms and return them to stock rather than attempt to use them for distribution from taps placed one to two blocks apart on the cable. The removing of open wires when the cable is placed,

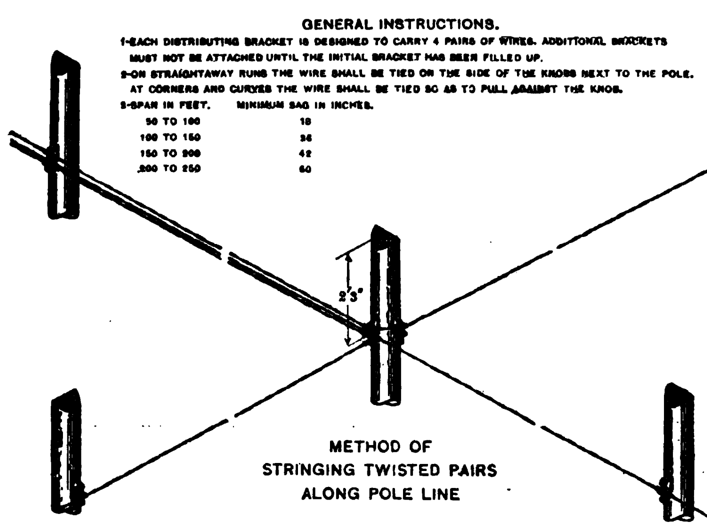


FIG. 19—Method of stringing twisted-pair wires along a pole lead

cleans up the line in good shape, makes it easy to maintain, and far more sightly to the public It would seem that the aerial cable system of distribution of telephone lines is the most ideal system now known for districts where for the present conduits are not justified. Practically all the large telephone companies have realized the economies to be obtained by its use, and during the last three years thousands of miles of this kind of cable distribution have been placed.

Since the wire plant requires the major portion of the money expended for a telephone system, and since there are so many varied and complex factors entering into its design, the greatest care should be given to its engineering. The most important problems in connection with the wire plant are:

1. The development plans which must be carefully worked out by the engineer so that not only the first cost of the plant will be a minimum, but so that the plant can take care of increases in business from time to time without unnecessarily large expenditures for redesign and reconstruction.

2. The transmission must be carefully studied so that there will be a good volume of talk between any two connected

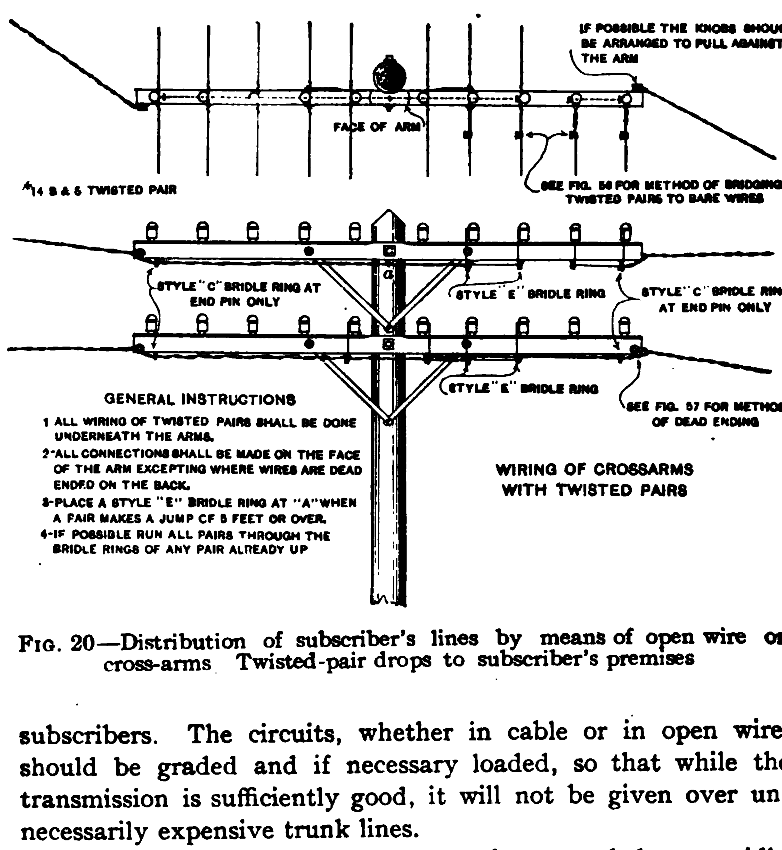


FIG. 20—Distribution of subscriber's lines by means of open wire on cross-arms Twisted-pair drops to subscriber's premises

subscribers. The circuits, whether in cable or in open wire, should be graded and if necessary loaded, so that while the transmission is sufficiently good, it will not be given over unnecessarily expensive trunk lines.

3. The underground system must be extended as rapidly as it is economical to do so, and direct terminal or interior block connections made with the maximum number of subscribers.

4. In the outlying districts where pole lines will still be

resorted to, every effort must be made so to design and construct these lines as to have them of low first cost and annual charges. They must be but slightly affected by the elements, and free from interference from electric light and power circuits. These aerial systems must be made sightly to avoid the criticisms of the public.

5. The engineer must constantly seek for new and improved types of material and construction methods to be used in the wire plant so that the first cost and maintenance can be reduced.

DISCUSSION ON "THE TELEPHONE WIRE PLANT" AT NEW YORK, APRIL 26, 1907.

John J. Carty: From the paper it is evident that the telephone wire plant consists of the conducting wires joining points distant from each other, and a large amount of auxiliary apparatus pertaining thereto. This distinguishes the telephone wire plant from that part of the plant which is composed of switchboards, telephones, transmitters, and the various classes of apparatus associated therewith.

The paper does well to call attention to the very great magnitude of the telephone wire plant as compared to the switchboard plant. The switchboard apparatus, all being assembled at the central office, can readily be viewed as a whole, and presents a commanding appearance. Very likely for this reason in the usual discussion of switchboards and switchboard apparatus those factors have been brought into undue prominence as compared with those parts of the plant which have been discussed to-night. The switchboard has too long held the center of the stage, and it is high time that attention has been directed to some of the numerous other features, aside from the switchboard, which are necessary for a complete telephone system.

The telephone wire plant of the city of New York and the suburban territory tributary to it consists in round numbers of one million miles of copper wire. Most of this copper wire is enclosed in lead-covered cables. The superficial area of the lead pipes covering a particular one of these cables amounts to 7.6 acres. The superficial area of the lead pipes covering all of the cables in this system of one million miles of wire amounts to 190 acres. All of this lead pipe is needed to protect from water and moisture the delicate paper-covered wires within, as a puncture in one of these pipes no larger than a pin-hole will admit moisture, which sooner or later causes a fault that produces an interruption of the service of one or of all the circuits within the cable. All of these 190 acres of lead pipe must therefore be maintained free from punctures even as small as that which would be produced by a pin, so that in the manufacture and laying and maintaining of this part of the telephone wire plant very important and serious problems are presented.

A few words concerning the development of this type of lead-covered cable may be of interest as bearing upon the subject under discussion. In the first telephone installations the wires, as a rule, were overhead and composed of iron, following the standard telegraph practice of the time. Soon it became necessary to extend telephone wires across rivers, and here for the first time telephone cables were used, the gutta percha or rubber-covered cables employed by the telegraph companies being imported into the telephone service for the purpose. As the number of wires increased, rubber-covered wires in cables were used to run upon poles and house-tops.

Some use was also made of overhead cables composed of cotton saturated with beeswax and protected with rubber tape and braid. As might be expected in the light of our present knowledge, these cotton and beeswax cables failed. This failure, taken together with the bad experience obtained with paraffin-covered cotton office wires, led to the conclusion that cotton was a bad insulator and for some time, where cables were employed, rubber was the material used.

Owing to the high specific inductive capacity of rubber, the transmission obtained through rubber cables was extremely defective and the cross-talk was almost intolerable.

Experiments were also made with rubber-covered wires at an early date, laid in underground ducts. These wires were unprotected by lead pipe, and besides being open to the before mentioned objections to the use of rubber cable, were especially subject to decay in many places underground.

All of these experiences led to a search for something better than rubber. Foremost among those who worked upon this problem was Mr. William R. Patterson, whose scientific investigations and remarkable practical skill brought forth a cable consisting of cotton and paraffin, in this respect resembling very much the cotton and beeswax cable which had been the cause of so much disastrous experience. It was difficult to convince anyone that cotton and wax could be a good insulator, but it was shown that perfectly dry cotton was an excellent insulator and that the former failures were due to the fact that, owing to its hygroscopic nature, cotton had absorbed moisture from the atmosphere and in the process of manufacture, and thus had its insulation destroyed. It was demonstrated that if the cotton core of the cable were throughly dried in an oven and then quickly hauled into a lead pipe and sealed up at the ends, that insulation as high as one thousand megohms or more per mile might be obtained, and that this high insulation would persist as long as moisture was kept from the core. The introduction of such a cable involved an entirely new state of the art and required that all those engaged in telephone construction should reform their ideas in the light of the new knowledge. After much agitation and discussion, and after a vigorous campaign of education, the superiority of the fibre cable, properly made and installed and maintained, was demonstrated. From that time the use of rubber cable began to decrease.

After much experience, it was found that the filling of wax might be omitted from the cable and yet the moisture could be kept out. This resulted in dry-core cotton cable, which had the advantage of much lower capacity than the filled cable and was not so much affected by heat as was the cable containing wax. The step from the use of dry cotton to the use of paper was a very important one and accomplished much in the way of economy.

The underground telephone cable of to-day is composed of copper wires covered with paper, all enclosed in a hermetically sealed lead pipe. This type of cable has persisted so long and seems to answer its purpose so well, that telephone engineers are fairly well content with it, and are no longer agitated by those serious questions which I have just discussed.

The tendency in cable construction and in telephone line construction generally has been to drive rubber insulation out of the field which it formerly dominated. Its use is now restricted to distributing wires, inside wiring, and certain special switchboard wiring. While the use of this rubber insulation has relatively decreased in the absolute amounts used, there has been a tremendous increase in the mileage employed. So important still is the use of this rubber wire that the question of its durability and cheapness is one of very great concern, and I am glad to see that in the paper just read there are some valuable data concerning the durability of rubber wire under certain conditions. Reliable data on this subject are much needed.

The open wires used in the first telephone lines were usually made of iron, and, as a rule, especially when employed in lines of any great length, they gave impaired service. The reasons for this are of course now well understood, but at the time of which I speak not much was known concerning the laws of transmission, nor of the electrical and magnetic properties of iron. There was a long period of groping in the dark. Where long-distance wires—at that time forty or fifty miles was long distance—were used, imperfect results were obtained, and in some cases it seemed that by using larger iron wires matters were made worse. During all of this period of fumbling and groping, there was one engineer with clear vision who perceived that if copper could be obtained with suitable mechanical qualities, it would be an excellent material for telephone lines. He directed his attention to this subject and produced hard-drawn copper wire in suitable form for telephone lines. I refer to Thomas B. Doolittle, who was the first one to use hard-drawn copper wire as the material for telephone lines. Hard-drawn copper wire was thus used by him at an early date at Ansonia, Conn. The results obtained were satisfactory, and, after a number of years had elapsed, a practical demonstration of the value of hard-drawn copper wire for long-distance lines was made by stringing a circuit extending from Boston to New York. The success of this circuit, using hard-drawn copper wire, demonstrated the feasibility of long-distance telephony. Here again the art of stringing wires had to be reformed. Linemen, foremen, engineers, and managers had to be taught how to handle the new material, the factories had to be instructed in its making, and even a new joint had to be perfected. The size of wire to be used had to be determined, and this was found out when the New York-Philadelphia long-distance line was established, upon which wires of various sizes were strung.

Those which were mechanically weak were eliminated and many valuable data were obtained. Since those times, hard-drawn copper wire has been found to be the only material suitable for long-distance lines. Compound wires of various sorts have been suggested from time to time, but invariably they have been found unsatisfactory for long-distance transmission. Whatever use they have must be for local lines and the precise function of this bimetallic wire in such lines is yet to be generally agreed upon.

While much has already been accomplished in the perfection of the telephone wire plant, much still remains to be done; and to make our record of future achievement as worthy as that which has already been accomplished we must constantly direct our efforts not only along broad and comprehensive lines, but we must also pay strict regard to each and every one of the thousands of small pieces of apparatus, many of which are dealt with in the paper, and all of which go to make up the sum total of the telephone wire plant.

Hammond V. Hayes: The methods of telephone plant development which Mr. Grace has described represent those which we are now employing and which have been employed by the Bell engineers for a number of years past. Practically every city and town in this country has been studied, and all new work is carried out on well-considered lines as formulated by development plans of this character.

The development plan is simply a forecast, what someone, I think Mr. Carty, has called a guess based on scientific or engineering principles as to what may be expected for the future of the telephone business in each particular locality. So difficult is this forecast of the future, and so inadequate are any rules or formulas, that it has been our custom to employ for this work, as far as has been possible, a group of young men who have gained special training by the varied experience derived from the preparation of plans of this character for cities and towns scattered throughout the country. We find that in many parts of the country the optimism of local men is such as unduly to distort their judgment as to the future size and importance of their own towns; and, occasionally, although rarely, there is such insufficient appreciation of telephone possibilities that there is a tendency to create plants of insufficient size. Even engineers that are detailed for this work have methods of estimating and checking their work which cannot be definitely formulated. In fact, it is their judgment based on wide experience which prevails. I have no doubt that in very many cases as good or better estimates for the future can be made by men of good judgment and good sense without resorting wittingly to the elaborate method such as we describe; I say this but to emphasize the fact that in this as in every other engineering problem it is good judgment based on ample and proper premises which is of importance.

Mr. Grace has talked and spoken of an "all-cable" plant. I want to emphasize that the all-cable plant as described refers simply to the distribution of lines within a city. All the planning done in every city and town in the country is to arrange the plant so that the distribution of the wires to the sub-stations may be satisfactory and that it may be possible that each sub-station in each town will be capable of talking with every other sub-station in other towns. This placing of lines in cables cannot be applied to the wires used for long-distance circuits to any great extent, for the reason that the cables tend to cut down the efficiency of service; what must be done is to keep the wire plant of the system not only the best possible for maintenance reasons, but to arrange it so that it is capable of rendering possible communication over the widest possible range of territory.

I am much interested in some of the mechanical features of the plans that Mr. Grace has shown us, and I hope that I may take the liberty of speaking of the cable-box. Mr. Grace has with great modesty said but little about it. This box is his own work; he designed it and perfected it, and I hope that it will be used very generally in the future throughout the United States.

I would like to say one word more about the question of steel and copper wire, following substantially the same thought that was in Mr. Carty's mind. Wire of this character was used some years ago in this country and has been on the market in Europe for many years. I am very glad indeed that the experiments with this wire are being carried out by Mr. Grace. I hope that he will continue the experiments, and will tell us at some later time what his success is and if such a wire offers an additional means of line distribution. I feel, however, that the wire plant is so important a feature of the telephone system that it would be well to go slowly and consider a material of this character as an experiment until such time as it has been more thoroughly tried out.

G. M. Yorke: The system described by Mr. Grace contains a minimum amount of open wire. As Mr. Hayes has said, this system is mainly used for connecting the subscribers' stations with the nearest central office. This portion of the plant has to be made compact and sightly. But a large percentage of its use is merely for communications between stations only a very few miles apart. Now, when we consider that other very important portion of the telephone plant, used for connecting central offices together many miles apart, hundreds of miles apart, we see that such an extensive use of cable is quite impossible. The reason for this is that cable circuits have always been very inefficient in transmitting speech. This inefficiency still exists in spite of the improvements in cable manufacture that have been touched upon and also in spite of other general improvements in the art. As an example of the inefficiency of cable circuits, take the type of circuit used for the longest distances in this country. These circuits are about fifty times as efficient as the form of cable circuit described by Mr. Grace, and used so largely for subscribers' lines. In other words, one of the regular lines from New York to Chicago talks as well in volume and in quality as a cable circuit only twenty miles long of the sort described by Mr. Grace. A further point is that if we connect only ten miles of such cable to this long open wire circuit, it is necessary, in order to keep the transmission efficiency at the same point of loudness and quality, practically to double the weight of copper in the long line circuit. Of course this is an extreme illustration. In view of this relative inefficiency of cable circuits, we are not going to speak right away of an all-cable long-distance plant. It is necessary to bring the open wires as near to the center of the terminal cities as is practicable and to keep all cable out of intermediate cities if we can. This becomes more and more necessary in view of the increasing amount of cable that it is necessary to use in subscribers' lines. I simply want to point out that the open wire is not to be abandoned just because it is unsightly. We are going to keep it if we are going to keep long-distance telephone service.

F. L. Gilman: As has been said several times, a material advance has been made in the art of cable manufacture, and the present paper-insulated cable has been used in its present form for a good while with satisfaction. One great effort in recent years has been in the direction of getting more wires into a given amount of space without increasing too much those electrical characteristics of the cable which are harmful to transmission, and without using sizes of wire that cannot be handled easily.

Mr. Grace has spoken of the braided rubber-covered wire used between the cable terminals and the subscribers' stations. Perhaps if I outline briefly the conditions which obtain, the problem of this rubber-covered wire will be realized more clearly. In telephone lines there is constantly a difference of potential existing between the two sides of the line and between one side of the line and ground; and throughout its entire length, in the kind of distribution of which Mr. Grace has been speaking, the line is composed of twisted wire. This is true of the rubber-covered wire as well as of the rest of line. The two wires are twisted together to keep outside disturbances from affecting the telephone transmission. Furthermore, the resistance of the part of the circuit including the rubber-covered wire has certain limitations. Then again, as can be seen from the pictures, this part of the plant runs anywhere and everywhere; it is on walls and fences; it is generally outdoors where it is exposed to sleet and rain; in the summer-time it is subjected to excessive heat, and in the winter-time to extreme cold. In other words, this wire is everywhere in the system and in nearly every telephone line in the large cities.

Now, if the wire is not in first class condition and has not first-class insulation there are a number of different troubles that exist. In the first place, there is a waste of current and the possibility of electrolysis. Then there is sensitive apparatus in the central office which will be affected. More important than these is the transmission which is also in jeopardy. If there is a leak on one wire of the pair, the line will be noisy; or if there is a leak between the two wires of a pair, reduced transmission will result because of the short-circuit. Another reason for first-class insulation is the fact that this braided rubber-covered wire is fairly expensive to start with, and the running of it is also expensive, so the life has to be long in order to make such construction economical. Furthermore, because of the moving of subscribers, this wire may have to stand taking down and putting up again.

What I want to bring out clearly is the fact that it is requisite that the wire used for this purpose shall be of first-class quality and maintain its insulation. Of course we are more or less familiar with braided rubber-covered wire, but perhaps we have not all realized just what the vital point is. The rubber compound itself will not last unless it is properly protected. The usual method of protecting the braid is a cotton braid, but that will not stand the heat and rain of summer unless it is properly protected, so the whole gist of the matter is the protection of the braid—some protection that will not run off in summer and will not crack in winter.

Kempster B. Miller: I wish that the Institute might have more telephone papers of this kind, wherein plants in different parts of the country are described not only in general terms but with a considerable amount of detail. Such description of practices in different parts of the country, and a frank discussion of them, are just as necessary and desirable in telephony as in any of the other arts, and I think perhaps more necessary, because they have been less common.

It is often interesting to watch the tendency of growth in the development of any art. From what has been said to-night, it is evident that there is a tendency to decrease gradually the use of bare wire in local telephone plants—I am speaking of the local plant as distingui hed from the long-distance plant. There are some who contend that there should be absolutely no bare wire in a local telephone plant, and several plants of considerable magnitude have been constructed in which I understand there is not a foot of bare wire. The practice that Mr. Grace has outlined stops just short of this extreme, and it seems to me that it stops in just the right place. To say that there shall be absolutely no bare wire in the plant, simply for the purpose of being able to boast that there is none, is in the nature of riding a hobby rather than of good engineering.

Another tendency that has been brought out, not only by Mr. Grace but by Mr. Carty and others, is the diminishing use of rubber-insulated wire in telephone plants. Not long ago we did put a little rubber wire into almost every cable; that is, at the outer end of the cables. The practice that Mr. Grace describes does away with this in a large measure, certainly on all the small cables. He terminates the paper cable directly in a terminal sealed with an insulating compound so that there is no rubber-covered wire in that part of the plant. This means that the only rubber-covered wire is in the drop wires and in the house wires.

Perhaps after hearing of the beauties of the paper cable as outlined by Mr. Carty, people in other arts than telephony may be so impressed that they will adopt paper cable where it may be dangerous to do so. The paper cable is used in telephony because there is no other form of cable that we know of to take its place. Whatever may be said of paper cable, it is subject to one very serious drawback—any slight puncture of the sheath is liable to put all the wires out of business. While such troubles as these are readily repaired, yet they are very apt to occur. In other systems of communication where the high frequencies of telephony are not employed, it is feasible to use rubber, or gutta-percha, insulated wires, and their reliability is infinitely greater than that of paper-covered wire. For this reason where the cable is difficult of access, as in submarine work, or where reliability is of paramount importance, as in the fire-alarm telegraph, the paper cable has little place.

A paper presented at the 218th Meeting of the American Institute of Electrical Engineers New York, April 26, 1907.

LIGHT FROM GASEOUS CONDUCTORS WITHIN GLASS TUBES—THE MOORE LIGHT

BY D. McFARLAN MOORE

Energy can be conveniently classified under six general heads: mechanical motion, sound, heat, electricity, light, chemism.

The term "light" should be used, not as the name of an effect on the eye, but to designate one of the great divisions of all energy. Each division always contains a percentage of all the other divisions, and the less this percentage the purer is the division sought after. The less heat, etc., light contains the more efficient we call it. Science should know how efficiently to change or convert any one of these divisions into any other one. For example, we do know how efficiently to change electricity into mechanical motion; namely, by the use of an electric motor, but we are ignorant concerning many of the other 29 combinations, which indicates that there remains plenty of scientific work to be done by future generations.

Since all energy is really the same thing, we should become proficient in magnifying or suppressing, at will, any particular division or divisions, corresponding with rate of vibrations which we have settled upon and named largely because they affect in a distinctive manner the different organs of our bodies.

Some years have passed since I first realized that there then existed no form of artificial light that could truthfully be said to imitate daylight. Believing unalterably that such a light was to be the next logical step of great importance in artificial illumination, I commenced an investigation that still continues.

To duplicate daylight closely, three premises were soon determined upon which have never been abandoned:

1. Large light source, the practical solution being a long glass tube emitting light.

2. Use electricity flowing through a gaseous-conductor, not a solid conductor.

3. Perfect imitation of daylight color values.

Immediately on beginning investigation on these premises, the gaseous-conductor became the factor of greatest importance. The life of the first lamps or tubes constructed was extremely short, since, as then expressed, "the vacuum deteriorated" Up to date, four methods have been developed and used and thousands of experiments have been made concerning the replenishing of the gas and thereby overcoming this vital difficulty of the gaseous-conductor becoming non-conducting, due to the peculiar chemical reaction that must occur when electricity passes from a solid conductor to a gaseous-conductor. These methods are as follows:

1. By obtaining a cycle of events through catalytic action. The intensity of light possible was found to be very low.

2. Obtaining a cycle by evaporation and condensation. Probably mercury is the only element that can ever be used in this way in glass tubes.

3. By re-supplying the necessary gases automatically by the action of heat on suitable substances.

4. By automatically feeding gas to the tube when needed, which is the method used at the present time.

Inventing intricate theories for explaining vacuum-tube phenomena was easy compared with furnishing a merchant a practical tube light to sell his goods under. For some years past there has existed a great mass of theoretical literature on gaseous conduction etc., but practically none that dealt with watts and hefners under commercial conditions. The old "pith-ball" phenomena of elementary physics is still a good working hypothesis for explaining the passage of electricity through gases, especially at less than atmospheric pressures. It is apparent that movements of the almost infinitely small "pith-balls" or ions is regulated largely by the potential and degree of vacuum. A collision of two moving bodies results in heat. The general law of all light sources applies also to the vacuum-tube light: namely, the higher the temperature the greater the efficiency. The absolute temperature of the individual particles of matter within the tube after collision is greater than that of any other temperature on earth. But the quantity of heat of each of these ultra incandescent, though infinitesimal, bodies, is so small that there results that which at first would seem paradoxical: namely, the "coldest" source of light. In this expression we crudely refer to the external temperature of the entire tube. Some gases are easily ionized and conduct well, yet give practically no light, which may indicate that their chemical constituency and therefore their emissivity is not suitable for light production.

In two previous papers which I had the honor to present to this Institute*, certain statements were made as to what would probably be the system of illumination which would finally, in great measure, supplant the systems then and now existing. The subject of improved artificial lighting methods is one of the greatest economic problems of the day. Time and space will not permit in this paper a historical review either of these investigations or of the art as a whole. The way has been long and strenuous, but always interesting. Careless criticism has been plentiful and professional support rare. The system herein described has become known as the "Moore Light" and therefore I trust you will pardon, on simply the ground of expediency and brevity, my reference also to it by that name, there being no alternative.

The present system has passed the experimental stage. It is a result of twelve years of experimenting, but its advance from year to year has always been steady. It is now fitting that an authoritative technical record be made of the essential facts at present connected with it. At the outset I venture to assert that if one thoroughly versed in the art of illumination should formulate entirely on theoretical lines complete, ideal specifications for an artificial illuminating system, that he would unconsciously describe he essential features of the lighting system described in this paper. It contains no "make and break" apparatus whatever.

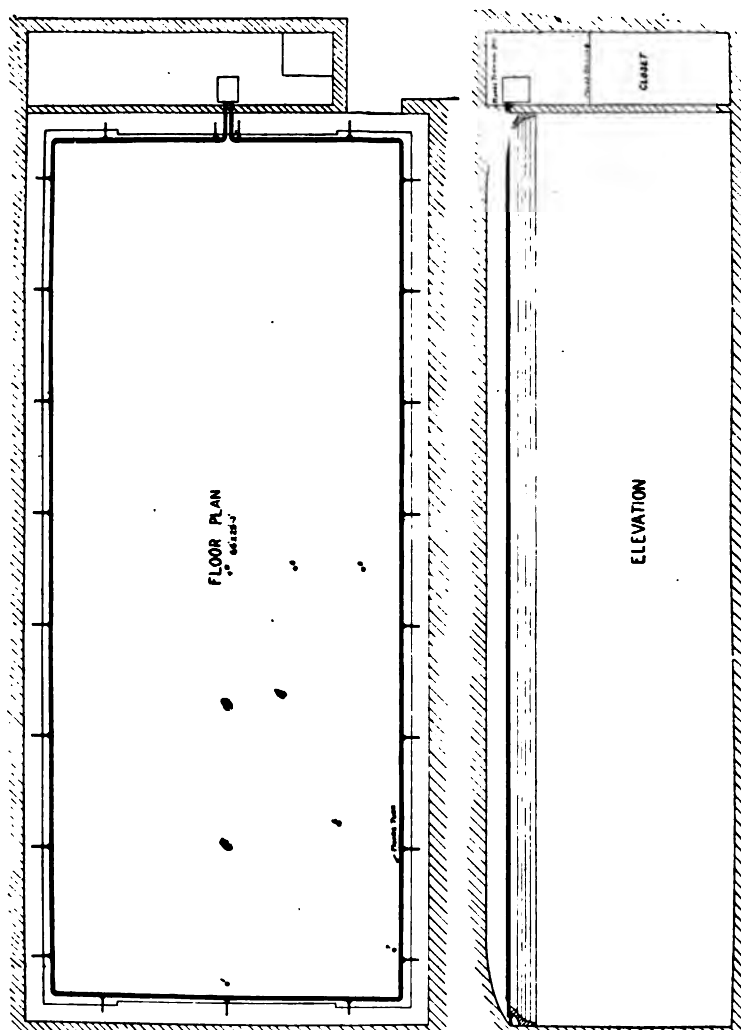
For many years all scientists have agreed that a vacuum-tube light would be right theoretically: commercial men who have had their electric lighting bills reduced now know of its practical value.

The illumination of this assembly room, Fig. 1, at the present moment by a so-called Moore vacuum tube, greatly facilitates making clear not only its mechanical construction, but also its many other

* "A New Method for the Control of Electric Energy," September 20, 1893; "Recent Developments in Vacuum Tube Lighting," April 22, 1898.

salient advantages and characteristics. The electrical energy is obtained from the alternating-current street mains.

It will be noted that the light emanates with absolute uniformity from the entire area of a single, continuous glass tube 1.75 in.



Figs. 1 and 2

in diameter in the form of a large rectangle 62 ft. by 25 ft. which is supported on the cove designed to conceal the incandescent lamps. The glass tube is 13 in. from the ceiling and 16 ft. from the floor, as shown by Fig. 2.

It is supported by plain brass rings 1⅞ in, in diameter attached to small procelain insulators inserted in the ends of brass fixture tubing which of course contains no wires.

The two ends of this continuous tube at the center of the rear side of the rectangle approach within such a short distance of each other that the gap is scarcely discernible from the floor. They then extend horizontally through the wall and into a rigid

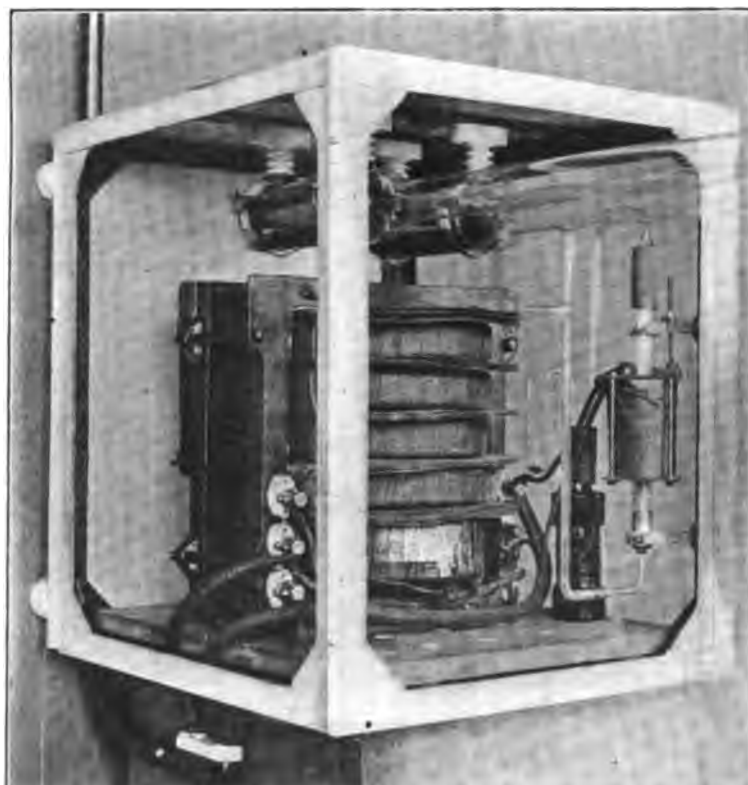


FIG. 3—Interior of terminal box

steel terminal-box located on the wall of the closet at the rear of the hall. This terminal-box contains all the necessary electrical apparatus and corresponds in form and size with that shown in Fig. 3. It is fed by 60-cycle alternating current at 220 volts. Besides the two carbon electrodes of the tube, the terminal-box contains a step-up transformer and a small specially designed valve with its solenoid, which represents an entirely new departure in vacuum tube lighting and also one that is vital to its success. The electrical circuits from this apparatus are extremely simple and are shown in Fig. 4. There is no distributed or high-potential wiring. The high-potential terminals of the transformer within the terminal-box are only two or three inches in length and are attached directly to the electrodes within the box. All the high-potential wires, therefore, always remain within the box which has a wire

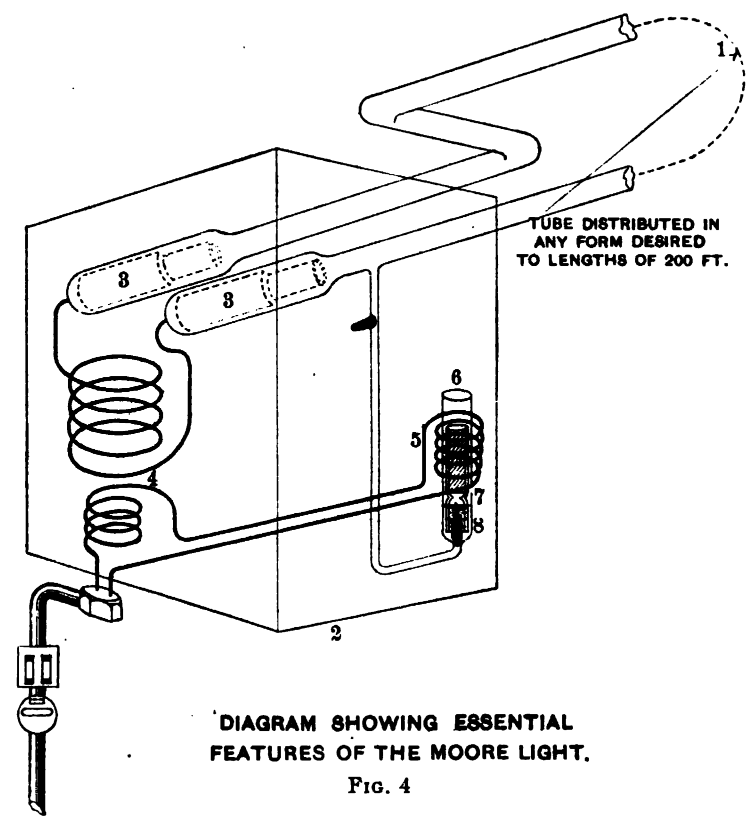


DIAGRAM SHOWING ESSENTIAL FEATURES OF THE MOORE LIGHT.

FIG. 4

seal placed upon it. A hand can be placed on each of the glass tubes near where they emerge from the two holes in the side of the box, but the glass tubes insulate the gaseous-conductor within them so well that no shock can be felt.

Since the feeder-valve operated by the solenoid just mentioned is an essential feature of this system, a description of its operation will be interesting. Any vacuum tube when commercially luminous will, in a few minutes, seriously alter the degree of its vacuum unless special provision be made to replenish its gaseous-conductor. Due to the flow of current, a portion of the residual gas within the tube is absorbed; that is, changed to a solid form, and thereby the degree of vacuum in the tube becomes higher.

This higher degree of vacuum so increases the resistance of the tube that at first the light simply becomes unsteady but rapidly changes to a condition of violent spasmodic flickering, which soon entirely ceases and the tube gives no light whatever. The light has actually died for want of air. This simple fact

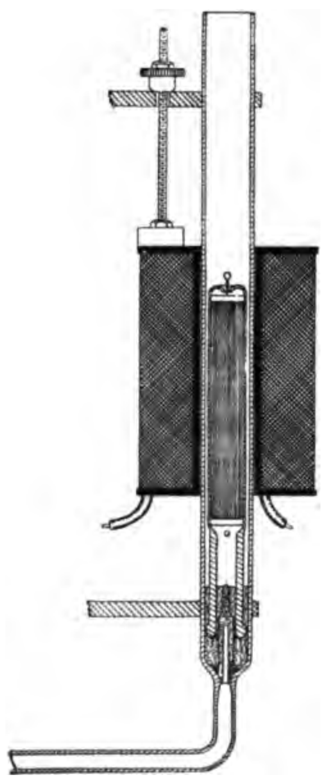


Fig. 5—Feeder-valve

was not recognized for many years by prominent investigators in this line of phenomena. The problem, therefore, was to devise thoroughly practical means for replenishing the gaseous-conductor of a vacuum tube. This is the function of the feeder-valve which permits air or other gas to enter the tube only when it is needed and in such a manner that it is entirely automatic. A piece of $\frac{7}{8}$ in. glass tubing is supported vertically, see Fig. 5, its bottom end is contracted into a $\frac{3}{8}$ in. glass tube which extends to the main lighting tube. At the point of contraction at the bottom of the $\frac{7}{8}$ in. tube there is sealed by means of cement a $\frac{1}{4}$ in. carbon plug, the porosity of which is not great enough to allow mercury to percolate through it but which will permit gases easily to pass, due to the high vacuum of the lighting tube connected to the lower end of the plug, and approximately atmospheric pressure above it. This carbon plug is normally completely covered with what would correspond to about a thimbleful of mercury which simply seals the pores of the carbon plug, and therefore has nothing whatever to do with the conducting properties of the gas in the main tube which produces the light. Partly immersed in the mercury and concentric

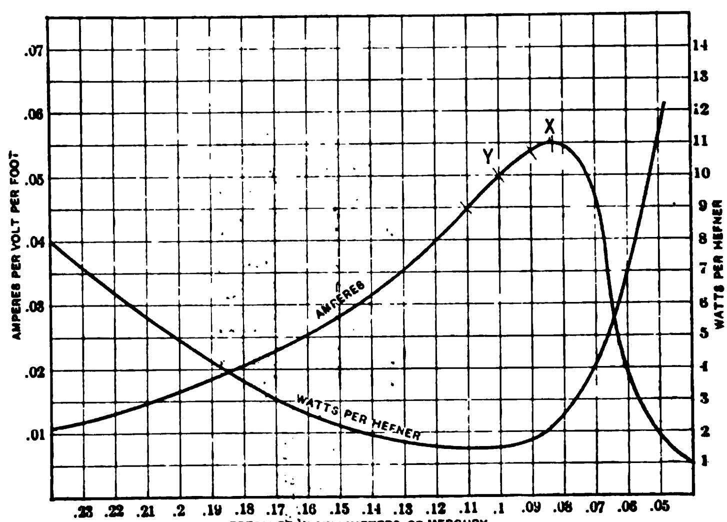


FIG. 6.

with the carbon plug, is another smaller and movable glass tube, the upper end of which is filled with soft iron wire, which acts as the core of a small solenoid connected in series with the transformer. The action of the solenoid is to lift the concentric glass tube partly out of the mercury, the surface of which falls and thereby causes the minute tip of the conical shaped carbon plug to be slightly exposed for a second or two, and an extremely small quantity of air or other gas filters through it and then finds its way into the vacuum tube proper. In normal operation, most of the tubes expose this carbon tip for about one second every minute. Therefore, this system, broadly speaking, consists in continuously burning air electrically.

Fig. 6 will explain the theory of this action still more clearly. This curve shows the relation between conductivity and degree of vacuum. Of course there must be a critical degree of vacuum at which the conductivity is a maximum; this point corresponds to X. By means of the adjusting screw at the top of the solenoid

FIG. 7—Lobby of a theatre

the degree of vacuum is kept normally at a lower vacuum corresponding with Y, therefore as the electricity uses up the gaseous-conductor, the vacuum of course becomes higher, the conductivity better, and a greater current flows through the solenoid causing it to lift the displacer and expose the carbon tip above the surface of the mercury. In viewing its action, one

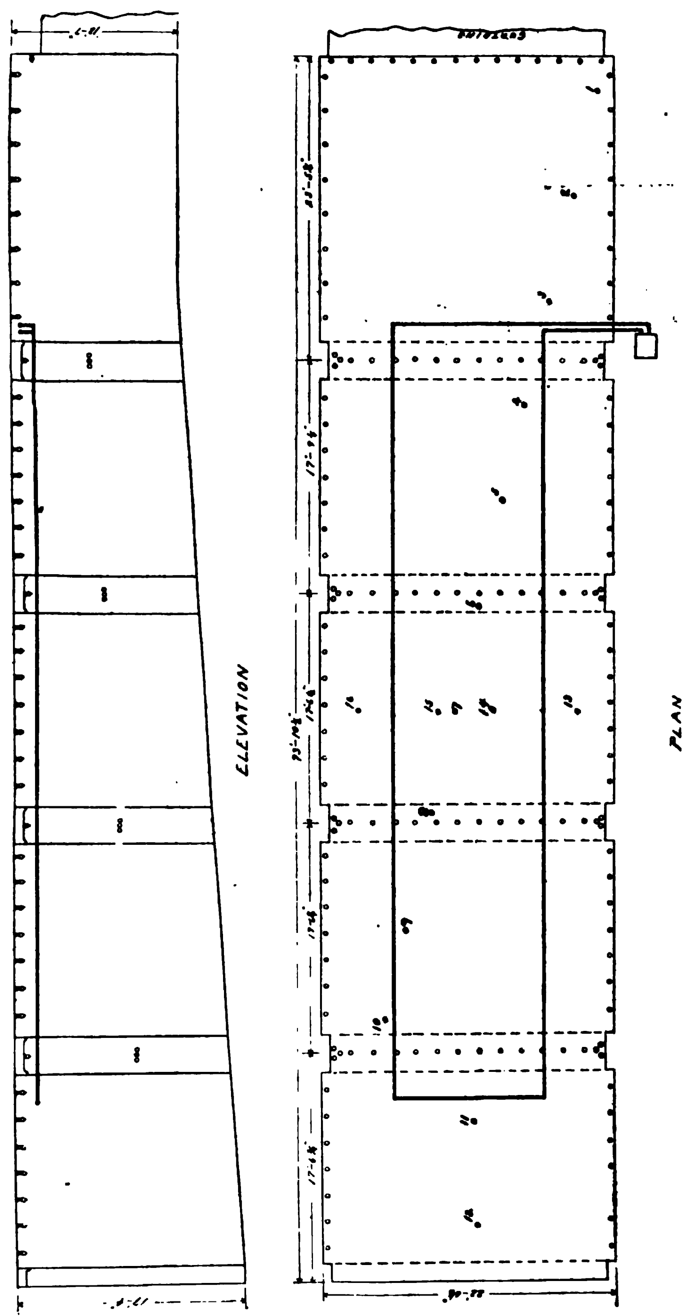


Fig 8

is vividly reminded of a mud-turtle taking a breath of air on a mill-pond. As others have expressed it, this apparatus actually breathes. Immediately upon the air being admitted the vacuum falls, its resistance increases, and the current through it decreases as does also the current from the mains; therefore, the feeder magnet weakens and the displacer falls, thereby shutting off the air or gas inlet. This cycle is repeated about once a minute throughout the life of the tube, which is indefinitely long. Of course when the tube is not in service there is no leakage of air or other gas through the mercury covering the plug.

The following comparative illumination tests were made between the Moore tube located in the lobby of a large theatre (Fig. 7) and the incandescent lamps formerly used to light the same area

ILLUMINATION MEASUREMENTS IN HEFNER FEET IN THE LOBBY OF A THEATRE

Station	Moore Tube	Incandescent System
1	0.795	1.05
2	2.33	1.05
3	6.48	1.27
4	4.38	1.25
5	3.48	1.25
6	3.81	1.34
7	3.20	1.05
8	3.30	1.34
9	2.86	1.02
10	2.73	0.88
11	2.20	0.74
12	1.19	0.52
13	3.39	1.14
14	3.47	1.14
15	2.96	1.25
16	3.30	1.31
Mean illumination (average hefner-feet of 16 stations)	3.12	1.09
Average variation from mean	27%	16%
" volts	222 a.c.	115 d.c.
Amperes	21	51.75
Watts total	3075	5470
Power-factor	66	——
Area square feet	2110	2110
Watts per square feet	1.46	2.82
Illuminating efficiency $\frac{\text{Mean hefner-foot x area}}{\text{watts}}$	2.15	0.39

Therefore the tube system has 5.1 times the illuminating efficiency of the incandescent lamp system under the same local conditions. The useful illumination has been increased 450%, yet the current consumption is reduced 45%.

Although there are many factors which it is necessary not to lose sight of in determining the true value of any form of illuminant, nevertheless the sine qua non is the matter of efficiency. Does this apparatus produce more light for a given expenditure of energy than the other forms of illuminants with which it must naturally compete, is a question of vital importance?

A new and excellent type of portable illuminometer recently developed by Mr. Marshall was used to make these illumination measurements. At all stations it was placed 32 in. from the floor, although the floor of the lobby slopes towards the entrance end.

Fig. 8 shows a plan and elevation of this lobby. The tube is not provided with a reflector of any kind and therefore the ceiling was much brighter than when the incandescent lamps were used, most of which were located directly on the ceiling. The walls and ceiling are covered with a buff-colored paint. The tube operated directly from the street mains, 220 volts, 60 cycles, single phase.

If this tube had been longer its efficiency would have been still better, and by equipping it with a simple white reflecting enamel on the exterior of its upper half it would have had the benefit of a reflecting surface like most other forms of light in normal operation. Measurements of tubes so equipped show an efficiency corresponding to less than one watt per hefner and therefore approaching the theoretical limit for a light of such a commercially good spectrum.

The entire basement floor of a department store, which is solely lighted by four tubes each about 200 feet in length, is shown in Fig. 9. This basement was formerly lighted with enclosed alternating-current, 6-ampere, 60-cycle arc lamps. The goods are generally displayed on tables and shelves on the side walls, and the plane of measurement was chosen at the average height of the tables; that is, 36 in. from the floor.

The ceiling is 10 ft., 3 in. high and coated with gray paint. "B" tube is 199 ft. long, operating directly from the 60-cycle street mains; that is, there are no auxiliary devices to be taken into account as with some other forms of light. The center of the tube is 8 ft., 9 in. above the floor and the center of the arc lamp 8 ft., 6 in. above the floor. It was noted that various articles are suspended from the ceiling in this department, and that with the tube light the ceilings and walls were well illuminated, while with the arc lamps, due to their reflecting shades, the ceilings and walls were very dark.

The following comparative illumination tests were made between tube "B" when fed with pure nitrogen and therefore giving a yellow light, and the nine arc lamps provided with 15-in. white opalescent reflector shades formerly used to illuminate the same area.

ILLUMINATION MEASUREMENTS UNDER TUBE "B," DEPARTMENT STORE

Station	Moore Tube	Arc Lamp System
Vert. 1	2.84	1.30
2	1.76	1.14
3	4.66	1.25
4	2.02	0.68
5	2.84	0.59
6	3.75	0.75
7	1.34	0.45
8	1.91	0.68
Vert. 9	1.09	0.79
10	4.30	3.30
11	2.24	2.80
12	1.71	1.06
13	2.64	1.72
14	2.16	1.31
15	3.73	1.08
16	2.14	1.33
17	2.02	0.45
18	2.24	1.02
19	2.24	1.42
20	1.82	0.73
21	2.56	0.82
22	5.05	0.79
Mean illumination (average hefner-feet of 22 stations)	2.6	1.16
Average variation from mean	31.8%	40.4%
" volts	230	122
Amperes	24	53.1
Watts total	3500	4500
Power-factor	62.5%	70
Area square feet	3753	3753
Watts per square feet	0.93	1.2
Illuminating efficiency $\frac{\text{Mean hefner-foot x area}}{\text{watts}}$	2.79	0.967

Therefore the tube system with yellow light has 2.9 times the illuminating efficiency of the enclosed arc-lamp system under the same local conditions.

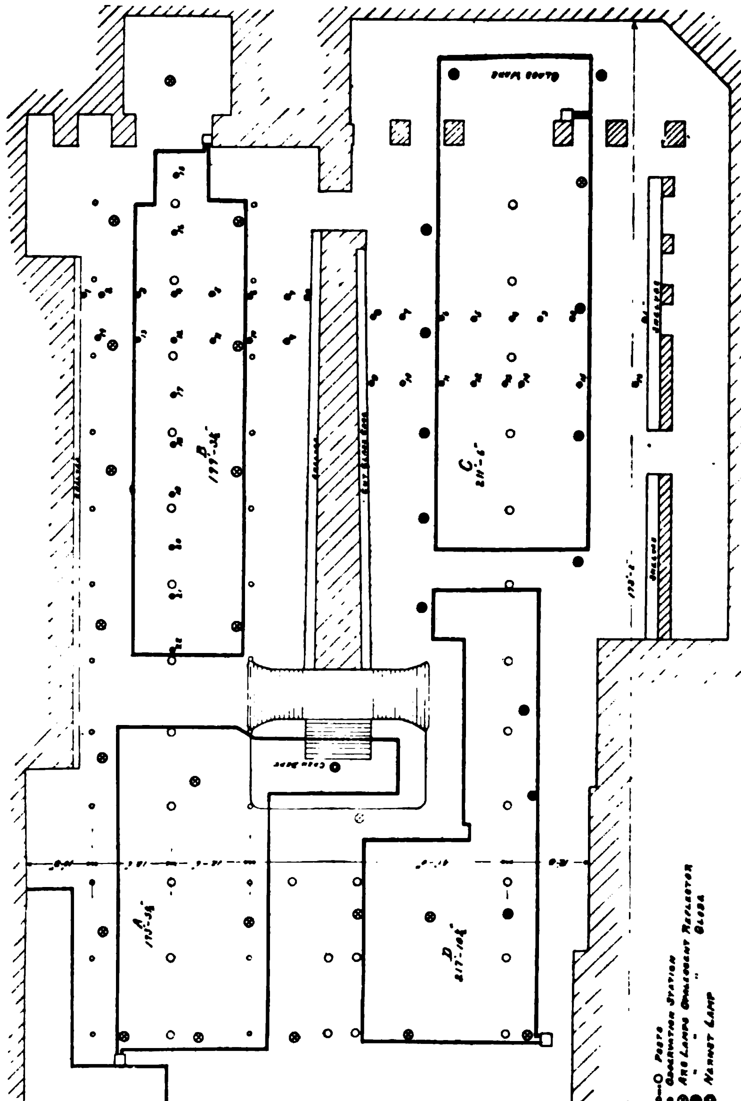


FIG. 9

The efficiency of this tube in terms of watts per hefner instead of watts per hefner-foot was determined by direct photometric measurement instead of by illuminometer measurements.

An accurately constructed photometer placed upon this tube showed it to be operating at 12 hefners per foot, which is equivalent to 2388 total hefners and an efficiency of 1.4 watts per hefner power from the street mains. This figure is obtained by simply dividing the total watts delivered to the tube from the city service mains by the total number of hefners. This bunsen photometer consists of a black wooden box 5 in. square and exactly 3 ft. between light sources. The tube passes through one end of this box transversely while at the other end is located a certified standard Reichsanstalt hefner-von altneck amyl acetate lamp. If the losses of the terminal box are deducted, the actual efficiency of this tube, simply as a light source—which is the manner in which practically all other light sources are usually rated—reaches the remarkably high figure of 1.3 watts per hefner. When a Moore tube is diffusing its

FIG. 10—Basement of department store

yellow light, one seems at least to be able to see far better than when it is producing the same hefner power of white light.

The useful illumination has been increased 220%, yet the current consumption reduced 22%; this amounts to a saving of 10c. per kilowatt-hour. At 65 hours per week this means $338.00 per year on this one tube. On the four tubes for the entire basement it means a saving of $1350.00 per year.

On account of the remarkable color qualities of the white Moore light, a request was made to change two of these yellow tubes over the china department to a white color, and the following comparative illumination tests were made between tube "C," 211 ft. long, when fed with pure carbon dioxide gas, and therefore giving a white light, and the ten 6-ampere, 60-cycle arc lamps provided with 12 in. spherical opalescent globes.

Fig. 10 is a photograph of this department taken solely by the light of the tube.

ILLUMINATION MEASUREMENTS UNDER "C," TUBE BAMBERGER BASEMENT

Station	Moore Tube	Arc Lamp System
1	0.91	0.34
2	1.71	1.73
3	0.89	0.36
4	0.75	0.40
5	1.06	0.63
6	2.18	1.51
7	1.31	0.97
8	0.47	0.45
9	0.49	0.29
10	1.11	0.51
11	1.96	0.54
12	0.88	0.57
13	0.66	0.23
14	0.63	0.32
15	1.71	1.11
16	1.25	0.43
Mean illumination (average hefner-feet of 16 stations)	1.12	0.65
Average variation from mean	37.5%	51.7%
" volts	227	122
Amperes	42	59
Watts total	5750	5000
Power-factor	61%	70%
Area square feet	4275	4275
Watts per square foot	1.34	1.17
Illuminating efficiency $\frac{\text{Mean hefner-foot x area}}{\text{watts}}$	0.83	0.55

Therefore the white tube is 1.5 times more efficient than the enclosed arcs.

The delicately colored china ware is now exhibited under exact daylight conditions, and the general illumination is a marked improvement over that furnished by the arc lamps. The fact should be emphasized that the arc lamps hung much lower than the tube and produced a bad effect. The arc proper of the arc lamps was 28% nearer the plane of measurement than the tube. With the tube there located it would also show an economy over the arc lamps of about 78%.

Although the above tests indicate that this system is now the most efficient light source known, nevertheless not only theory but experiments already made show that greater advances in efficiency are yet to be made. The best gaseous-conductors particularly adapted for selective radiation must be determined upon. For example, nitrogen has about twenty times the efficiency of hydrogen. A gaseous-conductor must also be selected that not only has proper color values but must maintain high efficiency over wide ranges of intensity; for example, mercury vapor (to say nothing of its color) is very inefficient in the long-tube system. It is only efficient at intensities which should be considered too high, and which is also the reason why the mercury tube is so sensitive to temperature changes.

Moore tubes are now used in lengths varying from 40 to 220 feet. The following curves show the watts per hefner for 40 feet to be 2.5, and for 220 feet to be 1.4, on the basis of a yellow light. Therefore when tubes are operating at 12 hefners per foot, which is the average intensity now used, tubes from:

40 to	70	feet	use	a 2-kw.	transformer.
80 "	125	"	"	a 2.75-kw.	"
130 "	180	"	"	a 3.5 "	"
190 "	220	"	"	a 4.5 "	"

In order to insure steady light, the power-factors of the circuits supplying these transformers average at present 65%. This is obtained either by using a shell-type transformer of special design with a leakage reactance of about 65%, depending on the size of the transformer required, or there can be used a standard type of core transformer, operated in series with a special type of adjustable inductance consisting of two opposing coils on the center leg of an iron core of the shell-type formation.

Feeder-valve solenoids of four sizes have been found sufficient, and are usually connected in series with the low-tension circuit of the transformer and inductance, although they are sometimes operated by the high-tension circuit.

Although the average power-factor is now about 65%, there is no theoretical reason why all these tubes should not operate at a considerably higher power-factor. In fact a very recent improvement in the valve which has entirely eliminated capillary attraction, has made it practical to adjust tubes to a power-factor as high as 84%—which is a decided improvement over some of the first tests published, and makes the tube far better than either the alternating-current motor or the arc lamp in these respects. Since all of the electrical factors of the entire system are based on the conductivity of the gas column, it is possible to vary the power-factor over a wide range simply by changing the degree of vacuum by regulating the amount of gas fed to the tube.

The following curves show the relations existing between the salient factors that have to do with the tube performances.

Curve *A* shows how the amperes of the low-tension side of the transformer at 220 volts vary with the length of the tube.

Curve *B* indicates that the actual voltage on the tube terminals for 40 feet is 3146, and for 220 feet 12,441 at 12 hefners per foot.

Curve *C*. Since the no-load transformer losses and also

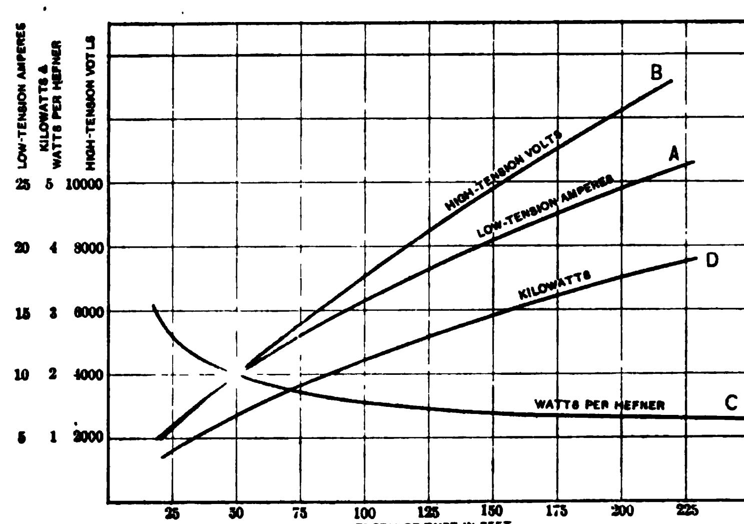


FIG. 11

electrode losses become a larger percentage of the total watts as the tubes are shorter, therefore the watts per hefner grow less: that is, the longer the tube the better the efficiency.

Curve *D*. Doubling the length of a tube does not double the kilowatts required.

Curve *E*. These tubes soon become seasoned; that is, use up all foreign gases, and then their intensity remains perfectly constant for an indefinitely long period of time.

Curve *F*. The efficiency also remains constant.

Curve *G*. The efficiency does not vary over a wide range of supply voltage.

Curve *H*. The light intensity is directly proportional to the voltage, not as the square or the cube of the voltage as is the case with incandescent lamps. This is an advantage of great practical importance.

Curve *I*. The light intensity is nearly proportional to the watts.

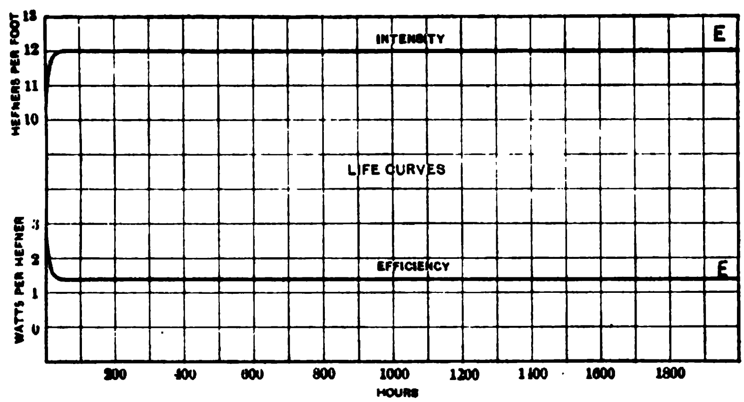


FIG. 12

Curve *J*. The light intensity is proportional to the tube amperes, and that a tube radiating 13 hefners per foot of yellow light requires three tenths of one ampere.

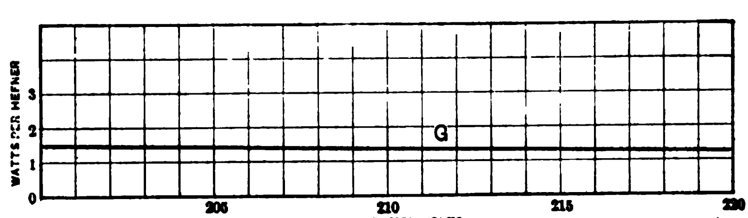


FIG. 13

The degree of vacuum required in these tubes is about 0.10 of a millimeter which, comparatively speaking, can be called a high vacuum. This vacuum is maintained within 0.01 of a millimeter or 0.00001% of an atmosphere either above or below the normal degree of vacuum. The solution of this very difficult problem of maintaining a degree of vacuum so nearly constant, was found by taking advantage of the fact that but slight changes in the vacuum cause enormous changes in the electrical resistance of the gaseous-conductor. For example, a tube 220 feet long at its lowest vacuum (0.11mm), takes 24 amperes, but at the end of every minute this has crept up to 25 amperes, when a new supply of gas causes the amperes slowly to drop again to 24. Of course it is impossible to detect this slight oscillation either in the steadiness or intensity of the light in the tube. Making use of electricity to govern the vacuum is equivalent to using a multiplier of about 400,000.

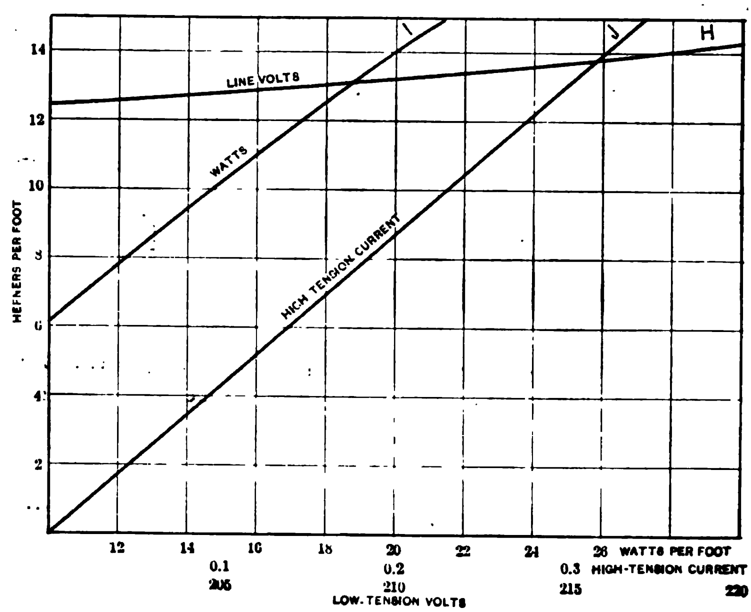


FIG. 14

These long tubes are built in place by hermetically sealing together 8 ft. 6 in. lengths of 1.75 in. glass tubing, with walls $\frac{1}{16}$ in. thick, by means of a new blast illuminating gas-fire or double-flamed torch. This work can be done rapidly and cheaply since in a 100-ft. tube about a dozen joints are needed and only about two minutes are required for each one. This has necessitated the development of a new trade: namely, "glass plumbing."

The two ends of the tube within the terminal box each contain a graphite cup electrode 8 in. long. Immediately in front of one of these electrodes a branched small-bore tube extends to the bottom of the feed valve, see Fig. 3, and the other branch is available to be connected temporarily by a rubber hose to a new small portable oil vacuum-pump. The electricity is turned into the tube shortly after the pump is started and the amount of light resulting indicates in a measure the degree of vacuum in the tube. But in investigating a field of this nature a simple, rapid, and accurate vacuum-gauge was found to be very necessary, and it has proved to be as valuable an instrument as a compass is to a mariner. It can be calibrated to measure to one ten-millionth of an atmosphere.

As soon as the vacuum of the tube is sufficiently high, the feed-coil is adjusted to feed at proper intervals the right quantity of air or other gas. When the light automatically and continuously feeds itself from the atmosphere, the supply of which is of course inexhaustible, its life can be said to be indefinitely long. When it is desired to feed the tube on nitrogen only, the air is simply made first to pass through a small iron cylinder containing enough phosphorus to last several years. Should a longer life than this without any attention be desired, several cylinders can be used in series and these can be renewed an indefinite number of times at a negligible cost. Effectually to prevent more than is necessary of the atmosphere from coming into contact with the phosphorus, or being continuously in contact with it when the tube is not in use, it has first to pass through a small mercury trap.

To feed the tube CO_2, a bottle containing a piece of marble and a little hydrochloric acid automatically generates this gas only when the tube requires feeding. Therefore this small gas generator needs only a new piece of marble at the end of several years.

Various portable or unit forms of this light have been designed. For example, the one shown in Fig. 15 resembles somewhat an arc lamp. It operates at 220 volts and requires 25% less watts yet gives 25% more useful illumination than an enclosed arc.

The automatic feeding-valve is of course applicable not only to alternating-current vacuum tubes but also to direct-current vacuum tubes. It can be made invaluable for all kinds of vacuum-tube apparatus, such as X-ray tubes, vacuum oscillographs, wireless telegraphy or telephony transmitters and receivers, vacuum or vapor rectifiers or lamps.

A careful analysis of this system of illumination in general, discloses the large number of advantageous features it possesses. It is the first artificial light that can rightly be called imitation daylight. Natural daylight is the only ideal light that can ever exist and the eye accords with it, therefore the nearer any light source approaches it the better, and vice versa The absence of the red rays in daylight, for example, would far from improve it. This system is so much nearer natural light

FIG. 15—A small unit of Moore light

imitation that it is in a class by itself. But these tubes furnish a perfect diffusion of light because the light radiates from such extremely large areas as compared with all the old style spots of light, and therefore if desired a more nearly shadowless light can be produced than any other known means.

The recently appearing types of incandescent lamps having improved efficiencies, such as the osmium, tantalum, zircon, graphitized carbon, tungsten, osmin, osram, titanium, and helion lamps are all obtained by causing solids to get overheated due to electricity passing through them. These new lamps—all based on an old principle—are only of transient interest, an interest of a vastly lower order than the interest that should attach to obtaining illumination by electricity passing through, not solids, but gases. They will not bring about a permanent radical change in the lighting situation. But such a change is now gradually being brought about by the vacuum-tube. However, by this it is not meant or claimed that all other forms of light will be abandoned. The candle business is larger to-day than ever before, and history shows that the electric lamp has interfered very little with gas. But changes must come. Each form of light has its own particular sphere of usefulness, which varies in size in accordance with its intrinsic worth and age. Some are just starting on their campaigns of usefulness, and others have reached their prime. Light resulting from gaseous conduction, it can truly be said, is right both theoretically and practically and therefore will probably survive for centuries.

It is simply claimed that this new system of electric lighting gives the up-to-date illuminating engineer one more available method for solving some of his problems and that some of its fields, as is the case with all other lights, are exclusively its own.

It should be remembered that the enclosed arc rapidly displaced the open arc, due to better diffusion and lower maintenance cost, notwithstanding a 50% loss in efficiency, but this new system in turn excels the enclosed arc in all of these factors.

The recent high efficiencies that have been obtained by other forms of illuminants have always been gained at the loss of some other salient factor; for example, such as life or color, but not so with this tube light. It is based throughout on thoroughly well known engineering principles that are properly applied. "The proof of the pudding is in the eating thereof," and the proof of every electric light is the illumination thereof. The term spherical candle power manifestly cannot apply any more logically to a long tube than can the law of inverse squares be properly applied to its light emanation. It is an indication of broadmindedness to have a complete indifference for all new forms of lights that have even a higher intrinsic brilliancy than the older forms with which we have long been familiar.

In this connection it is well to notice that many of these new forms of spot lights have enormous intrinsic brilliancies, because it is impossible to make them in lower candle powers. Besides the disadvantages of the high candle powers of these new point light sources, mechanical difficulties may make the ordinary used voltages impracticable. Few persons realize how comparatively little need there really is for small units of light, such as were contrived and used by our forefathers.

Abundant light is becoming more and more of a necessity and less of a luxury every day. There will always remain a small field for localized light sources, but so long as any new form of light is in the form of a spot; that is, so long as it is a highly concentrated light source, it is not worthy of much serious consideration so far as the great bulk of the lighting that is now needed by commerce is concerned. Large areas represent at least 80% of the lighting business. They should be illuminated by diffused light, therefore the only proper procedure is directly to generate a diffused form of light; that is, use a large and cool vacuum-tube, not a very small and a very hot filament and then try to scatter or soften its light and thereby waste about 50% of it, either by a diffusing globe or a reflector of some kind, to avoid glare. The long-tube system has the necessary natural characteristics that make such devices superfluous. Its enormously greater area is responsible for its correspondingly low intrinsic brilliancy.

Since it is possible and practicable to use these tubes graduated from an intensity of light per foot that is almost negligible up to 30 or more hefners per foot, it is impossible to state arbitrarily just what is the intrinsic brilliancy of a Moore tube. The average long tube now in use operates at 12 hefners per foot. The following table compares the tube with some other illuminants on the basis of hefners per square inch.

Moore light	at 6 hefners per foot	0.33
	at 12 hefners per foot	0.66
	at 36 hefners per foot	2.
Cooper Hewitt mercury tube		19.
Incandescent filaments		250.
Nernst glower		600.
Arc crater		10,000.

Some authorities have stated that an intensity greater tha about 5 hefners per square inch is beyond the theoretically correct limits, therefore this light is the only one that has a low enough brilliancy not to fatigue the eye. This has also been demonstrated by practice. It is remarkable that an intrinsic brilliancy as low as 0.33 per square inch is commercially thoroughly practical. Fig. 16 shows a tube that has been operating at this low intensity for over two years. It was also the first tube to be operated on alternating current from street mains. Even at this low intensity, the store is far more brilliantly and satisfactorily lighted than with the 16 c-p. incandescent lamps hanging low on flexible cords which were formerly used. So far as primary brilliancy is concerned, the tube far excels all other electric lights—all of which certainly need to be amply equipped with diffusing shades, etc.

FIG. 16—Interior of hardware store.

That great progress has been made in tube lighting is clearly proved by calling attention to the fact that the tubes in the "Moore Chapel" at the Madison Square Garden Electrical Show of 1898 operated at only ¼ of a hefner per foot while now a hundred times this intensity is easily reached.

Posterity will probably comment on the boast of one of our greatest illuminating companies, that it had to screen every light source in its model new building. Vacuum-tube illumination will obviate the necessity of a law prohibiting all kinds of glaring lights.

Illuminating engineers should not lose too much time by giving undue attention simply to the utilization of light, but should also rapidly come to a realization of the prime importance of the best methods of producing artificial light.

The Moore light is generated in such a manner that it needs no unsightly and expensive auxiliary apparatus either to distribute it by reflection, or to diffuse and soften it. It should be borne in mind that illumination from gaseous-conductors is a comparative infant in the commercial world. There is a marked difference between the illumination produced by a Moore tube and intense-point sources. This very marked contrast is shown best by suddenly throwing off the tube light and immediately throwing on incandescent lamps—especially if there are many of them and bare, and suspended by flexible cords.

After becoming accustomed to the tube light, workmen, whether machinists or employees in packing and shipping departments; very much appreciate the fact that they "can't get into their own shadows." For reading addresses or markings on loading or shipping platforms it can scarcely be surpassed.

This tube lighting accurately resembles cove or concealed lighting, yet there is no necessity for concealing the tube; should it be desired to conceal the source of light the cove itself is not needed, because all that is necessary is to place an opaque reflector on the lower side of the tube so that all of its light would be thrown toward the ceiling and illuminate the room therefore entirely by reflected light.

Incandescent lamps were originally placed behind coves because of their objectionable high intrinsic brilliancy, and the tendency is to allow the sins of the incandescent lamp to be visited upon the tube. The only reasonable excuse for placing a tube behind a cove is that the light source is concealed; but even this reason is not logical, because the intensity of the tube can be adjusted to be but little brighter than the ceiling is as a reflecting surface. Take for example the tube now lighting this hall. It is in front of the cove or cornice, not concealed in any way, yet its simplicity prevents it from being obtrusive. It harmonizes with its architectural surroundings and its height places it entirely out of the direct line of vision. Even though it be deliberately stared at, it does not dazzle the eye in the least nor distract one's attention as does the dim and streaked ceiling when the incandescent lamps are used. The most common kind of natural light is almost shadowless and always pleasing, as is also the lighting of many large areas by means of skylights, and so are artificial imitations of diffused daylight if made intense enough. A lack of uniformity in intensity does not rest the eye.

All authorities insist upon the avoidance of bright spots. This is accomplished by other systems at an enormous sacrifice in efficiency. Take for example the really beautiful lighting of many auditoriums using light diffused through glass ceilings. However, from the four standpoints of efficiency, simplicity, safety, and first cost, a little thought would convince the most skeptical of the enormous advantages, both in theoretical conception and practical application, of simple exposed glass tubes which would accomplish the result sought after equally well, yet at an enormous saving in operating expense.

It is the blinding brilliancy of the mercury tube that makes even a direct glance at it so very harmful to the eye. It is true the mercury tube is a light-source of larger area than all point sources, but a careful analysis will clearly show that in this respect it is but a short step in the right direction, and that its area for a given quantity of illumination will have to be multiplied a score or more times, as it is in the Moore light, in order to obtain an intrinsic brilliancy low enough to meet conditions both theoretically and practically correct.

A study of the history of the development of all light sources shows the vacuum-tube to be a logical conclusion of the progress of evolution. All portions of a long Moore tube are uniformly luminous. It has a governable intensity from zero to dazzling brightness; therefore any theoretical specifications can be met in practice by resorting, for improved methods of illumination, to the gaseous-conductor, not to a solid one. Carefully tracing the evolution of all forms of light from remote ages down to the present time as regards the following seven most important factors: diffusiveness, color, steadiness, absence of heat, efficiency, safety and first cost, all—clearly prove this long tube system to be a natural sequence and that the times are now ripe for it.

Widely spaced 50- and 100-c.p. lamps were commonly used twenty years ago, but custom and necessity gradually changed them to 8- and 4-c.p. lamps. Next they were placed close together in rows and then laid horizontally (as they are behind the coves of this room) clearly pointing to their natural successor in the direct line of progress; namely, the tube.

The arc lamp has changed from, first, the unsteady short open arc, to the much longer enclosed arc which multiplied the area of the light source many hundred times, to the enormous " diffusers " now used to improve as much as possible what I believe to be the fundamentally wrong principles of arc lamps and incandescent lamp clusters. The flaming arcs go one step further both in lengthening the arc proper and increasing the apparent light source to the entire area of a large globe. The Moore tube virtually consists of an " arc " drawn out to a length of several hundred feet.

Steadiness is a factor of vital importance to any form of light, and in this respect the long tube is excelled by none. Of course it does not flicker like an arc lamp and is much less affected by voltage variations than all forms of heated solid conductor lamps.

Stroboscopic tests of the light of the tube reveal an image better than that obtained from enclosed arc lamps, notwithstanding the fact that the heat-constant of the tube as the current wave passes through zero is less than that of any other form of light. Therefore when the supply switch is opened the tube light " goes out " quicker than all other lights, a fact which should be valuable for signalling but which also in a measure explains the high efficiency of the tube. Tubes of this nature will operate successfully on all frequencies, but at frequencies as low as 25 cycles the images will probably become too pronounced unless two- or three-phase currents are available, in which case by the use of multiple tubes the images of moving objects are entirely removed. The highest frequency in use at present for operating these tubes is 480 cycles, and is furnished by a motor-generator on 220 volts direct current. Careful tests on various frequencies up to about 10,000 cycles have shown that the number of alternations of the current used to excite these long tubes has nothing to do with their efficiency.

The only commercial and proper method of comparing all sources of light is on the basis of their ability to produce useful illumination, and not by any other basis. I have advocated for some years past the comparing of all lights by measurements of illumination and not by candle powers, and now see indications of this procedure becoming standard. The term hefner-foot will soon replace the unsatisfactory candle power, and contracts for lighting any area will be based on specifications calling for a definite intensity in hefner-feet on each square foot or square yard of the area to be lighted. This is far more practical than agreeing to furnish a lamp which is supposed to require no more than a certain number of watts per candle power, at the beginning of its life. All light users want to deal with terms that have to do with useful light, and this is one reason why the term " watts per candle power " has always been so extremely unsatisfactory. There should be used a single commercial quantity or figure that would correctly express the " illuminating efficiency " of each and any system of lighting used to illuminate a given area. If the area, and, therefore, all of its accompanying reflecting surfaces be changed, the relative values of this figure for each system is also liable to change, because some systems (for example arc lamps) are more benefitted, comparatively speaking, than are others by certain reflecting surfaces and other local conditions. Such a figure or value is readily obtained by dividing the average of the hefner feet measured at a suitable number of stations by the watts per square foot. This method will finally be widely adopted not only by illuminating engineers but also by the intelligent public—now that simple and perfectly self-contained illuminometers are available. The term hefner-foot is preferred because the hefner is the only practical primary standard. There is no longer any excuse for using the term candle power, and it should rapidly be dropped. The foot is still the commercial unit of length in this country.

If incandescent lamps were generally used as individual light sources, then watts per candle power would be the salient term, but since the vast majority of incandescent lamps are not used individually but simply as inconspicuous parts of a system of illumination, then the average hefner-foot becomes the factor of prime importance: that is, the illuminating efficiency, not the efficiency of an illuminant. We should be a little concerned about the specific efficiency of the lamps behind the cove in this hall, but very much interested in the ability (that is the efficiency, of the incandescent system as a whole to produce the result sought after: that is, to illuminate uniformly and without glare every square foot of this floor with a minimum expenditure of energy. Watts per hefner-foot is the important factor, not watts per hefner.

I believe that the proper way to compare all forms of illuminants would be approximately on the following basis:

1. The area to be lighted should be about 40 by 80 feet, and of approximately the shape indicated by these dimensions.

2. The illuminants must not extend below a horizontal plane 10 ft. above the floor.

3. The award is to be made entirely upon the results of illuminometer tests in a plane 30 in. above the floor and the stations of which are to be located as follows: ten equal spaces on the center line of the longer dimension, ten equal spaces on the center line of the shorter dimension, and ten equal spaces on the diagonal. The average of these thirty readings is to be divided by the total number of kilowatts used from the street mains by each form of illuminant, and the highest quotient (light units per energy unit) will determine the placing of the award.

It is not surprising that the tube should surpass the incandescent lamp both in efficiency and diffusion in the lighting of an area of this size, because the incandescent lamp is wrong theoretically—too far away from natural light—it is too small, too red, too hot. The highest temperature at which glower lamps operate would make them do better, about half as well as the tubes. So with all the incandescent types of lamps, to say nothing of the bother and expense of replacing them, either in whole or in part. Arc lamps would be out of the race, because of inefficiency, glare, flickering, wide variations in candle power between feedings, poorly distributed light, noise, dirt, etc., besides the maintenance expense of recarboning and cleaning. Compare the simplicity of the method of obtaining diffused light by means of the tube with the really commendable attempt to obtain a comparable diffusion by equipping arc lamps with concentric diffusers that are as enormous as they are crude so far as the means to the end is concerned. Especially is this the case where light balancing selector diffuser ceilings are installed. They very pointedly indicate the need of a tube light.

During the first year of its use—1903—the gaseous-conductor of the Moore tube was produced by chemical means, which has been comparatively recently superseded by the automagnetic valve. Therefore the lapse of time since the first automatically fed tubes were installed being so short, it is not now possible to state definitely what their final life will be, beyond the general statement that some of these tubes have already been in operation over 4000 hours without change, and that there are good reasons for believing that they should continue to run at least again as long, which is a much longer life than any other form of illuminant yet invented. This whole system is one with an exceptionally large number of variables, and this also applies to its life, because it depends partly on the intensity at which the tube is operated and the particular gas used. Since air or other gas is regularly admitted to the tube and changed to some solid form, due to certain electrochemical reactions, it is certain that the time of operation without any attention whatever cannot be prolonged indefinitely. Before adopting the chemical method of obtaining a nitrogen supply for the long tubes, it was stored under about three pounds pressure in a small tin cylinder placed in the terminal box, which supplied an average tube before needing to be recharged for considerably over a year. Therefore the quantity of gas (nitrogen for example) necessary to support a light of 12 hefners per foot is so small that a tube of average length should remain in perfect condition for a number of years before it would be expedient to remove the small quantity of dark-colored powder which may have accumulated only within or near the graphite electrodes.

When a tube has been properly exhausted, the discoloration in front of the electrodes should not at any time extend more than two or three inches. When a tube is striated, it indicates that other gases are present that are foreign to the one decided upon to be used.

The light source of all other lights needs to be renewed, but in this case the light-giving tube itself will last an indefinitely long time, since it is neither consumed nor becomes blackened in the least. Should any renewal be required it is at the electrode which can be replaced comparatively cheaply.

The cost of a long-tube installation, due to its being construction work, varies with its location, its length, its shape, the intensity of the light required, the kind and number of fixtures desired, and other local conditions; but is already less than the cost of a first-class incandescent lighting system with its necessary wiring, fixtures, and shades. Eventually it will be far cheaper. It should be borne in mind that the first cost of this tube corresponds with the entire cost of an incandescent lighting system—its iron piping, wires, cut-outs, fixtures, shades, and lamps—and also that the first cost should be considered only in connection with the fact that in many instances this tube will pay for itself several times over during its first year of use from the amount saved on what the current bills would have been if incandescent lamps had been used to produce the same amount of useful light.

This system is extremely simple. Only two parts are essential: the light-giving tube and the terminal box. We are so thoroughly familiar with the ordinary incandescent lighting system that it is hard for us to realize that it has become really very complicated with its hundreds of different devices. Its most enthusiastic supporters a few years ago would have declared the present conduit system as entirely prohibitive, especially when concealed. But now almost all of it can be eliminated by simply installing a light-giving tube, even after the decorations have been completed, as was done in the last few days in this room.

Architects have long considered electric wiring problems one of their most vexatious burdens. Now a terminal-box can be used as a center of distribution from which there radiates a number of long tubes to illuminate portions of the same floor, or extend to floors above or below. A tube provided with a reflecting enamel on one side is a far simpler device for lighting show windows than the extremely cumbersome combinations of rows of incandescent lamps with mirrored reflectors in sheet metal troughs, etc. This tube system has no complicated mechanism like arc lamps, for example, but instead the only moving part is the displacer of the feeder valve which in its design is about as near being frictionless as is conceivable. Normally, its movement is less than 1/32 of an inch, and some of these valves have required no attention and yet have been in active use over 4000 hours. They should continue to operate an indefinitely long time.

As a scientific instrument this automatic valve is another combination of ruggedness with marvelous sensitiveness, in which respects it resembles a telephone receiver. The very nature of this system is such that the liability of a normal tube being broken is very slight; yet in case of accident a new piece of tubing can be quickly and cheaply inserted. The ideal and rapidly approaching final position of such a tube is against or almost against the ceiling, the illumination then most closely resembles light coming from the sky. But many users, notwithstanding the high efficiency of the tube light, desire to reduce their bills still further by using a less number of hefners per foot, and support the tube on long fixtures. When a tube is cracked or broken the inrush of air of course instantly extinguishes the light, but the electrical apparatus is in no way disturbed.

This is a hardy piece of apparatus, not a delicate mechanism like the incandescent lamp. Glass tubing properly supported is far stronger and more flexible than most people realize. The voltage on a tube's terminals can either be raised or lowered without harming in the least either its life or its efficiency. The conductivity and light of these tubes are practically unaffected by temperature changes, especially those emitting yellow light. Another installation which depicts a quality of this light peculiarly and exclusively its own is fifty feet of tubing skirting the bottom of a large aquarium. The fishes are not disturbed in any way by its presence; that is, neither by shocks nor by heat. Scientific glass experts predicted great trouble from expansion and contraction but neither the direct summer sun or long icicles has had any apparent effect. This is the only form of light from which icicles can hang, which indicates its approach to light without heat. Neither moisture nor fumes affects these tubes. There is no multiplicity of sockets and wires to become damaged or short circuited; and the tube can be most easily cleaned.

The light-giving tube itself is harmless either to life or property. The terminal box is made of steel with a slate bottom so that even though the small transformer within it should completely break down, smoke only would result. It is impossible for the exterior of the terminal box to get hot enough to set fire to anything. It is carefully designed so far as ventilation is concerned, and is always mounted so that there is an air-space all around it. With this loop tube system, aside form the ordinary short feed circuit, there is no part of it to be classified as a " risk " since all of the purely electrical apparatus is securely contained in a fire-proof terminal-box.

Fig. 17 shows the terminal-box, but it also shows, inadvertently, though most strikingly, the contrast between the simplicity of the tube and the complexity of the network of wiring on the ceiling which it has supplanted.

Owing to the high efficiency of the tube and the large area from which any heat accompanying the light can radiate, the temperature of the tube is remarkably low, being in the neighborhood of 100° fahr., therefore it cannot injure either perishable goods or the health of those working under it. In basements for instance in summer time, the fact that only about one sixth as much heat is dissipated as would be if incandescent lamps were used is a matter of prime importance to the problems of ventilation, etc. Large areas like department stores for example, can now be electrically lighted without an inch of wire within their walls, by placing the technical boxes of these tubes on the exterior of the building. It is wireless lighting. It was of much scientific interest to note that tubes at the same degree of vacuum with the same amperage flowing produced a widely varying quantity of light as the kind of gaseous-conductor was varied and that the temperature of the tube was higher with the gases producing the most light.

This system, from a number of standpoints possesses great flexibility. This is illustrated, so far as the distribution of the

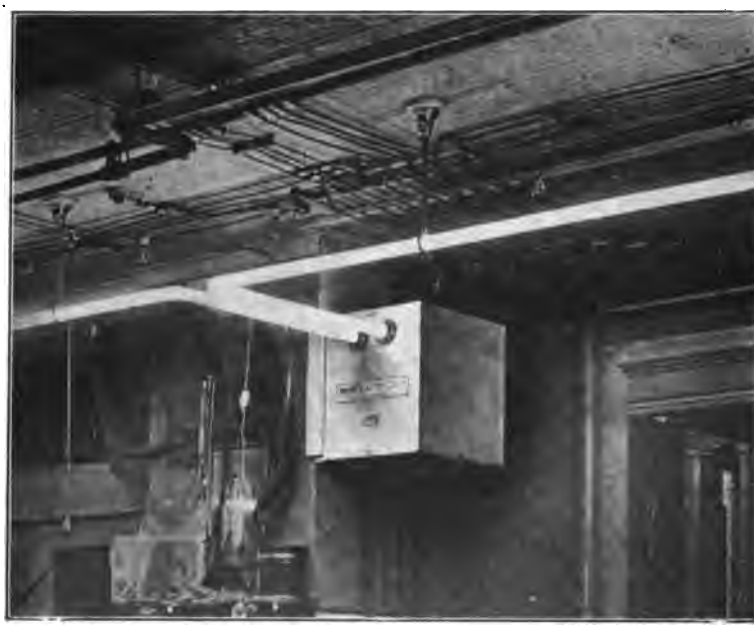


FIG. 17--Exterior of terminal-box.

tube is concerned, by Fig. 18, which shows the layout of tubes on the mezzanine floor of a public building office. These remarkably varied shapes and lengths are due to the necessity of light being located to suit each particular desk, table, set of files, etc. Since tubes can be made of any diameter and form, the artistic possibilities of electric lighting are multiplied many fold.

Flexibility is again demonstrated by the facts that the intensity and also the color of these tubes can be varied over wide ranges. The higher refinement of the art of illumination is bringing into view more and more prominently the color of all light sources. Not their individual colors, however, but the color values they give to surrounding objects, is fast becoming, next to efficiency, the most important fact in connection with any light. This light is the first and only illuminant the color

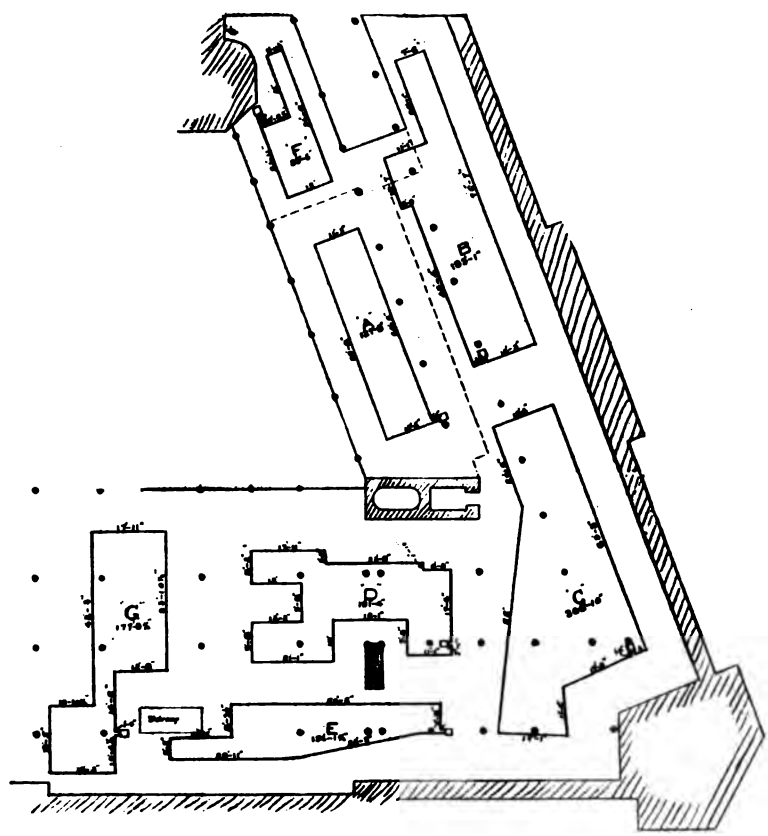


FIG. 18—An installation showing various shapes of Moore tubes.

of which can be changed at will over a wide range. This is accomplished by changing the character of the gas within the tube. If a tube is permitted to feed itself on plain air, an efficient pink light results, but if the air is first caused to pass through a cylinder of phosphorus to absorb its oxygen a golden-yellow light is produced that is the most efficient light source known. When operated at higher intensities than 12 hefners per foot, and viewed in line with incandescent lamps, it is apparent that the colors are about the same as well as the color values of all objects viewed under it.

Although our firm purpose should always be to imitate daylight, nevertheless its color values are not constant quantities at different hours of the day. Fortunately, the spectrum and color values resulting from the use of carbon dioxide gas as a gaseous-conductor in a clear glass tube should be decided upon by scientific societies as accurately representing average diffused daylight, not direct sunlight. It will finally be recognized as the only standard of light. Specifications can be drawn and adopted which will enable the accurate reproduction of such a standard at will. Already all of our present so-called primary standards are acknowledged as being too red, but such a vacuum tube as a standard will have a color value which will remain perfectly satisfactory so long as daylight lasts. Further than this these specifications can be made to determine with great accuracy a definite intensity. We thus have a primary standard as regards both color and intensity.

When these tubes are supplied with CO_2 they appear pure white. Most inexperienced persons, especially when contrasting the tube light with reddish lights, criticize the color as being too blue without realizing that daylight is a decidedly bluish-white. The laws of nature make the operating expenses of the pure white light tube almost double that of the yellow-light tubes, because the eye is effected to a maximum degree by yellow rays, But the white tubes which simply contain CO_2 have been used for over a year by stores in their ribbon departments for matching colors, day and night, because its spectrum remains absolutely constant. There are many other industries where color values are of vital importance. Also, since the color factor is now under perfect control, those light rays can be scientifically selected which are essential for the forcing of all kinds of plant life, flowers, fruits, and vegetables. The color of the light can be varied by feeding the tube any gas as each has its own spectrum, or by using multiple valves, etc., mix various gases within the lighting tube itself. White tubes are daily being put to most vigorous tests at the works of one of the largest silk dyeing establishments in this country, but no difference can be detected in the most delicate shades when matched either under the tube or in average natural daylight. For some time past artists have been mixing their colors at night under the white tubes. Portrait photographs are also being made under it that equal those of natural light. Since the yellow tube light is about the same as that of the incandescent lamp it is being used successfully by clothing merchants and florists. Also on account of its uniformity of intensity it has proved its superiority for photographic printing.

It is interesting to note how different the same tubes lighting an ordinary store window appear in the afternoon when the sun is shining and after seven o'clock at night. The tubes that are yellowish white at night time appear orange colored during the day, and the tubes that are a pure and dense white at night appear a pale blue during that day—in fact if exposed to brilliant daylight no light can be seen in them at all.

Users can obtain the exact quantity of illumination desired on a given area more easily than with any other system, because without changing the tube its intensity can be varied without loss in efficiency.

This light could be used in subways and tunnels, in which cases the terminal-boxes would be eliminated and miles of tubing in 100-ft. lengths placed end to end and operated in parallel directly from the adjacent high-potential mains. The eyes of the motorman would then be subject only to a light of definite intensity and color.

Art galleries, surgical operating tables, exterior illumination of ferryboats, street lighting, shop show-windows, advertising signs—all these and many other industrial and artistic enterprises will be vastly benefited by the application of this tube light.

It is believed and hoped that the ideas advanced in this paper are simply in the direction of progress. Aside from all theory, the facts show that electric illumination resulting from incandescent gases or vapors has vastly less limitations because their molecules or atoms are free to vibrate while those of solids are not, and therefore at the high temperatures necessary are subject to rupture. "The signs of the times" clearly indicate that we have reached the beginning of the end of lighting by solid conductors and the end of the beginning of lighting by gaseous-conductors.

Discussion on "Light from Gaseous Conductors Within Glass Tubes—The Moore Light," at New York April 26, 1907

Gano Dunn: While we are waiting for the remainder of the tests which are to be made upon the tube and the lamps strung around the room, we may as well proceed with the discussion. I feel that we have been listening to the exposition of a new art. My mind goes back to 1893, 1896, and also to 1898, the time of the "Moore Chapel," when the Institute heard from Mr. Moore before. In those days what he had to show compares with what he shows us this evening as Stevenson's original "Rocket" compares with the modern Atlantic type of locomotive. Two years ago on entering the Madison Square Garden, I was greatly impressed with the appearance of a Moore tube in the lobby, and admitted then that I made a mistake in considering the Moore system not a success. I had had the impression that it was good only for illuminated signs and relatively unimportant work. The Madison Square Garden tube was a revelation.

We should be careful not to estimate the value of the Moore system solely by its efficiency. There are radical differences in the character of its distribution, its color, and its method of operation, from any one of which important advantages may spring. For instance, on account of its longitudinal source, the intensity of the Moore light does not vary inversely with the square of the distance, and from this follows freedom from shadows and a certain similarity to daylight.

The effectiveness of a luminous source should not be measured by how much light it emits, but rather by how much light it delivers where the light is wanted. A lamp of high intrinsic brilliancy, that is, of concentrated source, over-illuminates surfaces near it, while it under-illuminates surfaces somewhat removed from it. To the under-illuminated surface full credit is not given for such illumination as exists, because the eye usually rests upon this surface after having rested upon a brighter surface or possibly upon the lamp itself. There has to be an excess of light on surfaces near the lamp in order to bring surfaces away from the lamp up to the desired minimum of illumination. The excess illumination being unnecessary, is wasted. Worse than this, having fatigued the eye, it renders less evident the illumination that does actually exist upon the under-illuminated surface. The largely distributed source (a tube many feet in length) is what I had in mind when referring to lighting by Moore tubes as a new art. Other sources of light are not larger in volume than a nutshell.

We must be ready to see disadvantages in Moore's system as well as advantages, and I hope both will be clearly brought out in the discussion.

C. P. Steinmetz: The second part of this paper is extremely interesting, and I believe is a valuable addition to the literature of producing light by what may be called an improved Geissler tube. It is the old Geissler tube in the form of a commercial illuminant. If we look back on the history of Mr. Moore's work, we find that originally he produced a varying-in-pressure-contact, some kind of a flimsy device in a vacuum, and then proceeded to operate Geissler tubes at extremely high frequency, using motor-generator sets. Here at last we find the light at commercial frequencies, and in a commercial installation, taking its place as one of the commercial illuminants.

The paper gives the first actual engineering data of this kind of light, the energy, volts, and amperes and some data on efficiency, etc. The author gives comparative data on the illumination produced by the Moore tube and the incandescent lamp. Later on, comparisons are made between the arc lamp and other systems. I am not impressed with the comparative values given, except that they show that incandescent lamps and arc lamps can be installed in such a manner as to get very little light from very much power. That fact was known long ago, without having special tests made. If the installation of the incandescent lamp is left to the artistic sense of an architect, or to mere accident, such a condition will obtain, but the comparison is not fair. If an unsatisfactory incandescent light system, unsatisfactory by reason of poor installation, poor type of reflector, etc., is replaced by an intelligently installed system, the advantages of the latter will be apparent. I have no doubt that if Mr. Moore's hopes are fulfilled, and in future all the plumbing establishments in cities and villages and country towns have a department of glass plumbing, and if a future illuminating engineer goes around in the country towns or villages, he can use the old 3.1 watt incandescent lamp and replace very many Moore tubes installed by the local plumber and show a vast improvement in efficiency by intelligently installing with proper reflectors, the old incandescent lamp. That does not mean anything: it only means that if the old installation of incandescent lamps was made by an illuminating engineer, he should have his license withdrawn, if such a thing existed.

Some illuminating efficiency measurements are expressed in terms of in hefner-feet. I regret the use of the word hefner here. In the United States illumination is measured in British candles, not in hefner candles. The hefner candle is 0.88 times the British candle, so that the values given in the paper have to be multiplied by 0.88 to bring them to the American standard of illumination. Mr. Moore finds an illuminating efficiency, mean hefner-foot per watt, of 2.15. One British candle as a source of light of one mean spherical candle-power gives an illumination of one candle-foot at one foot distance. One mean spherical candle-power then gives 4π candle-feet, or

12.56 candle-feet, dividing this by 0.88 to reduce it to hefner-feet, gives 14.28 hefner-feet per mean spherical candle-power. Mr. Moore gets 2.15 mean hefner-feet per watt; reduced to mean spherical candle-power, this means that his light consumes in the useful illumination 6.64 watts per mean spherical candle-power, if one counts only the light which reaches the illuminated plane. It means, then, that a very considerable part of the light is thrown away, absorbed by the walls, ceilings, etc. I do not believe it is an unfair estimate, for such a class of light, to say that 50% of the light is wasted. That is estimating that half the flux or light radiated by the tube reaches the plane of test. That would give an efficiency of 3.72 watts per candle.

It is instructive to apply this to the last column headed " Incandescent system," and that will bear out what I stated, as to what should be done to the illuminating engineer who installed these incandescent lamps, which show but 0.39 hefner-feet per watt.

Assuming 4 watts per mean spherical candle-power, which is a reasonable value, one should get, for all the useful light in the illuminated plane, 3.57 hefner-feet per watt, or eight times as much as is given here. It follows that if these were four-watt incandescent lamps they would lose seven-eights of the light before the light reached the illuminated plane. This explains the enormous difference in illumination by these two sources.

The values given in comparing the Moore tube with the arc lamp system, allowing for the Moore light half of the light wasted before it reaches the illuminated plane, indicate an efficiency of 2.56 watts per mean spherical candle-power, and 14.8 watts per mean spherical candle-power of the flux of light sent by the arc lamps on to the illuminated plane, a ridiculous value. It seems probable that the arc lamps were hung without reflectors or diffusers anywhere on the ceiling.

In the photometric tests the most efficient tube gives 1.4 watts per hefner-foot. That means at right angles to the tube. The light in the equator of a linear source is $\frac{2}{\pi}$ the average or mean spherical. Dividing by 0.88, to reduce to our standard of light, the British candle, gives 2.5 watts per mean spherical candle-power or per lumen, that is, per unit flux of light. The test of the illumination measurements gave 2.56, and probably this is about the efficiency of light production of the Moore tube.

Leaving out all illuminating questions, and merely considering the matter of the flux of light per watt, the next point to consider, then, would be the distribution of the light. But the first and important question always is how much light is got from the source of light? The best efficiency of the Moore tube seems to be about 2.5 watts per unit flux of light, that is, per lumen. This gives about the same efficiency of the tantalum lamp, or not very far from the enclosed arc; it is better than the carbon filament incandescent lamp, but inferior to the tungsten lamp.

The carbon dioxide tube is recognized as less efficient, and I do not need to refer to it. I desire here; however, to draw attention to the fact that the efficiency of the Moore tube has arrived at that stage where it is now in the range of commercially practical efficiencies as an illuminant. It is not any more an inefficient illuminant, although it naturally is not of the same class in efficiency as the mercury-arc lamp.

Efficiency of light production is, however, not the only thing to consider. The essential question is to make use of the light, and that leads to the question of distribution. A useful feature is the low intrinsic brilliancy which eliminates the dazzling and blinding glare, with this new source of light, while the tungsten filament, for instance, is rather bad in this respect. However, too much importance must not be attributed to this feature, because even a point source of light can be diffused by diffraction or diffusion, a holophane or frosted globe. Light is lost by this procedure, but if five hefners per square inch is considered as a proper low intrinsic brilliancy, a 32-c-p. tungsten lamp enclosed in a frosted globe three to four inches in diameter brings the intrinsic brilliancy of the whole globe down to five hefners per square inch, probably less, with from 15 to 20 % loss of efficiency, and still leaves an efficiency far higher than that of the Moore light. You can allow in favor of the low intrinsic brilliancy from 15 to 20% lesser efficiency, but not more, because you can get low intrinsic brilliancy by diffraction with this loss.

The last part of the paper is a rather voluminous discussion of illuminating engineering matters, which would be very essentially improved by greatly shortening it, and would then have more value by making it more probable that the busy engineer would read through it, and there are some features in it which are well worth reading, but they are buried among so many pages that life, as a rule, is too short to afford time to go through it. I read it, however.

The author refers to the blinding brilliancy of the mercury tube. I have never noticed that. I am using the mercury tube exclusively as an artificial illuminant for any work that I may have to do. I would not think of using any other source of artificial light and find it by far the best. Further, the author says:

> The only commercial and proper method of comparing all sources of light is on the basis of their ability to produce useful illumination, and not by any other basis.

I should challenge that. This is the ultimate purpose, and the customer who makes a contract to light his premises with an economical amount of power specifies this; but to the illuminating engineer who takes the contract to put in the lights, the important question is what type of light to employ, so as to use the least amount of power to produce the best illumination. For the illuminating engineer the most important question is what source of light gives the maximum flux of light for a given amount of energy, the maximum quantity of light per watt. The next question is, whether this source of light is suitable for direct distribution, or how much of the light may have to be wasted so as to get the proper distribution. The statement quoted above rather begs the whole question of illuminating engineering.

The statement is made that photometric tests do not amount to anything. That is an old statement, and has been repeated very often, but I do not think that anyone will accept the dictum that the mean spherical candle-power does not mean anything. While with a light source of this kind one cannot speak of mean spherical candle-power, one can speak of the total flux of light; and it does mean something to determine how much total flux of light can be got per watt; indeed, as stated above, it is the most important question in the matter of artificial illumination.

So we must know how many lumens per watt we get, and since the lumen is the total flux of light which one candle-power gives, it is a convenient substitute to speak of mean spherical candle-power; but when we speak of mean spherical candle-power with a linear source of light, as the mercury lamp or the Moore tube, the mean spherical candle-power means the unit of flux of light, or the lumen, and that is independent of the shape of the source of light.

In regard to the proposed method of comparing lights, by lighting a room 40 by 80 feet, for instance, in lighting my house this would not help me much, because my house has no room quite so large. Light is used not only to illuminate stores and halls but a great deal is used for other purposes. However, if illuminants are to be tested in a 40-by 80-ft, room, to find out which illuminant requires the least energy to give a certain illumination in such area, there would be found, first, the mercury lamp, then a long interval; then the tungsten lamp, and another long interval; and then the Moore light, the tantalum lamp, and the enclosed arc, and finally the different other metal-filament incandescent lamps and carbon lamps and Nernst lamps, etc. So after all, neither the Moore light, nor any incandescent light, has the same degree of efficiency as the mercury lamp.

While criticising the character of the paper, especially the first and third parts, one must not forget that the second part contains some very valuable and important information. Mr. Moore is to be congratulated on the great advances he has made in the last few years, in reaching commercial conditions with his light, commercial frequencies, commercial voltages. There are some things which have not been especially dwelled on, among them the remarkably ingenious valve arrangement of feeding air or gases into the tube and maintaining a constant vacuum. We must remember that the vacuum in this tube is about $\frac{1}{8000}$ of atmospheric pressure. To maintain constant such a low pressure, not visible any more in a mercury gauge, and maintain that constant within.a few per cent. is a very remarkable achievement. So while criticising a part of the paper, I do not want to convey the impression that I do not admire the work which has been done by Mr. Moore. I recognize that he has made enormous steps in advance since we last heard from him. I also very much appreciate the very ingenious way of feeding these gases into the tubes, and the method of getting rid of the oxygen in the air, and feeding nitrogen or carbon dioxide. These are remarkable and ingenious devices which can only be admired.

Percy H. Thomas: Mr. Moore, has, I believe, given us a very timely and generally satisfactory paper. In addition to the general information about and description of his actual apparatus. he has called attention to a number of valuable points. For example, a great many people do not realize the value of lighting a room from one outlet and doing away with the pendants and fixtures and small outlets. Not only is a great deal of expense saved, but a good deal of fire-risk as well. The elimination of the cost of multiple outlets and many units, fuses, cords, etc. is one of his largest factors of economy over incandescent lamps. This is an advantage that his system of lighting shares in some degree with the Cooper-Hewitt light.

Mr. Moore has always maintained, and very emphatically, that his tube produces artificial daylight, and he apparently expects us to assume that there is no difference between the Moore light and daylight. This statement should be challenged. In the first place daylight gives practically a continuous spectrum. Mr. Moore's light comes from gases and must be a banded spectrum, a few colors well distributed over the spectrum, it is true, but still unable to give the same effect as a true continuous spectrum. How much practical importance this deficiency will be found to have can only be determined when a sufficient number of commercial installations have had considerably extended use.

In the second place, the tube does not give a strictly perfect diffusion, though at first sight it may seem that this is the fact. Illuminated surfaces are plain surfaces and have two dimensions, but the Moore tube has only one dimension, so to speak. The diffusion is perfect in one direction and very imperfect in the other direction. Place a pencil between a piece of paper and the light, with the pencil parallel to the tube, and there results a relatively dense shadow. Place the pencil crosswise and there will be no shadow at all. This shows the failure to diffuse across the tube.

It is even possible with incandescent lamps distributed over the ceiling to get a more perfect diffusion than with the Moore tube. The discontinuity added by the use of incandescent units in the direction of the length of the tube is not as important in disturbing uniform distribution as the large gaps between the tubes in the other direction. Dr. Pupin with his "load-coils", which he used in telephone circuits, found that a few, perhaps seven or eight coils per wave length, had nearly the same effect as distributed inductance and capacity.

Furthermore, I cannot agree that daylight necessarily produces the best spectrum. This a matter purely of experiment and experience. If the eliminating of the red or the violet from daylight is found to make an improved light to work by for any particular purpose, it is then better to suppress the red or the violet rays. I believe for many purposes that this suppression is advantageous.

There are a few more statements that perhaps require challenging. Mr. Moore says:

> It is now impossible to state definitely what their final life will be, beyond the general statement that some of these tubes have already been in operation over 4000 hours without change, and that there are good reasons for believing that they should continue to run at least as long again, which is a much longer life than any other form of illuminant yet invented.

If he will take pains to inquire, he can find out a great many places where commercial tubes of the Cooper-Hewitt type have operated for 10,000 hours; in this I am speaking of commercial installations.

He also says:

> It is the blinding brilliancy of the mercury tube that makes even a direct glance at it so very harmful to the eye.

I wish to state here that this statement, the equivalent of stating that the mercury vapor lamp is very harmful to the eye, is diametrically opposed to my own experience with this type of lamp.

Mr. Moore disposes very summarily of the new types of incandescent lamps, but perhaps they can take care of themselves.

In regard to Fig. 8 of the paper, Mr. Moore has taken a number of stations at different points in a room and determined the intensity of illumination at each, and then averaged the results. These points are well chosen to determine the intensity of the illumination at different locations, but it is not fair to average these values as they are taken, to get the average illumination, because some of them represent a very much smaller area than others. The proper way to obtain such an average is to divide the surface into a number of equal units, determine the illumination of each unit, and average these.

Though Mr. Moore's mercury valve for supplying gas regularly is very ingenious, yet I question its reliability if the lamp is left unused for a considerable time. Mercury-sealed valves while practically tight for a short time are not usually so indefinitely; after a while the mercury absorbs a little air on the surface exposed to the atmosphere and delivers it by diffusion on the vacuum surface. Once the tube leaks sufficient air, by being out of commission for a month's time perhaps, it would not start up again.

Some difficulties, I imagine, will be found; for example, the great inconvenience of a failure. This room, for instance, is entirely dependent on each particular part of the tube; any crack or damage done to the tube in any part will put the room in darkness. Furthermore, repair is not a matter of taking a spare tube out of the closet and putting it up. Dependance must be placed upon the manufacturer. The organization of a well-disciplined "trouble force" can eliminate some of the trouble, but in many cases it will be found a serious handicap. The power-factor seems to be a variable question. If the power-factor is made very high it means the elimination to that extent of the resistance or inductance backing which absorbs voltage, and will allow more variation in the current which might become a serious factor. Where power is bought from a lighting company and paid for by meter, a low power-factor is not serious because only the drop in the wiring needs consideration; but for those who do their own lighting the capacity of the generator must be considerably greater for a low power-factor load to get a given quantity of energy than with the high power-factor. This will be an added charge against the Moore tube in cases where the power is used largely for supplying these tubes.

With the whole illumination dependent on one or two or three outfits, it is impossible to light a small portion of a room only. In a factory two men who are working in a corner cannot light that corner only, but must perhaps use ten or twenty times as much energy as otherwise would be required. This objection cannot be urged against the Moore tube in all places; it simply shows a certain limitation when the broad field is considered.

Summarizing: it is a little too soon to tell what the commercial field of the Moore tube will be; undoubtedly there is a field for such a light.

Its good points are its relatively high efficiency (not the best, but relatively good—probably better than most carbon incandescent lamps), its even diffusion, and the fact that it has no bright spots and requires very few outlets.

Clayton H. Sharp: I think we all greatly admire the persistency of purpose and the courage with which Mr. Moore has tackled and has kept tackling for ten or fifteen years this great problem of the production of artificial light by the incandescence or luminescence of gases. Certainly the goal toward which he was striving, and the end which he sought to reach, was a most tempting one. We have all heard a great deal about the low efficiency of all of our ordinary illuminants; very few of them approach five per cent. luminous efficiency. Some of them may reach the value of 10% possibly, but most of them are perhaps of only two or three per cent. luminous efficiency. It certainly is a very attractive problem, that of producing an illuminant working at a luminous efficiency of 90% instead of 5%. I think we all regret sincerely that, judging by present indications, in his endeavor to reach this worthy goal Mr. Moore has failed. He has, however, succeeded in producing a practical illuminant which will undoubtedly find a field for itself in certain applications and which has an efficiency that brings it on a par with many of the other illuminants of the present day.

Mr. Moore says that the watts per hefner of the yellow tube vary from 1.3 to 2.5 watts per hefner-candle; or, in other words, from 1.5 to 2.9 watts per candle measured at right angles to the tube. The white tube, the carbon dioxide tube, has a lower efficiency, but no data are given on the watts per candle of the white tube. However, we may arrive at a value by comparing the conclusions drawn from two of the illumination tables which Mr. Moore gives: we find in this way that the white efficiency bears a ratio to the yellow efficiency of 1.5 to 2.9, or about 1 to 2. In other words, the yellow tube is about twice as efficient as the white tube. I do not think we can lay much weight on these comparisons, since, as Mr. Moore himself has stated, all comparisons of illuminants made by taking illumination values under certain specific conditions, are practically valueless as general criteria for the illuminants themselves. However, taking this comparison, we find that the watts per candle of the white tube would range from 3 to 3.8. The yellow tube, according to this, shows an increase in efficiency over the carbon-filament lamp, but this increase is by no means revolutionary. On the other hand, its efficiency, according to these data, is considerably less than that of the tungsten lamp. Consequently we can say in a general way that the Moore light does not represent an essential gain as compared with the other illuminants at the present time. If, therefore, it is to find a place as a practical illuminant, it must show certain other advantages which the illuminants with which it competes do not possess.

What are some of the advantages? It gives a diffused light, that is perfectly true; it is a light of low intrinsic brilliancy, it has no bright spots to blind the eye; it does away with a certain amount of wiring in the building. What are some of the disadvantages. I think some of us might say that the color of it is not all that it should be; it may be the color of daylight, but it is a peculiar kind of daylight; it has the great disadvantage of not being divisible, we throw a switch and turn on all the light into a room; we cannot have a little light here or there, as we need it. This point was brought out by Mr. Thomas. This indivisibility of the Moore light makes it necessary, it seems to me, in all or nearly all of the installations where it is used, to supplement it by some other system of lighting which has the feature of divisibility. It would hardly do, it seems to me, to place all the reliance for the lighting of a room of any importance whatever on a tube of this kind, for we know something about the fragility of glass. I do not think that we can consider the tube to be absolutely immune from breakage, and if it breaks we are in the sad position of being obliged to call in, not the ordinary plumber, but the glass plumber. The glass plumber may be available if we have our installation within a proper distance from the factory, but this feature would be a very disadvantageous one in any installation which is at a distance from these special glass-plumbing facilities.

Another serious disadvantage, noticed here to-night, is the flickering due to the alternating current. This is an exclusively alternating-current lamp at the present time, and when it is used on alternating current of a commercial frequency, such as this, we notice a very marked flickering on objects moved quickly in the light. In cases where the objects have to be handled with rapidity this would be a serious practical disadvantage. In any room where the objects are moved rapidly the effect produced could be scarcely called anything less than weird; unless it is possible to overcome this disadvantage in some practical way, and it is hard to see how this is possible, we must mark this down as a serious detriment to this style of lighting.

Another result of the indivisibility of the lighting is its inapplicability to localized lighting. Diffused and distributed lighting such as we have in this hall is excellent for many purposes, but we do not want it for all purposes. Where localized lighting is desired rather than distributed lighting; the economical illumination of certain portions of a room rather than uniform illumination of the whole room; we must use something which is capable of division, and the Moore tube would appear to be ruled out in such cases.

Let me say one word regarding illuminometer comparisons of various illuminants. This method is undoubtedly excellent for many purposes. If we have a certain room that we wish to illuminate, and if we could carry out illuminometer tests with the various kinds of lighting appliances that are available, we could determine the best system for lighting that room, but unfortunately research of this kind is something which cannot be carried out except under very special conditions. Ordinarily the matter of illuminating a certain space has to be given into the hands of an illuminating engineer who must work with such data as are available, and from the results of experience he has had in similar installations, to choose the kind of illuminant he considers best for the purpose and install it to the best advantage he knows how. As Mr. Moore said, comparisons of illuminations made under certain specific conditions are generally worthless for the purpose of generalization. We need to be able to generalize. We should know how much light a certain source will emit with a given amount of energy. In order to do this we have to study the source itself and determine its total flux of light per watt. This does not mean a test of the illumination in a certain specified room, 40 by 80 feet, but a study of the source of light itself. Without wishing to depreciate the value of illumination tests—for illumination tests I thoroughly believe in—I do not think we could accept the general validity of results that would be obtained under certain specific conditions, in showing the availability or non-availability of all sources of light. In that connection I wish also to raise my voice in deprecation of the term "watts per hefner" and "hefner-foot". It is bad enough to have the "candle-foot", because the candle-foot ought to mean the product of the candle-power by the feet, but it does not mean that. When we lug in an extraneous unit of light which is represented by a most excellent standard of light; namely, the Hefner Alteneck amyl acetate lamp, but which is not practically recognized as a unit in this country, we are going far astray and getting badly mixed up in our units of measurements. If Mr. Moore had used the hefner-metre in measuring the illumination I should have less quarrel with him because the metre and the hefner go together. The hefner knows nothing about the foot, and the foot does not know much about the hefner.

Another statement should be challenged, and that is that the average watts per candle of incandescent lights used in the city of New York is in the neighborhood of five. By a comparison such as one can make from a casual investigation of incandescent lighting in New York and London, I am inclined to think that perhaps the figure of five watts per candle might apply to the lighting in London, but I do not think that it applies to New York conditions.

John W. Howell: I am not going to say anything about incandescent lights. It has been my pleasure to know Mr. Moore and to know his work during the entire 12 years he has been working on this vacuum tube. At first he showed us a small Geissler tube, and for a long time afterward it was a simple Geissler tube, and when everybody thought that Mr. Moore was chasing rainbows he stuck to his work with a persistence, courage, and enthusiasm which I have never seen equalled. The light which we see to-night is a development from the Geissler tube, and it has been accomplished only by this most persistent work, the progress having been made little by little, step by step, never any very long steps until quite lately. He has at last produced a commercial result. As he says, he has added a commercial illuminant to those which the electrical engineer has at his disposal, and one which has a good many uses in which it excels others.

There may be things in Mr. Moore's paper to criticise. I could criticise some things which have not been alluded to yet, but I have no mind to do it. My only wish is to congratulate Mr. Moore on his work.

Among the uses to which Mr. Moore applies his light the first he names is art galleries. My friend, Dr. Berliner, has just remarked to me that there are many art galleries in Europe which are open only during daylight hours because there is no illuminant safe enough to be trusted in those galleries. I think this light would be admirable for such work, because there is no possible danger, except possibly in installing it. If this light could be once installed, the public could have the use of the galleries for much longer hours and with perfect safety.

Leon Gaster: The researches made in obtaining light from gaseous conductors within glass tubes form a decided advance in the conversion of electric energy into light. Bearing in mind however, the progress recently made with the manufacture of incandescent lamps by the use of metal filaments like tantalum osmium, tungsten, zirconium, titanium, etc., or alloys of those metals, with some of which efficiencies are now obtained of about one watt per candle, the practical application of gaseous conductors is somewhat reduced. The great advantage claimed of obtaining properly diffused illumination by the use of the Moore vacuum tube system, can now, to a very large extent, be obtained by the use of the more modern lamps, in combination with proper shades, globes, and reflectors, and by a judicious distribution of the lamps. There is no doubt that a vast field still remains open for the application of this gaseous tube method of illumination.

Will Mr. Moore kindly say whether he has had an opportunity of studying the effect the pink, yellow, etc., colors have upon the eyes because for the present there seems to be a great difference of opinion as to what the ultimate effect upon sight will be, by the permanent use of such illuminants as the Moore or Cooper Hewitt types. I should venture to suggest that the illuminating engineers should conveniently have such an investigation carried out, contributing thereby to settle the prejudices and objections which are raised against the use of such types of illuminants. Facts and data gathered from unbiased investigators would form a valuable guide to those who have to advise in these important matters.

Gano Dunn: I am in sympathy with what Mr. Howell has said about the work of Mr. Moore. It is an example of persistence that has seldom been exhibited before. We have known Mr. Moore as harping on his light for so many years that he has become a symbol of the persistent inventor. I am not forgetting to-night, as we are taking the easy course of looking backward upon his work, how very different the forward look was during all the years when we longed for the day when we should have cold light. I was Tesla's assistant at the famous lecture he delivered on cold light at extremely high frequencies; I know of other work in that direction that has failed before and since; I know how we all dreamed of the day when the secret of the fire-fly should be revealed and we should have sticks of cold light wherever we wanted them. Those sticks of cold light we actually see around us in this room. They represent the accomplishment of an ideal the engineering and scientific world has long been struggling for.

I venture to comment on that criticism of Mr. Moore's paper, advocating photometric efficiency measurements as the only proper comparison of illuminants, by saying that we have a right to take a practical view. Here we are sitting in a room with three alternative systems of illumination at command. Readings which I was permitted to observe just before the meeting, show that when the illumination comes from the ordinary source of lights behind the cove, 10 kilowatts of electrical energy are required. When the illumination comes from the naked lights strung around the border, five kilowatts are required, and when the illumination comes from the tube, four kilowatts. It is obvious to every one of the two hundred members present that the tube consumes less energy and gives a brighter light than either of the other sources. This is a practical fact that no discussion of photometry or brilliancy or efficiency can do away with, and we should give Mr. Moore credit for having accomplished it.

D. McFarlan Moore: I am asked how much gas enters the tube and how often it has to be replenished. The paper states that some tubes have already run about 18 months, corresponding to about 4000 hours, without replenishing. The paper states also that any tube can be replenished, that is, the phosphorous bottle can be replenished, at a neglible cost, so that this tube light is unlike other lights to the extent that the life of the tube itself is practically unlimited because it does not blacken. I am asked what vacuum gauge I referred to. It is a new vacuum gauge, which I developed for this particular work. I did not go into a description of it because the paper is long enough and I wish to reserve that together with a number of other subjects for future papers. I am aiso asked why does not the air enter the tube when the light is out. Mr. Thomas referred to this matter and doubted the ability of a mercury seal to hold the vacuum indefinitely. I know of a number of cases where mercury seals have held perfectly for years. Besides such a valve can be fixed very easily in case there should be any leakage.

Practically all Mr. Steinmetz' criticisms will be found to be answered in the paper. There is one thing that will not be found in the paper and that is a criticism of the illuminating engineers who installed the other systems of lighting which were compared with the tube; in fact they need to be commended, not condemned. The highest talent in the country was procured for the lighting of this splendid hall and the incandescent lighting is done well in all respects. The same can be said in reference to the arc lamps that were compared with the tube. The paper shows the location of these arc lamps, and I am sure that the majority of illuminating engineers would agree that it would be a very difficult problem to locate these arc lamps in any more desirable or advantageous positions than they were located in, in the basement where they were supplanted by the tubes. So with the location of the incandescent lamps in the lobby of the well-known theater, which is one of the tests referred to. These lamps are installed in the regular orthodox fashion; that is, in long rows. Fig. 8 shows that they are located in the best possible manner. The solution of the diffusion problem, when using the incandescent lamp system, is to place them as we have them in this room; viz. 92 separate machines in a row to accomplish a certain result which can now be better obtained by one machine, a plain simple tube.

This system of lighting undeniably differs radically from all of the old style systems. It is self-evident that the light diffused from such a large tube more nearly imitates daylight than any illumination that could possibly be obtained from any intense-point source. I maintain that man cannot do better than try to imitate daylight. No form of light will probably imitate it absoluely, but it should be our endeavor to imitate it as closely as we possibly can. Fortunately, it so happens that simple carbon dioxide comes closer to an exact imitation of average daylight color values when used in a vacuum tube than any other form of light. Its superior color values place it in a class by itself. The most delicate shades of colors have been matched under the tube when it is producing the pure white light due to $c\ o_2$. You will note that the 16-ft. tube on the platform which early in the evening gave a 30 hefner per foot light when using nitrogen is gradually changing to a pure white light because it is now adjusted to feed itself $c\ o_2$. The tube lighting this room is being feed with nitrogen and therefore a yellow light results which is the color that gives the greatest efficiency. According to the laws of nature, about twice as much energy is required to develop the necessary wave lengths for a white light, that is, to produce a spectrum that closely corresponds with daylight, than is required for yellow light which has a maximum effect upon the human eye.

The length of life of the tube has been referred to. I said that 8000 hours would be longer than any other form of illuminant—I refer to thoroughly commercial forms of illuminants—and then also assumed the illuminant to be still in perfect condition at the end of the test. It is true that some mercury tubes have had a long life, but at anything like the end of an 8000-hour run a mercury tube is far from clean. This tube will remain at the same degree of transparency for an indefinite period of time, and therefore the maintenance cost for long tube lighting is exceedingly low. My statement about the brilliancy of the mercury light was carefully made. I said a direct glance at the mercury tube. Judging from personal experience, I again state that the mercury tube is harmful to the eye if one looks directly at it. Mercury tubes seem to be efficient in terms of watts per candle-power but a number of them could not light this room as efficiently as this long tube does, to say nothing of the mercury tubes prohibitive color. The matter of breakage has also been mentioned. In all matters of engineering it is well to have duplicate units, and therefore large areas are now provided for by equipping them with a number of tubes so that the absence of lights from one tube will be comparable to the going out of an arc lamp or several arc lamps. Such large areas as department stores, for example, can now be perfectly lighted without an inch of wire within their walls.

Fears were expressed that these tubes could not withstand temperature changes without serious difficulties arising due to expansion and contraction of the glass, but practice has proved such trouble to be practically nil and therefore this system is applicable to street lighting. A continuous line of tubing can extend directly above the curb or be supported from the buildings to illuminate the show windows, sidewalks, and streets with a perfectly distributed light.

The best answer to the discussion on power-factors is to state the cold fact that this tube is now operating at this moment at a 75% power factor. Dr. Sharp and Mr. Steinmetz referred to thematter of efficiency and also spoke of the spherical candle-power of the tube. The curves in the paper show the watts per hefner obtained by horizontal measurement of a portion of the tube. I prefer the hefner after having had years of practical experience in trying to use other so-called standards of light. A committee of this Institute after a thorough investigation has recommended the hefner lamp. So far as divisibility is concerned, that is, having lights in small units, much can be said, but I will simply refer you to Fig. 15.

The images of moving objects have been referred to. It is true that a higher frequency is advantageous to a tube of this kind. For a number of years I investigated various methods for overcoming these images; I succeeded to a great extent, but found when I put the tubes on the market that the images were not an important factor at all. Of the two miles of tubing in use to-night there has not been a single practical commercial objection raised on this question. In this connection it should be noted that all who have actually worked under the light speak of its softness and the absence of any eye-strain whatever. Even in machine shops, where it was anticipated the movement of the lathes would be important, turned out to be negligible. On frequencies higher than 60 cycles per minute this trouble disappears entirely, at least so far as the average eye is concerned.

In reference to the tests proposed in a room 40 by 80 ft., I still most decidedly believe that such a method is the only practical solution of the problem of obtaining true commercial relative values of the various forms of light. I said that local conditions must be stated in every test of this kind, but of course I am assuming the local conditions to remain constant for any series of tests on different lights. This room, for example, has a neutral color and uniform fittings, and therefore each light would have a fair opportunity to do its best if the tests were made as directed in the paper. I believe it is the duty of all electrical organizations to aid in every way possible to standardize all forms of light, and I do not think this can be accomplished until a room such as I have described has been equipped, and I believe in the interest of science such a room should be established at some convenient place.

The following data were obtained by comparative illumination tests made in this assembly room of the Engineer's Building this afternoon between the Moore tube lighting system and the regularly installed concealed incandescent lamp system and the temporary rectangle formed by rows of exposed incandescent lamps which is the same size as the rectangle formed by the Moore tube.

FIG. 1—Assembly room No 2, Engineers' Building, illuminated by the Moore tube light

In these tests a portable illuminometer was used to measure the intensity of the illumination in hefner-feet at nine stations and at a uniform height of 35 in. from the floor.

The Moore tube is made of clear glass and is located as shown in Fig. 1. It is 176 ft. long and forms a rectangle 62.5 by 25.5 ft. It is 1.75 in. in diameter and is not provided with a reflector of any kind. This tube is automatically feeding itself nitrogen, therefore the color of its light is about the same as that of incandescent lamps. Horizontal photometric tests on a portion of the tube 0.5 in. long showed the tube to require 1.6 watts per hefner from the 60-cycle street mains. It was operating at 14.8 hefners per foot, or a total of 2600 hefners.

The tube having only been recently installed has run only some 25 hours and has not reached its final efficiency, which will be 1.4 watts per hefner after about a 50-hour run and thereafter it will maintain this efficiency indefinitely.

The concealed incandescent lamp system. The tubular 8-c-p. 119-volt incandescent lamps are located behind the cove as shown by the detailed drawing of Fig. 1. A two-way socket is located every 16 in. therefore 288 lamps are in use. Immediately behind each lamp there is a reflector. The lamps and entire equipment is new, having only been used a very few hours. Equally spaced on the longitudinal center line of the ceiling of the room are located 3 incandescent clusters which are concealed by opalescent reflectors each containing 6 lamps of 25 candle-power.

The exposed incandescent lamp system. The temporary circuit of incandescent lamps is installed to parallel the tube throughout its length. It is therefore located close to the tube, between the tube and the edge of the cove so that all of the lamps are exposed and not shielded in any way. They are all new 3.5-watt 117-volt incandescent lamps. They are spaced 24 in. apart, and therefore 90 are in use. Each lamp is in a vertical position.

MEASUREMENTS OF ILLUMINATION.

Engineers' Building, Assembly Room No. 2.

Hefner-feet.

Station	Moore tube system	Concealed incandescent system	Exposed incandescent system
1	4.72	1.72	2.67
2	3.67	2.83	2.37
3	2.90	1.90	2.31
4	2.83	2.40	1.89
5	3.14	1.98	2.07
6	3.83	1.83	2.31
7	4.40	1.61	3.85
8	3.66	1.90	2.47
9	4.90	1.77	2.37
Mean illumination (Average hefner-feet)	3.68	1.99	2.48
Power-factor	75%	1	1
Area square feet	1930.	1930.	1930.
Watts per Square feet	2.15	5.31	2.62
Volts	225.	118.	119.
Amperes	24.5	86.4	42.4
Watts total	4150.	10250.	5050.
Illuminating efficiency $\left(\frac{\text{Mean hefner-foot}}{\text{Watts per square foot}}\right)$	1.71	0.375	0.95

Conclusion

1. That the Moore tube lighting system has 4.6 times the illuminating efficiency of the concealed incandescent lamp system as installed under these local conditions. The Moore tube produces 85% more useful illumination, yet requires 60% less wattage than the incandescent lamp system. This test emphasizes the inefficiency of concealed lighting, and in many cases where the light of incandescent lamps is used to penetrate opalescent skylights an exposed tube can produce an equivalent effect for about one-tenth the power.

2. That the tube produces 57% more useful illumination, yet requires 18% less wattage. Under average commercial conditions this tube would have shown its superiority over exposed incandescent lamps on the basis of 2 to 1. It was noted that the intrinsic brilliancy of the exposed incandescent lamps was too great, but not so that of the tube.

The following tables show the results of the tests that have been made this evening, while this meeting has been in progress. The illumination readings for each of the three systems have been taken at stations Nos. 2, 3 and 4, Figs. 1 and 2.

For convenience in comparison, a table of the readings on the same three stations is abstracted from the complet test made this afternoon.

Measurements of Illumination.

Engineers' Building Assembly Room No. 2.

Tests made previous to meeting. Hefner-feet.

Station	Moore tube system	Concealed incandescent system	Exposed incandescent system
1			
2	3.67	2.83	2.37
3	2.90	1.90	2.31
4	2.83	2.40	1.89
5			
6			
7			
8			
9			
Mean illumination (Average hefner-feet)	3.13	2.38	2.19
Power-factor	75%	100%	100%
Area square feet	1930.	1930.	1930.
Watts per square feet	2.15	5.31	2.62
Volts	225.	118.	119.
Amperes	24.5	86.4	42.4
Watts total	4150.	10250.	5050.
Illuminating efficiency $\left(\frac{\text{Mean hefner-foot}}{\text{Watts per square Foot}}\right)$	1.45	.45	.84

MEASUREMENTS OF ILLUMINATIONS.
Engineers' Building, Assembly Room No. 2.
Tests during meeting. Hefner-feet.

Station	Moore tube system.	Concealed incandescent system.	Exposed incandescent system.
1			
2	3.2	2.7	1.44
3	2.72	2.7	1.11
4	2.33	3.8	1.22
5			
6			
7			
8			
9			
Mean illumination (Average hefner-feet.)	2.75	2.97	1.25
Power-factor	72%	1	1
Area square feet	1930.	1930.	193 .
Watts per square feet	1.97	5.61	2.41
Volts	228.	119.	117.
Amperes	23.	91.	40.6
Watts total	3800.	10840.	4650.
Illuminating efficiency $\left(\frac{\text{Mean hefner-foot}}{\text{Watts per square foot.}}\right)$	1.4	0.52	0.52

It will be noted that the "illuminating efficiencies" agree closely with this afternoon's test of the tube system and the concealed incandescent system. The exposed incandescent system is, however, 61% lower because in this afternoon's test the volts were higher than the rated voltage of the lamps. This serves to illustrate forcibly a well known characteristic of the incandescent lamp; that is, their rapid falling off in efficiency with a drop of voltage, for it will be noticed in the first test the volts were 119 as against 117 in the second. The latter being the rated voltage of the lamps, represents the true efficiency based on these three stations. Moreover, since the same ratio would hold for all stations, the illuminating efficiency 0.95 given in the complete test should be 0.6, which would make the tube system about three times more efficient than the exposed incandescent system in this particular case, and after the end of 50 hours' run when the tube will have an efficiency of 1.4 watts per hefner the ratio will be 1 to 3.4. Finally, after 500 hours run, when the average efficiency of the incandescents will be about 4.5 watts per hefner, the tube would show an illuminating efficiency over four times that of the exposed incandescent lamps.

It will also be noted that neither a similar change in the tube voltage nor a considerable change in the tube watts due to adjustment of the gas valve has materially altered its illuminating efficiency.

The complete test covers symmetrically one quarter of the room, which is also symmetrical, and therefore represents accurately the average illumination of each system. Therefore a room of this kind can be lighted by the Moore tube for one-fourth the cost at which it can be done by incandescent lamps. Similar comparative tests with all other commercial lights will prove the long tube the most desirable. However, there is no cause for alarm, because the adoption of the tube must be gradual and the commercial field is so great that there is plenty of room for all forms of illuminants, each of which will continue to occupy its own particular field. The efficiency race between gas and electricity has always been keen, but I believe the tube has placed electricity in the lead once more.

Reference has been made to art galleries. I will merely add that in order to grasp the spirit of a painting it should always be viewed under the same quality of light it was executed under; namely, daylight. Therefore, the picture should be viewed in the closest imitation of daylight possible and this can be done by using plain carbon dioxide in a vacuum tube.

Mr. Gaster referred to the color problem, and asked as its effect on the human eye. The paper answers that question. The light that comes nearest to the natural light is the one that is best. The nearer we approach to daylight the further away we shall be from doing injury to the eye. There are three factors of importance in connection with injury to the eye so far as light is concerned: color, intensity, and steadiness. The object should be to generate a light at such a low intensity that it can be used in its initiative condition and final condition; that is, without the need of shades, etc. The incandescent lamps or any of the point sources of light need shades either to soften the light or to reflect it, or diffuse it or tone down its color. With the tube method we can decide before we make the lamp just what color we need and obtain it by using the proper gases. I wish to refer to a remark I first made about 10 years ago, namely, that I believe the most important scientific advances of the near future would in one way or another be connected with the vacuum tube. The theory and facts I have presented to-night will, I think, sustain this contention.

Clayton H. Sharp (by letter): In considering the color of the tube with which this hall is lighted, attention should be called to a well marked phenomenon, which doubtless all of you have noticed and which to my mind is very significant. We have seen that when the incandescent lamps are turned on after the Moore light has been in use for so long a time that we no longer find its color particularly strange—the incandescent lights have a very decidedly greenish hue. Their light looks very much like that from an old style incandescent gas mantle when the latter is viewed in comparison with an incandescent lamp. Now we know from actual spectro-photometric measurements that the old style incandescent gas mantle does contain an excess of green in its spectrum, and we know also that this is most distinctly not the case with the light from an incandescent lamp. The spectrum of the latter light is continuous and approximates very closely to the spectrum of an absolutely black body; that is to say, all colors are emitted with equal facility. How then do we account for the fact that this light looks greenish when viewed by eyes which have grown accustomed to the color of the Moore tube? It seems to me that the explanation is to be sought by a consideration of some of the simple facts of physiological optics. The green sensation which we get on looking at the light of the incandescent lamp is a color contrast effect. It is produced by the influence on the eye of long exposure to a light which contains an excess of red. In other words, the continuous exposure to the excessive red of the Moore tube causes a temporary red blindness due to retinal fatigue. Under these circumstances any light containing a normal amount of all the colors will necessarily appear strongly tinged with green. It should be noted, therefore, that the green which is seen is not actually in the incandescent light itself, but is a subjective phenomenon induced by the unnatural color of the vacuum tube light. This state of affairs opens up at once a wide field for speculation and experiment on the possibility of more permanent and perhaps harmful effects being produced upon the eye if the Moore tube were used habitually as an artificial illuminant. The advocates of the mercury-vapor light claim that a greenish-hue light is best for the eyes as far as fatigue is concerned, and that red is harmful. If this claim is founded on fact, the light from this Moore tube must suffer greatly by comparison with the light from the mercury-vapor tube. But is this claim well founded? Do we know what hue a light must have in order to make it best for the eyes? We have frequently had expressions of individual opinions on these matters, but as far as I know no thorough-going investigation of our variously colored sources of light to determine what hue a light should possess to enable work to be done by it with the minimum of fatigue has ever been carried out and published in such a way as to furnish practical engineering data on this most important subject. With the widely ranging hues which the illuminants of the present day exhibit, this problem has a significance which was absent fifteen years ago, when parti-colored illuminants were unknown, and it seems to me that the time has come when it ought to be attacked by illuminating engineers and by oculists working in coöperation with each other.

R. A. Fessenden (by letter): A member of the Institute has good reason to be proud of the achievements of his fellow members in considering the history of electric lighting. At the beginning we have the incandescent lamp of Edison and the arc lamps of Thomson and Brush; at the present time it is to members of this Institute that the world is indebted for the most efficient developments in the four great classes of electrical illuminating devices. These are:

1. The point incandescence source, represented by the helion lamp of Messrs. W. G. Clark and H. C. Parker.

2. The point arc source represented by the magnetite lamp of Doctor Steinmetz.

3. The tube vapor source represented by the Cooper-Hewitt mercury lamp.

4. The tube gas source represented by the Moore lamp.

It is always unsafe to put a limit to developments in any particular line, but I am inclined to the opinion that these four types will not be greatly improved upon and will remain the standard methods of illumination until they are supplanted by some purely chemical means as suggested by Professor Elihu Thomson. This is not likely, however, for a good many years.

The various other types of lamps such as the tantalum, osram, osmium, tungsten, graphitized filament, calcium arc, Nernst lamp, etc., must I think all be considered as transition apparatus.

The labor and energy spent in devising these types of lamps is not, however, wasted. The development of the metallic-filament lamps, for example, has placed within our hands new methods of obtaining the rarer metals in workable form, and, as in the case of tantalum and osmium, has furnished us with new materials which are bound, sooner or later, to be of use in other lines.

It will be noted that the efficiency of all these types of lamps is in the neighborhood of one watt per candle, and I am inclined to think that by no method in which the light is produced by electricity will this efficiency be much exceeded, except possibly from a monochromatic source.

Mr. Moore's paper must be considered definitely to mark the beginning of a new era in electric lighting. Now for the first time we have a source of electric light which is not intrinsically brilliant and does not need to be shaded or diffused. Also for the first time a uniformly distributed illumination can efficiently be obtained.

Some doubts have been expressed as to the accuracy of Mr. Moore's measurements, but the objections are based upon lack of knowledge of the elementary principles of photometry. It is too self-evident to require argument that a much higher uniform intensity of illumination will be obtained with the same amount of energy from a distributed source than from a localized one.

With reference to the efficiency of the Moore lamp, this agrees almost exactly with some measurements made by me and published in 1901*

Of vacuum tube lamps, many have been suggested. It must be nearly thirty years ago that the first attempt was made to light a mine with vacuum tubes and induction coils. Since then we have had many types, as, for example, Crookes cathode bombardment lamp, and others

*"Light without Heat," *Electrical World and Engineer*, January 5th, 1901:

which, surrounded by a cloud of non-luminous verbosity, have not done much actual illuminating. The only approach to success, of which the writer is aware, is the admirable work of Macfarlan Moore. I know of no reason why his lamp should not ultimately prove a success for certain classes of work, where very long tubes and high potentials are not objectionable. In 1890 I made measurements on the efficiency of vacuum tube illumination, by passing the current a certain time, measuring the candle power of the tube, due to the light from the gas, and then dropping the whole tube into the water. (I was fonder of glass blowing then than I am now.) From the energy put in, (for an ammeter I used a hot wire voltmeter, with silver instead of platinum; this is a good instrument for such work) the heating of the water, and the candle power, the efficiency was determined. It came out quite high, *slightly less than 1 watt per candle power*. Most of the loss was found to be in the heating of the anode and cathode, and this it was attempted to overcome in two ways. First by lengthening the tube, which gave good results, though not commercial, and secondly by making the gas itself the secondary of a transformer. This failed because of too great hysteresis loss in the iron, though one type was not so unpromising.

Some question has been raised as to the commercial future of the Moore lamp. I do not agree with those who hold that its use will be a limited one. While the introduction of any new system is always more or less slow, I believe that in the not far future the greater part of the interior light load of city stations will consist of Moore lamps. The construction of the Moore lamp is especially suited for the coming types of concrete building architecture, and were I an architect I should not consider the lighting of any public hall or lodge room by any other means than a Moore lamp. While it would not pay to alter the present method of lighting the auditorium of the Engineers' Building, I would suggest that it might be worth while ascertaining whether the Moore light could not be advantageously used in lighting the library and some of the halls of the building.

At the same time that we admire the results obtained and the ingenious means by which they are accomplished, we can not help but extend our admiration to the pluck and perseverance with which Mr. Moore and those associated with him have worked on in the face of apparently insurmountable difficulties until they have now finally reached I believe the point of commercial success. It has sometimes occurred to me that much more courage is sometimes shown in financial undertakings than in actual warfare.

A paper presented at a meeting of the Boston Branch of the American Institute of Electrical Engineers, Boston, Mass., May 15, 1907.

AN ANALYSIS OF THE DISTRIBUTION LOSSES IN A LARGE CENTRAL STATION SYSTEM

BY L. L. ELDEN

The central station system under consideration is typical of those in service throughout the country, serving the larger centers of population and including adjacent suburban districts within a radius of upwards of fifty miles from the main generating station.

This system, as is the case with many similar systems, comprises the business of a number of companies that have been amalgamated into one large organization. This larger organization, with its greater financial resources and highly trained administrative and engineering forces, has naturally proved better fitted to meet the demands for service arising from an area of 450 square miles, in which thirty cities and towns, having a population of 1,000,000 persons, are served by the system.

Of the 1800 miles of streets included in the territory, 750 miles are covered by the lines of the system, which extend 43 miles in a single direction from the generating station. The total 50-watt equivalents connected to the system aggregate 1,600,000, equal to 80,000 kilowatts. This load comprises the usual mixture of power, heating, and lighting apparatus which constitute the business of a central station system. The maximum demand is approximately 44% of the connected load at the time of the yearly maximum, and approximately 27% during the average days of the year. These two results are indicated by Fig. 1, which shows the average load curves of the system for the maximum and average days of the year 1906.

The generating equipment consists of two main generating stations, one generating three-phase, 60-cycle alternating current exclusively, and the other generating low-tension direct current. In addition there are two small generating plants located at remote parts of the system, which are still in service independent of the main system. When convenient, these will be discontinued as generating stations and converted into sub-stations supplied with current from the main generating station. To facilitate the distribution of current over the large territory, sub-stations are maintained at suitable centres, at which points the high-pressure transmission lines deliver 60-cycle, three-phase, alternating current for conversion to direct current and alternating current at voltages suitable for commercial purposes.

As will appear in some of the tables given later, three transmission pressures are used; namely, 2300 volts, 4600 volts, and 6600 volts. In explanation of the apparent complication of voltages in the transmission system—it was found more convenient and economical to maintain certain installations of underground cables and motor-generators which were acquired in the purchase of another company's plant, than to abandon the large investment represented by such equipment. All new installations are made at 6600 volts, it being the intention gradually to eliminate the lower transmission voltages as conditions may dictate.

Throughout the entire system but three forms of service are supplied for commercial purposes; that is, either low-tension direct current, single- or three-phase alternating current.

The low-tension, direct-current district, representing slightly less than 1% of the total area of the system, is supplied exclusively by three-wire direct-current at 115–230 volts. This is used indiscriminately for power, lighting, and heating service.

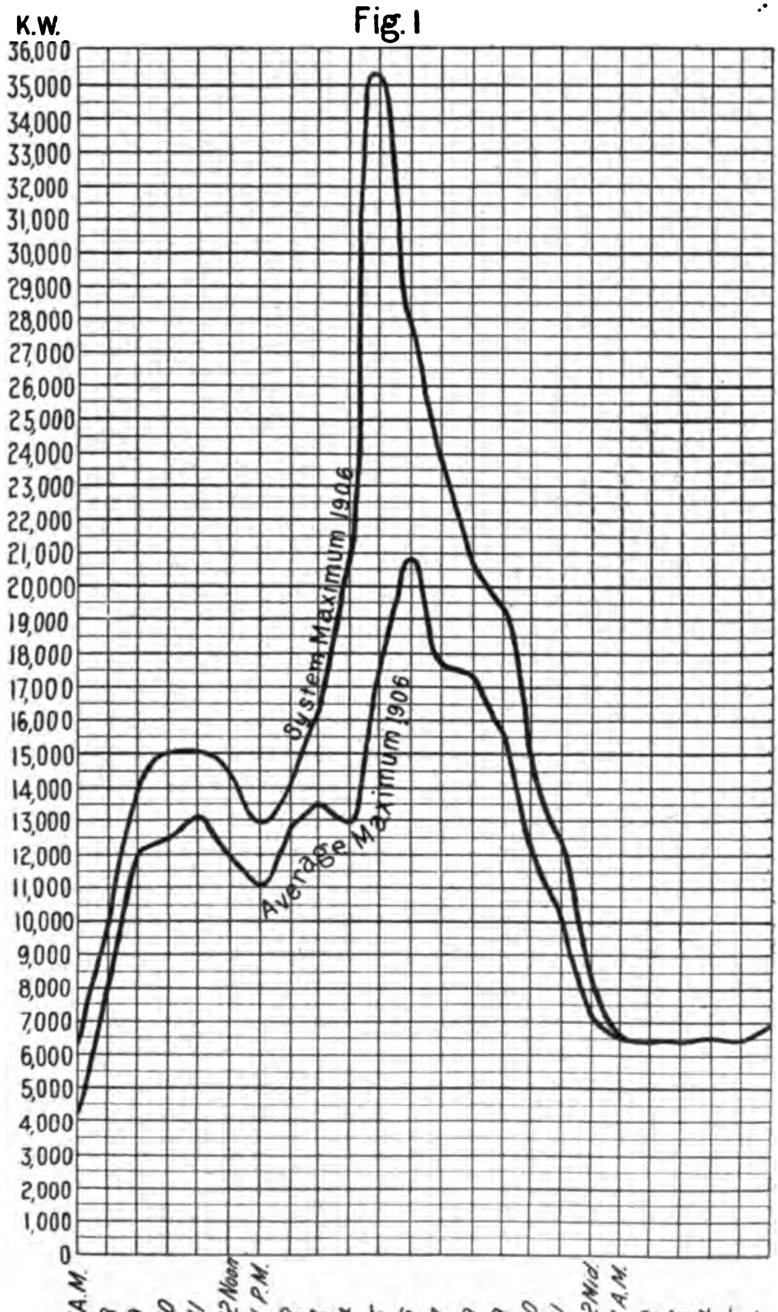
Similarly, the alternating-current district, embracing 99% of the area, is supplied exclusively by the alternating-current system of distribution. Three types of primary distributing circuits are used in the various sub-station districts, according to the demands for service, as follows:

1. 2300-volt, single-phase circuits in resident districts where only lighting and small power service is required.

2. 2300-volt, three-wire, three-phase circuits are used in districts of limited areas where mixed lighting and power service of considerable amounts are to be furnished.

3. 2300-volt, four-wire, three-phase circuits are used in

Fig. 1


K.W.
36,000
35,000
34,000
33,000
32,000
31,000
30,000
29,000
28,000
27,000
26,000
25,000
24,000
23,000
22,000
21,000
20,000
19,000
18,000
17,000
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
System Maximum 1906
Average Maximum 1906
7A.M.
8
9
10
11
12 Noon
1 P.M.
2
3
4
5
6
7
8
9
10
11
12 Mid.
1 A.M.
2
3
4
5
6

districts covering large areas where mixed lighting and power service is furnished.

In each of these cases, however, service is furnished to the customers at 115–230 volts, single phase, for lighting and small power service, and 230 and 550 volts, three phase, for power service.

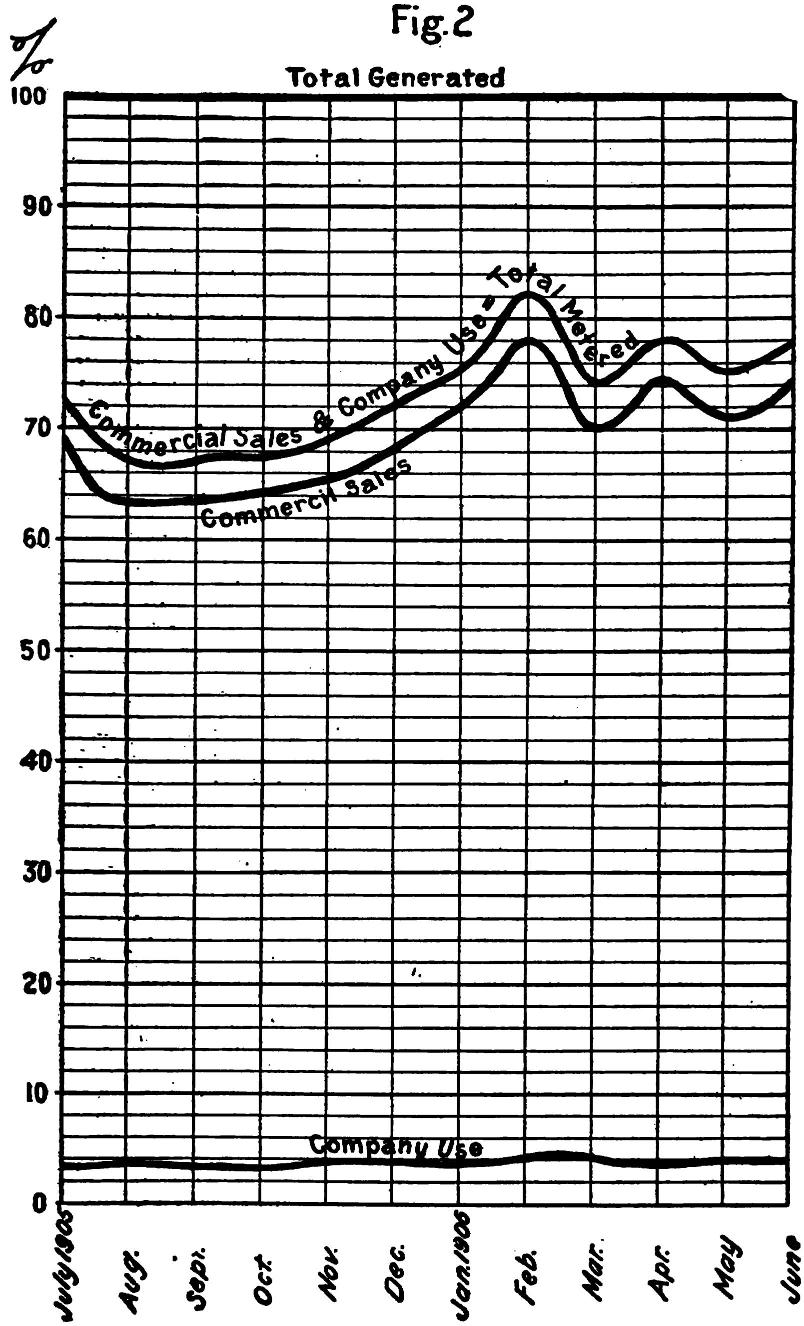
In addition to the types of service previously referred to for commercial service, there remains the street-lighting service, which is supplied at 6.6 amperes direct current, or alternating current, for both series-arc and incandescent lamps. In one district 3.5 amperes series incandescent lamps are used, but this is not considered as standard, and is subject to change when convenient.

To place the system on the basis described above has not been so simple a procedure as may seem from a cursory reading of the preceding statements. With the acquisition of each new interest and its territory, it was found that special forms of service were being supplied to customers, in most cases differing from those which are now considered as standard. As a result, at one time in 1903 some twenty different forms of service were being supplied to customers, with the attending complications in operating. Special apparatus was maintained and operated to supply these different services, with results far from economical; and, while much of the apparatus in service was as modern as it was possible to be, some could scarcely be considered in that class.

It was apparent from a comparison of the kilowatt-hours sold, with the kilowatt-hours generated, that the difference was too great to be consistent with good practice. To ascertain the reason a complete survey of the whole system was undertaken with a view of eliminating the uneconomical features. This investigation involved an examination of each customer's connected load and demand; the capacity of and demand on each transformer in the alternating-current district; the losses in transmission lines, feeders, and mains, the operation of all station apparatus; the accuracy of all recording meters—in short, all the details of the uses of current by the company and its customers. As a result of this inquiry, it was deemed advisable to proceed with the necessary changes. These changes which were commenced in 1903 affected the following parts of the system.

A certain district was specified in which no form of service other than the three-wire, 115–230-volt, direct-current service

Fig. 2


%
Total Generated
100
90
80
70
60
50
40
30
20
10
0
Commercial Sales & Company Use = Total Metered
Commercial Sales
Company Use
July 1905
Aug.
Sept.
Oct.
Nov.
Dec.
Jan. 1906
Feb.
Mar.
Apr.
May
June

would be supplied. This made it necessary to transfer all the alternating-current customers affected, to the direct-current system, remove all transformers in this district, and re-connect the alternating-current mains as a part of the direct-current system.

The 500-volt direct-current service was abandoned, and all motors located in the direct-current district were adapted for 230-volt, direct-current operation, while such as were outside of the direct-current district were replaced by alternating-current motors.

A number of new sub-stations were installed in the direct current districts to provide for serving the rapidly increasing business of the company, and, at the same time, to reduce the excessive losses in feeders and mains by shortening and rearranging the distributing points of existing feeders, as well as the addition of new ones.

In the alternating-current district secondary networks were installed and the number and capacity of transformers reduced, the total reduction in this case being 30% of the installed capacity. Changes in sub-station apparatus were effected by the introduction of new apparatus, all adapted to supply the standard forms of service.

The results of these changes may be seen by reference to

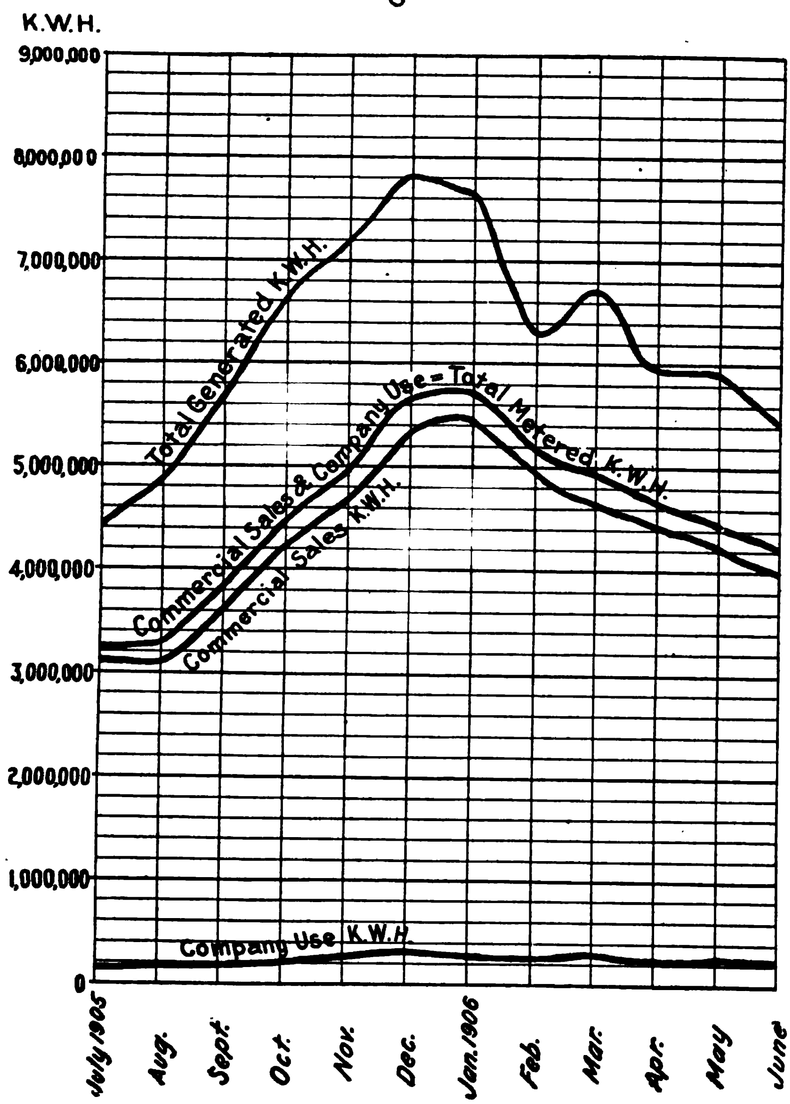
TABLE II.

	Kilowatt-hours generated.	Kilowatt-hours sold.	Percentage of kilowatt-hours sold
Year ending June 30, 1903	49,122,344	31,569,741	64.26
" " " " 1904	57,531,315	37,220,199	64.67
" " " " 1905	64,161,987	41,910,281	65.31
" " " " 1906	74,582,311	52,003,000	69.82

To illustrate further the increased efficiency, Figs. 2 and 3 are presented, covering the operation of the system for 12 months ending June 30, 1906. Fig. 2 shows the percentage of sales and company's use for the year by months, and Fig. 3, the actual sales and company's use in kilowatt-hours for the same periods.

In Table II, it will be seen that there was an increase in four years of 5.56% in the sales as compared with the manufactured kilowatt-hours. This result, however, is an average for the whole year 1906. Referring to Fig. 2, it will be seen that for the last six months of the year the average is much

Fig. 3

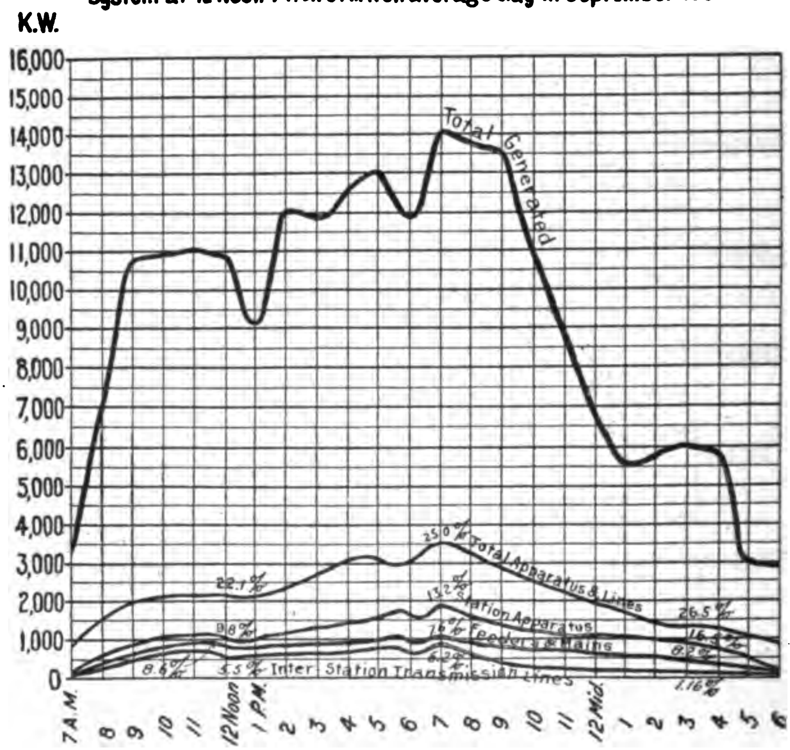

K.W.H.
9,000,000
8,000,000
7,000,000
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
Total Generated K.W.H.
Commercial Sales & Company Use = Total Metered K.W.H.
Commercial Sales K.W.H.
Company Use K.W.H.
July 1905
Aug.
Sept.
Oct.
Nov.
Dec.
Jan. 1906
Feb.
Mar.
Apr.
May
June

higher, it being actually 73.65%, this figure indicating future possible results.

It will be noted that the curves in Figs. 2 and 3 show an abnormal percentage of sales for the month of February; this is explained by the fact that the station data on manufactured kilowatt-hours for February represent a month of 28 days, while

Fig. 4

Curves of Instantaneous Losses in the Electrical Equipment of the System at 12 Noon 7 P.M. 3 A.M. on average day in September 1905

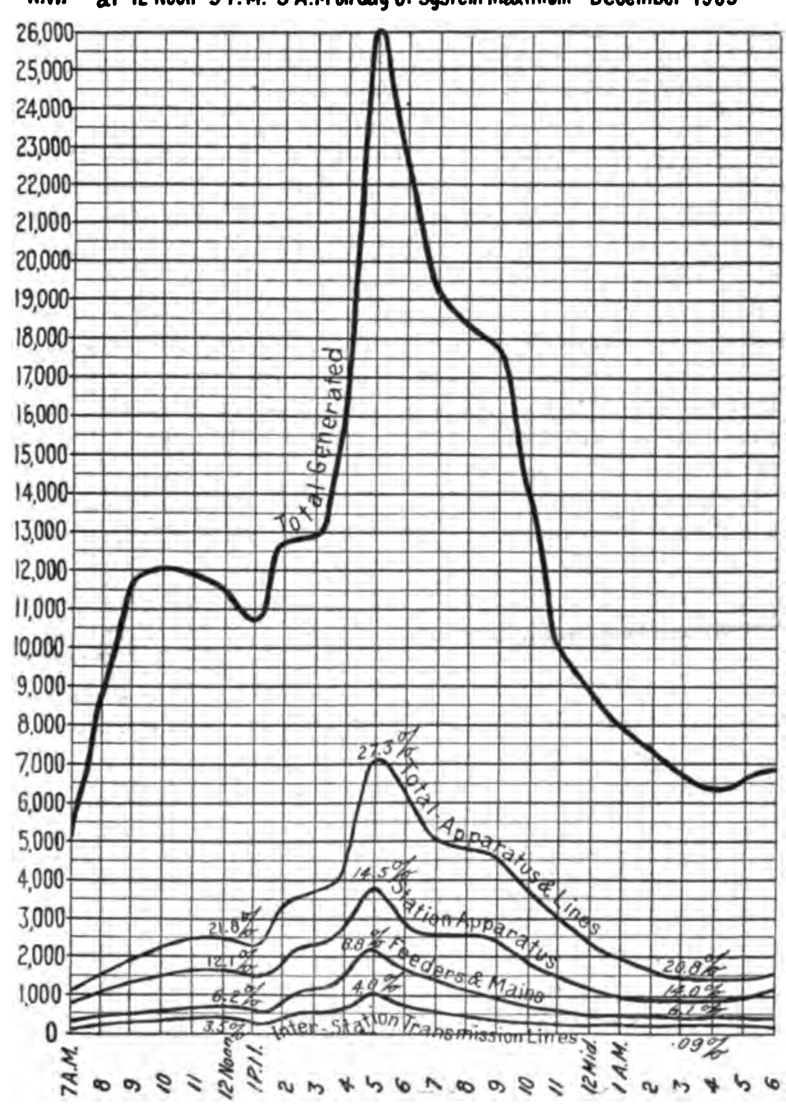


the total sales represent an average month of 30 days. Other points in these curves which do not coincide may be attributed to the same cause.

Using the data for 1906 as given in Table II as a basis, it will be seen that it would have been necessary to manufacture approximately 5,000,000 kilowatt-hours more in that year to sell the same amount of current, if the conditions had been

Fig. 5

Curves of Instantaneous Losses in the Electrical Equipment of the System at 12 Noon 5 P.M. 3 A.M on day of System maximum - December 1905



the same as existed in 1903. Further, if the average of the last six months of 1906 had been maintained throughout the year, a further saving of 5,000,000 kilowatt-hours would have been made during the year. While the resulting economies have in themselves justified the time and outlay necessary to make the changes, the increased capacity of the system, as well as the simplifying of the operating conditions, have been results far outweighing all other considerations.

In Figs. 4 and 5 are shown curves representing the maximum generated kilowatts, also the instantaneous losses which occur in the system at different hours on the average and maximum days of the year. These data, while of no particular value, may be of interest in comparison with the continuous duty losses shown in some of the succeeding tables.

As it is the practice of this company to use motor-generators in preference to synchronous converters, to transform the three-phase current to direct current for the supply of service to the 115–230 volt, three-wire, direct-current system, it may be suggested that a further economy could have been effected by the use of converters.

The motor-generator equipment of the company comprises 36 units having a total capacity of 10,210 kw., and varying in size from the 1,000-kw. direct-connected sets, to the 60-kw. Edison bipolar belted units which have been retained in service in some of the smaller stations. In Table 3 are shown the actual results of the operation of this apparatus for the year 1906. There is also shown the estimated results of the use of converters of the same sizes, operated in the same manner as the motor-generators, and at an assumed efficiency calculated from the manufacturer's data on such sizes of apparatus.

TABLE III.

	Kilowatt-hours received.	Kilowatt-hours delivered.	Per cent efficiency.
230-volt motor-generator..........	31,331,406	25,803,990	82.4 actual
230-volt converters...............	30,004,639	25,803,990	86. assumed
Kilowatt-hours saved by use of converters........................	1,326,767		

The operating efficiency of the converters is estimated at 87%, less 1% for the current used by the cooling apparatus, while the efficiency of the motor-generators was 82.4%. The table shows a saving of 1,326,767 kilowatt-hours by the use of converters, this representing the premium paid for the use of the more reliable apparatus, in addition to which there is to be added the slightly larger investment necessary in the purchase of motor-generators. Owing to the well-known difficulties incident to the operation of 60-cycle converters in a large system where continuous service is placed above all other considerations, it is a question of individual opinion whether a company is justified in adopting either type of apparatus.

TABLE IV

Comparative data of alternating-current and direct-current systems

	Alternating current	Direct current
Area of system per cent. of total	99.1%	0.9%
Connected load per cent. of total	21. %	79. %
Commercial service, street lighting service omitted		
Total losses from generating stations to customers' meters	41. %	20. %
Efficiency of system	59. %	80. %
Total losses from sub-stations to customers' meters in percentage of current delivered from sub-station	24. %	7.5%
Efficiency of distributing system	76. %	92.5%
Street lighting system		
Total losses from generating stations to street lamps	15.2%	31.9%
Efficiency of system	84.8%	68.1%
General data		
Connected load in kilowatts	17300	62700
Capacity of transformers installed on distributing circuits	10388	——
Capacity of transformers in per cent. of connected load	60%	——
Approximate kilowatt-hours delivered to each system in per cent. of total generated	30%	70%

Table 4 presents some data illustrating the comparative losses in the alternating-current and direct-current systems as operated. In the alternating-current system the total losses, including transmission, step-down transformer, distributing circuit losses, and meter losses, aggregate 41.1%, equivalent to an efficiency of 58.9. Eliminating the losses in transmission lines, step-down transformers, regulators, boosters, etc., the total losses in the distributing circuits, meters, etc., aggregate

24.2% with a resulting efficiency of 75.8% from the sub-station to the customers' meters.

In the direct-current system the total losses, including those in transmission lines, motor-generators, tie-lines, feeders and mains, meters, etc., aggregate 20%, equivalent to a system efficiency of 80%. Eliminating all losses in the direct-current system, except those which occur between the direct-current switchboard in the sub-stations and the customers' meters, a total loss of 7.54% is shown, or an efficiency of 92.46%.

Two forms of street-lighting service are in use, each involving the operation of different types of apparatus. In one case

TABLE V.

DISTRIBUTION OF CURRENT FOR THE YEAR ENDING JUNE 30 1906

	Kilowatt-hours.	Loss in per cent. of total generated kilo-watt-hours	Per cent. of generated Kilowatt-hours transmitted
Commercial sales	52,003,000	69.82	
Company use	2,774,383	3.72	
Total losses	19,270,616	25.87	
Unaccounted for current	441,437	0.59	
Total generated	74,489,436	100.	
Sub-division of Total Losses			
Losses in station apparatus	10,586,117	14.21	16.6
Losses in inter-station transmission lines	2,920,653	3.92	5.92
Losses in feeders and mains	5,763,846	7.74	10.50
Total losses station apparatus and lines	19,270,616	25.87	

motor-generators are used to convert alternating current to 6.6-ampere series direct current, and in the other case constant-current-transformers are used to obtain the 6.6-ampere series alternating current for similar service.

The total losses in the 6.6-ampere direct-current system are shown to be 31.9%, giving an efficiency of 68.1%. For similar service from the alternating-current system, the total losses are 15.2% with a resulting operating efficiency of 84.8%.

The methods employed in preparing the data by means of which the losses in the system are determined may be understood by reference to Tables 5, 6, 7, 8, and 9. These tables present a summary of the year's operation. Similar tables are prepared monthly which deal with the shorter period of time.

It should be understood that with the exception of such items in these tables as are preceded by an asterisk, all the data shown are the results of records taken from recording wattmeters. In such items as are excepted, computations were necessary, all of which were made from reliable data furnished by the manufacturer of the apparatus in question, supplemented in many cases by tests made by the company's representatives.

The losses in the individual commercial distributing circuits were determined by the drop-of-potential method, a constant being obtained for each circuit by taking a large number of

TABLE VI

LOSSES IN STATION APPARATUS FOR THE YEAR ENDING JUNE 30, 1906

	Kilowatt-hours	Loss in per cent. of total power generated	Loss in per cent. of input
230-volt motor-generators	5,527,416	7.42	17.6
500-volt motor-generators	373,059	0.50	33.6
Series arc motor-generators	2,403,471	3.22	25.5
Step-down transformers	1,010,848	1.36	3.23
*Constant-current transformers	118,548	0.16	5.40
*Potential regulators	65,353	0.09	3.53
Batteries	807,067	1.09	43.2
Boosters	211,264	0.28	63.0
Balancers	67,725	0.09	
Water rheostats for testing	1,366		
Total	10,586,117	14.21	

pressure tests under all conditions of load. The losses in the direct-current mains were estimated in the same manner. The losses in the street-lighting circuits were calculated from the known length of the circuits, and these results further checked by voltage readings at the station while the circuits were in operation with a known number of lamps burning.

Every year the company makes thousands of tests of the meters in use on the customers' premises. For the year 1906 the results of all such tests showed that the average meter error was 2.6% slow. This factor has been used to account in part for some of the unknown losses, the total thus accounted for being approximately 1.5% of the total power generated.

Table 5 shows, in the first part, a summary of the principal

TABLE VII

LOSSES IN INTER-STATION TRANSMISSION LINES FOR THE YEAR ENDING JUNE 30, 1906

	Kilowatt-hours	Loss in per cent. of total power generated	Loss in per cent. of input	Per cent. of total generated power transmitted
Three-phase 2,300-volt lines	1,556,981	2.09	8.41	24.8
Three-phase 4,600-volt lines	98,813	0.132	1.52	8.7
Three-phase 6,600-volt lines	770,577	1.04	3.55	29.1
230-volt direct-current tie-lines	494,282	0.66	18.30	3.6
Total	2,920,653	3.92	5.92	

TABLE VIII

LOSSES IN FEEDERS AND MAINS FOR YEAR ENDING JUNE 30, 1906

	Kilowatt-hours	Loss in per cent. of total power generated	Loss in per cent. of input
*2,300-volt commercial lines	1,854,854	2.50	25.1
230-volt direct-current feeders	1,901,948	2.55	4.93
*230-volt direct-current mains	641,343	.86	2.00
*500-volt direct-current feeders	74,466	0.10	9.15
*Street-lighting circuits	809,103	1.08	9.53
*Meter potential losses	482,132	0.65	
Total	5,763,846	7.74	10.5

TABLE IX

DIVISION OF KILOWATT-HOURS SOLD BY DISTRICTS FOR THE YEAR ENDING JUNE 30, 1906

Station	Per cent. kilowatt-hours received	
1-13	68.9	
14	100.	
15	100.	
16	75.	
17	98.3	
18	63.5	
19	55.4	
20	52.4	
23	55.9	
25	72.8	
	69.8	Total system sales

items without subdivision. The latter part of the table subdivides the total losses in the system into divisions which are treated individually in the later tables.

In Table 6 the losses in station apparatus are subdivided and distributed among the various pieces of apparatus used in the operation of the stations.

Table 7 indicates the losses in the inter-station transmission lines.

Table 8 shows similar data on feeders and mains.

Table 9 shows the percentage of sales in each sub-station district as compared with the current delivered to that district for distribution. In explanation of this table, it should be noted that stations 1 to 13 include the direct-current district and a portion of the alternating-current district. Stations 14, 15, and 17 represent stations to which current is sold wholesale, to be redistributed by the local companies controlling these districts. Stations 16, 19, 20, and 23 represent sub-stations, each of which distributes service to one or more cities or towns in the suburban districts. Stations 18 and 25 represent small generating stations which are still in service in two of the recently acquired suburban districts.

In making comparisons of the several districts, some of the individual characteristics of each district should be understood. Station 16 supplies a district where large amounts of power are used, also a large amount of street-lighting service. Station 18 supplies a district similar to 16, except that the amounts of power and street lighting service are relatively less.

Stations 19, 20, 23, and 25 supply service to districts covering large areas where resident lighting and a moderate amount of street lighting are the only uses made of the service.

The preparation of these data involves the labor of one man for a period of approximately one week each month. It is his duty to watch the operation of the system through the statistics furnished him by the operating and sales departments, comparing them with data which have been prepared representing the possible maximum conditions of efficiency of operation of every piece of apparatus and reporting for investigation any divergence from the estimated average operating losses. The curves, which are prepared monthly, show the percentage of losses in the current handled by each motor-generator, storage-battery, balancer, booster, exciter, step-down transformer, constant-current transformers, or any other station apparatus, thereby providing means for immediately detecting any unusual results, and furnishing an invaluable check on the operation.

Aside from the value which these data may have from an operating point of view, it is of considerable interest in indicating the characteristics of each district as a revenue producer, thus making it possible to judge accurately of the advisability of making extensions for the different classes of service.

If there should be undertaken at this time the construction of a generating and distributing system similar to the one under consideration, the installation would be made under conditions which would eliminate the disadvantages encountered in reconstructing existing equipments, as in the present case. This would be particularly true in certain parts of the country, where the limitations placed by the local authorities on permissible operating conditions are less severe, and where the quality and the continuity of the service are not of such paramount importance,—all such conditions tending to greater economy and reduction of operating losses than is possible in the present system.

A paper presented at the 219th Meeting of the American Institute of Electrical Engineers, New York May 21, 1907.

SOME FACTS AND PROBLEMS BEARING ON ELECTRIC TRUNK-LINE OPERATION.

BY FRANK J. SPRAGUE.

Certain memorable opinions, recently uttered by railroad men whose creative and administrative work, and wide experience entitle them to preeminence, command attention. In March last, the New York *Times* contained an interview with Mr. E. H. Harriman, who discussed at length various features of the present steam railroad situation; the influence of national and state legislation; the developments, needs, and present difficulties of operation; and the vital necessity of increase of capacity, measured in its broadest terms. Expressing his individual opinion that perhaps it might be better, considered from the standpoint of the steam locomotive, if a wider gauge than the present standard had originally been adopted, he went on to say:

> But perhaps it is chimerical to think now of rebuilding the railroads of the entire country, and of replacing the entire railroad equipment. If so, what is the best thing? Obviously, electricity. And I believe that the railroads will have to come to that, not only to get a larger unit of motor power and of distributing it over the train load, but on account of fuel. That brings up another phase of the existing conditions. We have to use up fuel to carry our fuel, and there are certain limitations here just as much as there are in car capacity or motive power, particularly when you consider the distribution of the coal producing regions with respect to the major avenues of traffic. The great saving resulting from the use of electricity is apparent, quite aside from the matter of increasing the tractive power and the train load. * * * * * * *
>
> The only relief which can be obtained through economies of physical operation must come through the outlay of enormous amounts of money such as would be involved in a general electrification or a change in gauge.

At the April meeting of the Buffalo Chamber of Commerce, Mr. W. C. Brown, senior vice-president of the New York Central Lines, likewise comprehensively discussed the present railway situation, and the influence of legislation and management upon credit, pointing out the "appalling blow to that credit," not so much because "of what has been done, as the manner and temper with which it has been done, and the fear of what may follow." The pressure upon the railroads, the imperative and continuing need of development and improvements, and the limitations in available capital—all were specially emphasized by this statement:

If the development and expansion of the nation is to go on, if the progress made during the last ten years may be accepted as in any respect

FIG. 1—Section of present steam terminal, New York Central.

a measure of progress to be made during the coming decade, almost as much money will have to be expended in increasing the facilities of existing railroads, and in building additional railroads, as has been expended during the eighty years since the beginning of the construction of railroads in the United States.

These opinions are confirmatory of that of Mr. James J. Hill, who some time ago startled the investing world by his estimate of a billion dollar annual expenditure, now actually confirmed by detailed estimates.

Coming from such high sources, from men who are fitted by nature and experience to survey the whole field with special clarity of vision, and to summarize their conclusions with extraordinary judgment these utterances are pregnant with meaning; for coupled with the remainder of their remarks, they tell us that if there is the proper coöperation between the national and state governments and the railroad corporations, a permanently established confidence between the public and those who serve it, based upon integrity of management and equity of treatment, and a reasonably surety of a fair return on money invested—all absolutely necessary to command the confidence of capital—then, in spite of temporary setbacks or trade reactions, this country has entered on an era of unequalled expansion, and when planning for future developments the steam railroads must keep in view the possibility of a change in motive power, and the adoption to an increasing extent of the use of electricity is some form.

But it is especially to be noted that while fuel economy, not only in the matter of power generation, but also as affected by its own transportation (often a most serious matter), must be kept in view, the keynote of the prophecies of the future is more specifically sounded in the word *capacity*. It is this fact which must be always borne in mind.

Increase of capacity, not only such as is possible and individual to electric application, but also such as is common to the larger developments of railroads, however operated, means of course economy in its highest sense, that is, saving in passenger and ton-mile operation, assuming that traffic increases at least in proportion to capital account, because of increased loads, reduced train crews, higher operating schedules, better distributed service, less dead time on sidings, less interruptions to schedule and greater freedom from accidents.

I believe that this question of capacity will be a far greater controlling factor in the electrification of trunk-lines than that of economy as narrowly measured by the cost of electrical horse power. I do not know of a single instance in which electricity has been adopted in which this feature has not been paramount, nor do I know of a road operated to-day which would sacrifice capacity to economy.

How much has been actually spent in steam railroad development, to which I assume Mr. Brown's reference is confined, it is impossible to tell, but that it is a stupendous amount, giving some suggestion of future capital demands, is evidenced by the fact that the total of the outstanding stock, bonds, and other obligations of the steam railroads in the United States now aggregates about $13,800,000,000; while similar obligations of the electric railroads, which began their commercial expansion with the signing of the Richmond contract almost twenty years ago to-day, exceed $3,500,000,000.

These are indeed stupendous totals, and when confronted with the possibilities of the future we may well be hopeful, while we ask: Along what lines will this great development naturally proceed? What improvements must necessarily take precedence? How shall the continuing expenditure of capital be conducted so as to safeguard a dividend on it?

We electrical engineers are ambitious, fairly courageous, and given to prophecy. We have much warrant for it, and every reason to be proud of what has been accomplished in an unmatched industrial progress; but we are a little apt to be prejudiced in favor of our own work, and perhaps somewhat partisan in promoting it. I think we often lack in large measure the familiar knowledge of railroad finance and operation that is necessary in dealing with the larger railroad problems, in order to insure our fairly weighing the importance and value of all the elements which must be considered.

Such, at least, is apparently the opinion of the friendly, but yet mildly sarcastic and somewhat pessimistic editor of the *Railroad Gazette*, who, referring to the recent meeting of the Institute of Electrical Engineers on the occasion of the presentation by Messrs. Stillwell and Putnam of their paper on the substitution of the electric motor for the steam locomotive, remarks:

> The pity about the meeting referred to is that there was no speaker there who knew as much about the practical requirements of railroading as he and the others did about the advantages and economies of electric propulsion.

This is quite likely true, for most people know a little more about their specialty than about the details of every business collaterally connected with it. But, really, the electrical engineers of the country, many of them professional civil and mechanical engineers as well, are not entirely destitute of a knowledge of both steam and electric operating conditions, nor can they all fairly be classed as a lot of unthinking enthusiasts; their knowledge and experience amount in the aggregate to a very respectable total.

But we must not take our genial critic too seriously, nor be over-much discouraged by his limitations of vision, for his is not the only publication that has trailed after accomplished facts in the electrical world, nor his the only voice that has been raised in doubtful protest on the eve of great developments. Heed, however, must be taken of the fact that trunk-line operation is in many respects a very different thing from that of urban or interurban railways, and the attempt to introduce electricity into steam railroad operation must observe in the fullest measure these differences. We can, therefore, take the criticisms made of us in good nature, and I think win the proper support of steam railroad men, and come nearer to

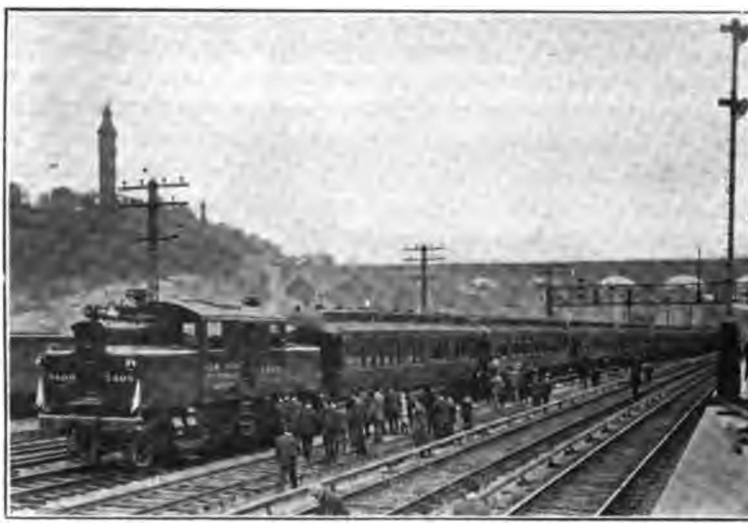


FIG. 2—**First New York Central electric train, September 30, 1906. Leaving High Bridge for Grand Central Station.**

the successful introduction of electricity where justified, by setting forth with entire frankness the facts as they have been, are, and promise to be, and avoiding too strenuous and arbitrary prophecies of what must be. You will note that I do not except myself from this generalization, and therefore I trust my engineer confrères will not deem me lacking in impartiality in formulating this gentle criticism.

Many of my hearers are young in years, and some of them just starting in railroad experience. Many statements made to-day may therefore have an air of novelty, but there are certain fundamental truths referring to the electric equipment of steam-operated trunk lines which have always, since the beginning of this development, been broadly true. I have stated them time and again during the last twenty years, and in a score of publications. I cannot state them any more fully now, but inasmuch as they are expressive of my present as well as past beliefs, and having been made at various times may now in part be lost sight of, I take the liberty of referring to them in an appendix to this paper, and I will briefly summarize a few extracts.

Fifteen years ago, in Chicago, I had the honor, as president of this Institute, to make my inaugural address on the subject: "Coming Developments of Electric Railways." On that occasion, I may remark in passing, I expressed my fervent hope for a "single circuit alternating current motor," my conviction of the necessity of the use of an "overhead conductor, practically rigid in character, following very nearly the center line of all tracks and switches, with no movable overhead parts, and with return through the rail," and especially my belief in higher potentials and gearless motors.

My attitude on the broad question of trunk-line operation was then the same as it has consistently been since, for it has not been altered by more intimate contact with the trunk-line development. It may be briefly summarized in the simple statement that, taken as a whole the electrical equipment and operation of trunk lines is essentially more of a financial than a technical problem. It is certainly not solvable by ingenious methods of bookkeeping, or transmission of burdens to posterity. In that address I said

> Any predictions which are made concerning the future of electric propulsion, either in ignorance or disregard of the possibilities of steam duty, and the limitations necessarily existing in all systems of transportation, deserve and will receive little consideration from those charged with the responsibilities of conducting our great railway system, for unless passengers and goods can be moved over a system with increased benefit to a community, or at a reduced cost, or with a commensurate return on capital invested, an electric will not replace a steam system.

The commercial success of electric operation is a question of relative and absolute density of train movement.

> It narrows itself down to the one question as to the number of trains operated between the two terminal points. Make that number of trains sufficiently large, and the electric motor is the best means of electric propulsion Decrease this number, and steam is to be preferred.

In closing that address, after pointing out the difficulties surrounding trunk-line operation, and the electric developments which it seemed to me would take place, I added:

> Temper your enthusiasm with prudence; limit your attempts to the solution of those problems which will prove of practical benefit. Do not chase rainbows, but seek lessened costs of operation for equivalent duty and increased return on invested capital.
>
> All this is said in no spirit of discouragement, for I yield to no man in my confidence in the future of electric traction. No new field is so rich, none more pregnant with great possibilities.

Where do we find ourselves to-day? Has there been any essential change in the essential governing facts?

Two years ago, we celebrated, and very rightly, the "Triumph of Electric Traction,"—not the wholesale replacement of steam by electric operation, that would have been somewhat prema-

Fig. 3—Early Sprague, Duncan, and Hutchinson—1000 h. p. electric locomotive.

ture—but the magnificent results which had been achieved. A new industry had been created, affording investment for thousands of millions of capital, and employment for hundreds of thousands of men. Time, distance, and mountain elevations had been abbreviated, great vistas opened up, barren spaces peopled, new homes created, towns linked to each other and to their neighboring cities, and animal drudgery relieved. Direct-current, single-phase, and polyphase equipments were in operation; and a new system of power aggregation and control, the multiple unit, had solved elevated and underground problems, and made possible enormous concentration of capacity. The power and speed of the heaviest steam locomotives had been equalled or surpassed, and some of our great trunk lines had contracted for improvements costing over a hundred millions of dollars, made possible only because of the availability of electricity. But again referring to the broad question of trunk line operation, I felt impelled, even in that hour of elation, to say:

> What, then, will determine the future? Solely the financial factor, as it must the future of any other great industrial problem. When savings in operation and the increased returns from traffic on any road will more than pay a fair dividend on money invested for electrical equipment then, and then only will trunk lines, great or small, be operated electrically. As I have often stated, the problem resolves itself into a question of relative density and the character of load-factor, and these essentials are of course vitally connected with the allowed working potential.

Let us consider for a moment the evolution of the steam railroad. As a rule, it has started with a single track, with such contour and grades, weight of rail, and character of ballast as the money to be expended and the probable return in traffic have seemed to warrant, and generally handicapped by such extravagant or attempted profits in construction as have resulted in a long-continuing burden. Turn-outs and sidings were gradually supplemented by more sidings and longer turn-outs, and then such short sections of double tracking as the demands of capacity, traffic, schedule, and commercial conditions have required or permitted. Then there came a time, on many a road, of receivership, followed by reorganization and an extended period of recuperation; or if not receivership, then a long time of nursing into a condition of reasonable commercial health. As the demands of capacity increased, there followed the introduction of, or improvement in signal systems, additions to rolling stock, increases in the number and capacity of locomotives, until the road found itself with an equipment of extraordinary variety of varying conditions of efficiency; meanwhile, intermingled with a part of its own were all kinds of freight equipment from roads throughout the country. Through service for freight, express, passenger and sleeping cars, and terminal connections with other roads marked the transition from a road of more or less local to one of "through" character, The new relationship made an increasing demand on capacity. and double tracking became essential for a part, or perhaps for the whole of the route; and with this new demand likewise the necessity, oftentimes carried out beforehand, of some relocation of tracks, changes in alignment, reduction in grades, improvement in ballast, abolition of the more serious grade-crossings, especially near terminal cities, and extensions and improvements in, and enlargement of terminals and freight yards.

Now every one of these developments has been dictated primarily by one requirement—increase of capacity. This is the keynote of all railroad development, however rated, for it makes possible an increase of revenue miles of freight or passenger traffic which can be carried on a given trackage or operative mileage of road, and results in a net comparative economy of cost per ton of freight or passenger moved. These improvements are all vital, no matter what the motive power, and they should ordinarily and naturally precede the application of electric power, for it is absolutely certain, except in specific instances, that if these have not been made before the use of electricity is considered, they must be taken up in connection with its introduction.

Here, as during the whole period of growth, the financial question is always present, ever dominant. There probably never was an official charged with the maintenance and operation of a railroad who could not see opportunities for judicious expenditure of capital, and whose requirements have not generally been greater than would be acceded to by the directors and stockholders of his road. On the other hand, it is probably rarely the case that those same directors and stockholders have not wished that the demands made upon them for capital were less than the actual demands, even where granted. The practical question, then, which confronts every railroad is how best can such capital as can be raised on reasonable conditions—which conditions are always variable, and sometimes appallingly oppressive—be expended to meet the actual requirements of the road and to get the largest net return.

The enormous cost of railroad developments has necessarily in a large measure been first met out of the profits of operation, because of the difficulty of raising additional money on account of early extravagances in capitalization, expenditure, and management. Much of this cost often never appears in capital account, but in the end additions thereto must naturally and very properly be made to replace in some degree the amounts diverted from revenue.

In spite of many gross examples of railroad dishonesty, and many unfounded charges affecting railroad officials, it is but proper to repeat a statement made privately a short time ago by one of the best known of the higher railroad officials in this country, a man who has grown up from the ranks and is now in a position that commands the universal respect and esteem of all who know him, that, certainly within recent years, for every thousand dollars which has been added to capital account many thousands have been put into road and equipment from earnings that has never so appeared.

Electricity is no panacea for railroad ills, any more than freight and passenger rates arbitrarily determined without regard to cost of service is a panacea for the body politic. I know of no business in which universal averages as a guide for individual decision can be more unfortunately applied; and this is equally true, no matter what branch of the railroad business

FIG. 4—New York Central 2200 h.p. direct-current electric locomotive.

is considered. Statistics covering the operation of all the roads in the country may demonstrate to the mind of the mathematician that if all the power used were supplied electrically from central stations instead of by steam locomotives, there would be an enormous saving in cost of power, and therefore electricity should be adopted, no matter what the other demands for capital, or what the net result of an equal expenditure in other directions might accomplish. Such a comparison would, if anything, seem to mean that on those roads where traffic is congested, and where the demand of power per mile of road is not only large in the aggregate but on the average, considerations of power economy should be much more influential; but they distinctly do not afford the slightest reason for assuming that the possible saving in power is of sufficient importance to lead to general consideration of electric operation on extended lines with sparse traffic, no matter what systems may be developed.

This criticism, if it may be so called, was objected to on the score that railroads of this latter class, while not properly present subjects for electrification, were changing their character, and that in time the density of traffic would be sufficient to warrant such adoption. This is precisely the point of my criticism. There are roads which can now properly consider the adoption of electricity. There are others which by no stretch of imagination can seriously consider it for many years to come, and the only time when they can do so will be when, by growth of traffic, development in the character of their equipment, and augumentation in financial strength they shall have arrived in the first rank of railroads. Why then dilute whatever advantages there are in the matter of economy—all of which are needed on even the best railroads—by consideration of such as are plainly out of present reach of electric equipment?

In discussing the subject of electrification of trunk lines, there is a tendency sometimes to ignore the varying conditions on the roads, and also the changes in methods of operation which the introduction of electricity may make possible. The railroads seem to be often regarded as systems which must be conducted very much on present lines, that is, operated with locomotive-drawn trains. In order to come to any clear decision, on many roads at least, this conception must be changed. There is no hard and fast rule of classification. A trunk line may generally be considered as a system joining important terminal cities, over which is conducted all kinds of traffic, through and local, passenger, express and freight, and, in the larger systems, a heavy suburban passenger service. The divisions and character of service of course vary widely, but the constant tendency is towards an increasing density of traffic, multiplication of tracks, and extension of the limits of local and suburban services.

When taking up the question of the adoption of electricity, railway officials are met at the outset by an unfortunate and confusing condition of affairs, largely due to manufacturing rivalries, individual partisanship, professional dicta, and gratuitous advice. These are in no small measure responsible for an apparent division of the engineering world into two camps, alternating and direct current, as in the earlier days of electric lighting, a division which it seems to me is entirely unnecessary and misleading.

At a recent meeting of the New York Railroad Club, the argument was advanced by one speaker that the general question of the adoption of electricity should be determined by a railroad quite independently of any details, and that systems, equipment, and methods of operation could then be safely determined. With this view I wish to dissent. A change of motive power involving vast expenditures of money and radical changes in methods of operation, cannot safely be determined upon except

FIG. 5—Group of eighteen 2200 h. p. electric locomotives.

after presentation of a comprehensive report, and a general plan of equipment and operation based upon an investigation of previous practice, present or pending developments, and an analysis of important features and details. And this seems all the more essential, for at the present time the technical press is filled, and the public ear vociferously afflicted, with the rival claims of the advocates of direct- and alternating-current systems; the merits and defects of single-phase, polyphase, and direct-current motors; and the beauties and ugliness, the danger and safety of various types of overhead and third-rail constructions. High and low potentials, 15- and 25-cycle frequencies, gearless and geared motors, and air and electric controls—all are actively exploited. Detail costs and economies, new methods of finance and bookkeeping, and changes in railroad operation and management are presented to the bewildered railroad man with enthusiastic confidence.

But above the discordant notes, and in the turmoil of varied developments there arises now and then the cry of standardization, not only such as is natural and not prohibitive of new advances in the art, but wholesale, explicit, and exclusive. For example, in a recent paper before this Institute, the view was expressed that but a single plan—the high-tension overhead trolley, with 15-cycle single-phase alternating-current motors—was possible of serious consideration on trunk line service, and that this system should now be adopted and standardized, despite the fact that there was not in existence a single equipment of this character in practical railway operation!

I do not intend to burden this paper with statistics, or abstruse mathematics—one can prove almost anything by them —but just here I will epitomize certain conclusions which I think will bear the test of time.

1. Of the two broad lines on which electrification can be considered, if increased economy, that is, reduction of operative expenses by replacing the steam locomotive with an electric one, with concentration of prime power and perhaps the use of water power, be deemed the dominant reason for change of motive power, then every wheel in an electrified division should be turned electrically; and the savings affected should pay not only a fair rate of depreciation of the total equipment, but a satisfactory rate of interest on the new capital expended, in fact a better rate than if spent in some other way.

2. Increase of capacity, both in locomotive haulage, schedule speeds, motor-car trains and terminal facilities, of a character impossible to steam service—all resulting in augmented traffic, and increased use and capacity of the dead part of the systems, the tracks and roadbed—will ordinarily be the more potent influence in leading to the adoption of electric operation, and will often warrant heavy capital expenditures.

3. Every large road is a problem which must be considered financially and technically on its own merits, and in most features other than those which without effort can be harmonized its decision will be of little practical concern to other roads.

4. The adoption of electricity will ordinarily begin with those divisions where traffic is comparatively dense, and once

adopted the territory over which it can be extended will naturally increase.

5. Terminal properties in great cities, underground and tunnel sections, and heavy mountain sections where duplication of tracks because of extra heavy construction cost is prohibitive offer an immediate field for the serious consideration of electrification.

6. There cannot now be safely established any final standard, or any single system selected as the best for all roads. What is the best for one might easily be less advantageous for another, and there is no valid reason why any road should adopt something fitting to a less degree its particular requirements because of the action of some foreign road.

FIG. 6—Ganz 1500 h.p. polyphase electric locomotive.

7. Extraordinary advances have been, and are being made, and new discoveries are always possible. The limits of none of the systems now in use are clearly defined, and it would seem both natural and wise that the various manufacturing, technical, and inventive activities should pursue every lead to its logical conclusion, for the best will be none too good.

It is not my intention in the present paper to investigate railroad economies, or to formulate any final conclusions in the matter of steam railway electrification, but rather briefly to analyze, and make running comment upon various phases of the problem often discussed by engineers; to give some comparative facts as they have thus far developed; to describe sundry developments in electric locomotive construction; and to illustrate in some detail features specifically characteristic of the three typical initial equipments now commanding attention.

Motor equipments. In discussing the selection of any system, the first thing to investigate is the motor. In railway operation that which is to be replaced is a steam locomotive, in other words, a motor supplied by a local boiler, furnace, and coal-bin: that which is proposed in its place is another motor, or group of motors supplied through a wire by bigger boilers, furnaces, and coal-bins, or by energy from a water power. The working conductor, with everything connected to it in transmission or generation, although essential, is tributary to the motor and its requirements.

It is not sufficient that the source of power can be made of any desired size, although it is an essential feature; in any case such concentrated generating equipment must supply a number of motors. What *is* essential, and in the last analysis vital, is that the new motor shall have not only certain mechanical advantages, to the extent of eliminating the evils of reciprocating parts and reducing the cost of up-keep, but above all it must have capacity, measured not alone by drawbar pull or speed, but by both, and it must be of sustained character; and this capacity, to accomplish more than the steam locomotive, must be greater than that of the latter. Such capacity should naturally be attained, first, by increase of the capacity of the individual motor or locomotive, and then, when this increase has reached its limit, by combining motors or locomotives under a common control by the multiple-unit system.

Limitation of design. The designing of electric railway apparatus is handicapped by certain physical limitations which it is not in the power of the designer to change; for example, gauge of track, size and number of drivers, length of rigid wheel-base, dead and total weights per wheel and axle, clearance of motors above the track, permissible speeds of parts, provision for accessibility and repairs, and capacity for heat radiation. Every steam locomotive, when properly designed, has capacity to slip its drivers on sanded tracks, and it can maintain nearly its maximum average drawbar pull for a considerable range of speed as long as its boilers can make sufficient steam. Although at the disadvantage of having reciprocating parts, its drivers being coupled together cannot slip individually. In short, it is designed of a weight necessary to get the tractive effort required to pull a definite load, and then for all the capacity in the matter of speed which its fire-box and boilers can provide for. Essential defects are that its drawbar pull varies widely, depending on the position of the connecting-rod, that it does not materially increase below a certain speed, and the steaming power is limited. Hence comes the limitation of the "ruling grade."

On the other hand, the electric locomotive, when likewise properly designed, provides a drawbar pull of constant character throughout the revolution of the driver, it increases to an extraordinary degree when necessary, and the capacity of the boiler supplied at the central station is ample. On all service, however, high *continuous* capacity of the motor is essential.

Capacity being, therefore, the keynote of the equipment, I shall discuss at some length the characteristics of conductors and motors used with direct current and with alternating current. In so far as these comments relate to single-phase alternating-current operation, they will in some measure be based upon the only existing commercial development of this character now in the United States, that is, upon the series-wound, commutating, single-phase motor with compensated fields, operated at 25 cycles.

Lowering the number of cycles to increase the capacity of the single-phase motor, as has been suggested although not yet developed in commercial practice, of course merits serious consideration, and I shall add some comments upon this proposed change.

Behavior of conductors. Both motors and conductors when used for direct current or for single-phase alternating current, present certain differences of such inherent character that there seems no present likelihood of material change; and this conclusion is as sound in regard to the motor-differences as it is in regard to conductors.

When used for single-phase alternating currents, conductors offer, by reason of self-induction, an impedance or resistance to current materially greater than they present to direct currents. This impedance, and the consequent loss of energy at any particular potential delivery, depends upon the shape and material of the conductor, upon the frequency of alternation, the density of current and the power-factor. Under ordinary conditions, a round copper conductor of, say, No. 0000 size, has at 25 cycles an impedance of about 1.6. But with iron or steel conductors this impedance is increased many times, because the magnetization of the iron and the self-induction drive the current toward the skin of the conductor, so that the body of it is useless, and it might as well be a shell of very much less weight.

This effect in steel rails increases with the quality and with the cross-section of the rail. For example, according to the report of the Test Commission of the recent International Electrical Congress, on 50-lb. traffic rails the ratio of impedance to direct-current resistance at 25 cycles and 300 amperes is about 5.4, while on 80-lb., rail this ratio with the same current is 9.0, with the curious result that increasing the cross-section of the rail does not apparently increase its actual capacity for carrying single-phase currents. Quite the contrary, of course, is the fact in regard to direct currents, the conductivity increasing with the cross-section and quality.

These statements are made not because of special novelty, but in emphasizing certain inherent differences in conductors in their behavior toward the two kinds of current additional weight is lent to the statement that the differences inherent in direct-current and single-phase alternating-current motors are likewise radical, and are probably permanent in character.

Types of motor. Among the many types of motors proposed for railway service, four are now being exploited:

Polyphase	alternating-current	motor	
Single-phase	"	"	repulsion type
"	"	"	series type
Direct-current		"	

Of these, two, the direct-current and the three-phase motors, each have a continuous rate of energy-input, while the single-phase motor has an intermittent and variable rate. Moreover, there is combined in the single-phase motor two distinct functions, those of a motor and a transformer, and the latter cannot be entirely eliminated. The result is a reduction in both continuous and overload capacities.

It is in this particular that the single-phase motor, despite a great amount of experimental development, has remained defective; and while not prohibitive to the extent of making it an unworkable machine, its defects are so inherent as to place it at a serious disadvantage in individual comparison with other types of motors. To attain the preeminence hoped for, the external advantages in current supply must be very marked. In fact, rated in the same manner and under like physical conditions, it is only about half as good as the direct-current motor. Or to put it another way, the weight of the complete single-phase electrical equipment on a car or locomotive, including transformers, motors, and controlling apparatus, for continuous hard service, and with like physical limitations and ventilation, is about twice that required for direct-current apparatus. In addition to this there is, of course, a material increase in the mechanical equipment necessary to carry the electrical apparatus. The reason is simple—it is because of the heat generated on account of lower electrical efficiency, and the

FIG. 7—New Haven 1000 h.p. alternating-current electric locomotive.

working the fields of the motors at a reduced magnetic flux.

When considering locomotives, the net result is that the total weight of a single-phase alternating-current locomotive, with a service capacity equal to that of a direct-current locomotive of like armature speeds and permissible temperature-rise (this temperature-rise being the ultimate limitation of a motor for continuous service) will easily be from 30 to 50 tons more.

An increase in the total weight of a train amounting to from 3% to 10% is perhaps not of itself of so much importance, because such a difference in net power demand can easily appear for various reasons; but a ratio of 2 to 1 in capacity for the limit of equipment possible to install within given allowable dimensions and number of units is a matter of vital importance.

If an increased weight is permissible for any given capacity, there must be some ample compensation for it. Of course this is claimed to be the fact in the single-phase system, but another possible advantage which might prove important is the abolition of gearing and bearings, and simplification in motor and locomotive construction. Both advantages can hardly be hoped for.

Comparative weights of direct-current and 25-cycle single-phase alternating-current motors. While testimony is practically universal that not only is any single-phase motor, whatever the number of alternations, more or less inefficient than a direct-current motor of like weight or capacity, the differences of efficiency, excluding the losses in the gearing, are variously estimated.

A curious illusion relating to this subject seems to possess a number of well-known men, as was illustrated by an active discussion before the English Institution of Electrical Engineers of Mr. F. W. Carter's paper on, " Technical Consideration in Electric Railway Engineering," at the meeting in January, 1906. Mr. Mordey, while stating that there is a large difference in the efficiency of direct-current and single-phase alternating-current motors, claimed that inasmuch as we are concerned with the efficiency of the whole system it makes no difference where this loss appears, and that this difference of energy may easily exist in a direct-current system if the cars are not properly handled. Mr. Carter very properly corrected him, and pointed out that the location of this loss is vital, as it determines the heating of the motors, and if appearing in them it meant from two to three times the heat generated to be dissipated from the equipment. This is but another way of saying that a greatly increased weight of equipment is necessary with the machines of lower efficiency.

The reason for the reduced efficiency of the single-phase motor (whatever the actual amount, which depends upon a number of factors) is inherent, and is due to the transformer action which by increasing the losses limits the output of the motor. There is an additional loss of considerable consequence. Electrical efficiency, it must be borne in mind, is the ratio between the real output and input. The net input is, however, not the product of current and potential, as in a direct-current motor, but is affected by the phase-relation, commonly known as the power-factor; and when this is below 100% it means that the actual watts input is less than the product of potential and current or volt-amperes. To put it another way, the actual current input is greater than would be required if the power-factor were unity. As ordinarily rated, efficiency does not take account of this fact, but the increase of current actually means an increased I^2r loss, hence greater heating, and a consequent further reduction of motor-capacity.

It is well, just here, to point out that an increase of 10% in the amount of current used on a direct-current system, because of improper gear-ratio, change of schedule, or careless handling of equipments by motormen does not mean that this excess energy is dissipated in internal losses in the motors, for these may be increased only about one per cent. The situation in regard to the single-phase motor is, however, entirely different, for it is subject not only to increased power consumption with its proportionate losses because of careless operation, but it also has its individual increased internal loss, which is variously estimated to be much more than that found in properly designed direct-current motors of equal weight and like physical limitations.

Much, indeed, has been stated, and denied on this subject of the relative weights and capacities of direct-current and single-phase alternating-current equipments. On several occasions I have stated that, measured by equal physical limitations in speed and clearances, and for the same temperature-rise with natural ventilation, the total weight for any given service would be twice as much with the alternating-current apparatus as with the direct-current. A similar view has been expressed by other investigators, among whom I may mention Carter, Parshall, and Hobart.

Statements of this character, no matter how authoritatively and carefully made, seem to lie under the suspicion of individual prejudice. Since this is an engineering matter of so much importance, I have endeavored to get some exact facts. These will, I think, prove interesting, and I will show graphically, illustrating somewhat further by specific statements, the actual comparison between two motors of almost exactly the same weight.

It is customary to adopt a single-phase alternating-current motor rating which is based upon the performance of some direct-current motor. For example, a 125-h.p. single-phase machine is supposed to do the same work, that is, handle the total number of tons on some specified service, as a 125-h.p. direct-current motor. This may be an ingenious comparison, but it is a very specious and misleading. The fact is that such a motor equipment, including its transformer, will be very much heavier than the motor equipment with which it is compared, and consequently the net load which it can handle will be much less.

What *is* of vital consequence is a *comparison of capacities for equal weights*, not only of motors but of total apparatus which must be carried on a car, and also to compare the speed-relation and the polar-clearances, in other words, the allowable wear of bearings, all of which is quite aside from gear and commutator brush considerations, which are of themselves serious.

Valatin and others have indicated one measure of comparison between motors of different makes, types, and capacities—the "weight-coefficient,"—which for convenience may be expressed by the following equation:

$$\text{Weight-coefficient} = \frac{\text{Nominal rated horse power}}{\text{Revolutions} \times \text{weight in tons}}$$

This is a factor of the greatest importance, and it should be considered not only for the one-hour 75°-rise load, but throughout the whole thermal curve.

Let us investigate two motors, which for convenience we will call X and Y, both standard modern machines.

An initial comparison is as per this table.

Machine	*Type*	*Voltage*	*Air-gap*	*1-hr. rating*	*Weight*
X	d.c.	550	0.25	240 h.p.	5,473 lb.
Y	25∼a.c.	225	0.10	125 h.p.	5,274 lb.

The weights are minus pinions, gear, and gear-cases. There is a difference of less than 4% in net weights, or about 2.5% in total weights. They can, therefore, be very properly compared.

In passing, I would call attention to the air-gaps, that of the direct-current motor being nearly three times that of the alternat-current motor—a difference of vital importance as affecting allowable bearing-wear, and the proper functioning of the armature circuits under practical operating conditions.

The accompanying curves (Fig. 8) show graphically, almost startingly, the comparative speeds, capacities, and weight-coefficients of these machines, all referred to the time required to

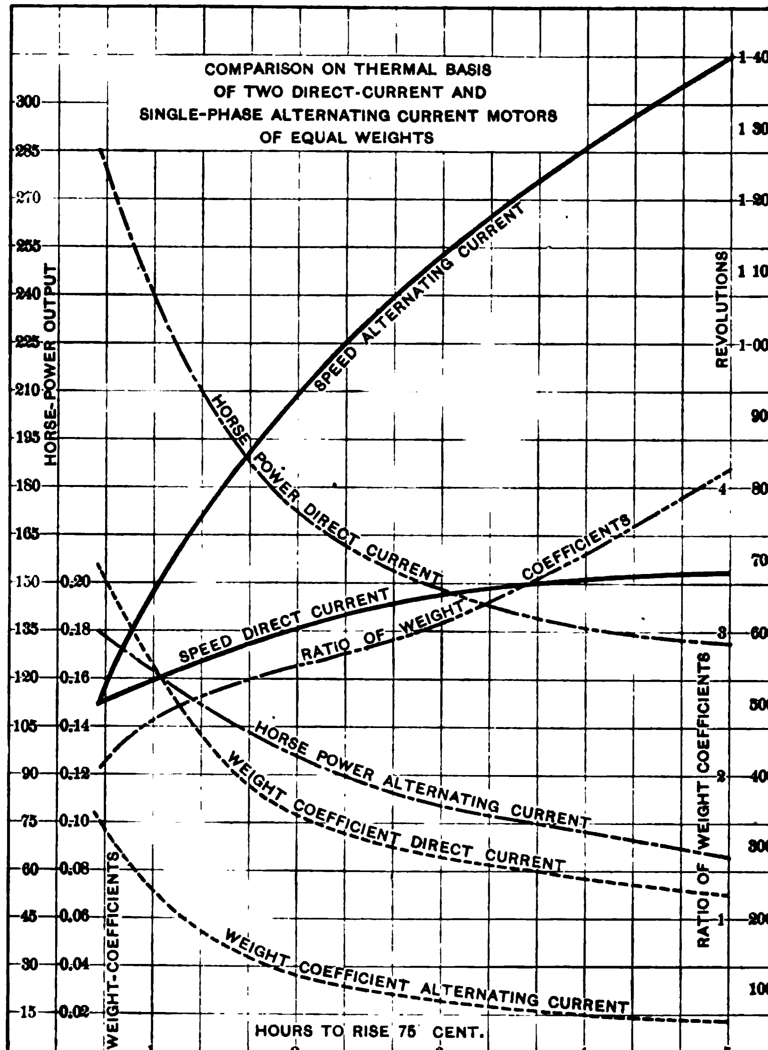


Fig. 8.

rise 75° in temperature when operating at full normal potential under varying loads and with natural ventilation.

It so happens that these two motors have the same speed—

500 revolutions—when run at their proper potentials for 39 minutes with such loads as will give temperature rises of 75°, and hence this will be taken as the starting point, and the characteristics noted for various runs up to five hours.

Inspection of these curves shows the following comparisons:

Time for 75° rise	Capacities D. C.	Capacities A. C.	Ratio of capacities D.C. + A.C.	Speeds D. C.	Speeds A. C.	Ratio of speeds D.C. + A.C.	Wt. Coefs. D.C.	Wt. Coefs. A.C.	Ratio of Wt. coefs. D. C. + A. C.
39 min.	285	134	2.13	500	500	1.00	0.208	0.101	2.06
1 hr.	241	122	1.98	530	664	0.80	0.166	0.070	2.37
2 "	172	95	1.81	602	932	0.65	0.104	0.038	2.74
3 "	148	81	1.83	650	1130	0.57	0.083	0 027	3 07
4 "	137	72	1.90	670	1270	0.53	0.075	0.021	3.57
5 "	132	64	2.06	690	1398	0.50	0.070	0.017	4.12

Generally speaking, it will be noted that: starting at 500 revolutions for a 39-minute run, the capacity of the direct-current motor averages approximately nearly double that of the alternating-current throughout the thermal range; the speed of the alternating-current motor rises at a much more rapid rate, until on a five-hour run it is double that of the direct-current motor, despite the fact that it is only developing one half the power; the direct-current motor has a 5-hour capacity in excess of the 1-hour capacity of the alternating-current motor; and the ratio of the weight-coefficients, beginning at a trifle of over 2 to 1, rises to more than 4 to 1 in favor of the direct-current motor on the longer runs. This comparison of weight-coefficients does not include the collectors, control-switches, rheostats, transformers, or wiring, which in the aggregate are enough heavier for the alternating-current motor to maintain these disparities.

It is evident, therefore, that a pair of these alternating-current motors can handle only about one half of the total load of the direct-current motors, with all the disadvantage of higher armature speed and smaller air-gaps; and considering the excess weight of the control apparatus, the net load over and above the electric equipment would be considerably less than one half.

This general comparison is not, so far as the relative characteristics are concerned, individual to this particular size of motor, but seems to be equally applicable through a wide range, and indifferently as to the make, or whether the alternating-current motor is of the series-compensated or the repulsion type. Furthermore, these differences are seemingly so inherent that there is little chance for improvement at 25 cycles.

Let us see the practical application of these facts. The passenger service on a certain typical trunk-line division requires cars of such size that, operated on a direct-current system they would be equipped with 2 X's, and if on a 25-cycle current system with 4 Y's. With equal seating capacity the following are actual comparisons:

a. Total weights of electric equipment, including 500 lb. excess on trucks:

Alternating current,	(4 Y's)	35,000 lb.
Direct current,	(2 X's)	16,000 "
Excess a.c. over d.c.	(118%)	19,000 lb.

b. Total nominal rating of equipments:

Alternating current,	(4 Y's)	500 h.p
Direct current,	(2 X's)	480 "

c. Rating per ton of total weight, including car-body and seated passengers:

Alternating current,	(4 Y's)	9.92 h p
Direct current,	(2 X's)	10.67 "

d. Approximate costs of electric equipment:

Alternating current,	(4 Y's)	———
Direct current,	(2 X's)	———
Excess alternating current over direct current	(100%)	

Polyphase and direct-current motor characteristics. Opposed to the two types of single-phase motors are the polyphase and the direct-current motors, the former with a rotating field, and the latter with a field of fixed character. They have similarly high weight-efficiencies, the former having somewhat the advantage when compared with the ordinary type of direct-current motor.

The polyphase motor, however, is a normally constant-speed machine. It can, through a rearrangement of fields, be run at two different speeds; but each is practically a constant one. Or where there is a plurality of motors, half and full speed can be obtained by having one of different character from the other, and operated in cascade relation to it, with the necessity, however, of throwing one-half of the motors out of service when running at full speed. With cascade operation and field changing combined there can be three running speeds. These motors, so far as their supply is concerned, have been limited for practical reasons to a potential of 3000 volts on the trolley, because the supply requires, besides the rail, two wires overhead, although a recent undertaking in the United States, the operation in the Cascade Tunnel, is to be attempted at 6000 volts.

Polyphase motors have an enormous overload capacity, and the fact that they run at synchronous speeds with a very small slip, and if the frequency is unchanged will run upgrade nearly as fast as on a level, would indicate at first

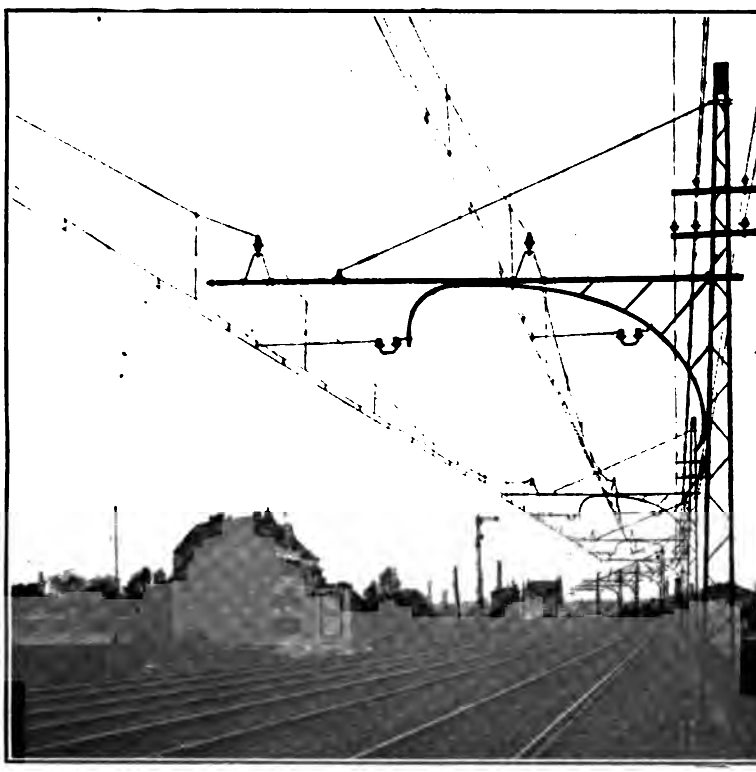


FIG. 9—Multiple catenary on Blankenese-Ohlsdorf Railway

sight excessive loads on main and sub-stations. But a curious and perfectly natural result has been pointed out by Cserhati and von Kando, namely, that with suitable provision for regulation at the central station, so that with excessive loads the generators will drop in speed, there will, with such speed reduction, be not only a temporary cessation of drawing power by the locomotive, but there may actually be a return of energy to the line while slowing down. While of course this slowing down affects all trains on a system, it is quite conceivable that when there are a number of trains in operation a mean result may easily be attained which will, in the matter of load-fluctuation, compare favorably with that of any other system. Multiple-unit grouping and operation is ordinarily impracticable because of the small slip. In spite of the splendid work done by the Ganz Company, and the strong support of many Italian engineers, I feel that, all things considered, neither the motor characteristics nor the limitations of overhead construction are acceptable for such service and conditions as exist on our trunk-line roads.

On the other hand, considered by itself, the direct-current motor, with its high average weight efficiency, simplicity of construction, facility of control, automatic response in torque and speed to varying grades and curvatures, and great sustained capacity for enormous torque at low speed, besides the advantages of speed-ranges obtained by motor-grouping, and the use of a single conductor and track return, offers a most effective machine to meet the conditions of railway service. Through it, as with the polyphase machine, the "ruling grade," often of limited length, is eliminated, for the motor can always respond to these temporary demands up to the limit of track adhesion.

In the matter of speed-variation, the ordinary four-motor locomotive has, with proper control, three impressed electromotive forces, for each of which there is the same torque with a given current, while the aggregate current from the line varies as does the speed of the locomotive itself at any fixed torque, about 400 per cent. For each of the combinations there is a wide controlled automatic range of torque and speed, which as the sustained torque increases is far beyond the limits of the single-phase motor, and for a wide range of torque there is possible a considerable variation of speed by field-shunting.

These various features of torque- and speed-control are of the utmost importance when, under some abnormal conditions of traffic, it may become necessary to relieve the demand on the supply, although maintaining a high draw-bar pull, or when, as in the operation of snow-plows a number of pushing locomotives under a single control must run at slow speed for considerable periods of time.

Direct-current motor improvements. During the last two

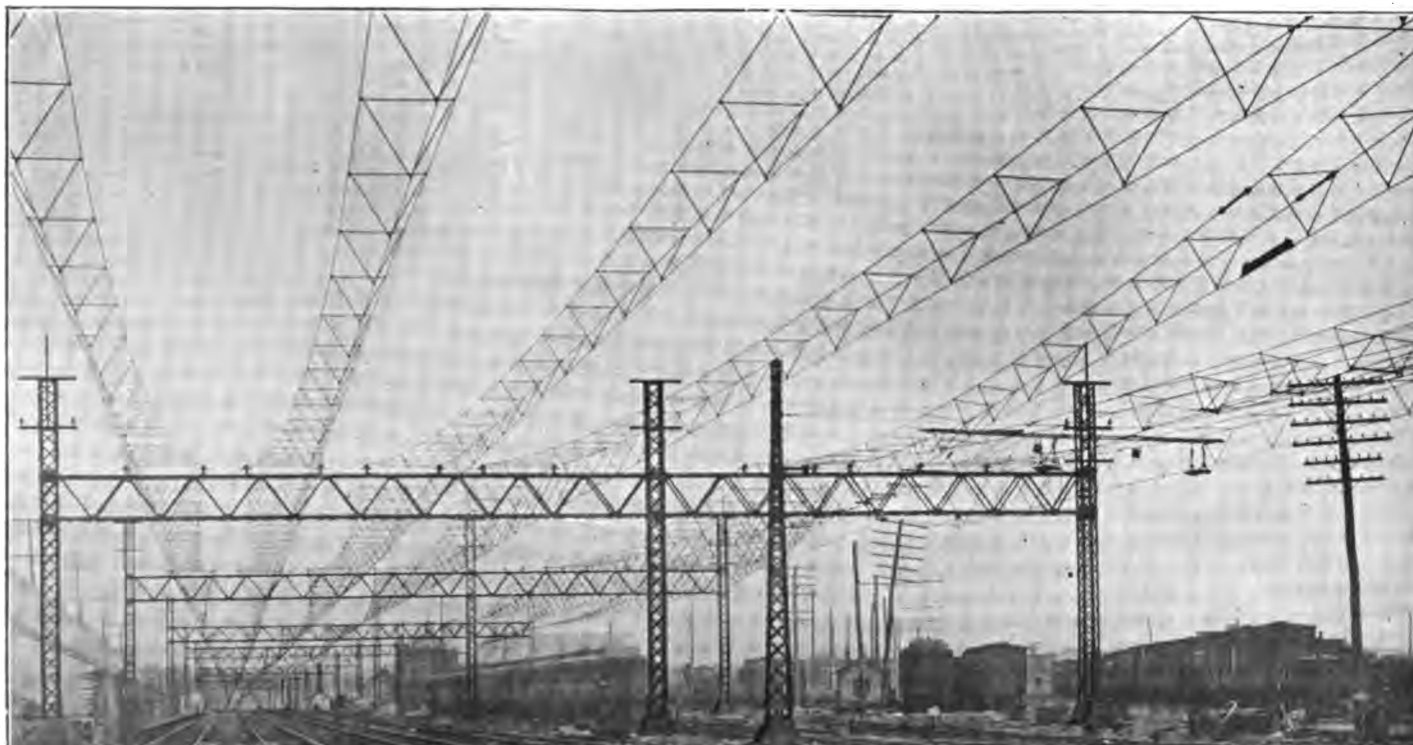


FIG. 10—Double overhead catenary trolley on New Haven Railroad. Four tracks and siding

years important developments have taken place in direct-current motor construction which materially change any preconceived conclusions as to its limitations.

The first is the introduction of the commutating pole, which has practically eliminated commutator troubles, such as sparking, undue heating, and flashing over, so that even a four-pole machine, within a wide range of potential and load, runs absolutely black at the brushes. That this improvement has reached a high degree of commercial standing, despite very recent technical criticism and opposition, is evidenced by the fact that orders for nearly a thousand railway motors have been placed within the last two months.

This improvement makes possible the shunted-field addition to the series-parallel control of speed, the construction of motors for operation at much higher potentials, and the operation of two motors in series at double potential. The partial dependence of one motor on another when two machines are in series is not individual to this combination, for with single-phase alternating-current motors, especially of the larger capacity, the heavy currents required because of the low potential at which the motors are operated—200 to 250 volts—has led to permanent series or series-parallel connection of machines.

An especially important development is that illustrated by the gearless locomotives built for the New York Central Railroad (Fig. 4), in which the hitherto invariable practice of maintaining a fixity of relation between the armature, or rotating part, and the field-magnet, or fixed part, has been abandoned; the armatures are mounted directly on the axle, the field-magnets forming a part of the locomotive-frame, supported by its springs and hence movable with regard to the armatures. In this construction, therefore, there are no armature or field bearings. This locomotive is of the simplest type possible, electrically and mechanically; and when operating under conditions for which it is properly applicable it has not only the highest weight-efficiency, but the lowest cost of repairs of any direct-current machine, and much lower than is possible for any single-phase locomotive. It is structurally a natural high-potential machine on account of having but two poles.

Since the capacity of electrical apparatus depends upon the speed at which, with any magnetic flux, the armature conductors move, this gearless type of locomotive, if used for the slow speed and heavy torque required on freight service, can only

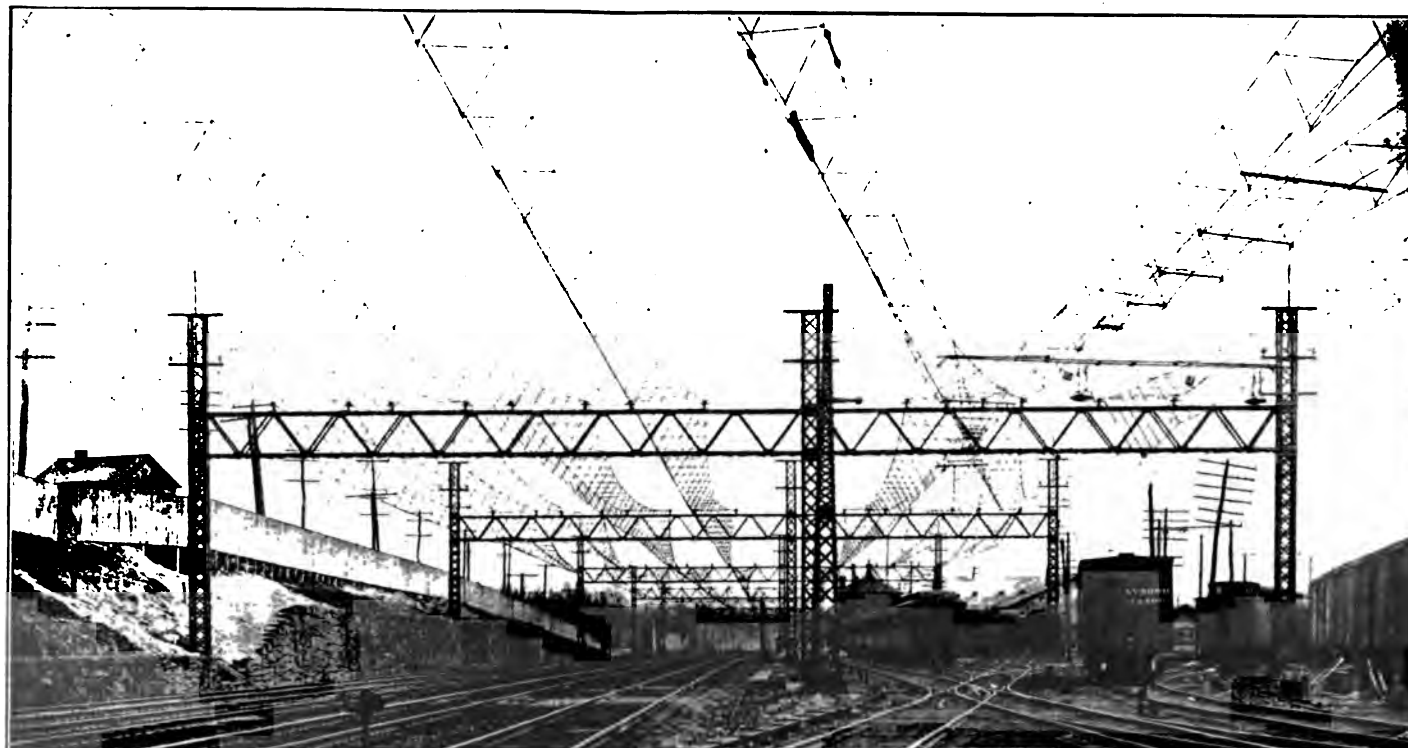


Fig. 11—Double overhead catenary trolley on New Haven Railroad. Four tracks and cross-over

be constructed with reduced weight-efficiency as compared with geared locomotives; but despite this handicap there are so many special advantages that it can be seriously considered even for this service.

Difference between direct-current and single-phase alternating-current motors. The present inherent differences between single-phase and direct-current motors may be briefly summed up as follows:

1. The input of current in one is continuous; in the other intermittent.

2. One has a single frame, the electrical and mechanical parts being integral; the other has a laminated frame contained within an independent casing. Hence there is not equal rigidity, or equal use of metal.

3. One has exposed and hence freely ventilated field-coils; the other has field-coils imbedded in the field-magnets.

4. One has a large polar clearance, and consequently ample bearing-wear; the other has an armature clearance of about only one third as much, and hence limited bearing-wear.

5. One is operated with a high magnetic flux, and consequently high torque for given armature-conductor current; the other has a weak field, and consequent lower armature torque.

6. One has a moderate sized armature and commutator, and runs at a moderate speed; the other, with equal capacity, has a much larger diameter of armature and commutator, and runs at a much higher speed.

7. One permits of a low gear-reduction, and consequently a large gear-pitch; the other requires a higher gear-reduction, and a weaker gear-pitch.

8. The windings of one are subject to electrical strains of one character; in those of the other the strains are of rapidly variable and alternating character.

9. The mean torque of one is the corresponding maximum; the mean torque of the other is only about two thirds of the maximum.

10. The torque of one is of continuous character; that of the other is variable and pulsating, and changes from nothing to the maximum fifty times a second.

11. One has two or four main poles only, two paths only in the armature, and two fixed sets of brushes; the other has four to fourteen poles, as many paths in the armature, leading to unbalancing, and as many movable sets of commutator brushes.

12. One can maintain a high torque for a considerable time while standing still; the other is apt to burn out the coils which are short circuited under the brushes.

13. In one, all armature-coil connections are made directly to the commutator; in the other, on the larger sizes resistances are introduced between the coils and every bar of the commutator, some of which are always in circuit, and the remainder always present.

14. In one the sustained capacity for a given weight is within the reasonable requirements of construction; in the other it is only about half as much.

15. Finally, the gearless type, with armature and field varying relatively to each other, is available for one, but this construction is denied to the other.

Consideration, then, of the characteristics peculiar to each class of motor indicate, not that the single-phase motor cannot be used, but that if adopted the weight or number, and the cost of locomotives or motors required to do the work must be much greater; that the depreciation of that which is in motion will be much higher; and that there will always be an excess weight of fixed amount per unit which must be carried irrespective of the trailing or effective loads. We must, therefore, in many cases be led to the selection of the direct-current motor, that motor which has the higher weight capacity, the greater endurance, and the lower cost per unit of power.

Electric braking. Recuperation of energy to reduce the amount of power used, and to make the motors act as brakes to retard the acceleration of a train, has been a favorite project, and attended by many prophecies since the beginning of the electric railway industry. I confess to having been very early infected with this economic ambition. In fact, I demonstrated mathematically quite correctly and satisfactorily a good many years ago, before the Society of Arts in Boston, that if the Manhattan Elevated Railway of New York could be equipped electrically with shunt-wound motors whose speed-variation was effected partly by resistance in the armature circuit and then by variation of field strength, there would be a reduction of central-station capacity of fully 40% as compared with a system which did not use the motors as braking generators; and not only was there this theoretical reduction in capacity, but since every stopping train, and every train on a

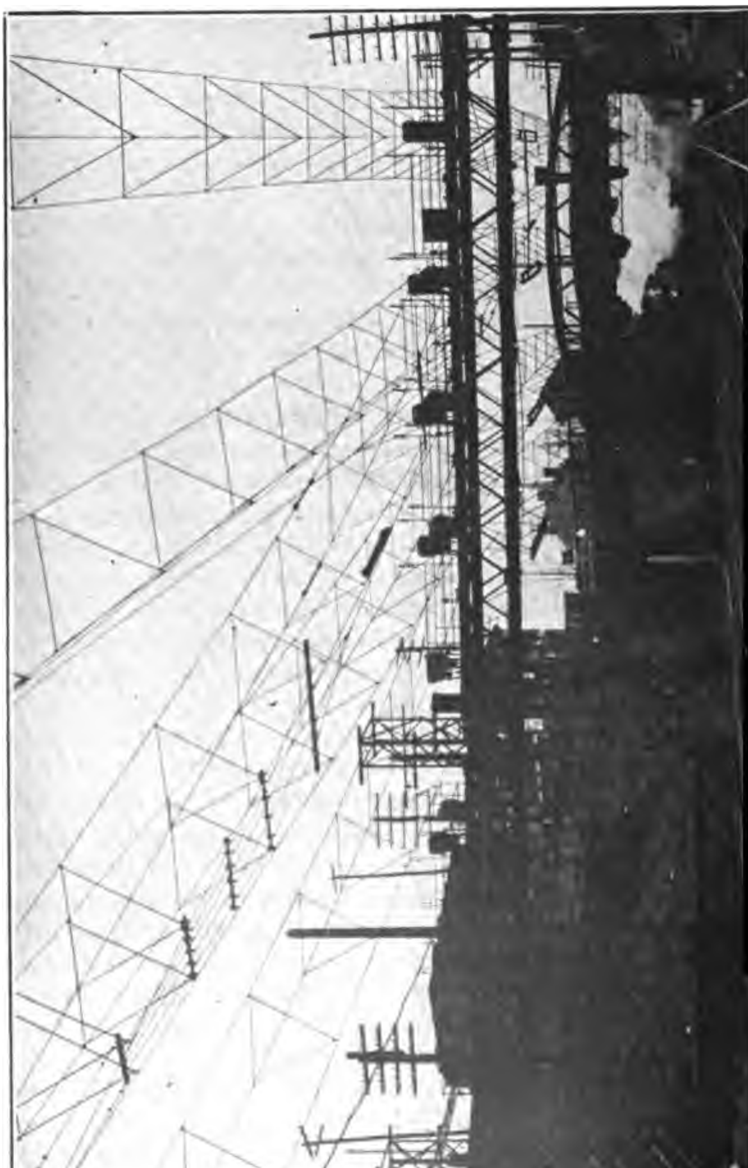


FIG. 12—Double overhead catenary trolley on New Haven Railroad
Cross-over, anchor bridge, and section switches

down-grade was a moving generator there would naturally be materially less losses on the line. These facts were demonstrated practically. by experiments carried out on the Thirty-fourth

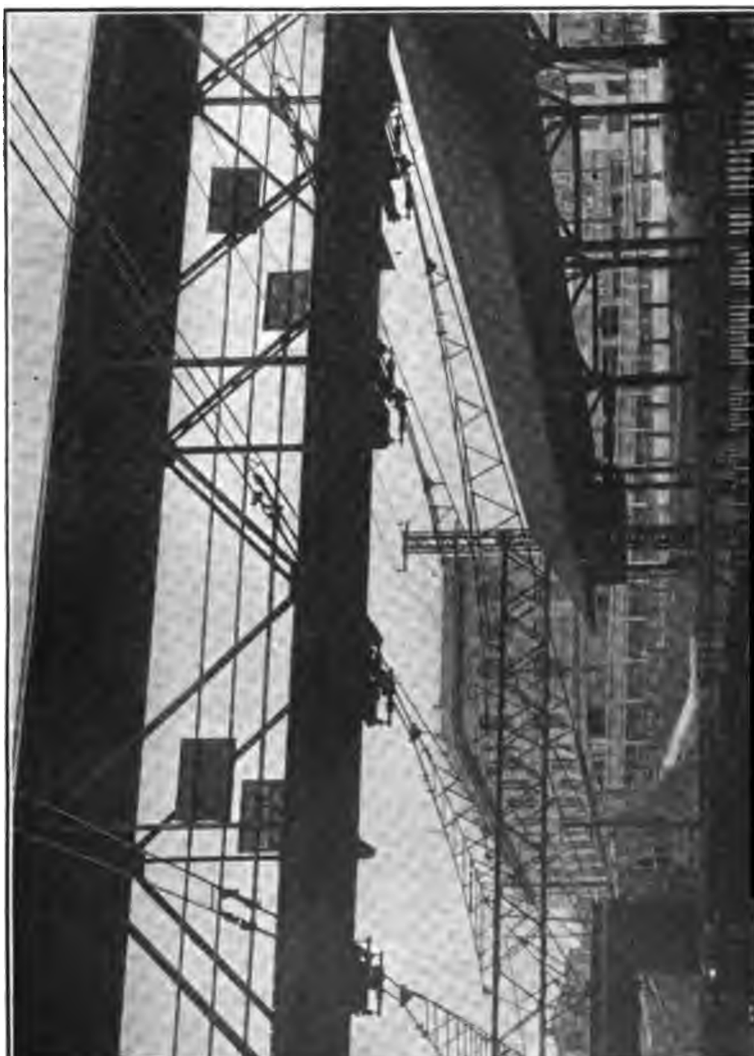


FIG. 13—Double overhead catenary trolley on New Haven Railroad. Depression under crossing highway bridges

Street branch of the elevated railroad for several months in the winter of 1885–6. But the system is not used to-day, despite its enormous possible saving of power and station capacity, because it required the use of shunt motors with their fine-wire field-windings, and hence necessary reduced capacity compared with the modern series motor; it required, also, a very exact equalization of the characteristic of motors and maintenance of like wheel-diameters, and an increase of motor-capacity and weight because of the double duty and consequent heating. Here again capacity has been an important and finally determining factor in motor requirements and practice.

On ordinary railroads the gradients are not sufficient to make it worth while to attempt any recuperation of energy; the acceleration due to any excess of gravity-coefficient above that necessary to overcome the friction of the train is usually welcomed. On mountain roads, however, electric braking may become an important adjunct, not because of power economy, but for safer operation. In any case, simplicity of application and absolute reliability of action are first essentials.

There are two general methods available: one, in which the energy of the descending train drives the motors, acting with shunt- or independent-field characteristics, at an aggregate potential above that of the line at the rail, and sending current back into the line; another in which the motors are disconnected from the line, and driven as self-exciting generators on a closed circuit, as much of the energy of the descending train as desired being used up in heating rheostats.

The first method is dependent on the line, requires external excitation of the field-magnets, and where direct-current motors are directly connected to the line, two armatures should be thrown in series if the power to slow the train down to or below its ascending speed on heavy grades is desired. This is because the excitation of the fields is carried to saturation on ascending work, when the motor electromotive force is much less than that of the line plus the drop on the supply conductors, and permits of no further increase of flux to raise it. Such independent excitation of fields should be through a motor-generator set to get the current of low potential in large volume necessary for the series fields.

This method is, of course, possible of application, and will give a range of control of speed from about the mean speed on ascending grades to double that speed; but it will be with inequality in heating of the armatures and the fields, the latter running cool, and the former practically at their average maximum.

It is not practical to set the control for a given down speed, and then to vary speed by the air-brake, for the braking power of the motors is measured by the relation of their potential to that of the line, which is variable. To be effective, this potential must be raised sufficiently above that of the line, wherever a locomotive may be, not only to send back current, but current in considerable volume over the conductors intervening between it and such other locomotives or stations as may be able to take up the energy thus created. The motors are therefore under a constantly varying condition, and are also subject to excess potential strains. Application of the air-brake to slow down a train would under such circumstances reduce or destroy the braking power of the motors unless their controllers were simultaneously moved. In fact, such air-brake application could readily convert the machines into motors taking current from the line, and hence put double duty on the brake-shoes.

The second method of braking is to use the motors without disconnecting the field and armature circuits from each other, simply closing them upon themselves, and varying the resistance in circuit, the reversers on down grade being set for backward movement. This method requires no change in the organization of the machine, puts equal duty on armatures and fields, as in ascending grades, and the duty on the armatures being considerably less than in the other method of braking they will heat much less.

This method, if provision be made for moving the controller, is independent of the line, and permits of the most complete variation of speed, from the highest permitted to the lowest at which it may be desired to operate, without any use whatever of the air-brake, unless desired, and without in any manner interfering with the application of the latter, although, of course, to get the best effect, both motor-controller and air-brake should be used with regard to each other. There is, however, no possibility of the application of the latter entirely destroying the braking power of the motors.

This latter method of braking does not depend upon line supply, nor require the interposition of any motor-generators, and is therefore more direct and reliable. Another fact of importance is that the aggregate motor potential strains are less. Provision for both methods of braking, although possible, is not advisable because of the introduction of too great a variety of apparatus and methods, which may give rise to confusion and accident, and which in all cases of railroad operation should be avoided as far as possible.

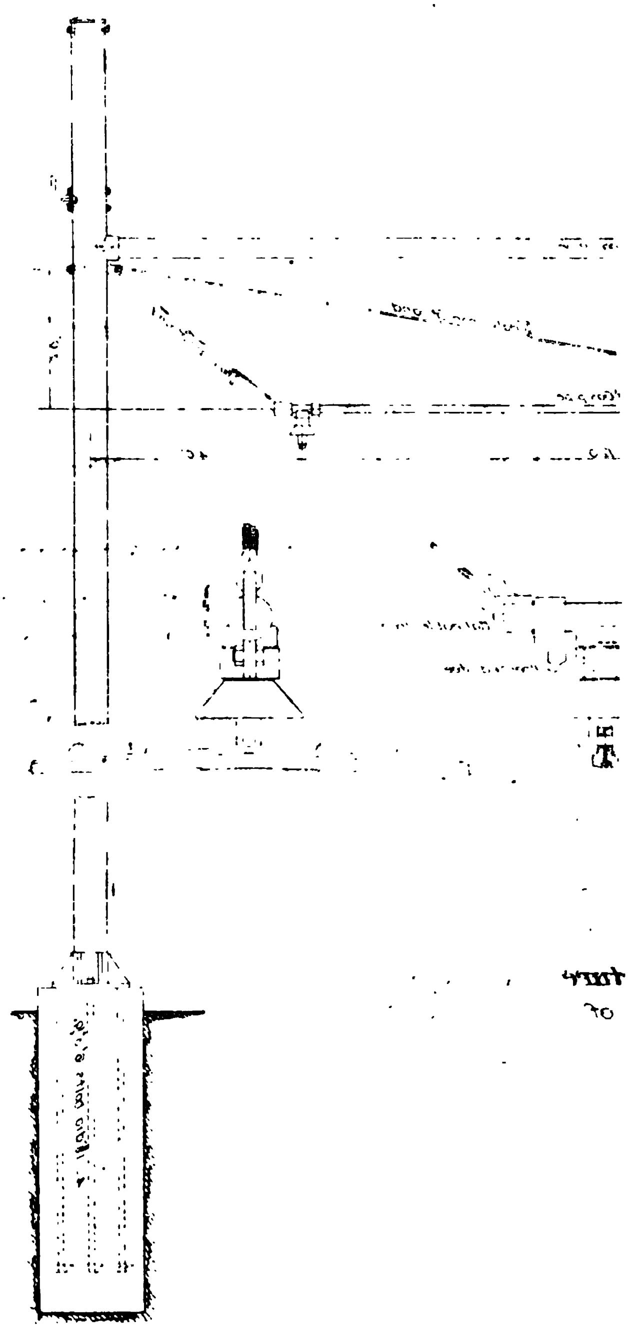
With polyphase motors kept in connection with the line, the braking effect is very similar to that of pure shunt motors, and the excess of down speed is very small. It is doubtful, however, whether with the varying grades and curves of our mountain roads it is desirable to run down-grade at an approximately fixed speed, but rather it seems likely that the existing practice of speeding where the grades and curves are light, and reducing the speed where the grades are heavy and the curves are sharp will remain the preferred practice.

Self-exciting braking is impracticable with polyphase motors.

Comparison of direct-current and alternating-current braking. On the general subject of braking it should be pointed out that with direct- or continuous-current motors there is always a residual magnetism in the fields because of their construction, and the fact that the exciting current never changes direction. Such machines, therefore, can always promptly build up automatically when properly closed upon themselves and the reverser is set in the proper direction.

A similarly effective method of braking has been claimed for motors operated by single-phase alternating currents, but it would seem that in this case there is not the same degree of reliability. In such motors the field is laminated to the last degree to cut down heat-losses and to increase the capacity; it will hold but little residual magnetism under any circumstances, and furthermore the field is excited by a rapidly varying alternating current. It is therefore possible that at times the field will be nearly inert, and comparatively slow, with its low-turn winding, in building up, or possibly the field may be entirely inert, and refuse to build up at all. There seems, therefore, no certainty whatever that a single-phase alternating-current motor, disconnected from the line, and without any other exciting source, will, when closed upon itself, always build up into a braking dynamo.

Aside from the ordinary objection of having such a possible failure, the consequence might be serious should it be necessary suddenly to call upon the machines to brake; as, for example, when getting underway, or when slowly ascending a grade there should be a failure of current, and the train begin to back down before the air-brakes were applied, or in case for any reason they should not be promptly available.



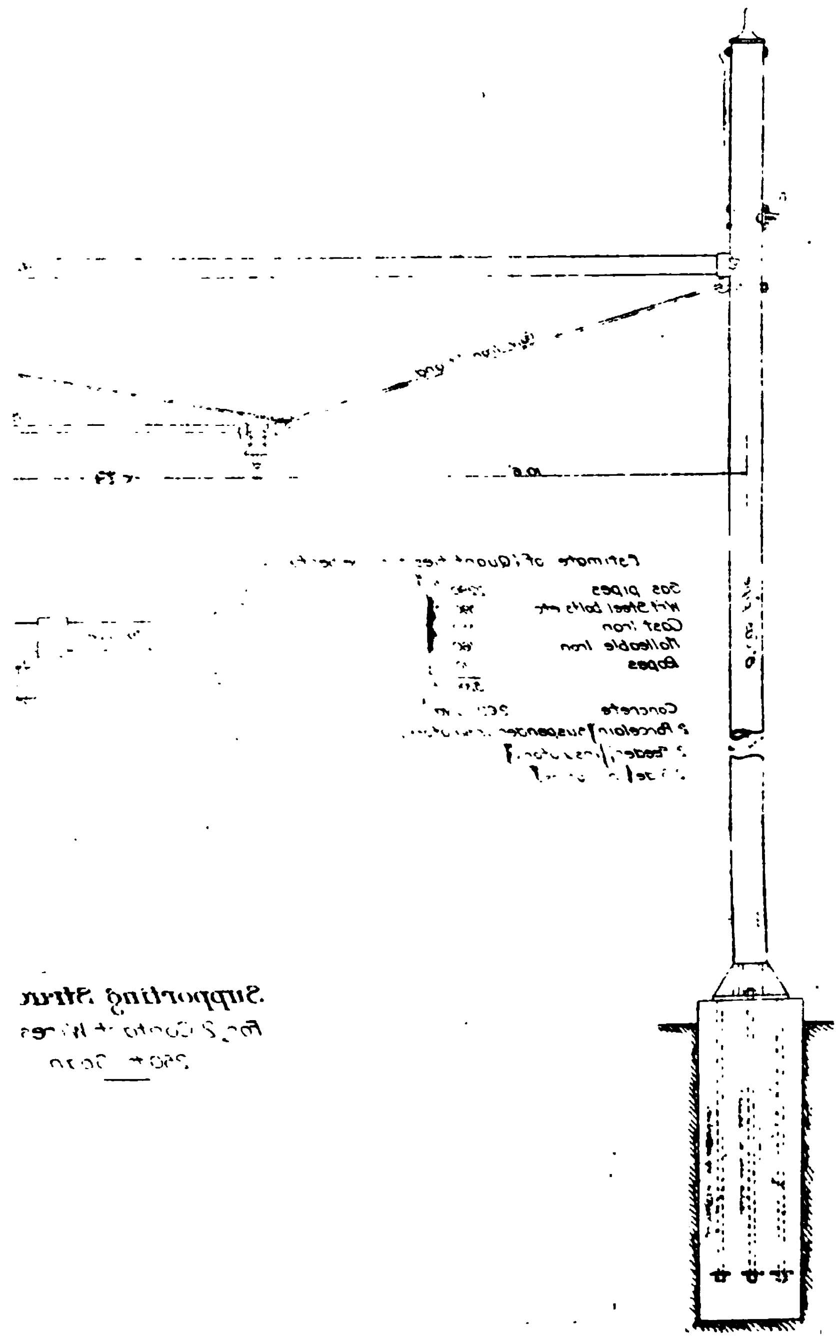


FIG. 14.—Joseph Mayer's method of

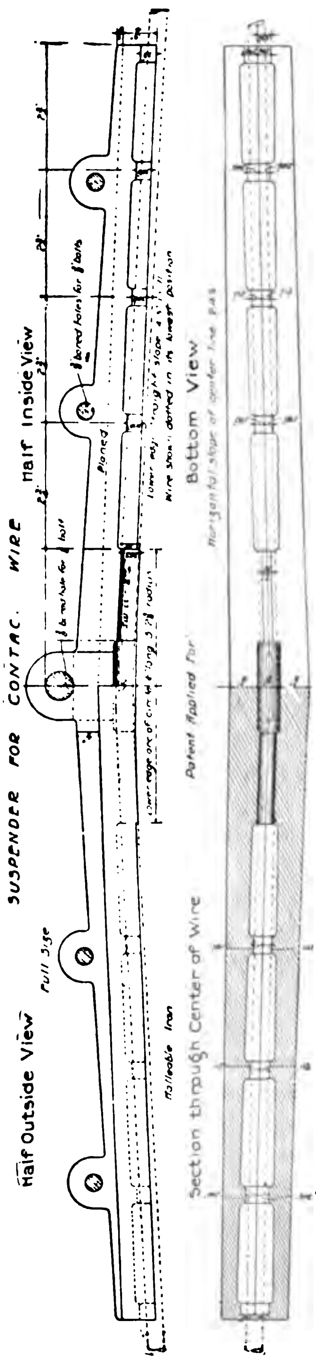

SUSPENDER FOR CONTAC. WIRE
Half Outside View
Full Size
Half Inside View
Malleable Iron
Planed
Patent Applied For
Bottom View
Section through Center of Wire

FIG. 15

All things considered, reliability and simplicity of operation dictate the use of the self-exciting method of braking with the direct-current motor, which lends itself to that purpose in the highest degree.

Extent of electric braking. However theoretically desirable it would be from an economic standpoint to utilize the energy of a descending train to generate current available for partial propulsion of trains moving on up-grades, it is to be borne in mind that the localized braking of an electric locomotive is not intended to, nor can it entirely replace air-braking; it is proposed primarily for the purpose of eliminating certain existing troubles unavoidable in connection with air-brakes when used continuously on long down-grades.

In trains made up of the average run of freight cars there is a non-simultaneous action of the air-brakes, and often, if after long continued application the brakes are released for a brief time so as to re-charge the train-pipe, the front end of the train being unbraked will surge ahead, and the rear part will for a brief time be held back by the non-released or partially released air-brakes, resulting in a parting of the trains.

Another serious trouble, overheating of brake-shoes and wheel-rims, leading to breakage of parts on account of expansion or sudden chilling, cannot well be avoided where there is such a continuous application of air-brakes as is required on free movement of freight trains on long grades; this is a difficulty which it is best to avoid by supplementing the air-brake by other braking means not dependent upon brake-shoe application.

The objections cited will be largely removed if the duty on air-brakes can be materially reduced, and sometimes entirely relieved. Electric braking on the method I have indicated will accomplish this, and it seems wise normally to divide the duty between electric and air-braking. For that reason I will give an illustration of the duty on the motors, as this will have a direct bearing upon the capability for the radiation of energy in the form of heat from the rheostats in circuit.

Suppose a 700-ton train operates on a grade requiring tractive efforts per ton of,

For lifting	25 lb.
For traction and curves	8 "
Total	33 "

On down movement, 17 lb. only will be available for acceleration of speed, which must be taken up by braking in some form.

If divided between electricity and air there would be required from the locomotive:

Average retardation per ton	8.5	lb.
Total for 700-ton train	5950	"
Foot-tons per minute, at 20 miles	5192	
Equivalent electrical rate	235	kw.
Dissipated in rheostats at 90% machine efficiency	212	kw.

which would be a light duty for four motors and rheostats, and would leave ample margin for them to take the full braking effort up to the skidding of the wheels whenever it might become necessary.

Working conductors. Whatever motors are used—and all the principal types will be used—there is a variety of methods of construction and use, especially as applied to locomotive building, and alternate methods of current supply and use.

Generally speaking, conductors may be divided into two classes; flexible or rigid overhead, and third-rail, One would suppose from many references and some of the arguments which have been made, that direct-current systems are essentially and necessarily dependent upon the third-rail, and that the overhead trolley is a thing individual to, and has been developed for alternating-current operation only. This impression should be corrected, not of course for the information of engineers, but because this somewhat erroneous idea is in danger of being accepted as a fact by non-technical men.

The overhead system has been a distinctive feature of all electric roads operated by direct current since the days of the historic Richmond road, with the exception of those using the third-rail; and until recently the only practical modification has been the somewhat limited use abroad of the sliding bow or roller in place of the grooved trolley-wheel. This latter, although used with high speeds on interurban roads, is unfitted for trunk-line operation, and where overhead trolley wires are used the long collector will probably take its place.

Physically, the overhead trolley is not individual to any particular system; practically, its use depends upon the amount of current which has to be collected. If at low potentials, then it must be either strongly reinforced, and there must be a plurality of contacts, or if these are diminished the amount of current to be collected must likewise be reduced and the potential raised. In the abstract, therefore, the possible use of the overhead trolley, no matter by what system, is a question of allowable operative potential, and the amount of current which can be practically collected.

Identified as I have been with the development of the overhead trolley, I cannot but feel a pride in what has been accomplished with it, nor shut my eyes to a certain fascination in the conception and knowledge that there may be transmitted over great distances, and taken at will from almost a spider's

FIG. 16—Oerlikon trolley in tunnel—single-phase M. G. Locomotive

web, an enormous power. An ardent advocate for years of the use of higher potentials, and fully aware of the limitations of the direct-current standard which has existed so long, I believed for a long time in, and advocated the use of the overhead trolley as the only practical working conductor for potentials above 1000 volts.

Until recently, the invariable practice with overhead construction has been to use a flexible wire supported at comparatively long distances on tangents, with pull-offs at curves, and easily yielding to the pressure of a trailing trolley. This is the practice which characterizes not only direct-current trolley operation, but has also distinguished practically all operation abroad where single-phase or polyphase currents have been used. The introduction of high tensions has, however, now made it necessary to provide by additional supports against the possible breakage of the trolley-wire. This had led to the introduction of catenary construction, the catenary being either single, and supporting the trolley at frequent intervals, or double to prevent lateral swaying. In the former case, the

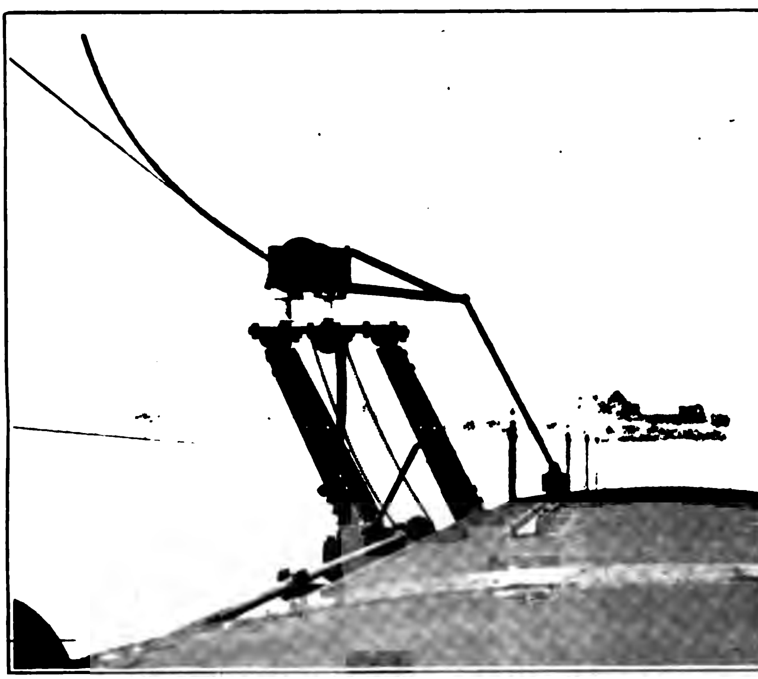


FIG. 17—Oerlikon trolley—over-contact

trolley is only partly flexible, and in some cases the support has been supplemented by an intermediate catenary, as on the Blankenese-Ohlsdorf railway (Fig. 9), where greater flexibility of the trolley-wire itself is insured by loosely suspending it from the lower member of the catenary instead of making the latter the trolley-wire, and providing for varying the tension. In other cases it is to some extent maintained by having less frequent supports, and also by introducing a movable part at the suspender.

The most recent and extended application of double-catenary construction is that on the New Haven road for use with its single-phase locomotives (Figs. 10-13). Here a trolley wire is put under high tension, and is supported at frequent intervals by solid clips attached to rigid triangles, in turn secured to galvanized iron wire cables carried on insulators on the top of bridges which span the tracks at intervals on tangents of about 300 feet. The catenaries are drawn together between the spans so

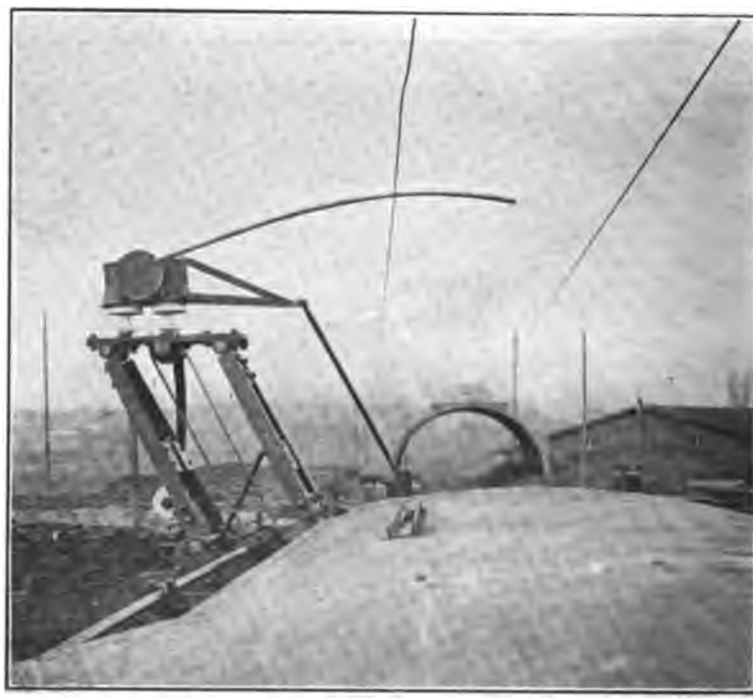


FIG. 18—Oerlikon trolley—under-contact

as to give the utmost rigidity to the whole system, the intent being to maintain the trolley-wire as nearly as possible in one plane. At cross-overs and sidings (Fig. 11) the supporting triangles overlap, and the angle between the junction and the trolley wires is filled with additional conductors, more readily to insure safe passage of the vertically moving sliding contact which has been adopted. At intervals of about two miles the trolleys are sectionalized at anchor-bridges, (Fig. 12) where are provided the necessary switches for cutting out sections, and for looping to extra supply conductors.

Among the innumerable trolleys which were tried in early days was a roller of considerable length, mounted at the end of a rod having a vertical telescopic motion in a tube carried on top of the car, and pressed against the wire by a spring in the tube. This was abandoned in favor of the trailing trolley which would more readily follow variations in the trolley-wire. The modern pantograph is an elaboration of this early idea, and has a very much greater latitude of vertical movement. It consists of a sliding or rolling contact, which forms the upper member of a light, yet strong collapsible structure maintaining an upward spring pressure. The theory of this system of collection is, of course, that a locomotive normally moves between two parallel planes, on one of which it runs and from the other of which it collects current, and that the ordinary motion of the contact will be inappreciable. This assumption is, however, modified in practice. The collectors are carried normally 22 feet above the track on a superstructure (Fig. 7) which must respond in some measure to track irregularities, and which has considerable inertia and some friction. There is a drag because of friction against the trolley-wires, and wind-pressure due to motion of the locomotive. This upward pressure must necessarily be changeable because of variation of angle, friction, and the resultant motion; to maintain contact it must rise and fall. When travelling 70 miles an hour it passes supports which are more or less rigid nine times a second, and between these supports the trolley-wire, no matter what the tension, will be convexed upwards. As the collector approaches any suspender the pressure will normally considerably increase, and, as it leaves, will diminish. The practical question arises, whether, considering all the forces acting on it and its inertia, it can satisfactorily respond, in addition to other requirements, to a double change in vertical direction nine times a second. If contact depended upon the whole structure of the pantograph moving thus rapidly some trouble might be anticipated, but possibly the elasticity of the upper part will prove sufficient.

It is interesting to note that Mr. Joseph Mayer, the former chief engineer of the Union Bridge Company, in a paper read before the American Society of Civil Engineers, and also in several other communications, has given a great deal of thought to the question of overhead construction, and has made elaborate calculations of strains involved. His conclusion was to the effect that no trolley wire put up under high tension, and supported in the rigid manner provided by the present catenary, offered either a sufficiently safe or economical method of construction, and he was therefore led to the development of two departures in practice. The first was the use of an overhead rigid iron rod 1.25 in. in diameter, suspended by catenaries, and provided with extension-joints; the second (the first method apparently having been found too expensive) is a method of flexibly supporting a trolley-wire at long intervals from inverted pivoted suspenders which provide a support for the various section-lengths according to the end-slopes (Figs. 14, 15). The suspender grips the trolley only along the center, and then it opens out in large radii to give a graduated resistance to both vertical and lateral deflection. Mr. Mayer's analysis of conditions, the mathematical deductions, and his proposed remedies as illustrated by his detail plans well merit serious consideration.

An ingenious method of making contact with an overhead single trolley-line is that developed by the Oerlikon company under the direction of Mr. Huber (Figs. 16, 17, 18). In this system the trolley is stretched with comparative rigidity on top of insulators supported on posts alongside the track, with cross-overs where needed. In place of the ordinary wheel and bow trolleys, a curved hinged arm of fair length, and sweeping over nearly one half a circle in a plane transverse to the line of track, is supported on insulators on the side of the car. Normally, this bow rests on top of the wire, pressing lightly on it, and thus avoiding the under formation of icicles. On cross-overs and in tunnels, where the trolley-wire is carried over the track, the arm swings toward the center of the car, and is depressed, making contact progressively from the top around to the side and then underneath the trolley-wire. In addition, the saddle which carries the bow is movable laterally, increasing the radius of action, Of course two bows can be used. I believe that in some of the experiments a roller has been tried. Two difficulties present themselves; one the fact that the wire is pressed down from the top, the strain of the weight being added to by the pressure of the contact bar, which can be, and I believe has been on one test minimized by having the wire supported by and above two catenaries, just the reverse of the New Haven practice; the other objection is that at cross-overs the trolley-wire is very close to the top of the car.

The system is somewhat similar to one originally proposed in my earlier trolley work, where two vertical rollers with uni-

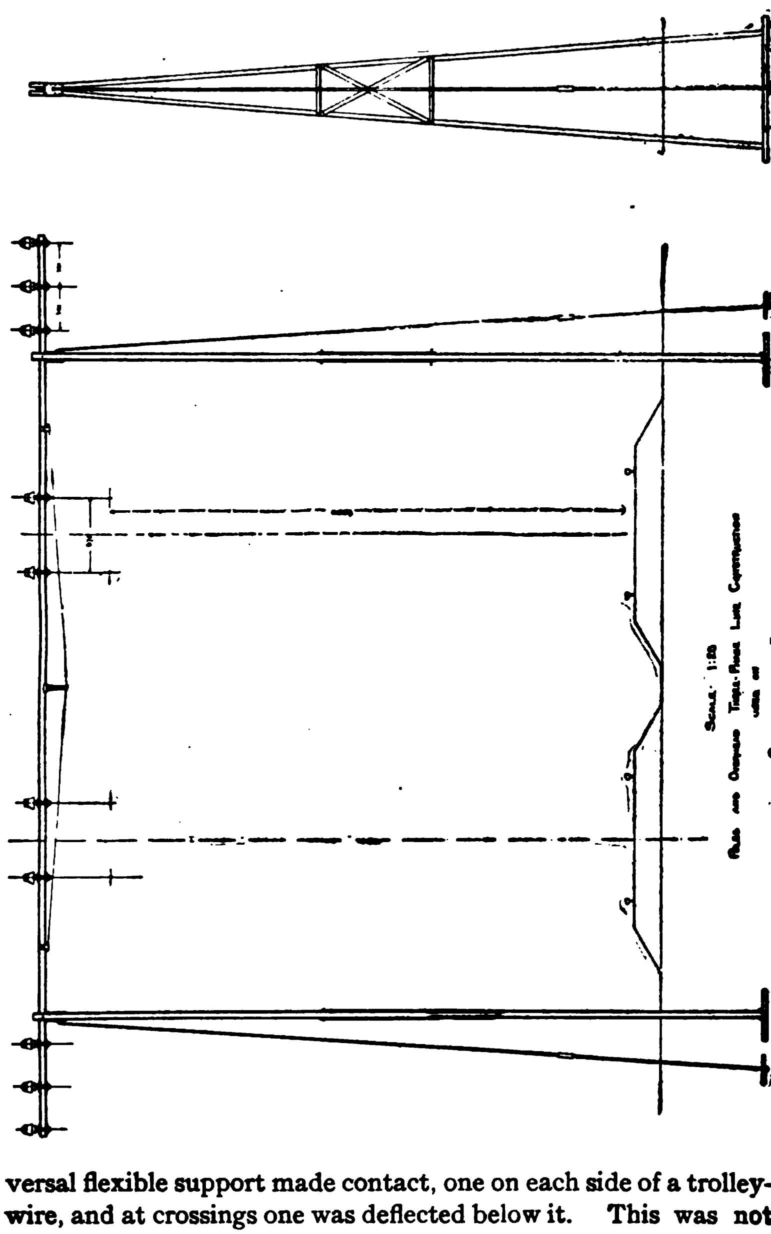


Fig. 19—Ganz overhead trolley support

versal flexible support made contact, one on each side of a trolley-wire, and at crossings one was deflected below it. This was not put into practice.

A very neat structure for the overhead trolley, whether of the ordinary or catenary suspension, is that designed by Mr. C. de Kando of the Ganz Company, (Fig. 19).

The alternative type of working conductor is the third-rail. already adopted on about forty roads, some of considerable extent, most of them with heavy passenger traffic, and operated under

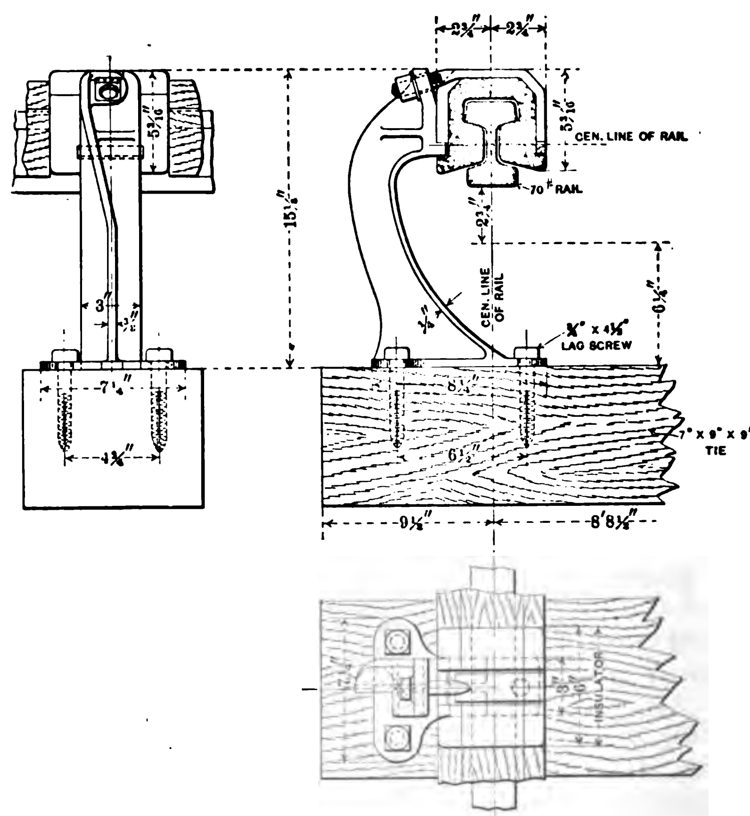


FIG. 20—Details of Wilgus and Sprague protected third-rail

greatly varying conditions. A large proportion of these roads have used the ordinary type of top-contact rail, carried by insulators on the ties, sometimes entirely exposed, and again partly guarded by side boards, as on the Manhattan Elevated, or by a wooden shield carried by yokes from the rail itself, as on the Interborough. While this is the simplest form of third-rail

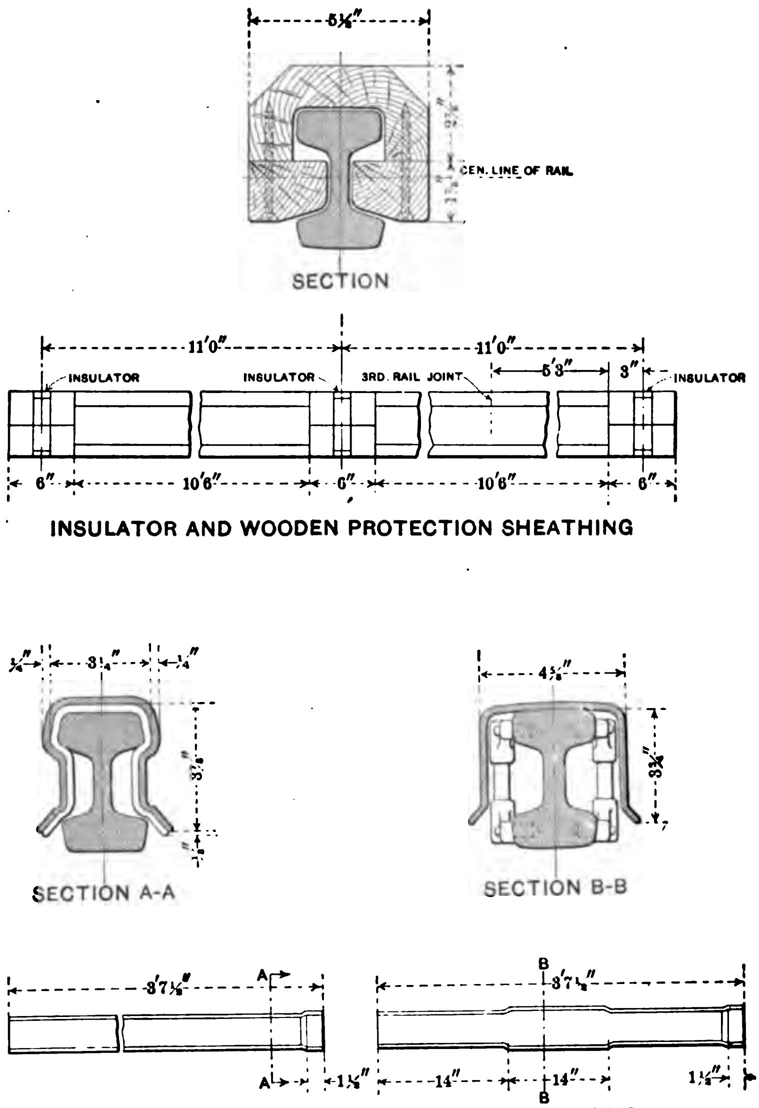


FIG. 21—Details of Wilgus and Sprague third-rail

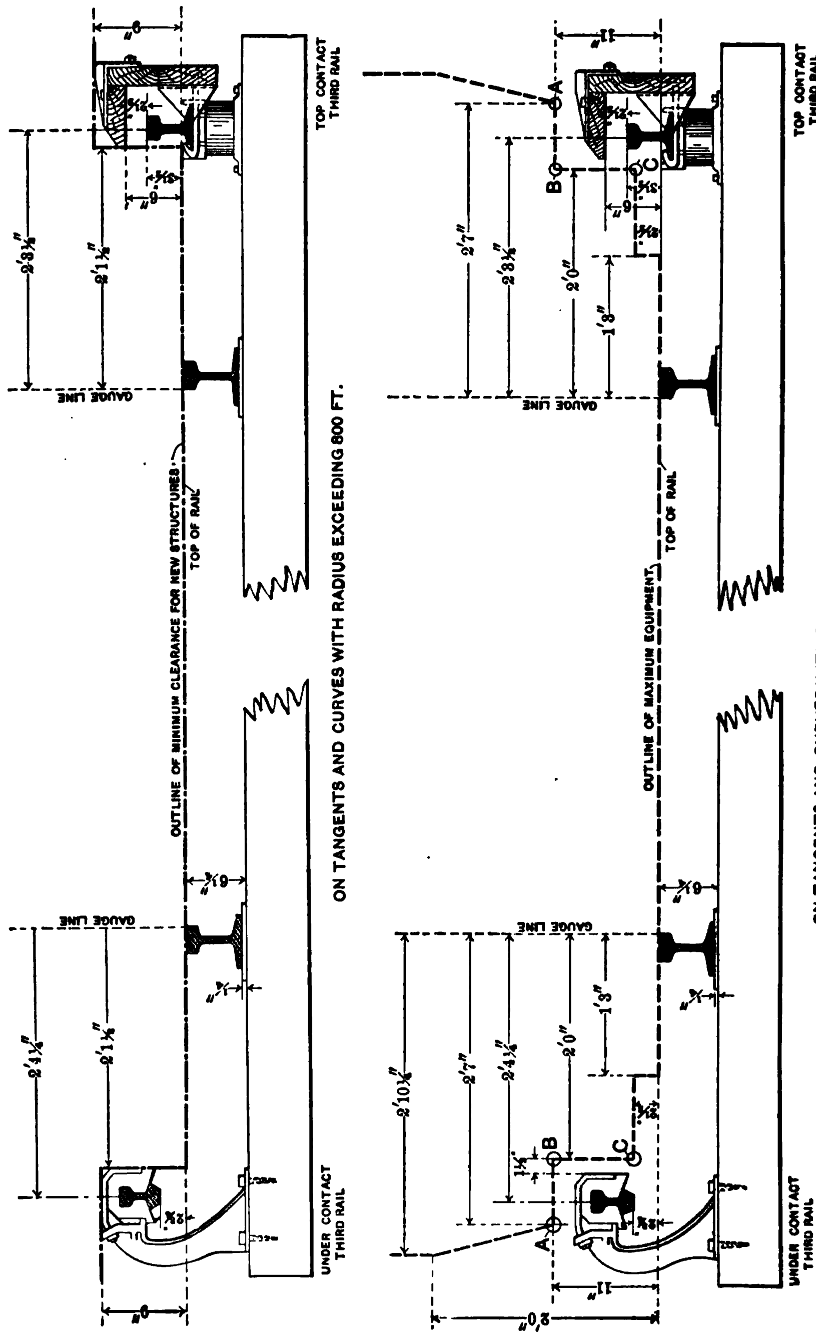


Fig. 22. Clearance diagrams equipment and third-rails

construction, and has given good service for years, it has certain disadvantages. If exposed, it is a constant menace, especially in yards; and even when guarded it cannot be wholly protected from snow and ice. The lower part is only about four inches above the tie, while the holding-clips generally used reduce even this clearance, so that the danger of grounding from accumulation of wet snow and ashes, and from flooding, is increased. In the latter case, over-all flooding has the whole rail-surface for leakage.

These various objections led to the abandonment of the top-contact rail in connection with the New York Central work, and the development by Mr. Wilgus and myself of a new type—an under-contact sheathed rail—supported by insulators from brackets carried on the ties, and with the body of the rail about nine inches clear (Figs. 20-29). The results have been so satisfactory that this type of rail has been adopted for the 285 miles of trackage under electrification, as well as on a number of other roads. It differs from the top-contact rail in that it affords far greater safety, more certainty of continuous operation, and can be used with higher potentials.

The structure consists, briefly, of a series of iron brackets carried on the ties, to the tongued vertical face of which are clamped non-charring moisture-proof insulator-blocks which loosley embrace the head of the rail. Intermediate between the insulators the rail carries an insulating sheathing, which embraces the head and reaches down nearly to the bottom face of the rail, but extends outward from the web to form a petticoat protection against snow and sleet.

The position of the rail depends primarily upon the clearance requirements. To meet those of ordinary trunk-line rolling stock, the bracket-height is made so that the under-contact surface of the third-rail is 2.75 in. above the surface of the traffic rail, and the center of the rail 27.25 in. from traffic rail gauge line (Fig. 22). On account of using the under-contact, the body of the rail is of course considerably higher from ties and ballast than that common in top-contact rail construction, being about five inches more.

On crossings, the horizontally extending flipper-shoe, pressed upwards by a spring, lifts and clears the traffic rail by a fairly safe margin. At switches, to accommodate the lateral displacement of a locomotive when taking the siding, while not reducing the clearance from the protective sheathing on the straight track, the lower head of the rail is specially formed; a similar construction is useful for engaging the shoe when entering a straight track from an angle.

For moderate potentials, say of 600 volts, the two halves of the insulator-blocks are alike, but for the higher potentials the inner insulator-block, that is, the one next to the face of the bracket, is extended so as partly to shroud the head of the bracket. The sheathing between the insulator blocks, depending upon local conditions and price of materials, as well as potential used, is formed of three wooden strips, one grooved on the under side

FIG. 23—Three states of third-rail construction, New York Central

and enclosing the head of the rail, and the other two, attached to and dependent from it, reaching in towards the web of the rail. Where good wood is not available, an alternate protection, costing about the same and having a higher electrical resistance, although not quite so good a mechanical one, is a semi-flexible shell of indurated fibre conformed to the rail-section.

To get the highest protection both mechanically and electrically, the two methods of sheathing can be used, or in place of the inner sheathing of indurated fibre the wood sheathing can be carried slightly removed from the rail-surface by non-hygroscopic saddles; this leaves an air-space between the wood and rail, prevents warping, and affords the necessary physical support for rigidity.

At passenger stations, where special precaution may be deemed advisable, and in freight yards, the double protection can be used, and any required thickness of insulation adopted without reducing clearances by reducing the cross-section of the rail at these points. The conductivity will of course be made up by the number of rail-circuits in parallel at these points.

FIG. 24—Protected third-rail on 4-track division, New York Central

This protection is of such character that passengers, as well as employees in the normal discharge of their duties are well protected. In sleet-storms none reaches the contact surface, small icicles only forming at the edge of the petticoats, and these are easily broken off by the passing shoe.

Of course there is no packing of snow between protection and contact rail, and the increased distance from the ground reduces the tendency to leakage. An accidental advantage is a reduction of the tendency to creep and buckle because of less abrupt and wide changes in temperature.

General comparison of working conductors. All working conductors are in many ways objectionable, but since they are a necessary connecting link between the source of supply and the motors, some comparisons may be made of the two kinds, the under-contact, protected type of third-rail and the overhead trolley, as affected by construction and operation.

The third-rail is an inert structure, it can be aligned accurately with the track, is not under strain, and its expansion can be readily taken care of. The overhead trolley is necessarily a

FIG. 25—Third-rail reconstruction after wreck

system under strain, and where permanency is desired and high potentials are used it must be carried by one or more catenary cables, which on roads of high curvature makes the construction more difficult. Its alignment in the latter case does not correspond with the line of track, and as ordinarily constructed it is subject to extreme variations of tension on account of weather changes.

The third-rail offers some hindrance to the ordinary maintenance of track; but overhead construction is inelastic, and the laying of additional tracks, or changes in grades or alignment require radical and expensive alterations or additions in permanent overhead structures.

Derailments will crush one form of conductor to the ground, forming a short-circuit which will cut off the section; but they may also knock down the supporting structures of the other, and, where there is a plurality of tracks, put them all out of service.

In wrecking, the third-rail offers some obstruction to the

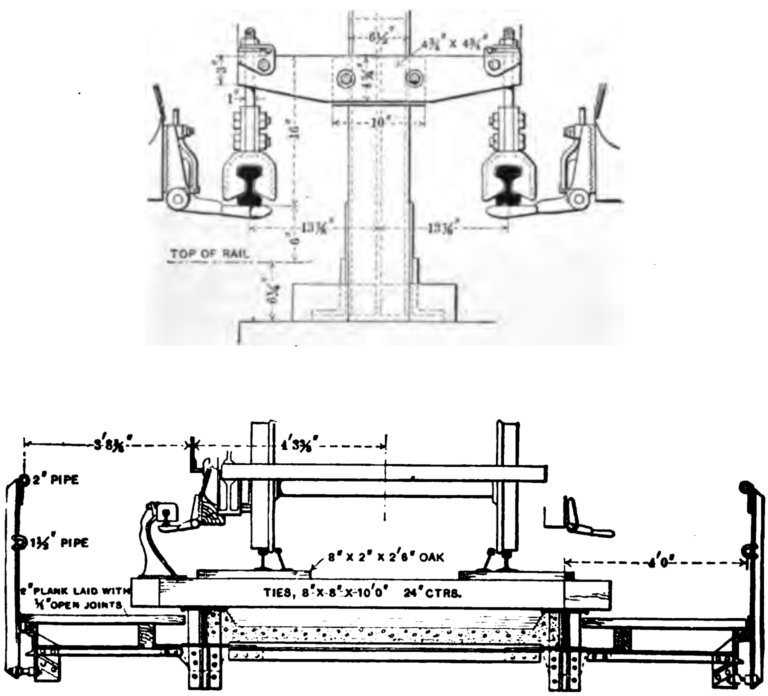


FIG. 26—Details of Wilgus and Sprague Protected third-rail on Philadelphia Rapid Transit Railway

throwing of the equipment to one side; but on the other hand, overhead conductors may interfere with the operation of the crane-booms of the wrecking car.

Where there are two or more tracks snow cannot be piled up between them if the third-rails are located there; but on the other hand, overhead conductors are a source of danger to train men, to snow-shed and tunnel repairers, and in the open are subject to troubles of sleet formation.

The third-rail will oftentimes be covered with snow, but is unaffected by sleet. Very thorough tests made in connection with the New York Central work show satisfactory operation, not only in sleet-storms but with the rail buried in snow. Additional depth should not add much difficulty. With regard to frogs and switches, there are no problems which cannot be solved with this type of third-rail, with an occasional overhead section, and any required amount of power can be collected at operative speeds.

On western roads, where a rotary snow-plough is used, over-

FIG. 27—Protected third-rail suspended from above. Philadelphia Rapid Transit Railway

head conductors and the supporting insulators, especially in yards, will be subject to a heavy bombardment of snow, ice, and refuse, with possible resultant breakage, and the under sides of the umbrellas of the insulators will be often filled up with wet snow.

As to danger to passengers or employees, this is largely overcome where the under-contact third-rail is properly protected, and is designed with due regard to equipment clearances. With an overhead high-tension trolley, there is, on trunk railways, where there are overhead street or highway bridges, tunnels, and snow-sheds, great possibilities of danger because of rearing equipment in case of derailments or collision, and the physical necessity of often bringing the trolley within a short distance of the cars.

Then there are corrosion and soot deposits when steam and electric operation are maintained over the same track. Where the steel supporting bridges also carry signals, as is proposed in some cases, there is increased danger to men engaged in cleaning, painting, or repairing overhead structures, and taking care of signals; and when spanning two or more tracks there is a possible interception of the train operator's view of signals because of dips in the railroad grades bringing overhead bridges

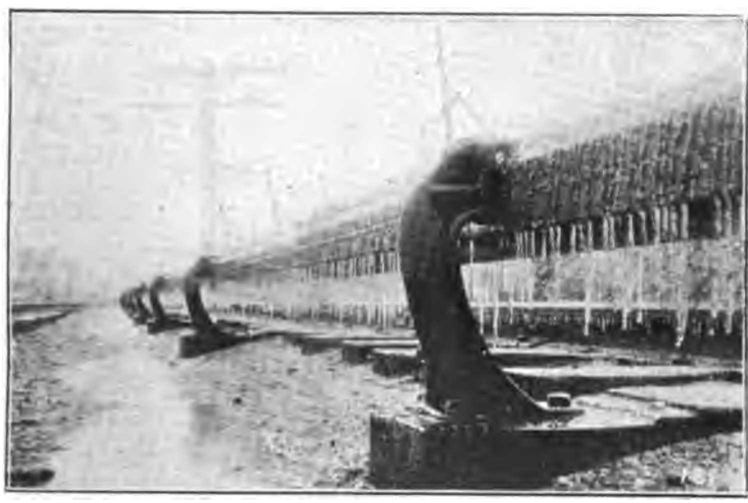


FIG. 28—Protected third-rail after sleet storm

in front of the semaphores, which likewise may be made less distinctive if they have truss members for a background.

In the matter of inspection, that of the third-rail can probably be carried on by the regular section hands, and ordinary repairs made without interfering with traffic. Repairs of an overhead system on a main trunk-line present some special difficulties. It will often require judgment and experience to determine just where trouble may exist, and in any case that particular section of the line must be absolutely cut out and made dead. If the repairs be other than at a rigid cross-suspension, it would seem that they would have to be made from the top of a structure. running on, and for the time being occupying the rails, and propelled by its own power. The old practice common to street overhead trolleys is of course unavailable; there a construction wagon can drive on to the track and off again at will, and the line even while alive can be readily repaired, but a practice possible with 600 volts would probably be fatal when attempted with the very high potentials now obtaining in single-phase operation.

In this latter system it seems vital in the interests of general safety that every crossing bridge, and every supporting structure should be mechanically and permanently connected with the

FIG. 29—Protected third-rail buried in snow

return circuit of the rails, to avoid the possibility of such structures being in partial or complete contact with the overhead conductors and not absolutely grounded, and at all crossings and highways both the catenaries and the trolley-wire should be thoroughly shielded from either accidental or wilful interference.

The time-honored tickler in universal use on steam railways to warn freight brakemen of the proximity of highway crossings, bridges, and tunnels seems unavailable with an overhead system; because if it did not catch in the pantograph collector it would be an ever present menace not only in wet but also in dry weather, because of the possibility of it coming in contact with the overhead line.

Where single-phase alternating currents are used, the magnetic and static inductive effects on telephone and telegraph circuits cannot be ignored, nor the danger of interference with signal systems disregarded.

The attitude of city authorities may in time raise effective obstacles to the use of overhead wires except where all crossings pass beneath the line of the road, and will I think, ultimately require new third-rail construction to be fully protected—even although on a private right of way.

Relative direct-current potentials in overhead trolley and third-rail. Now that the improvements in direct-current motor construction, not only those promised but those actually accomplished, have made it possible, quite irrespective of what may be done with alternating-current motors, to use much higher potentials than ordinary—not of course as high as those available in single-phase alternating-current systems—the question sometimes arises: Will not the permissible potential be high enough, taking into account certain other facts, to meet in large measure the demands of railroad operation, whether by overhead or third-rail?

Engineers have generally proceeded on the assumption that the use of a sufficiently high potential for practical purposes is possible only with overhead conductors. In the Siemens-Schuckert installation at Mazières, (Fig. 30) where 2000 volts direct current are used the current is taken from two trolley-wires of like potential supported by cross-wire catenaries from side poles of the same construction as is commonly used to carry the warning tickler.

Again, the third-wire system has been proposed, as on the Krizik road, and, on a recent installation with many grades and heavy tunnels in the Iselle mining district in France, where two overhead trolley-wires are used at 2400 volts, with the track as a neutral, and with the motors grouped in series of two, current being supplied by two Thury generators in series and grounded in the middle.

A comparison of potential relations giving the same losses on three systems is interesting. The systems are:

1. Three-wire, with 2 No. 0000 trolleys, and 75-lb. bonded single track.
2. Two-wire, with same trolley-wires and track-return.
3. Third rail, 70-lb. special, and with same track-return.

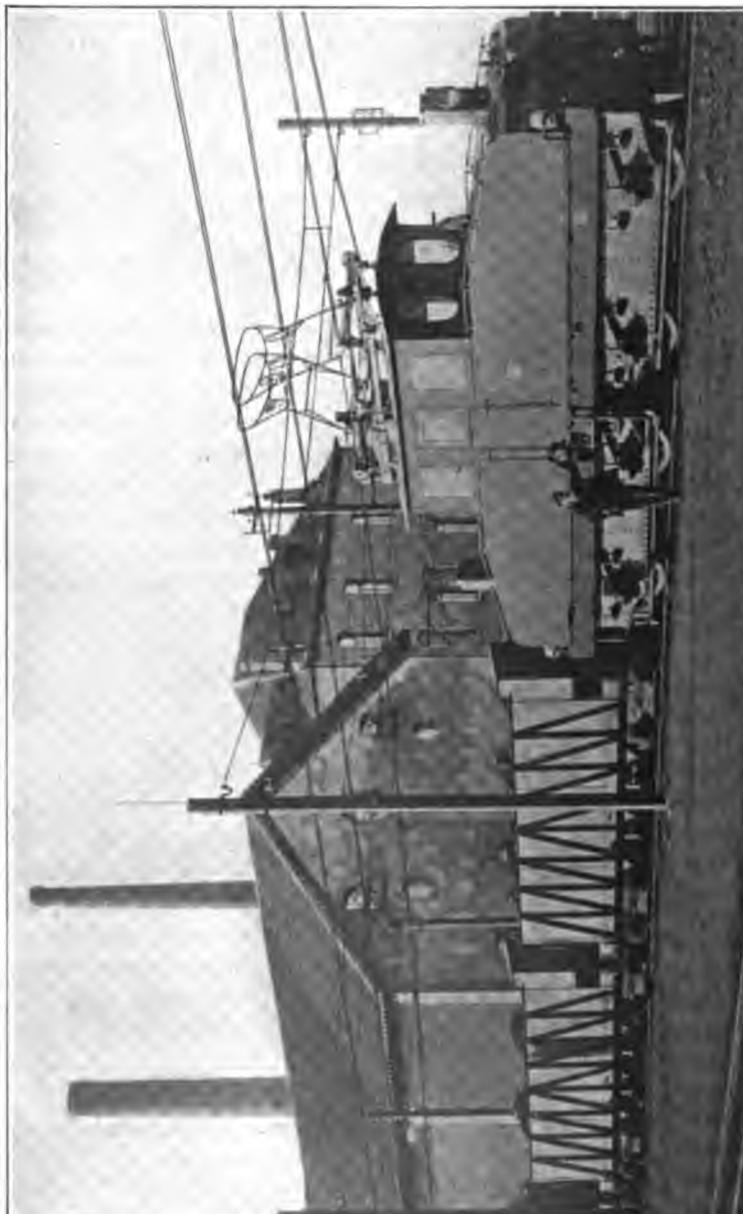


Fig. 30—Siemens-Schuckert 2000-volt direct-current installation at Mazières

The following table gives the comparisons:

System	Resistance per double mile	Ratio of Resistance	$\sqrt{\text{Ratio}}$	Comparative Voltages	
No. 1	0.52 ohms	6.6667	2.58	2400	3100
No. 2	0.165 "	2.1154	1.45	1350	1740
No. 3	0.078 "	1.0000	1.00	930	1200

On such a showing there is little excuse for departing from the lower potentials and the simpler systems, and being handicapped with the higher voltage problems and complication of switches in the three-wire system. If any smaller trolley-wire be used, then the disparity between No. 1 or No. 2, and No. 3 would be emphasized.

The relation of potentials indicated in this table raises the question whether, in view of the disparity of current conducting capacity between an overhead system and the third-rail, it is not also possible that a sufficiently high potential can be used on the latter if from a practical railroad standpoint the balance of advantages and objections should be enough in its favor to warrant its material extension.

Some time ago I stated that in my opinion it was practicable to operate at double the ordinary potentials with a properly protected under-contact sheathed third-rail. I am glad to be now able definitely to announce that it seems possible to construct and operate at these increased potentials with a degree of safety hitherto deemed doubtful. The details of the particular construction necessary must for practical reasons be withheld for the present.

Early alternating-current proposals. In all the discussion concerning direct-current and alternating-current systems, it should be kept in mind that the proposal to operate electric railways by single-phase alternating currents directly is not a novelty, but has had its ardent advocates for a good many years. The late Charles Van Derpoele was one of the earliest to propose this plan; Mr. Ward Leonard has for 15 years advocated the use of a single-phase trolley supplying a motor-generator to operate direct-current motors, a plan often now repeated; and Mr. Arnold attempted the solution by the combination of a single-phase motor operated in conjunction with a pneumatic engine. The Siemens & Halske company conducted the elaborate and costly high-speed Zossen experiments, and the Ganz company have been indefatigable workers in the polyphase field, their Valtellina and Simplon Tunnel installations deservedly commanding widespread attention. Finzi, Winter, Eichberg, La Tour, and others have developed the compensated repulsion type of single-phase motor, and committed themselves to its future. Lamme, Steinmetz, and our American manufacturers have essayed the solution with the compensated series type, at first with 25 cycles, and some now favoring 15 cycles or less.

It is, therefore, incorrect to say that the development is entirely a modern one while that of the direct-current motor has extended over a number of years, for that statement is misleading. Where a score of men were active in direct-current development in the earlier days, handicapped by lack of knowledge and experience, to-day the efforts of hundreds of highly trained men, with all the resources of great capital and manufacturing establishments, have been assiduously directed towards solving the single-phase problem. I think it is safe to say that there is little in its possibilities which has not for some time been fairly well known, and which could not be predicated very closely by theoretical investigation. Nor can I repress the feeling that the same amount of energy, money, and zeal spent on higher potential direct-current developments will produce some remarkable results.

Fifteen-cycle operation. The principal object sought, and certainly a most desirable one in the use of higher potentials, whether direct current or alternating current, is not now so much reduced cost of working conductors on a trunk-line system—for practice has shown that this cost is not materially affected—but lessened feeder investment, increase of sub-station distances, reduction of total sub-station capacity, and, in the single-phase system, the abolition of moving machinery in the sub-stations.

The raising of the potential on direct-current equipments will not be without some objections, not so much, as I have indicated, in the actual construction or use of the third-rail or the overhead trolley, nor because of difficulties in the matter of commutating and grounding, but rather on account of some reduction of capacity because of less slot and winding efficiency where the motors are individually constructed for the higher potentials, this feature being less important if two machines are operated in series. The controlling systems present some added difficulties, but nothing insuperable.

The degree of success of the alternating-current development will depend primarily on the development of capacity and all-round operative features in single-phase locomotive and car equipments. The 25-cycle motor (hitherto the only frequency actually installed for single-phase equipments), whether judged by individual comparison or specific equipments, as I have already illustrated, or the general testimony of electrical engineers of manufacturing companies, has proved inadequate when compared with its rival. To correct this defect it has been proposed to adopt 15 cycles as a standard of operation.

This number of cycles has been under consideration for some time. It is successfully used by the Ganz company in its polyphase installations, it has been proposed in this country by the General Electric and Westinghouse companies for important work, and has lately been urged as a standard by a number of engineers.

Considered solely from the standpoint of the series commutator type of railway motor, a reduction from 25 to some lower compromise number of cycles—15 if you please—has certain distinct advantages; for it should make possible the use of higher field induction, larger air-gap, higher armature potential, slower armature speed, and less sparking—all making for increase of motor capacity for any given weight, and affording greater mechanical freedom in construction and operation. It likewise increases the capacity of trolley and track circuits, and raises the power-factor both of the line and the motor; but against this is an unavoidable increase in the weight of transformers, which, according to such facts as I have at hand, about offsets the saving in motor-weight, It appears, then, that the total weight of single-phase apparatus on a car for a given capacity is approximately the same within a very wide range of variation of the number of cycles. There are, in addition, special objections in the matter of turbine and generator construction, as well as in other directions.

It is difficult to establish exact comparison of equipment weights unless one personally conducts tests, or has complete technical reports which have been made on identical bases; but the following table is one comparison of early estimated weights of complete equipments of two recent typical types of like nominal capacity.

Weight of 4-Motor Alternating-Current Equipments.

Motor	A	B
Cycles	15	25
Nominal capacity per motor	75 h.p.	75 h.p.
Individual Weights:		
Armature	1333 lb.	1146 lb.
Field	2414 "	2646 "
Gear, case, and pinion	398 "	407 "
Total Motor	4145 "	4199 "
Car Equipment:		
4 Motors	16580 lb.	16796 lb.
Transformer and rheostat	6750 "	4325 "
Controller and adjuncts	1000 "	1200 "
Trolley	500 "	500 "
Wiring, switches, etc. (?)	1950 "	1239 "
	26780 "	24060 "
Excess A over B	2720 "	

These totals are not final in either case, for the individual motor weights of each type will very likely be increased from 300 to 450 lbs. in regular manufacture. But allowing for such changes and corrections as seem reasonable, not only is no actual saving in *A* over *B* probable, but the excess of nearly a ton and a half against the 15 cycle equipment will remain in some makes. On the other hand, the manufacturers of *B* hope to show about 10% total saving in the weight of a 15 cycle equipment, but this hope is based upon theoretical estimates, not actual performance.

On other sizes it is probable that these relative differences will vary somewhat, but a comparison of the weight-coefficients of large 15 cycle motors and direct current motors of like weight show a ratio of two to one in favor of the direct current machine.

Motor and locomotive constructions. Motors are of the geared and gearless types, may be entirely separate units or partly integral with the truck-frame, and may be wholly or partly spring-supported. Locomotive designs, influenced in part by the type of motor adopted, show a great variety of constructions, and may be very generally classed as rigid frame with all weight on the driving axles and without leading trucks; rigid frame with either single axle or bogie leading trucks; and bogie-truck locomotives, the bogies being pivoted under the cab, and sometimes linked together.

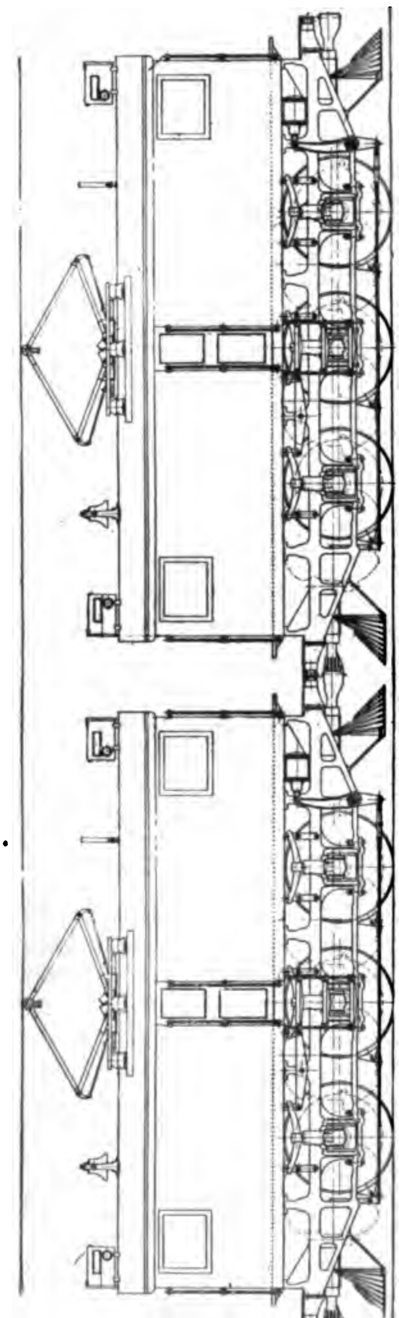


FIG. 31—1500 h.p. double-unit alternating-current locomotive—weight 140 tons.

On all multiple-unit trains, except such as are designed for very high speed, in which case there is a possibility of a gearless-motor development, the standard method of motor-mounting I introduced on the Manhattan Elevated Railway in 1886, and which has been in vogue ever since, bids fair to continue. It provides for centering the motor and carrying a part of its weight upon the driven axle, to which it is connected by any required ratio of gearing, the other end being flexibly suspended from the truck above the side springs.

Up to capacities of 250 h.p., about the limit required and permissible for motor-car equipment, single driving on one end can be used; but when this type of motor is built for larger sizes, in connection with locomotives, it seems almost necessary to provide for gear-driving at each end, which presents some difficulties in construction. To overcome these, the introduction of a spring has been proposed, but the use of an adjustable gear rim seems preferable.

To reduce the dead weight on the axle, one of the French railways some years ago centered the motor on a quill which surrounded, but was supported clear from the axle, connection being made from the quills to the drivers through springs.

The rigid wheel-base type of locomotive without leading trucks is illustrated by an direct-current machine built under the direction of some associates and myself a number of years ago for experimental work on one of the lines running out of Chicago, and also by one class of double-unit locomotives which has been frequently proposed by various companies for single-phase alternating-current operation.

The former, (Fig. 3) of 1,000 h.p. capacity, had four axles, on each of which was mounted the armature of a gearless motor, the field-magnets being attached to the axle-boxes. To insure equal duty on motors, and the maximum tractive effort for its 70 tons of weight, the drivers were coupled together and quarter-cranked, the connecting rods being balanced. The controller was operated by an air cylinder, and followed in time and degree the motion of a pilot lever.

Each half of the double-unit locomotive shown (Fig. 31) has three axles, to each of which is geared an alternating-current motor, after the usual fashion. Each section has a rigid wheel-base of about 12.5 ft., and weighs from 65 to 70 tons, making a total weight of from 130 to 140 tons for a unit having a rated capacity of about 1500 h.p. with forced ventilation.

An analysis of the action of a locomotive demonstrates beyond question that this general type of machine, that is, one having a rigid frame and no guiding trucks, is limited to moderate speeds, and would be unsafe if operated at high speed on a road with much curvature and special work. Notwithstanding the fact that it has been strenuously advocated, even recently, I think this particular type will not find favor among the railroad men, and it is already practically abandoned in the proposals of the manufacturers, in favor of a bogie-truck type, or an articulated type comprising two rigid frames with leading trucks at each end of the complete unit. It is also proposed to carry the geared motors, centered on a spring-connected quill, directly over the main driving-axles, and to support the entire motor by springs from the locomotive-frame.

Particular interest naturally centers upon the distinctive types of locomotives installed on four important railway systems, the Valtellina and the Simplon Tunnel in Switzerland, the New York Central, and the New York and New Haven, which well illustrate three of the principal methods of construction developed to meet the demands of different electrical systems. I will briefly describe each, as well as make some comment upon a few of the many other types recently proposed.

As illustrating a high order of electrical and mechanical engineering, the work of the Ganz Company merits special mention; for it is undoubtedly true that the present status of the polyphase system, which stands on a favored plane with many Italian engineers, is owing almost entirely to the efforts of this company.

The polyphase motor locomotives (Fig. 6) built for the Valtellina Railway and for the Simplon Tunnel are strikingly individual in their construction. The axle mounting of motors is abandoned, the motors being entirely separate units mounted on the locomotive frame, and coupled to each other and the 62-inch driving wheels through an ingenious combination of connecting- and side-rods. Of the three pairs of main drivers, the middle only is journaled in the main frame, each end-pair being journaled at one end of a pivoted guiding truck, at the outer end of which are guiding wheels about one half the diameter of the driving wheels. The end drivers have a limited end play, and one king bolt has a similar freedom of movement, while the other is fixed, resulting altogether in great freedom of adjustment to track curvature. The two motors, spring-supported through the locomotive frame, are each quarter-cranked, and connected to side-rods having downwardly projecting jaws which loosely engage the driving pins of the middle drivers, the centers of which are somewhat below the centers of the motors. On each side of the jaws of the side-rod are coupled the connecting-rods of the outer drivers, provision being made in all bearings for the necessary freedom of movement and adjustment.

In an earlier type, the locomotives were equipped with two sets of twin motors for high and low tension, the low tension to be operated in cascade relation to get slow speed in starting and for running on grades, then to be cut out and the regular running to be with the high-tension motors alone. In the latest machines the twin-motor construction has been abandoned, and the locomotives are equipped with two 15-cycle high-tension polyphase motors, one having 8 and the other 12 poles, and an arrangement of field-circuits in the latter machine such that it can be temporarily made a low-tension motor operated in cascade relation with the other. This combination permits of three regular operating speeds of about 16, 26, and 40 miles per hour. At the lowest speed the motors are in cascade relation, with high draw-bar pull; at middle speed the 12-pole motor is in operation alone on high tension; and at the highest speed the 8-pole motor is used alone, likewise on high tension. Of course, the physical connection of the two motors together and to all drivers makes this method of operation possible. The rated capacity of the motors, as given by Valatin, is extraordinarily high, that with the 12 poles being stated as 1200 h.p. and that with 8 poles, 1500 h.p., based upon the one-hour rise of temperature to 75 degrees. The motors average about 13 tons each.

The use of connecting-rods in this locomotive is not as objectionable as the use of the driving- and connecting-rods in a steam locomotive, because the strains are very different, and the rotative weights can be far more perfectly balanced. It can be fairly said to have the advantage that with the minimum possible weight of locomotive there is no such thing as slipping an individual wheel, a trouble which will occur at times with all locomotives having independently driven axles if equipped with powerful enough motors, because of variation in motor characteristics, track and wheel conditions, and unequal wheel pressure caused by the drawbar pull.

Almost the entire weight of the locomotive is spring-borne, and the behavior of the machine on curves, even at high speeds, ought to be very satisfactory. The same general construction would lend itself very effectively to the application of high-tension inter-pole direct-current motors, and may be very seriously considered in this connection.

The general characteristics of the New York Central type of locomotive (Fig. 4), the Batchelder machine as developed by the General Electric Company, is pretty generally understood, and my description will be limited. It consists essentially of a heavy steel frame in which are journaled four main axles, and which is terminated by pivoted single-axle ponies provided with spring resistance against deflection from the central position. The

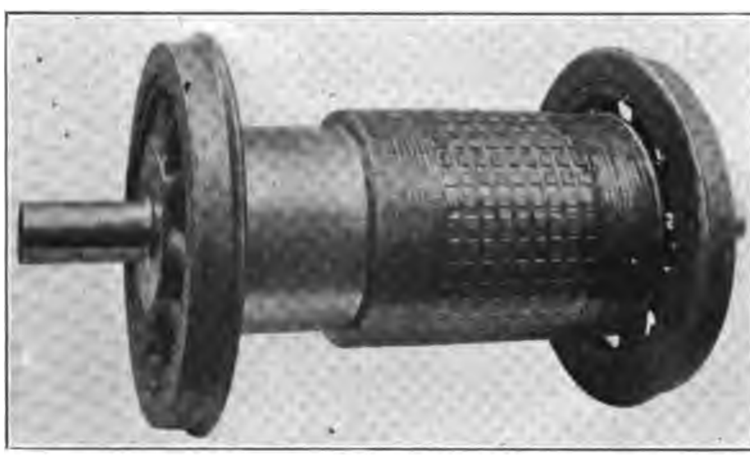


FIG. 32—Armature of bipolar direct-current motor

motors are the gearless type, the armatures being mounted directly on the axles, (Fig. 32) and the bi-polar field-magnets forming an integral part of the main frame; they are, therefore, carried with it by the equalizing springs, and have free motion relative to the armatures. In addition to the regular truck frame, an additional path is provided for the magnetic flux, which passes through all the armatures and field poles in series, by a heavy bar extending the length of the frame, and carried above the motors.

Being of the two-pole type, (Fig. 33) and with a quadrant winding, the motors are extraordinarily free from sparking tendencies; in fact, they are, structurally, natural 1200-volt machines, although only wound for present operation at 650. So marked is this characteristic, that the brushes, which are 180 degrees apart, instead of being carried on yokes concentrically with the commutator, are carried on arms attached to the field-magnet frame, (Fig. 34) and although moving with it function perfectly.

The electrical and mechanical construction is, therefore, reduced to an acme of simplicity never hitherto attained in electric locomotives, for not only are there no gears, but there are no armature or field bearings, quills, driving-spiders, or special

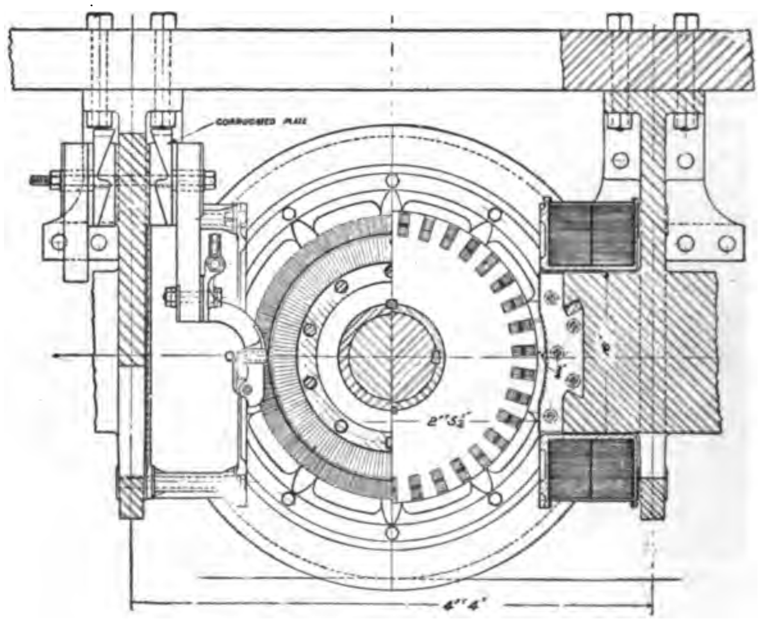


Fig. 33—Longitudinal section—bipolar direct-current motor.

spring connections, although all the weight of the motor except the armature is spring supported.

The air-gap is very large, and as the pole pieces are very nearly flat, a complete axle unit with its armature can be readily dropped out, and replaced without disturbing the balance of the motor equipment. This type of machine, of course, cannot be used with any form of alternating current directly, no matter what the frequency.

When first proposed, the design was considered so radical that its choice met with a good deal of criticism, but experimental trials extending over two years, with 67,000 miles of operation, amply demonstrated its remarkable reliability and efficiency, qualities confirmed by the operation of 35 of these locomotives now delivered and in regular service.

The total weight of the locomotive, without heating equipment, is about 95 tons, of which 70 tons is on the drivers. The nominal capacity, with 75 degrees rise and natural ventilation, is 2200 h.p., at which output with 600 volts the motors run at 300 revolutions, corresponding to 40 miles an hour. The rigid wheel-base is 13 feet, the total wheel-base 27 feet, and the length over all 37 feet.

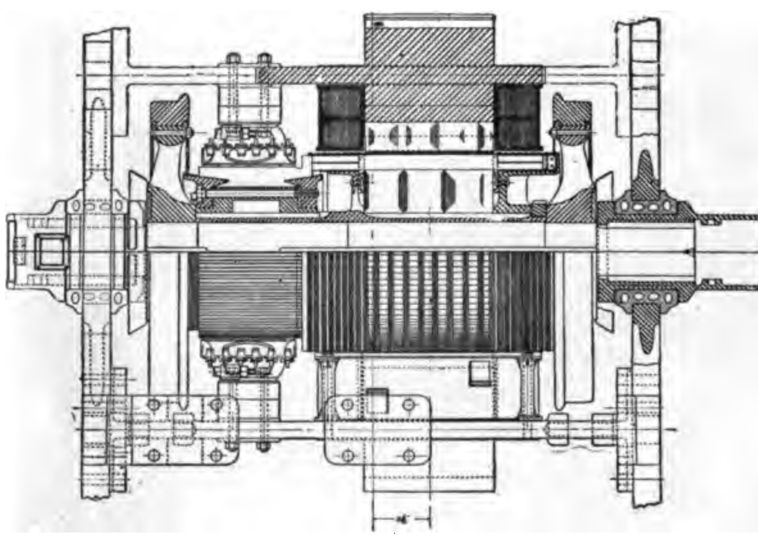


FIG. 34—Transverse section—bipolar direct-current motor

The individual control is the series-parallel bridge method, with resistance variation, the grouping of motors varying from four in series to four in multiple, and current is taken from the under-contact rail by side-extending flipper-shoes.

The original specifications required each locomotive to handle a trailing load of 400 tons on a specified service, two locomotives, under common control by the multiple-unit system, to be used with the heaviest trains on high-speed runs. It is most satisfactory to find that these locomotives have developed an extraordinary emergency hauling capacity, such that there is no train pulled out of the Grand Central Station, into which the first run was made September 30, 1906, which cannot be handled by a single machine at the speeds required within the limits of present operation.

The exigencies of service are responsible for a recent remarkable test of this tractive power. On April 26, the Lake Shore Limited, north bound, consisting of nine heavy Pullman cars hauled by a Central-Atlantic type of steam locomotive, was stopped in the tunnel under 66th street, on a 0.5% upgrade, because of some mishap to the engine. Following it was a train of seven standard day coaches, shop bound and hauled

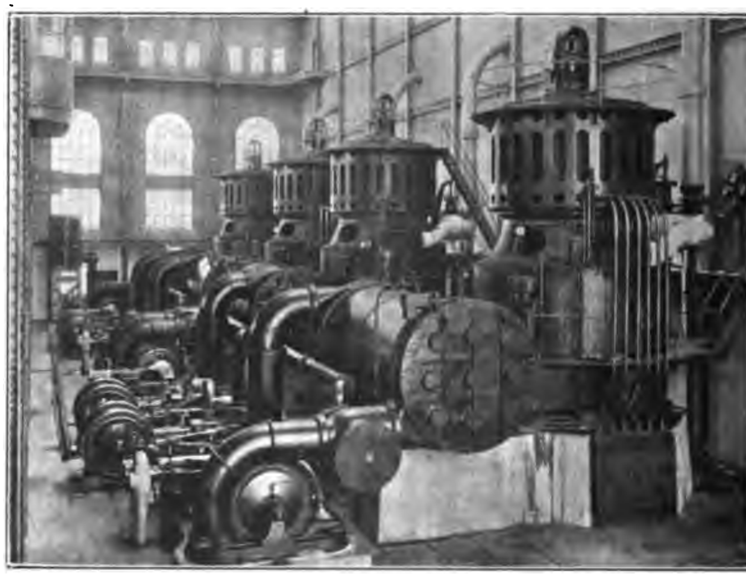


FIG. 35 —Turbine room, Port Morris power station

by an electric locomotive, which promptly coupled on to the leading train, and without any assistance from the steam locomotive, which was dead, started the entire load of 16 cars and 2 locomotives, weighing nearly 1,000 tons, with good acceleration, and made the run up a 1.02% grade, a half-mile long, at satisfactory speed and without difficulty.

Those concerned with the planning and installing of the New York Central equipment justly feel that it is epoch-making in forwarding the march of electrification, and it is gratifying to note that although the electric service was inaugurated only as recently as the 22nd of last December, has been developed under extraordinarily difficult circumstances, and has had to face much adverse criticism because of a serious accident due to extraneous causes, already 305 train movements, representing 86% of the present total of the New York Central and Harlem trains, both locomotive-drawn and multiple-unit, are operated electrically. The aggregate delay has been less than with the old steam service, a fact particularly noticeable in times of snow-storms. The main station (Fig. 35) output for 24 hours is but about 65,000 kilowatt-hours, and when the batteries are in service but one steam unit is required at time of maximum load.

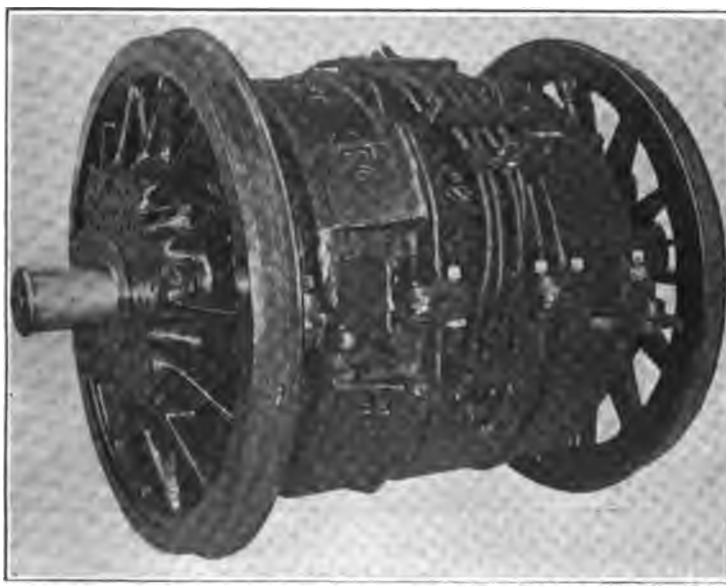


FIG. 36—Motor and axle unit of alternating-current New Haven locomotive

The New Haven alternating current-direct current locomotive, built by the Westinghouse Electric & Manufacturing Company, is of the 2-axle free bogie type, the bogies being pivoted under, and transmitting their effort through the frame which carries the cab, in which are mounted the transformers, blowers, rheostats, and controllers (Fig. 37). On each truck are mounted two spring-supported motors, each complete within itself. The armatures are carried on quills, terminating in spiders at each end, which engage eccentrically wound springs enclosed in pockets in the main drivers (Figs. 36-39).

The rigid wheel-base is 8 feet, the total wheel-base 22 feet, and the length over all 37 feet. The weight of the locomotive is 93 tons, having been raised considerably over early expectations. It has an hour rating, on the usual standard, of 1,000 h.p. when operated at 25 cycles, but is equipped with blowers to raise the average capacity. It is intended to handle a 200-ton trailing load at schedule, with some margin of performance.

Although built primarily for operating directly from 11,000-volt single-phase alternating current, these locomotives must

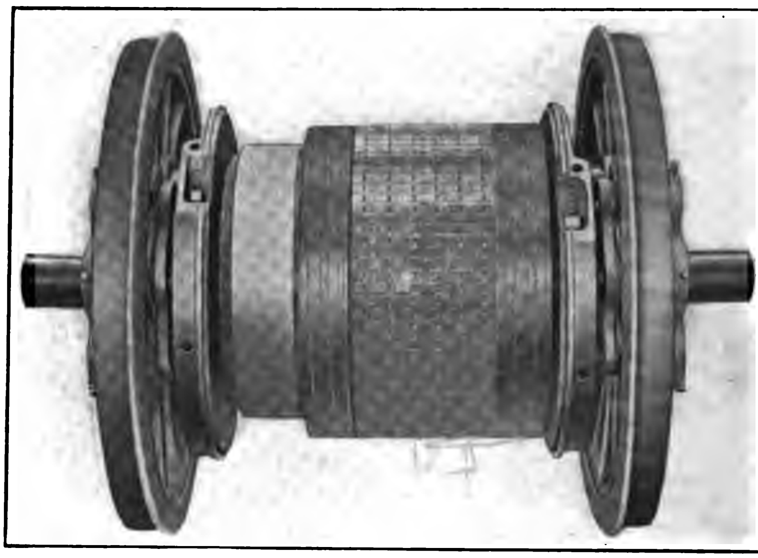


FIG. 37—Armature bearings and axle unit of New Haven alternating-current locomotive

operate also from the 650-volt direct current while on the Harlem tracks. They, therefore, have additional control provision, and besides the double-pantograph collectors, have contact shoes, those on the side being arranged for lifting by air pressure on account of limited clearances on a part of the run.

The motor armatures are wound for operation at a normal maximum of about 235 volts, and hence are connected in permanent series of two, while the field-circuits are arranged for each pair of motors in a separate group, and for series-parallel grouping independently of the armature circuits, to provide for the varying flux in alternating-current and direct-current operation. Of course, the two motor groups can be connected for series-parallel operation with direct-current supply, but with the disadvantage of using about double the amount of current at slow speeds that is required when four motors, each wound for the full potential, are in series.

The first of these machines, pulling a short train, made entry into the Grand Central Station on May 11, 1907, and in a short time the operation of equipment should be under service test.

Some question has been raised as to whether trucks with drivers of so large a diameter, 62 inches, on which are concentrated 15 tons of motors in a limited wheel-base, will track properly under all conditions of rail. Experience, however, is the final criterion.

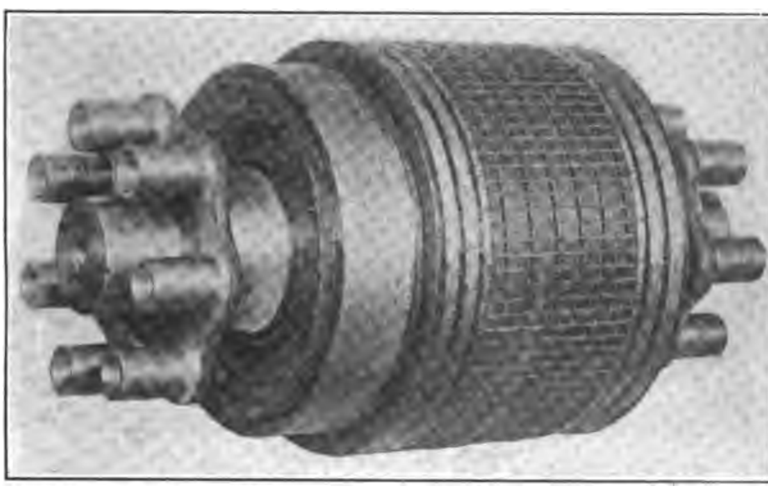


FIG. 38—Armature and driving spider of New Haven alternating-current locomotive.

In order to combine the possibility of single-phase alternating-current current transmission at high voltage by overhead trolley, and the unquestioned advantages of the direct-current motor, it has several times been proposed to introduce between the line supply and the motors a motor-generator set, comprising an induction motor taking current directly from the line, and driving a continuous-current generator to supply the motors, this converting set being carried in the main cab, with provision made for the extra weight by bogie trucks at each end, (Fig. 41) or in an independent tender taking the place of the steam tender in existing steam practice (Fig. 40). Of course this is the introduction of a moving sub-station individual to the locomotive which is operated by it, and makes the latter subject to all the idiosyncrasies of the intermediate apparatus, besides laying up an enormously expensive machine in case of any special trouble. Where the motor-generator set is carried in a separate tender, this disablement only cuts out a part of the equipment, which can be replaced by another like part, but in any case it is debatable whether such a moving sub-station offers any advantage over the stationary one.

Sometime since, I made a very careful investigation of the possibilities of direct-current gearless and geared motors, (Figs. 42-43) the former of the bi-polar type, for identically the same service, a very severe one.

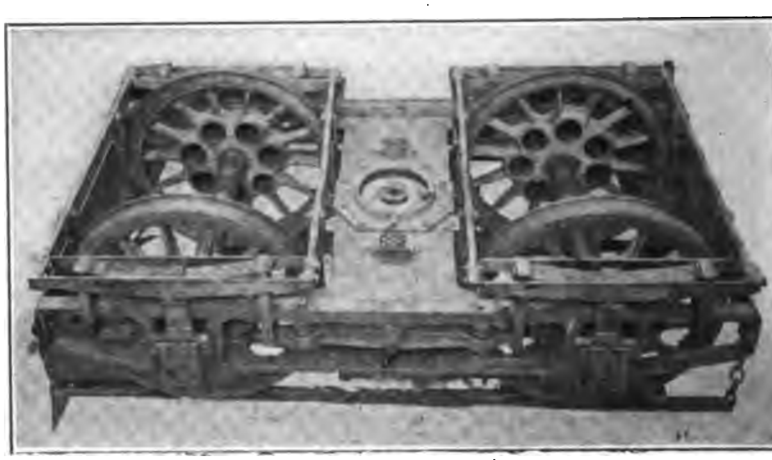


FIG. 39—Truck of New Haven alternating-current locomotive.

Both machines are of the four-axle bogie-truck type, the trucks being linked together. The geared locomotive weighs 93 tons and the gearless 126 tons, but the weight per axle is well within the usual allowance. On each truck are four motors, connected two in series, to be operated at a maximum line potential of 1500 volts. The geared motor construction is of the usual standard, but fitted with commutating poles, while the gearless machine has modified bi-polar motors of the N. Y. Central type.

A comparison of the efficiency curves of the two machines is interesting, these showing for each from 87 to 88% on a five-hour load, and falling only to 83% with 50% increase, while at

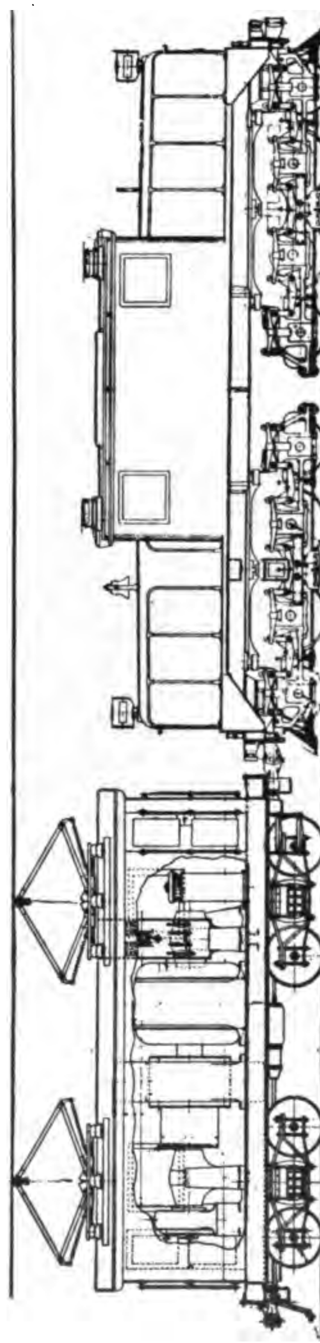


FIG. 40—Direct-current locomotive, with alternating-current motor-generator set in separate tender.

half this load the efficiency of the gearless machine is much higher than that of the geared. Some adequate idea of the capacity of the gearless machine may be gathered from a statement that it will maintain a drawbar pull of nearly 25,000 lb. at a good rate of speed for several hours continuously, and with natural ventilation. These extraordinary characteristics would, for the class of service for which these machines were considered, amply warrant the additional weight because of the simplicity of the gearless machine.

A very promising type of machine (Fig. 44), embodying many of the good features of those which had preceded it, is now under construction by the General Electric Company, for use either on direct current, or with a motor-generator set supplied from an alternating-current trolley. This machine is of the 4-axle free bogie type, the drawbar pull being taken through the main frame. On each truck, and forming an integral part with it, are two bipolar gearless motors driving the middle pair of axles, and at either end of each truck is a pair of leading wheels of smaller diameter, which have a limited, spring-resisted side play. The normal wheel-base of each truck is 12 feet, the total wheel-base 32 feet, and the length over all 36 feet. This machine should be capable of an almost unmatched speed and freedom in following irregular curvatures, and with special ease of track approach.

The various locomotives thus briefly described are but a fraction of those proposed by various makers to fit particular conditions and types of apparatus. Their construction does not, in many particulars, meet the preconceived ideas of some steam-locomotive builders, with whom a high center of gravity and all the weight possible carried on springs is a cardinal principle, and a very correct one when we consider the necessities of the steam locomotive. The electric locomotive has a lower center of gravity, that of the New York Central machine being about 44 inches, the New Haven 51, and the Ganz probably somewhat higher, while that of the steam locomotive is sometimes as high as 73 inches. The electric machine, therefore, will have less tendency to topple over, but a greater resultant side pressure in case of irregularity of track when entering a curve, or running on an irregular track, than its rival, a larger portion of whose weight heels over and increases the vertical pressure on the rail. Careful investigation, however, carried on through many sources, and inaugurated by reason of the recent derailment on the New York Central road, seems to indicate that with electric

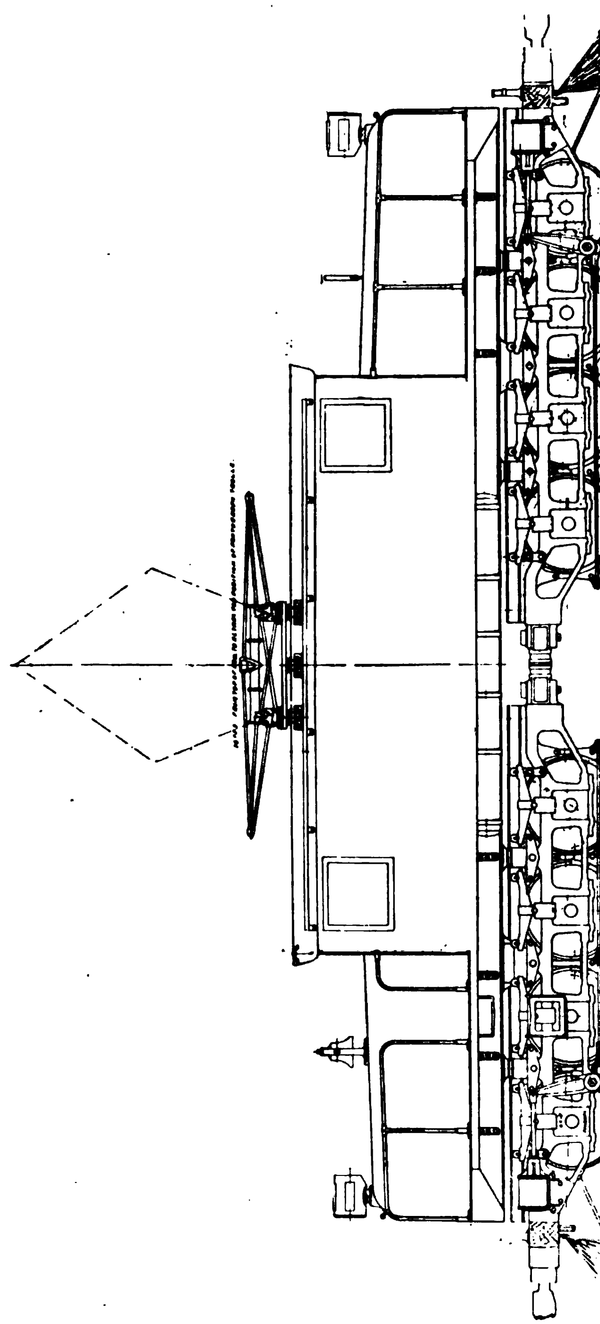


FIG. 41—1500-h.p. alternating-current locomotive, with gearless direct-current motors and motor-generator set. Weight about 160 tons.

motors properly guided any increased tendency to side-thrust is more than compensated for by certain other advantages

Train Control and Operation. Restriction of operation in an electric system to methods in vogue with steam operation would be a useless throwing away of one of the geatest possibilities of improvement in train operation where passenger service is heavy and terminal facilities congested. Ten years ago I inaugurated on the South Side Elevated of Chicago a new system of train control, which permitted the aggregation into trains of any number of independently equipped motor cars, and dead cars if desired, and their control from either end of any car, irrespective of train make-up. This system, now known the world over as the "multiple-unit," (Fig. 45) has made such advance that it is now generally recognized and adopted as the best method of handling trains wherever service is crowded and high schedules are required.

The essential result accomplished by this system is increase of capacity, by providing high power equipments, proportional to the length of the train, increased schedules and density of train movement, the lowest maximum speeds for any given schedule similarity of equipment, reduced switching and signal movements, increased safety, and generally the utmost independence and facility of operation. Whatever tentative plans may for the present be adopted, I believe that it is inevitable that all local and suburban passenger service on electrically equipped railways requiring train operation will be eventually conducted on the multiple-unit plan, and its use will spread over a continually increasing area, even to the operation of passenger cars run over divisions of considerable length.

But it must be borne in mind that we are dealing all the while with necessarily increased weights of considerable amount, because of the use of steel car-bodies, heavier trucks, and addition of motor equipment which must provide the power to propel itself as well as the cars. Increase of schedule also demands increased capacity of motors, and it is, therefore, of the utmost importance that capacity be got with a minimum of weight, and likewise with restricted armature speeds, which, where stops are frequent, add materially to the "virtual" weight of the car; because not only does the weight of the armatures have to be accelerated and carried in a linear direction with the inert parts of the car, but they must have energy stored in them because of their rotation, a considerable part of which is thrown away in braking. According to all present

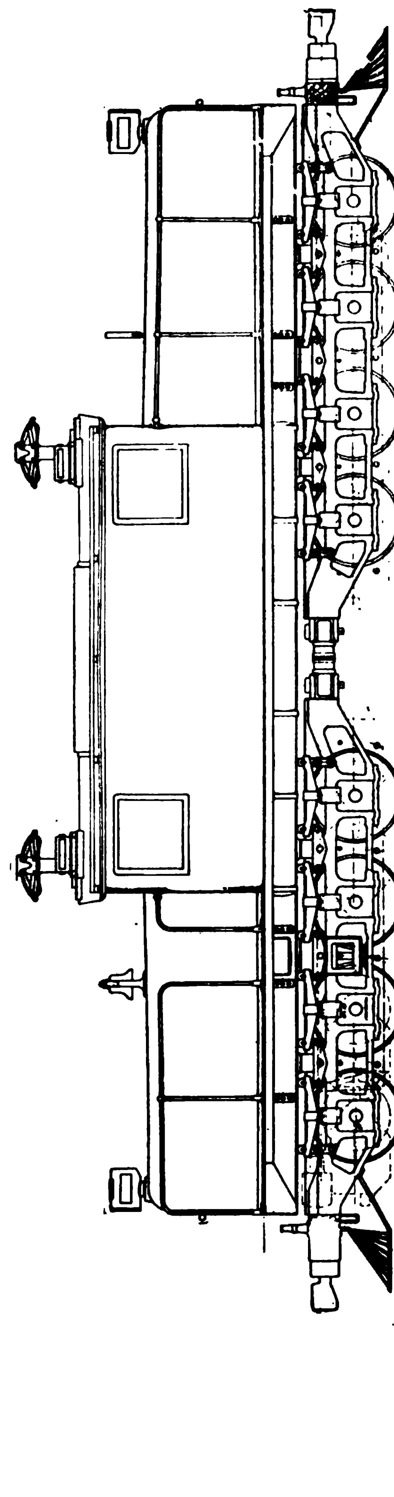


FIG. 42—1800 h.p., 1500-volt bogie truck locomotive, geared motors. Weight 93 tons.

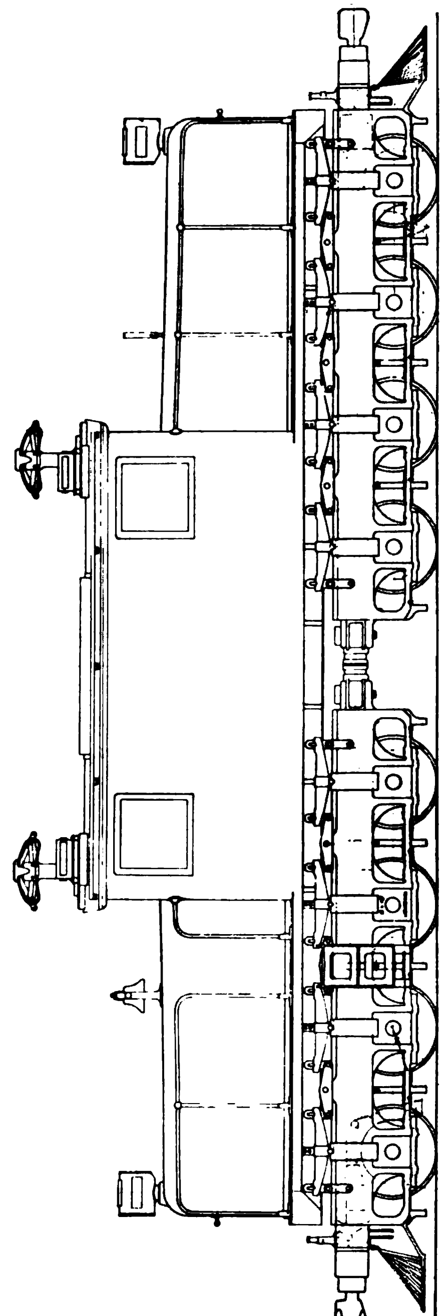


FIG. 43—1800 h.p., 1500-volt bogie truck locomotive, gearless motors Weight, 126 tons.

developments, as I have already indicated, the direct-current equipment has in this service an enormous advantage over any single-phase alternating-current motor equipment with its car transformer.

Irrespective of the benefits to passengers, and the influence in building up suburban service by providing a high schedule train system which can be absolutely adjusted to the needs of traffic, the influence on the capacity of the terminal facilities of a railway is of the utmost importance. It has been declared by a competent English authority that the use of multiple-unit trains in the suburban service of a congested station at least doubles the capacity of that station in the matter of track movements and the dispatch of trains, not only on account of the ability to operate the trains from any point and in any length, but also because of halving the number of switch and signal movements necessary where locomotives are used. In addition, the electric locomotives necessary on through trains, being double-ended, compact for their capacity, and needing no turn-tables, occupy much less track and yard space than steam machines. Again, the use of electricity makes it possible to double-deck a terminal, bringing through trains in on one level, and suburban trains on another, and using both for storage. As a net result, it may be safely stated that so far as train movements are concerned, the capacity of a yard, over and above that required for the storage of cars alone, can be trebled as compared with steam-locomotive-drawn trains. In addition, the yards can be roofed over, and the space utilized for streets, parks, or buildings.

The remarkable extension of the multiple-unit system, and its recent application to locomotive practice, as for example on the New York Central Railroad, has led to the suggestion that freight trains shall be equipped with secondary controlling lines, and that a plurality of locomotives, not only at the head of the trains but distributed throughout it, shall be handled by a single operator on the leading engine, whose controller shall be provided with the automatic safeguards common to the service which has already been developed. I do not hesitate to pronounce this an impracticable scheme for general application. Quite aside from the cost of equipping the hundreds of thousands of rapidly deteriorating freight cars, the majority of whose train lines would not be used, it would be against public policy, and contrary to the most ordinary safety of train operation, to leave such an extended and high-powered train in charge of a single man.

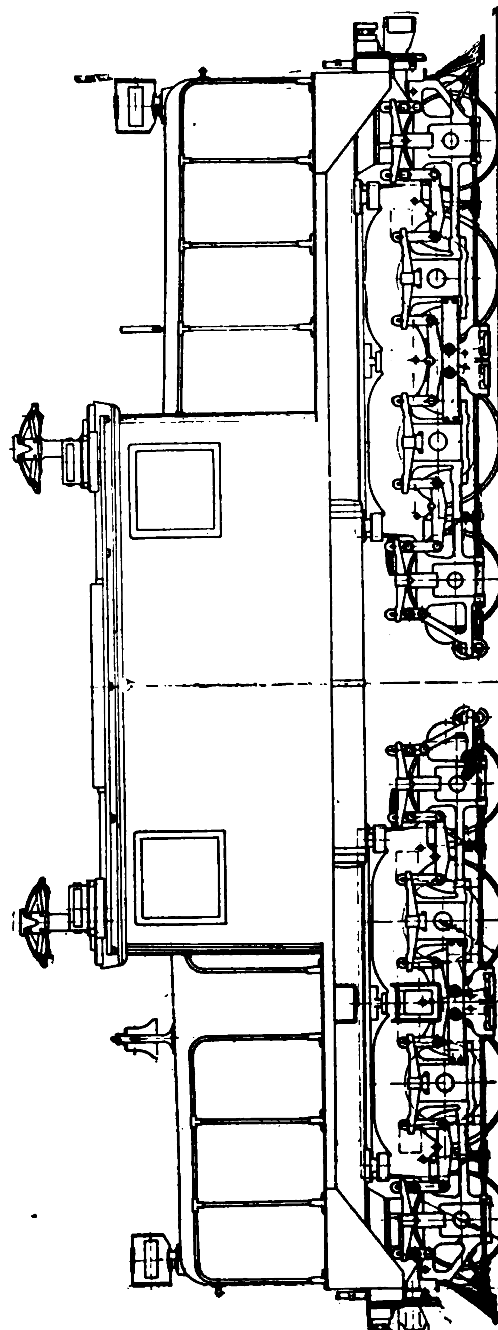


FIG. 44—High-speed bogie truck direct-current locomotive, gearless motors Weight 80 to 110 tons.

Locomotive operation is distinctly different to that on elevated and underground roads, and the operators make their runs under widely varying conditions. The handling of a long freight train is entirely unlike that of a train made up principally of motor cars; it has to be coaxed, favored, and nursed, for scarcely any two starts are alike. As useful as automatic controller advance is with the ordinary multiple-unit train, and even admitting, which is debatable, the advisability of connecting up the air-brake with the control, it is safe to say that in ordinary freight operation these features should not be added to the controller, and if they were the engineer in time would beat them.

While double-headers under a common control will undoubtedly be used when necessary on both freight and passenger trains, when one considers all the varying conditions of trunk-line operation, neither public policy, safe railroad operation, nor if you please, labor conditions, would permit the handling of a train with two or more locomotives so coupled up, with only one man in the cab. It should not be permitted even with a single locomotive, and I do not believe that any man who has had practical experience in riding locomotives will long continue to endorse any such proposal.

Storage-batteries. The use of the storage-battery in connection with electric railway operation is a proposal concerning which much may be said, for and against, depending largely upon what value one attaches to restriction of peak-loads on moving machinery and to insurance. That it has been, and is being used successfully in connection with direct-current equipment of moderate potential admits of no dispute, and it has been stated that it is equally available for alternating-current installations. This latter claim is misleading. On direct-current systems the principal function of a battery is that of an equalizer. If installed at a central or sub-station it is usual to provide boosters to govern the charging and discharging. These, however, are only of differential watt capacity, and while they are necessary for regulation, it is perfectly possible to use the battery in some emergencies by direct connection with the line. Sometimes the battery is used at an auxiliary sub-station without any boosters whatever, the charging and discharging being determined by the drop on the line, or by the use of an extra feeder.

With an alternating-current system, the battery at a sub-station plays an entirely different role. It must be charged by a

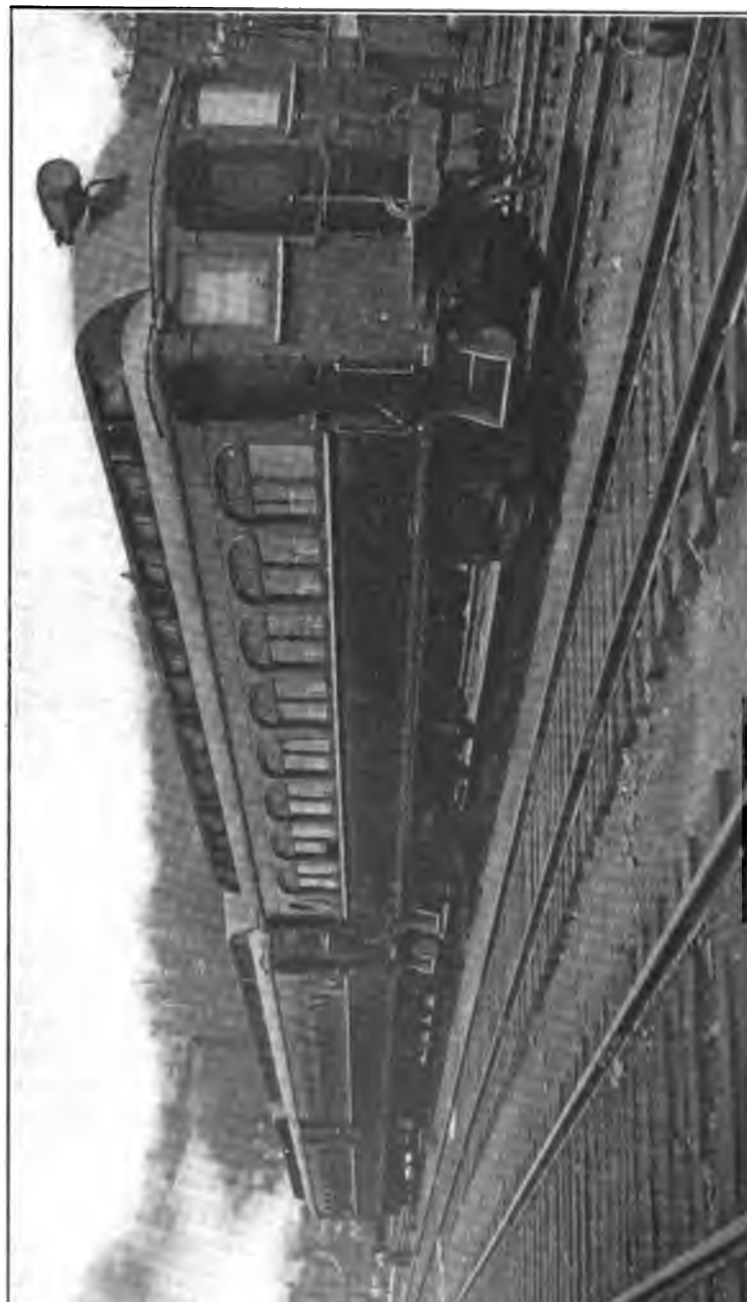


Fig. 45—New York Central multiple-unit train.

direct-current generator driven by an alternating-current motor, and in discharging drives the alternating-current motor as a dynamo through the direct-current generator acting as a motor. In addition to the introduction of moving machinery in an alternating-current sub-station, its watt capacity must be equal to that of the full discharge of the battery, and the latter can have no function in supplying current to the working conductor except through the medium of two rotating machines of large capacity.

Where current is purchased from a water-power plant, and it is necessary to change frequency as well as restrict the peak-load by which charge for power may be regulated, the battery may be used in combination with an alternating-current motor, a single-phase generator and a direct-current machine; the alternating-current motor driving the single-phase generator and the direct-current machine to charge the battery when the load on the line is light, and the alternating-current motor and the direct-current machine, operating as a motor supplied by current from the battery, together driving the generator when the load is heavy.

Use of step-up and step-down transformers. Where the distance is not great, as on the present proposed limited operation of the New Haven road, both step-up and step-down transformers have been omitted, and the 11,000-volt trolley-line is supplied from the station switchboard. This means direct connection between an extended system of overhead working conductors and generators operated at high potential, with one side grounded, with, of course, whatever protection lightning-arresters can provide. Such are the vagaries of lightning and the uncertainty of the very best arresters, that I cannot but feel that this practice, which subjects costly generating equipments to direct lightning attack and special grounding stress, will not obtain to any great extent; for the possibility of laying up a complete unit of great capacity, steam engine as well as generator, because of a lightning flash or accidental ground, is too great a penalty to pay for eliminating transformers, and is a special handicap upon the possibilities of transmission.

It is certain that standardization should be directed to the construction of generators. Any material increase of potential above that now common means reduced capacity and efficiency, increased danger of breakdown, and greatly increases individual cost, to say nothing of the capitalized risk of failure. Quite aside from the question of cost and efficiency, air cooling, the only possible method for generators, manifestly cannot be safely carried above that which is tolerable for static transformers, which, when wound for the higher potentials, are invariably oil-cooled. Therefore I expect to see standardization of generator potentials, the pressure being stepped up by transformers to whatever transmission potential is necessary, and then stepped down to the working pressure on the trolley-wire if alternating current be used, or to a lower pressure and converted if direct current be used.

The transformer, *per se*, is the simplest and most flexible device for changing alternating-current volume and pressure, and its moderate cost and high efficiency, taken in connection with the like elements of moderately high potential generators, will leave the total cost and efficiency of generating equipment roughly the same. There will be the added very great practical advantage that the generators not only work at lower potentials, but on closed metallic circuits, are removed from direct contact with working conductors and earth, and have interposed between them and the line at least one set of static transformers, which practical experience has shown to be one of the best generator safeguards against lightning, and which, if broken down do not involve large and costly units, nor wholesale sacrifice of capacity.

General cost comparison of direct-current and single-phase alternating-current systems. Summarizing briefly, the alternating-current—direct-current and the single-phase alternating-current systems have certain features in common, and others differing, which may be briefly stated as follows:

Each must have a central station, which in the former will generate three-phase currents delivered to step-up transformers to raise the voltage of the transmission lines to any required degree, while in the latter, single-phase currents will be generated at a practical potential, and likewise stepped-up for transmission. Assuming equal kilowatt outputs, the generating part of the three-phase system will be cheaper than that of the single-phase, because of the higher weight-efficiency of the polyphase apparatus; but the switching devices will be somewhat more costly, while the transformers will cost about the same, with the net result that the cost of installation per kilowatt, and with equal conditions in the matter of speed, reliability, and efficiency, will be somewhat less for the polyphase than for the single-phase equipment.

The transmission lines, especially where provision is made for duplicate or reserve circuits, may for the purpose of this general comparison be roughly considered as of equal cost.

Sub-station transformers must be provided on each system to lower the transmission to the operating or transforming voltages. There will be approximately an equality in these features.

Just here is a line of departure, the transformed current in the alternating-current—direct-current system being passed through synchronous converters, and delivered to either an overhead trolley or a third-rail, assuming for this purpose the latter, while in the single-phase system it is delivered to an overhead trolley. The converters and the necessary housing and switching apparatus is an excess cost chargeable to the older system.

We come now to the working conductors of the two systems. The third-rail, which is prohibitive to the alternating-current system, cannot be put in except on what may be fairly called a permanent basis, at a certain approximate cost per mile of track equipped. The overhead trolley for the alternating-current system can be put in on either of two plans, one more or less tentative and temporary, using wooden poles and wire suspensions; the other, which is practically the only way affording reasonable permanence, with steel poles or bridge supports. Under this latter condition of permanence, the cost of such an overhead system per mile of track will run fully as high, and in many cases higher than the cost of the third-rail installation.

The costs of section-houses, circuit-breakers, and automatic apparatus will be quite as much with an overhead system as with the third-rail.

Tracks in either case must be bonded, more heavily and hence at greater expense for the direct current than for the alternating, but the difference will often be met by features connected with the overhead system, such as extra cost of piers, pull-offs columns, changes necessary in telegraph and telephone circuits, and clearing the right of way from trees.

The remaining element is the locomotive and motor-car equipment; the motors for the direct-current system being operated on the series-multiple plan, with resistance variation and possibly with field shunts, those for the single-phase alternating-current system, except where there is the intermediary of a motor-generator set, through a secondary or autotransformer carried on the car. According to present developments, there is here very great difference in the weight and cost of apparatus, and in the number of motors necessary to perform any given service. Judged from every standard which I have been able to compare, the cost of this part of equipment with 25-cycle alternating-current motors is so much higher than that with direct-current motor equipments, that, assuming a reasonable operating potential on the third-rail, it is certainly a debatable question whether the increased cost, and cost of operation of the motor-car equipments will not fully offset the cost of the synchronous converters and the losses in their operation.

I have made many comparative analyses, involving millions of dollars, and I have found that where equal permanence of installation is provided for, and equal ultimate as well as average duty, there is not on demonstrated facts a very wide variation in the initial cost of plant.

Ordinarily, the signal systems used on railroads will have to be changed at considerable cost. Fortunately, methods have been developed which permit the use of all the rails for the main return-circuit by using a special alternating-current circuit for operating the signals. Where the tracks are used for direct-current return, reactance bonds are inserted which permit the flow of the direct current, but resist that of the alternating signal current. Where the tracks are used for alternating-current operation, and are likewise subject to the flow of direct currents, the signals must be operated by alternating currents of high frequency through apparatus which is inoperative to currents of low frequency or continuous currents.

Field of the single-phase alternating-current motor. It would be idle to deny, and I have no wish to belittle the good work done and the results achieved in the development of the single-phase motor, just as it would be equally unwise to ignore what has been done in polyphase and direct-current work. The results, whatever they are, are facts which must be dealt with in a judicial spirit; but facts, not contradictory and unwise or unsupportable claims, must eventually guide the engineer. No one can deny that if the single-phase motor be developed to a high state of weight-efficiency, unhandicapped by excessive weight of the collateral apparatus necessary on a car to utilize it, and if the capacity of conductors, especially steel conductors, for alternating currents can by any discovery be raised, the elimination of moving machinery in, and the simplification of sub-stations would open up a very extended and important field for the use of this type of apparatus.

But with developments as they are at present, what is the actual field? As there is no general agreement as to methods of construction, so, too, I find no fixed conclusions as to the field of commercial usefulness; rather, on the contrary the sharpest differences of opinion. Some, with enthusiastic catholicity, make it all-embracing for steam roads, quite irrespective of well known limitations. Others, although at times seemingly contradictory, are even more elastic in their claims.

For example, one engineer says: "It is recognized that for heavy railroad service, where all kinds of speeds should be obtained economically, the single phase railway system will undoubtedly show to great advantage compared to any known continuous current system." Again, the same authority states: "While suburban work was once thought to be the most important field for the single phase railway, it has now become evident that city work, where traffic is very congested in parts of the system, will prove to be one of the best fields." Another affirms: "Interurban electric traction work is the peculiar field of the alternating current system," but adds to this the statement: "When stops are few, the advantage of the alternating-current system is not so greatly marked. In short runs, the alternating current system can have the greater advantage."

It has even been stated that for such services as that on our elevated and underground rapid transit roads, with their congested train movements, quick accelerations, high schedules and limited clearances, the single phase alternating current motor would find a fruitful field. It would, but the fruit would be somewhat bitter.

It seems to me that the present principal field of usefulness of the single-phase system is on roads of considerable extent which operate an irregular and sparse traffic, and where only a moderately expensive, or what may be called a second-class overhead construction, which will keep down the ratio of line investment to that of the balance of equipment, is tolerable. As one departs from this condition, adopts more permanent construction, and faces the problems of denser traffics and higher capacities, any advantages of the single-phase system will disappear, and the superiority of the direct-current equipment, with such improvements as are in sight, become manifest. But whatever may be the future of single-phase operation under the conditions stated, any present claim for it as the preferable equipment for congested service demanding high schedules and great capacity is not worth a moment's thought, for in this field, at least, it cannot touch the direct-current system.

Without individual comment, I quote from the preface of the recent work by Messrs. Parshall and Hobart, "Electric Railway Engineering," the following interesting expression of opinion: "In our judgment, the limitation of the alternating current motor is fixed, in its relation of energy output to weight, by the inherent properties of single-phase commutator apparatus, and the limitation of the continuous-current motor will be determined by the maximum safe voltage at which a commutating machine can be worked. While the development of each class of machine has advanced beyond the point that could reasonably have been foreseen, and while it is impossible at the present time to predict where the limitations will be reached, we are satisfied that a careful comparison of the two types at the present time is decidedly to the advantage of the high tension continuous current motor."

In closing, let me again remind you that we engineers are not omniscient, or immune from mistakes. Feeling strongly and speaking confidently of those things in which we believe, it is not reasonable to assume that the great diversity of opinion which exists, often emphasized by individual experience along specific lines, reinforced by knowledge of what has been accomplished in other directions, and influenced by such personal bias as we are all subject to, emphasizes the necessity of the utmost development in every direction; and the probability, nay certainty, that there is at present no single system which can be selected as best for all purposes, but rather, that a wide and increasing use of each will be created, and in the majority of cases a compromise selection of the best elements of alternating- and direct-current practice will obtain.

While there are many things in railroading which have been standardized, and others which can now very properly be, and which of themselves do not militate against the independent judgment of operating railway officials in matters individual to their own systems, I think it is certain that these same officials will in the future, as in the past, consider the problems involved in a change of motive power from steam to electricity from an individual standpoint, and that they will demand from manufacturers, as well as from their engineers, all possible freedom from restriction, exercising in a large measure their own judgment as to the adoption of any system. I see no practical necessity to formulate conclusions by averaging conditions, and I cannot conceive the responsible officers of any trunk-line road being guided in their determination of what seems best for their own requirements by consideration of what some road thousands of miles removed in location, and enormously differing in operating conditions may do.

In any case, the most satisfactory system will be that one which will permit of continuous all-round operation under such conditions as will utilize to the utmost all the beneficial features of electric application. If any one system can be demonstrated to meet these conditions better than all others, then that system will become preeminent, no matter what standards may have been adopted or recommended, and no matter what our preconceived prejudices may be.

APPENDIX.

Among the publications containing my views on the subject of heavy electric traction, may be mentioned the following:

National Electric Light Convention, Feb. 1890. Paper on "The Electric Railway."

Forum, Sept 1891. "The Future of the Electric Railway."

American Institute of Electrical Engineers, June, 1892. Inaugural Address: "Coming Developments of Electric Railways."

Engineering Magazine, July, 1895. "Will Trunk Lines be operated by Electricity?"

Electric Power, Nov. 1895. Editorial Views on Replacing Steam Locomotives by Electricity.

Engineering Magazine, Feb. 1898. "The Possibilities and Limitations of Electric Traction."

American Institute of Electrical Engineers, Feb. 1900. Discussion of Boynton's paper: "Electric Traction."

Electrical Review, Jan. 1901. "Historical Notes of Electric Traction."

Institution of Electrical Engineers, Feb. 1901. Discussion of Langdon's paper: "The Supercession of the Steam by the Electric Locomotive."

Engineering Magazine, Oct. 1901. "The Rapid Transit Problem in London."

American Institute of Electrical Engineers, June, 1902. Discussion of Arnold's paper: "Relative Costs of Operating by Steam and Electricity."

Electrical World, March, 1904. "The Past, Present and Future of Electric Traction."

International Electrical Congress, St. Louis, Sept., 1904. "The History and Development of Electric Railways." Discussion of Arnold's papers: "Electrification of Steam Railways," and "Polyphase and Single-Phase Traction."

Discussion of Dawson's paper: "Electric Traction on British Railways."

New York Railroad Club, Jan., 1905. Discussion of Potter's paper: "Developments in Electric Traction."

American Institute of Electrical Engineers, Feb., 1905. Dinner celebrating Triumph of Electric Traction; "The Art and The Men."

Century Magazine, July-August, 1905. "The Electric Railway."

Street Railway Journal, Oct., 1905. An Unprecedented Railway Situation."

New York Railroad Club, March, 1906. Discussion of Lamme's paper: "Alternating-Current Electric Systems for Heavy Railway Service."

American Institute of Electrical Engineers, Jan., 1907. Discussion of Stillwell and Putnam's paper: "The Substitution of the Electric Motor for the Steam Locomotive."

Discussion on "Some Facts and Problems Bearing on Electric Trunk-Line Operation," at New York, May 21, 1907.

W. J. Wilgus: There are so many points on which I fully agree with Mr. Sprague that it is perhaps well at the outset to dwell on one matter where we appear to disagree, and that is the relation of those engaged in the conducting of trunk-line railroad operation to the electrical engineering profession which is now gazing with hungry eyes on that enticing field of new endeavor—the electrification of trunk-line railroads. Without intending to indulge in the sarcasm and pessimism ascribed to our friend, the editor of the *Railroad Gazette*, I do believe with him that the cause of electrical engineering would be much more rapidly advanced if an effort could be made to bring the steam railroad official more closely in touch with the practical side of the application of electricity to the art of transportation. It is true that in the past the majority of steam railroad men have rather looked upon electric railroads as beneath their notice, but recent important developments in the change of motive power on some of the more prominent railroads of the country have dispelled this idea; and I feel certain that all steam railroad officials are now looking upon the future possibilities of the electrification of steam railroad traffic with keen interest and with a full appreciation of the magnitude and dignity of the problem.

Unfortunately they have so far felt barred from an intimate study of the subject because of the befogging of their minds by heated claims and counterclaims of the merits and demerits of various electric systems, coupled with the use of technical phrases with which they are entirely unacquainted. After all, the main features of the electrification of steam railroads are understandable to steam railroad men if technicalities can be avoided and the essentials described in ordinary homely language that can be grasped by the men not versed in the technique of electrical engineering. I therefore venture the suggestion that in general discussions intended for the enlightenment of the non-technical steam railroad men, the subject be treated as broadly as possible, with an absence of partizanship and with the use of plain non-technical terms. Furthermore, I believe that it would be conducive to the best interests of the electrical engineering profession to attract practical steam railroad men to a discussion of papers bearing on the electrification of trunk-line railroads so as to secure an interchange of views.

With respect to the conditions that will justify the use of electricity as a motive power in trunk-line operation, I believe that *evolution* will govern rather than *revolution*. In other words, there will be no sudden general substitution of electricity for steam as a motive power, any more than there was as a sudden jump from the small locomotive of the DeWitt Clinton type to the Mallet compound of to-day. Railroads, like all other human achievements, cannot stand still; they must either move forward or backward. It is generally recognized that their ability to move forward is now limited with steam locomotive practice, and that the overcoming of the defects inherent to the steam locomotive can only be accomplished by the use of electricity. It now looks as if the first movement in this process of evolution is the substitution of electricity for steam in congested passenger terminals at large centers of population where the public demands a cessation of nuisances incident to steam locomotives, and where the increasing volume of traffic requires increased capacity that cannot be obtained with the present motive power. The success of the New York Central installation in both of these particulars is an illustration of what can be accomplished, and imitation will surely ensue at other places where like conditions exist. Coincident with the change of motive power in crowded passenger terminals, is coming the use of electrically propelled trains on existing steam-railroad tracks between large centers of population where frequent units are necessary to accommodate the public. We already have an instance of this in the electrification of the West Shore passenger traffic between Utica and Syracuse, a distance of about 50 miles. In addition to these instances, where at this time the wisdom of the adoption of electricity as a substitute for steam is self-evident, there are a number of places in the West where the capacity of steam locomotives of the highest type is entirely inadequate to handle freight traffic on the pusher grades, and the only manner in which the increased capacity can be obtained is by means of electricity. With a start in the substitution of electricity for steam in the operation of congested terminals, connecting lines between large centers of population, and long pusher grades with heavy freight traffic, we may look with confidence to a gradual expansion of the use of the new motive power in other directions. For example, in the case of the New York Central the primary object of the use of electricity was to abate the smoke nuisance in the Park Avenue tunnel and to increase the capacity of the Grand Central terminal. When this decision was reached, it became self-evident that the use of the motive power should extend to the end of the suburban territory at Croton on the Hudson Division, a distance of about 35 miles. While the northerly terminus of the main line is thus planned for the present at Croton, it is probable that just as soon as the developments in the electrical field will warrant such action, the electric zone will be extended as far as Albany, a total distance of 142 miles.

This brings up the question of the respective merits of the three electrical systems now warmly advocated by their respective friends; videlicet, the direct current, single-phase alternating current, and three-phase alternating current. Looking at the matter from an electrical standpoint, it is very much to be deplored that the advocates of each of these systems have seen so much to condemn in the others, as this practice has frightened the steam railroad men from taking any decisive steps when there is such disagreement among those upon whom they must depend for guidance. If instead of blindly teaching the merits of one system to the exclusion of others, the electrical engineers could unite upon the axiom that each special condition should be carefully studied and the system adopted best suited to it, I feel certain that the cause will be further advanced. For instance, direct current was adopted for the New York Central installation at New York, among other reasons, because the clearances in the Park Avenue tunnel and the ordinances of the City of New York absolutely precluded the use of overhead construction; and yet we are told that a great mistake has been made and that no other system should have been used but single-phase alternating current with overhead construction. Entirely apart from any arguments, pro and con, of the relative merits of the two systems, it will be seen that physical and legal conditions prevented the adoption of any system other than the direct current. When there are no limiting conditions, and the steam railroad engineer is free to give full sway to the exercise of his judgment as to the selection among rival methods, he asks first, which is the most *reliable*? Accustomed to the use of long-tried steam locomotives, the breaking down of any one of which does not necessarily affect the movement of many others on the line at the same time, he naturally looks askance at the adoption of a new method of moving trains that carries with it the danger that in case of a disturbance at the power station or transmission lines, every train on the line will come to a standstill.

This question of *reliability* is much more important with a trunk-line steam railroad carrying passengers from remote points, and mail and express from over all the country, as well as suburbanites, than with local street-car systems. For this reason the conservative steam railroad man does not feel like making experiments with untried systems, no matter how alluring their advocates may make them, but prefers to select from systems which by long tried experience are proved to be thoroughly reliable. In fact on the more important trunk-line installations storage-batteries are now felt to be a necessity, not only to provide for violent fluctuations of load much greater in range than with ordinary street-railroad systems, but also to afford insurance against interruption of traffic due to minor breakdowns in power stations and transmission lines. The New York Central in its desire to secure reliability has provided not only storage-batteries, but also duplicate power stations with access for fuel by both rail and water, either of which can, in the event of the disablement of the other, run the entire system, by utilizing spare units and working overload. Duplicate transmission lines have been adopted for like reasons. Since the commencement of electrical service last December, events have already proved the wisdom of these precautions.

The answer to this contention—that trunk-line railroads should use well-tried systems—is that no progress can be made unless something new is tried. In reply it may be stated that the trunk-line railroad is not the place to make experiments, but that interurban roads of minor consequence should be selected and the new system well proved before it is installed on a large scale in territory where its failure may have disastrous results.

Further commenting on the necessity for a study of local conditions, I have recently had in my charge the adoption of an electric system for operating combined freight and passenger service through a double-track tunnel now under construction. In view of the claims made by the advocates of different systems, it seemed wise to prepare the specifications so as not to cramp or restrict the judgment of the competitors, but leave the widest latitude for ingenuity and exercise of skill consistent with the accomplishing of the desired object. The invitation to domestic and foreign companies, in addition to asking for bids, also requested the filling in of blanks to show the annual costs, including interest charges, depreciation, taxes, and operation. The result showed conclusively that for that particular installation, the direct-current system was the cheapest in both first cost and annual cost, to the extent of from 20 to 25 per cent. less than its nearest competitor.

With your permission I would like also to give another illustration of the lack of wisdom in making broad generalizations from which to draw specific conclusions. We are often told that the overhead single-phase system should be used because of the advantage of requiring no sub-stations and sub-station attendance, but nothing at the same time is said about the higher cost of alternating-current locomotives for performing the same service, nor the higher cost of overhead construction as compared with the third-rail. About a year ago a pamphlet emanating from an eminent authority stated that on four-track trunk-line territory overhead construction would cost about $16,000 per mile, when as a matter of fact a recent actual installation has cost over $50,000 per mile! Also in a recent installation, while the first cost of the adopted system is somewhat less than one of the rival systems, still the increased consumption of current on one portion of the territory, capitalized, amounts to a very large sum. This amount added to the cost of installation, makes the equivalent cost considerably in excess of its rival. I am merely mentioning these instances as showing the necessity for fairly setting forth all sides of a problem before drawing a conclusion that may be entirely wrong; in fact I do not know of any important question of the day that so much requires absolute openness and frankness, with a careful examination of all sides of the case, as the adapting of electricity to trunk-line practice. Any concealment of the facts reacts sooner or later to the detriment of those responsible therefore and to the financial embarrassment of the suffering company.

I cannot too strongly endorse Mr. Sprague's remarks bearing on the wisdom of adopting the multiple-unit system for handling suburban service. The New York Central has already reaped its reward in adopting this method, in the elimination of practically all of the delays of train service at the Grand Central Station, delays that heretofore largely resulted from the multiplicity of movements of steam locomotives in passing to and from the engine-house facilities and in switching from the head to the rear end of trains; in fact, apart from other improvements made at this terminal, the use of the multiple-unit system has at this time resulted in an increase in the capacity of the station of at least 33 per cent. Moreover, the rapid acceleration of this character of equipment as compared with locomotive practice has resulted in the ability of the operating department to maintain schedules with a reduced rate of speed between stations. While on this subject of acceleration it might be well to add that in making a selection between the rival electric systems, relative acceleration should be compared not only in connection with the movement of suburban trains but also through trains hauled by electric locomotives. Some recent observations have demonstrated to me the marked difference of acceleration between the two principal electric systems. In changing motive power from steam to electricity on trunk-line railroads, this question of acceleration is one of the greatest attractions; it should, therefore, not be lost sight of in deciding upon any electric system which may offer no greater advantages in that regard than the steam locomotive that it displaces.

Another point mentioned by Mr. Sprague that seems worthy of special notice, is bonding of track rails. The New York Central has realized the wisdom of its course in adopting bonds concealed beneath the fish-plates, as there has been no loss from their theft; whereas I believe that on other roads where this precaution has not been taken, electrical operation has been seriously interfered with by the theft of exposed bonds.

In thus venturing a word of advice for closer relations between the steam railroad engineer and the electrical engineer, and greater frankness and cool reason in the discussion of the relative merits of the various electric systems, I may be pardoned a word to the electrical manufacturers in doing their part to popularize with steam railroad men the use of electricity in solving trunk-line problems. Always having in mind the primal elements of safety and reliability, all inventive genius of the great manufacturing corporations in this country should be bent on devising means of accomplishing a desired result at less cost, as this will mean in the end such an increase in the use of electricity as a motive power as to more than compensate for the comparatively small loss in decreased unit prices of apparatus. One of the promising movements in this direction is the hints that have been given of the possibility of substituting for the expensive synchronous converters and sub-station attendance of the direct-current system, a very simple device which will cost very little and require no attendance. This one feature, if successful, will go far toward strengthening the hand of the steam railroad enthusiast in extending the use of electricity more generally than now seems possible. The signal field is also one in which there is room for improvement in reducing costs of installation so as to make the use of electricity feasible from a financial standpoint. The use of electricity at the present day requires the throwing away of old type signals and interlocking systems and the installation of an entirely new system at a vast cost, due to the necessity for the use of the track rails for return propulsion current. On one of the branch lines of the company with which I am connected the substitution of electricity for steam has been indefinitely postponed because of the attendant greater cost of making a change in the block signals and interlocking apparatus; but I am pleased to say that one of the electrical companies now gives ground for hopes that a new method has been devised which will do away with the necessity for the more expensive portions of the apparatus and so far reduce the cost of the change of signaling as to make feasible the electrification of the branch road. It has seemed wise to give these illustrations as having a bearing on the rapidity of the process of evolution of change of motive power on trunk-line railroads.

As to the relative merits of overhead and third-rail working conductors, steam-railroad men have been more or less alarmed at the freedom with which contending enthusiasts argue as to the danger attendant upon the selection of either. It must be conceded that in return for the many advantages that come with the use of electricity, there are certain disadvantages; among these is the added danger from the use of working conductors, whether third-rail or overhead. The question simply simmers down to the selection of the system which appears to offer the least danger. Mr. Sprague has exhaustively covered the merits and demerits of each, and it remains for the steam railroad man to make a selection, having in mind the desiderata of non-interference with the view of signals, elasticity in the adjustment of tracks to new grades and alinement and the laying of additional tracks, minimum danger from derailments, safety to employes, and economy of maintenance.

I realize that my remarks on Mr. Sprague's exhaustive paper are very general and throw very little specific light on the problems that he discusses, but I feel that I might be pardoned for dwelling on a few of the features that have seemed wise for all of us to bear in mind in attempting to work together in bringing about as rapidly as possible the substitution of electricity for steam in places where progress demands increased capacity and the abolition of many drawbacks that necessarily accompany the use of the steam locomotive.

Lewis B. Stillwell: The Institute is to be felicitated upon the presentation of a long and interesting paper by a member who in the past has contributed largely, perhaps more largely than any other living man, to the utilization of electricity for traction purposes. With much, perhaps all, that this paper states in its first dozen or fifteen pages I am sure that we will find our opinions in agreement. We have noted a tendency of some electrical engineers to indulge in prophecy; the fact that some of us have difficulty in discussing railroad finance and operation unless we confine ourselves to glittering generalities has been frequently observed; that the hope of financial profit is the underlying motive which induces the capitalist to undertake electrical enterprises is a part of our engineering creed.

It is sometimes asserted also that an unfortunate tendency and limitation of engineers, as a class, is to concentrate their attention too closely upon certain features of a general problem and to lose sight of other features essential to a comprehensive and accurate mental prospective. Realizing this, it is satisfactory to note that the preliminary pages of the paper this evening aim to assist members of the Institute by suggesting a broad view of the general problem of electric trunk-line operation. It is distinctly disappointing, however, that, after casting his eye over the broad prospect which now appears to offer so inviting a field for the realization of increased earnings and decreased operating expenses by gradual, well-considered, and systematic extensions of electrification, the author should spend so much time and effort examining details of construction of assumed alternating-current and direct-current car equipments that he is able to bestow but a passing glance upon the sub-stations required for direct-current operation, and but hastily to examine the contrasted systems of transmitting power from coal pile to moving train. Herein the paper entirely fails to convey an accurate idea of their relative advantages and limitations.

In the paper of the evening, as also in his interesting contribution to the discussion of the paper which Mr. Henry St. Clair Putnam and I had the honor to present at the meeting of January 25, the author takes issue with certain opinions which I have expressed relatively to the question of standardization of electric railway equipment and the relative merits of direct-current and alternating-current motors for trunk-line operation. In the paper before us he says:

> But above the discordant notes, and in the turmoil of varied developments there rises now and then the cry of standardization, not only such as is natural and not prohibitive of new advances in the art, but wholesale explicit, and exclusive. For example, in a recent paper before this Institute, the view was expressed that but a single plan—the high-tension overhead trolley, with 15 cycle, single-phase alternating-current motors —was possible of serious consideration on trunk-line service, and that this system should now be adopted and standardized, despite the fact that there was not in existence a single equipment of this character in practical railway operation!

It is obvious that Mr. Putnam and myself failed to convey to the author of this evening's paper an accurate understanding of our position, and lest others also may have misunderstood our meaning I may be permitted to quote from the paper and its discussion the following paragraphs relative to " Standardization":

Engineers constituting the membership of this Institute owe it to themselves, as well as to their clients, to use every effort, without prejudice and without fad, to prevent waste by opposing the introduction of apparatus which from its limitations cannot solve the general problem of railway electrification; and it is to be hoped that they will use their united influence to fix proper standards as rapidly as this establishment may be consistent with progress. * * *

The necessity of proper standardization is obvious. Specifically it would seem feasible and eminently wise to agree upon standards of practice in respect to the following:
(a) Location of third-rail.
(b) Location of overhead conductor used with single-phase alternating-current-system.
(c) Frequency of alternating-current traction systems.
It is equally desirable but probably less easy to agree upon a standard system of multiple-unit control for train operation. * * *
The position which we take in this matter may be stated as follows:

a. A general view of the railway field, including freight as well as passenger traffic, obviously shows that for anything approximating a general solution the single-phase alternating-current system is decidedly superior to the 1200- or 1500-volt direct-current system. This conclusion is corroborated by calculations easily made and based only upon established facts.
b. The admitted advantages of electricity in respect to increased earning power and decreased cost of operation are such as assure in the near future rapid increase in the use of electricity by railway systems now operated by steam.
c. The necessity of standardizing frequency rests practically, although less directly, upon the same arguments as have induced railways to standardize track-gauge, train-line, and steam-line.
In other words, the significance of our estimates of comparative operating costs is that the results, viewed in connection with admitted facts in respect to increased earnings, indicate that a general electrification of important railway divisions, and even of trunk lines, is coming much more rapidly than has been generally realized, even by electrical engineers; and the lesson to be drawn from this conclusion is that we must standardize as promptly as possible everything essential to convenient interchange of rolling stock.

Mr. Putnam and I have said nothing which excludes from further consideration the three-phase alternating-current system or any other alternating-current system, neither have we opposed the use of direct-current motors at any voltage in any kind of service, except trunk-line service in which it is proposed to substitute the electric motor for the steam locomotive. The line which divides trunk-line service from interurban service, of the class to which hitherto electricity has been applied, is sufficiently distinct, in most cases, to be recognized without difficulty. For interurban service I have used, and may continue to use for some time to come, direct-current equipment. Every real improvement in electric equipment adapted to rolling stock, whether that equipment be of the direct-current type or the alternating-current type, has its value. Each specific case of proposed installation obviously calls for careful comparison of available and adequate systems. Such comparisons, however, if they are to lead to conclusions that shall stand the test of time, must take into account not only existing and available equipment, but must recognize also tendencies in the development of the art, and consider probabilities of future extensions and possible connections of the specific line under consideration.

For trunk-line operation I have held and still hold the opinion that the 15-cycle, alternating-current, single-phase system possesses, inherent characteristics which, in this class of work, constitute controlling advantages as compared with any direct-current system that has been suggested, or is liable to be developed into an operative system. With this opinion the paper of this evening joins issue. In the oral discussion of the paper of January 25, the author of this evening's paper stated his position with emphasis by saying:

> I am going to make a prophecy, that on a large number of lines which can by any stretch of imagination be considered as subject to a reasonable prospect of electrification, 1200 or 1500 volts will on any present development known, give better results in every way than the alternating-current, 15- or 25-cycle overhead system.

The paper before us while presenting certain data and opinions purporting to sustain the contention that the 1200-volt direct-current system is superior to the 15-cycle alternating-current system, presents no sufficient and fairly comparable data upon which any such conclusions can be based. The only data which it presents in the way of a comparison of the relative outputs, speeds, and weights of the contrasted types of motor are those in which a direct-current motor rated at 240 h.p. and an alternating-current, 25-cycle motor rated at 125 h.p. are compared. A pyramid cannot be made to stand long upon its apex unless propped up, and no conclusions as broad and far-reaching as that which this paper apparently endeavors to establish can be based upon a single comparison of this kind. Even this single exhibit obviously requires material correction before it can be used properly as a premise for the conclusions which the author seeks to draw. It is defective for the following reasons:

1. It compares two motors of equal weight. This comparison used as a basis for a general conclusion is, obviously, unfair to the alternating-current motor, as it takes advantage of the fact that increase in the size of motors of any type, alternating current or direct current, implies reduction in weight per horse power. Had the comparison brought together two motors of equal output, the ratio of weights would have been far less than is the ratio of output when equal weights are considered. The particular case of a motor-car equipment in which it appears that four 25-cycle alternating-current motors would be required to do the work of two 550-volt direct-current motors is one which has come up in my own experience, but, obviously, it is no proof that similar relations would hold, for example, in equipping a locomotive with a given aggregate horse power.

2. The comparison is made with a 550-volt, direct-current motor weighing without gear, gear-case, and pinion, only 23 lb. per h.p. (one-hour rating). This is extraordinary light and indicates that the motor is, in respect to the relation of weight to output, superior to anything in general use. The latest 200-h.p. motors offered within the last 60 days to the Interborough Company by our leading manufacturers weigh, respectively, 28 and 30 lb. per h.p. (one-hour rating). The alternating-current motor in Mr. Sprague's comparison, on the other hand, is characterized by a higher relation of weight to output than other single-phase motors of comparable output in the market.

3. The comparison is between a direct-current and an alternating-current motor operating at 25-cycles, not 15-cycles, which is the frequency suggested by Mr. Putnam and myself. The 25-cycle single-phase motor has a far higher ratio of weight to output than the 15-cycle motor of the same output.

The paper emphasizes the statement that "Capacity is the keynote of equipment." With this conclusion few will differ. In our consideration of capacity of equipment, however, we should not limit our attention to the motor but should take into consideration, also, the comparative methods of transmitting power to the moving trains. In general, the choice of a system will depend upon the ratio of capacity as measured in tractive effort to aggregate cost of equipment.

I have read the paper of the evening somewhat hastily and possibly may have overlooked an adequate statement of the advantages of the alternating-current systems which result from the elimination of the converter substations. These, as is well recognized, are a very expensive element of the direct-current system as it would be applied to anything resembling a trunk line—expensive not only in first cost but relatively still more so in annual cost and in complication of the distributing system. There are to-day in operation in this city somewhat over eighty 1500-kw. converter units for the purchase and installation of which I have accepted responsibility. While this machinery is doing excellent service, I know enough of its cost and limitations to realize that for trunk-line railroad operation in the broad sense a system which employs the converter as an essential link between the coal pile and the train must give way to a system which eliminates this link, provided the single-phase, alternating-current motor is designed and manufactured with anything approximating the care which to-day is bestowed upon the direct-current motor.

As I have said, a pyramid should not rest upon its apex; general conclusions, too, in respect to the very important question under consideration, should not be based upon comparison of a single representative motor of each size. Such comparison should rest upon comparative data prepared by competent designing engineers, working without prejudice in favor of one system or the other, and should comprise essential facts covering a considerable number of motors of various output, designed for the same service. It is to be hoped that some of the designing engineers of our manufacturing companies will prepare and present such data in connection with the discussion of this paper.

Meantime, however, I may say that only last week with reference to a specific installation which I am studying, I obtained from the engineers of one of our large manufacturing companies comparative figures relating to 15-cycle, single-phase, alternating-current motors of 200 h.p. at one-hour rating, and 600-volt, direct-current motors of the same output. These motors are practically identical in speed when delivering 200 h.p. The data in which I was particularly interested are the maximum vertical dimensions and the weights of these motors. The maximum vertical dimension of the alternating-current motor is 36.5 in.; that of the direct-current motor is 1.625 in. less. The weight of the alternating-current motor is 6280 lb.; that of the direct-current motor is 6000 lb.: both of these weights are exclusive of gear-case and pinion. The alternating-current motor requires a wheel-base one foot longer than is necessary with the direct-current motor. The ratings in the case of both motors are based upon the same rise of temperature without forced ventilation.

I am not sure that I understand the author's reference to the implied necessity of increasing the current-carrying capacity of steel conductors. He quotes from the report of the commission of the recent International Electrical Congress to show that on 80-lb. rails the ratio of impedance to resistance at 25-cycles is about 9 to 1. This difference is, of course, well known; but in transmitting a given amount of power by single-phase alternating current through overhead trolley and track return at 11000 volts, even when a frequency as high as 25 cycles is employed, the reduction in current implied by the increased voltage makes the total drop in the circuit, as measured in percentage of applied potential, less than $\frac{1}{10}$ the drop of a direct-current system operating through the same circuit at 1200 volts.

It should be noted carefully that while the only comparative data given with respect to motor performance relate to the 550-volt, direct-current motor, the paper implies that in competition with the alternating-current system a direct-current potential of 1200 volts will be used. It is for our designing engineers to supply adequate data, but I venture to express the opinion that comparing the 15-cycle, single-phase, alternating-current motor with the 1200-volt, direct-current motor, the latter will, in general, have very little, if any, advantage in respect to dimensions or weight. Moreover, it is not to be lightly assumed that synchronous converters delivering 1200 volts would be found as cheap and as reliable as the 600-volt machines now in use.

When we come to consider the auxiliary car equipment and wiring there is a very radical difference in favor of the alternating-current system. In this field as in the lighting field the transformer is the key to the solution of the general problem of transmitting energy at reasonable cost and utilizing it at safe and easily controlled potentials.

W. B. Potter: Using the word system in the sense of meaning the different modifications of direct and alternating current, I think all will agree that the state of the art is not such as to warrant the recommendation of any particular system as the standard and the only standard for future consideration. With reference to existing installations, the 600-volt, direct-current system and apparatus is certainly a recognized standard, which is more than can be said of the apparatus on any of the other installations, at least in this country. In nearly every case where a choice between systems is considered, there are controlling conditions with respect to financial advantages or local requirements which are of sufficient prominence to determine the particular system most suitable for the case under consideration. The proper attitude of the engineer toward commercial undertakings, with which most of us have to deal, should be that of an investor, his reputation being his capital and his dividends being in direct proportion to the economic success of the work for which he is responsible. I feel that Mr. Wilgus has well expressed this sentiment in saying that an important trunk-line railroad is not the place for experimental development, but that such work should be done on branch lines where failure or partial success would inconvenience a smaller number of persons. To a large degree new types of apparatus can be perfected by manufacturing companies, by experimental operation on suitable tracks; but in the actual operation of apparatus conditions invariably arise that do not develop under the control of the designers and which can only be eliminated by such advisable modifications in design as become apparent from a careful study of the apparatus in service.

For a number of years the improvement in direct-current apparatus has been principally with respect to its mechanical features. Within the last few years, by the application of commutating poles, there has been a decided improvement in commutation, particularly with direct-current railway motors. These motors, by reason of physical limitations and the fixed position of brushes necessary for operation in both directions, are particularly difficult to design electrically. From present indications it would appear that for other than bi-polar motors the recognized standard direct-current railway motor will undoubtedly be provided with commutating poles. Granting a motor of suitable capacity, the character of the commutation is of the utmost importance to the operator, since defective commutation means decreased reliability, increased cost of maintenance, and a degree of supervision out of all proportion to the other parts of the motor.

This problem of commutation, which has been so effectively solved in the case of the direct-current motor, is one of the principal difficulties to be overcome in the single-phase, alternating-current motor. The commutation of this is inherently inferior. Another feature of the alternating-current motoı incidentally affecting commutation is the number of armature revolutions relatively to the car-speed; the armature speed is somewhat higher than that of the direct-current motor. The higher speed of the armature is not necessarily a feature of single-phase motor design, but owing to the comparatively greater weight of this motor it is desirable to run the armature at as high a speed as is consistent with satisfactory operation of the bearings.

The single-phase motor is a comparatively recent development. We have good reason to expect substantial improvements in its design, particularly with respect to commutation; and I am pleased to say this evening that the prospects are particularly encouraging for a single-phase motor with commutation as good if not better than that of direct-current railway motors without commutating poles, and with an armature speed only slightly higher than that of the direct-current motor. As this improvement in commutation is got without the use of resistance leads, the internal losses incident to such leads, or the losses due to local current in the armature, are largely avoided and the efficiency of the motor is improved. The weight of such a motor will still be probably about 25% greater than that of a direct-current motor of the same rated capacity.

These improvements do not affect the application of the different systems, except that they may result in reducing the cost and maintenance of the single-phase apparatus. They do, however, raise the quality of the apparatus more nearly to that used in present direct-current practice.

The 1200-volt direct-current system, to which special reference has been made by Mr. Sprague, is substantially in line with present-day practice for 600-volt apparatus. The commutation gives every evidence of being as good as with 600-volt motors, the only provisions necessary being additional insulation both with respect to the coils and creepage distances on exposed surfaces. With respect to the higher voltage direct current, I would suggest that 1200 volts be accepted as the next higher standard above 600 volts. The use of a number of intermediate voltages would introduce a variety of apparatus not suitable for general use, and necessarily more expensive, as it would be manufactured in limited quantities only. On account of the practical relation of speeds easily obtained with the series-parallel combination of the motors, 1200 volts afford better opportunity for interchangeable operation with 600 volts than with any intermediate voltage.

As an illustration of the attitude of operating companies concerned in getting apparatus most suitable for their service, I would mention that at the present time there are being manufactured for use in this country, railway apparatus for 600- and 1200-volt, direct-current systems, a 6000-volt, three-phase system, and a number of 25-cycle, single-phase systems of different voltages.

Charles F. Scott: The author makes comparisons between direct-current and single-phase, alternating-current apparatus. I have been particularly interested to detect his method in arriving at conclusions which are so largely at variance with those of some other engineers.

First of all he lays stress upon the relative capacity of the motors of the two types as being one of the important and controlling elements in reaching a decision. He takes certain data and a certain basis of comparison, and from these reaches apparently logical conclusions. The question then arises, are the data and the basis of comparison correct? If not, are there not other data and another basis of comparison from which conclusions may be drawn by the same method, but perhaps with different results?

It seems to me that a number of points which Mr. Sprague has taken up are comparisons on a particular basis, and that he has not considered fully the different methods or conditions under which the two motors may operate; for example, in comparing the curves of the two motors, he shows that the alternating-current motor has at light load a much higher speed than the direct-current motor under the conditions which he has taken. There is an apparent conclusion, therefore, that the alternating-current motor is lacking in the excellent characteristics possessed by the direct-current motor. He has failed, however, to call attention to another point; that is, the ready adjustability of voltage in the alternating-current system by means of voltage taps from the transformer. By this means the motor, instead of operating to its highest speed under a single applied voltage, which is the usual condition with the direct-current motor, may have a lower voltage applied. It may, therefore, develop different torques at different speeds, depending on the controller position. Under the control, therefore, of the motorman, the alternating-current motor is not limited to a single law of acceleration, but may have different rates of acceleration, adjustable as desired; it may, for example, have the same mean acceleration from start to maximum speed as that of a direct-current motor, but with a less maximum rate of acceleration.

Another point in which changed conditions were not taken into consideration is that of rail-loss. Although the loss per ampere may be greater, the loss per kilowatt may, as pointed out by Mr. Stillwell, be much less.

It appears that the author, in his treatment of the subject has, unconsciously perhaps, assumed the direct-current motor and its characteristics as the ideal of perfection, so that wherever the other motor has different characteristics, these characteristics were naturally and *per se* objectionable. At any rate, he has apparently not recognized or emphasized certain advantages on the side of the alternating-current motor, In certain cases the voltage control can give a higher speed than normal to a motor in service. The application of higher voltage gives not only higher speed, but greater output as well. Something of the same nature is attained by field-control in the direct-current motor, but the field-control is a method of adjusting speed without increasing the capacity of the motor. The same voltage is applied, and the permissible current through the motor remains the same, and hence its capacity is not increased. But with the alternating-current motor an increased voltage is applied to the motor which gives an increased output, with the same current going through its armature, The paper, furthermore, gives but little consideration to the advantages inherent in the alternating-current system between the power house and the train, through the elimination of synchronous converters and the reduced current to be carried. The rheostatic losses in direct-current equipments, a matter which in some kinds of service is of considerable importance, has not been touched upon.

The matter of electrical braking has been referred to. A paper on braking with single-phase motors is to be presented at the next Convention by Mr. William Cooper. The paper will deal with a method which has been worked out and fully tested, whereby it is found that the single-phase motor lends itself admirably to braking, covering, as I recall, all the desirable qualities in braking which have been called for by the author and doing far more than has been shown possible with the direct-current motor.

N. W. Storer: The question of third-rail versus overhead construction for electric railways is a matter concerning which it is unnecessary to theorize, because, with the large systems now in operation or about to be put in operation, it will very soon be settled by experience.

I desire to take issue with the author in regard to some statements concerning single-phase equipment, as information that I have is entirely at variance with what appears in the paper. In the first place, there are given fifteen so-called differences between direct-current motors and alternating-current, single-phase motors. These might have been called, "The advantages of direct-current motors as compared with single-phase motors," as this is what they are made to appear. Although many of these are of little consequence they will nevertheless be considered in order.

1. " The input of current in one is continuous; in the other, intermittent." Quite true, but the draw-bar pull is quite as effective in one case as in the other

2. The direct-current motor has a solid frame like the single-phase motor It has, further, two or more laminated poles bolted in, and if the interpole construction is used has as many more relatively small and delicate poles. The alternating-current motor as built by the company with which I am connected has, in all sizes up to a diameter of 38 in. field punchings made in a single piece and built up and keyed in the frame,

making it as solid a construction as an armature on its spider. The claim for less rigidity in the single-phase motor is, therefore, not sustained.

3. " One has exposed and hence freely ventilated field-coils; the other has field-coils embedded in the field-magnets." It is known to most motor designers that coils in contact with iron will dissipate heat much faster than when in the open air. This is especially true of coils in an enclosed motor. I have repeatedly noticed that motor field-coils which have been removed on account of roasting, have shown the insulation in contact with the pole pieces to be in good condition, while other sides were badly roasted. I know, therefore, that in respect to ventilation of field-coils, the single-phase motor is superior to the direct-current motor. Smaller cross-section of coils also allows the heat to be radiated better in single-phase motors, and the fact that a large part of the loss in the motor is concentrated in the field iron will enable the motor to dissipate a much larger amount of heat for a given temperature-rise than will a direct-current motor.

4. Concerning " polar clearances." Many thousands of direct-current motors are to-day in operation with a clearance of $\frac{1}{8}$ in. to $\frac{3}{16}$ in. between poles and armatures, and in practically all cases where more than $\frac{3}{16}$ in. clearance is used it is for electrical reasons. Further, while the smaller air-gap used for single-phase motors was at first much feared, the fears have proved to be without foundation and the present clearances of from 0.1 in. to 0.15 in. have proved to be ample and fully as good as 0.15 in. to 0.25 in. in direct-current motors, because there is no unbalanced magnetic pull.

5. Concerning "torque." The torque of an armature is the pull it will exert at one-foot radius. Therefore it makes no difference in the result whether it is obtained with large flux and few armature conductors, or vice versa.

6. " A much larger diameter of armature and commutator, and runs at a much higher speed." This is a very general statement: what are the facts? The armature diameters ordinarily run from 5 to 15% larger than for direct-current motors of corresponding output. It is undoubtedly true that the armature speeds of the earlier single-phase motors were much higher than the speeds of corresponding direct-current motors; at the present time, however, the speed at the nominal rating of the motor is practically the same as that of direct-current motors, and the maximum operating armature speeds are within the safe limits set for direct-current motors.

7. Concerning " gear-reduction and gear-pitch." The gear-reduction depends, of course, upon the speed; and as far as gear-pitch is concerned, I wish to say that the same gear-pitch is used for single-phase motors as for direct-current motors of the same capacity.

8. " The windings of one are subject to electrical strains of

one character; in those of the other the strains are of rapidly variable and alternating character." No conclusion is drawn from this. It may be of interest to know that there have been a number of instances where the single-phase motor has broken down in service on a direct-current section of the line, necessitating cutting it out of the circuit; but when the car reached the alternating-current section of the line it has been again connected in circuit and operated satisfactorily, thus indicating that the electrical strains with alternating current are less severe than with direct current.

9 and 10. Concerning the "variable torque of the single-phase motor." No comment is made as to the relative merits of uniform or pulsating torque. In a recent discussion before the Institute, Mr. Potter called attention to certain characteristics of the torque exerted by an alternating-current motor, especially when it reaches the slipping point of the wheels. It was stated that there is an apparent advantage in the pulsating torque, because, when the motor starts to slip it does not immediately decrease its mean torque, as is done in the case of the direct-current motor, but slips in a series of jerks apparently regaining the hold on the rail at every pulsation.

11. Concerning the "number of poles." The paper states that the direct-current motor has "two or four main poles only." No direct-current motors built in the last 15 years except those on the New York Central locomotives have less than four poles. The paper states that the alternating-current motor has "eight to fourteen poles." The single-phase motors built by the company with which I am connected have four poles for all sizes up to and including 125 h.p. The largest single-phase motor thus far built has a capacity of 500 h.p. It has but 12 poles.

12. Concerning "a high torque while standing still." As we understand the matter, railway motors are designed to move a train rather than to hold it at rest. At the same time we know that the single-phase motor is amply protected against mistakes of motormen in leaving the current on the motor for a half-minute or so with brakes set.

13. Concerning "resistance in commutator leads." It is well known that the resistance leads used in single-phase amatures are for the purpose of reducing to a minimum the loss due to the transformer action in the short-circuited coil. Their presence is fully justified and the efficiency is higher than it would be if they were not used.

14. This refers to relative weights concerning which I shall have something to say farther on.

15. On this point I agree absolutely with the author. There is one type of construction to which the single-phase motor is not adapted. This is so far employed in only a single case.

More or less is said in the paper concerning the lower efficiency of the single-phase motor, and inference might be drawn that it is about 10% lower than that of the corresponding direct-current motor. Just to show what modern motors are capable of doing, I give below in parallel columns the efficiencies of corresponding sizes of direct- and alternating-current motors at different percentages of their full-load torque.

Per cent. of full-load torque	Direct-current 90 h.p. motor	Alternating current 25-cycle, 100 h.p motor	Direct-current 200 h.p. motor	Alternating current 15-cycle, 200h.p motor
125	86.25	82.	88.8	87.3
100	86.8	85.	89.	88.
80	87.	86.	89.2	88.3
60	86.5	86.8	88.8	87.7
40	85.	86.	87.	85.
25	82.	82.5	84.	82.

From this it does not appear, within the ordinary range of tractive efforts exerted by railway motors, that the single-phase motor is so far deficient. In fact, it comes remarkably close to that of the direct-current motor.

Concerning the comparison between the 125-h.p. and the so-called 240-h.p. motor contained in the paper, I take issue, with the author. In my opinion the only reasonable way to compare the performance of single-phase motors with that of direct-current motors is to assume a car with a certain seating capacity, and then consider what equipment, alternating current or direct current, is suitable for this service. It is not fair to assume, as is done in the book by Messrs. Parshall and Hobart, a car of a certain total weight, carrying in one case fewer passengers than in the other. The object of a railway company is to accommodate a given traffic. It follows, therefore, that an equipment should be provided which will be serviceable. Motors should be selected on the basis of their speed-time curves and in accordance with their particular characteristics, rather than upon the simple horse-power basis. Further, it is unfair to take an isolated case of a single-phase motor which may be heavier than the ordinary and compare it with a direct-current motor which is certainly much lighter than ordinary motors of that capacity. If, in seeking to compare the two types of motors, the author had taken the 25-cycle, 75-h.p., single-phase motor referred to later on in the paper his conclusions might have been quite different. The weight which he assigns is 4199 lb. The weight of the corresponding direct-current motor is 3500 to 4200 lb. Moreover, if the single-phase motor to which he refers were operated on 15 cycles instead of 25, its output would be 90 to 95 h.p., which would lead to conclusions quite at variance with others in the paper. The weight of a quadruple equipment of

90-h.p. direct-current motors furnished by the company with which I am connected would be approximately 20,000 lb. The corresponding weight of a quadruple equipment of 90 h.p., 15-cycle motors with oil-insulated transformers equipped for 11,000 volts would be approximately 27,500 lb., an increase of about 37.5%. This extra weight added to a 40-ton car would amount to about 10%. Owing to the greater efficiency in controlling single-phase motors, the power consumption of the car, including transformers, would in most classes of service be approximately the same as that of the direct-current motor at the trolley and would be much less at the power house. I wish to say, further, that a car for passenger service can be equipped with two 200-h.p., 15-cycle, single-phase motors giving ample clearance on 37-in. wheels, and that these two motors will operate a car with the same power consumption per car-mile at the car on runs as long as five or six miles as would be obtained with a car of the same capacity operated with an equipment of 200-h.p., direct-current motors. On shorter runs the relative power consumption would be less.

Now, concerning the use of high-voltage direct current. Motors can certainly be built to commutate satisfactorily on 1200 volts direct current. Such motors, however, must restrict the voltage between bars to a safe limit, and have extra space for insulation. The construction of this motor would therefore put it on a par with the 15-cycle, single-phase motor both in weight and dimensions. Moreover, it would have practically the same air-gap in moderate sizes of motors, and might possibly have to be designed with the same style of compensating winding on the field as is now used for single-phase motors. It would have in addition the disadvantage of a high voltage always present on the windings and brush-holders. If it were not for the greater possibilities of the single-phase system, there is no doubt but that the high-voltage, direct-current motor would be quite attractive. As it is, I believe that systems should be developed which offer the best solution for the entire railway problem. To attempt to develop a number of systems would result in not only scattering the energies of manfuacturing companies, but would retard the ultimate solution and supply the railways with a heterogeneous collection of equipments that would postpone standardization for many years.

G. R. Henderson: I am particularly pleased to find that the writer of the paper does not claim that electrification is a panacea for all railroad ills, but when applied to individual cases which have been intelligently studied and found to be suitable for such treatment, satisfactory results may be expected.

That success depends upon traffic density is made clear, and the importance of the load-factor is brought out, and I heartily agree with the assertion that trunk-line operation is vastly different from suburban service. As the two extremes, consider the New York subway, with constant trains at short intervals, and a division on a western road handling stock almost exclusively. There are one or two days a week when the stock must be brought to market, and perhaps from 12 to 20 trains will be run in one direction, possibly up-grade, at 15- or 30-minute intervals, as the market must be reached in time to avoid claims. Then for four or five days there may be nothing but one or two passenger trains and a local freight. Can any one imagine a railroad company rash enough even to think of electrifying its road in such a case? The power house and conductors would have to be proprotioned for the maximum traffic, but the average load-factor would not be ten per cent. Operating methods can no doubt be changed in many cases to advantage, in electric traction, but such traffic as I have referred to cannot be altered to suit transportation requirements.

The important factor of financial success is also brought out in the statement that unless a commensurate return on the increased investment can be assured, steam locomotives will not be abandoned. This item of first cost is an important one, when we consider that one horse power in steam locomotives costs about $10, and in power house, lines, etc., about $100. Electric locomotives themselves cost double the amount of steam locomotives, and as the average cost of coal in the Uinted States does not exceed $1.50 or $2 a ton, little may be obtained from fuel economy.

The great possibility of the electric locomotive in freight service (and this is usually the dividend-earning part of the traffic) seems to lie in the increased power available by small reductions in draw-bar pull corresponding to increase in speeds; but the relative value for each and every line can only be determined by making a careful study of all the factors involved for that particular piece of track. Comparisons with other roads may, therefore, be not only useless but positively dangerous, unless all the conditions are understood. These computations are laborious, but absolutely necessary. When we consider the different rates of pay and the cost of commodities in various parts of the country, and the effect of physcial conditions of the track, we realize the importance of careful analyses. By varying the train load we can run the cost of transportation per ton-mile to double the minimum figure, the charges for material and labor remaining constant, which shows how complicated will be the deductions from a thorough investigation of the subject, but unless so made they may be worthless. Characteristic power curves of both steam and electric locomotives would naturally form the basis for such a comparison, and these should be carefully laid out; and then by making combinations of diagrams representing the locomotive power and train resistance, the important fundamental advantages can be deduced for a variety of conditions.

According to the writer, regeneration is not promising as a method of reducing power consumption any more for electric than for steam traction, but it may reduce brake-shoe wear and lengthen the life of wheels. It could not replace the air-brake, however, for obvious reasons, but might be compared in its action to the Le Chatelier or Sweeney brake. Even air-brakes are now arranged so that they can be held upon the locomotive while re-charging the train on long grades, and retarded release is provided so that the rear-end brakes let go first.

I am glad to see that multiple-unit control is not considered feasible for freight operation, and that the great difference between this and suburban transportation is made clear. We heartily agree that it would not be wise to attempt to handle heavy trains on steep grades with one man, and the legislators would no doubt prevent it. The presence of a third man on locomotives of the Wooten type has often been discussed by our lawmakers, and the single man and multiple-unit control would certainly excite much opposition.

Having had twenty-five years' practical experience on railroads from the Atlantic to the Pacific, some of them operating on 3.5% grades over the Rocky Mountains, I cannot too heartily express my approval and endorsement of the very conservative statements and the sound logic enunciated in this paper; I believe that if these points are constantly kept in mind there will be few electrifications to criticise unfavorably, and that those who decide to abandon the steam locomotive will be able so to fortify their position with convincing figures and data that financiers will provide the funds and the results will justify the expenditures necessary for the work. While I do not expect to see the steam locomotive driven "off the earth", and am confident that for many years it will still be found performing most of the work of transportation in this country, yet I do believe that the electric locomotive is bound to increase rapidly in number and in favor, and that each in its own proper sphere, steam and electric traction, will coöperate to the advancement of transportation and the increase of prosperity.

William McClellan: It is to be regretted that the author has thought it wise to spend so much time comparing motors when it is well known that the single-phase motor is not equal in weight-coefficient or efficiency to the direct-current motor. From a practical standpoint the comparison should be made on the complete system from the coal-pile to the transported load. My experience in making comparisons of the several systems for different roads confirms the figures stated by those who have discussed the paper rather than the figures of the author. After operating an 11,000-volt, multiple-unit train under extreme weather conditions and heavy overload, it is a pleasure to report that the equipment is extremely flexible in every way and gives remarkably smooth operation. The control of motor voltages by the transformer taps seems to make for very smooth acceleration. The examination of the commutators with covers off showed, under heavy overload, sparkless or black commutation.

Even when one of the cars was acting more as a locomotive than as a motor-car this was true. In these circumstances it is particularly gratifying to-night to learn that even better conditions can be expected from equipments produced now.

The author's paper spells the word "capacity." First, capacity of the truck for motors; secondly, capacity of the trackage for traffic. We certainly must all agree with the latter argument. There is little doubt that the electric motor can be introduced on steam railroads more easily by showing that the capacity of the ultimate trackage in a given locality can be increased more by electrifying than by any other motive power. It is probable that hundreds of miles of trunk-line electrification will be installed for this reason, before there will be sufficient information on the relative cost of operation and similar data.

It does not seem, however, that the capacity of the truck to receive sufficient motor power will ever be a serious menace to the success of the alternating-current motor, even if the present weight-coefficient is not improved. This objection obtains chiefly in connection with locomotive design. It should not be forgotten that almost all electrification so far has been in connection with terminal work where an electric locomotive must receive a train from a steam locomotive for a short run through a tunnel or otherwise. The more I study the problem, the more I am convinced that when we come to the electrification of a whole division, we shall depart from locomotive practice and turn to multiple-unit equipment. Even for through service it is more than likely that it will be found cheaper in the end, more elastic, and less liable to cause delays on the road. This has been forcibly impressed on me recently, while making some trial runs with new multiple-unit trains on a trunk-line division. Several times minor accidents happened which, had the motive power been concentrated in one unit, would have stalled the train for some time. With the multiple-unit train, however, it was very easy to cut out one car and make a run in without seriously disturbing the schedule.

Even in connection with freight traffic our present ideas may have to undergo a radical change. As we understand it now, receipts are per ton-mile while expenses are per train-mile. There is a possibility, however, that with electric operation we may be able yet to show that the quickest and least expensive method of getting freight over a given division is not always by means of the longest train and the heaviest locomotive.

In view of the fact that most of the engineers who are ardently expressing faith in the single-phase motor are at the same time advising the use of, and installing, 650-volt third-rail and overhead apparatus, it is a pity that there should be an opinion held that we are divided into hostile camps. Arguments comparing overhead construction with third-rail have been made so exhaustively and so frequently that there is little use here in repeating them. Since both are being introduced in various places we can afford to wait for time to bring out the truth.

There are reasons, however, why, for trunk-line operation, opinion seems to be so strongly in favor of the single-phase motor: first, it is generally acknowledged that on account of expense and complexity of power distribution a 650-volt, third-rail installation, no matter how well done, will never solve trunk-line electrification. It seems evident that the case demands a high voltage, which in turn necessitates an overhead structure. If the present single-phase motor is not adequate or satisfactory, it must be improved or another type designed. If the present type of catenary construction fails in service, it may have to undergo radical change. In spite of these details, of the highest importance as they are, the general statement in regard to the system remains true.

Secondly, the electrical engineer must follow the engineer-of-way. The former must electrify whatever system of trackage the latter demands for moving his traffic. In large terminals and busy yards, unless present methods of switching can be revolutionized, the third-rail is not always available. I do not know of any extensive proposition where the third-rail had been adequate in such cases. The paper itself, though slightingly, refers to one large terminal where considerable overhead structure had to be introduced. This adds undesirable complexity to the car and locomotive equipments. In this connection it must be remembered that locomotive shoes will probably not span a gap much greater than 25 ft. This fact introduces troubles not met with in connection with multiple-unit trains.

Thirdly, every large road is a problem which must be considered financially on its own merits, but technically in relation to the whole system and to other roads with which it may come in contact. That system of electrification which may be most suitable for the operation of a large terminal may be one which it is unwise for the road to adopt, because sooner or later this may have to be extended to the whole system. Neither can the largest roads afford to ignore absolutely what other roads are doing in the way of electrification. The modern trend of enterprise is towards consolidation, exchange, and pooling. There is in process of formation, or perhaps already finished, a freight-car pool among the larger roads of the country; it is not beyond possibility that ten years from now may see a pooling more or less complete of passenger cars; and there is no doubt that many parallel roads to-day could adopt joint track agreements to the advantage of both and the great advantage of their patrons. It is these possibilities that a road must keep in mind when it starts to electrify, or it may later have to expend enormous sums of money to bring itself into conformity with a larger system of which it may become a part. Therefore, reasonable standardization is one of the things we should have on our minds all the time. No question should be decided without considering this point of view.

A. H. Armstrong: It is very difficult for the writer to share the confidence expressed by some of the previous speakers as to the exact trend of future railroad engineering. This is an age of development. Things change over night and impressions formed last week are quite likely to stand in need of modification in the light of more recent developments. In this connection I may state that my impressions of alternating-current motor performance, which have been gradually forming as the result of several years' experience with such motors, have been very agreeably shaken by tests witnessed during the last few weeks.

I had an opportunity to witness a test on a 125-h.p. series compensated alternating-current motor operating at 50% overload. The commutation was excellent, as good as that of present direct-current motors, and was obtained by certain recent modifications in motor design and connections.

New developments are not confined to any one type of apparatus. The direct-current motor has exemplified this in the vast improvements made in the last year by the introduction of the so-called commutating-pole type of motor, which practically eliminates the question of commutation as a disturbing factor. Owing also to the development of the commutating pole, it is possible, with the better results obtained, to wind such motors for 1200 volts. The commutation of these 1200-volt motors is even better than the 600-volt motors hitherto used. It is, therefore, hard to predict with any certainty just exactly what field is covered by any one type of apparatus. We now have offered direct-current motors of 600 and 1200 volts that give practically perfect commutation, very high efficiency, and an adaptability of design that makes such motors applicable to a wide range of railway problems. We have also recent evidence that the alternating-current motor can be so improved as to approximate closely the present performance of the direct-current motor not having commutating poles. Such improvements must have considerable weight in determining the future field of application of this type of motor. I will say for the benefit of those that are anxious to standardize the frequency of 15 cycles, that the tests I have reference to were made at 25 cycles, and seemed to indicate that a thoroughly good alternating-current motor could be built without the necessity of adopting a new frequency with all the incidental complications involved in so doing.

Mr. Ferguson has expressed an opinion to the effect that the railway load in and around large cities like New York and Chicago represents only about 25% of the total electric power developed. in these territories. The use of 25 cycles is almost universal in and around large cities, and it would become a very serious commercial matter, owing to like conditions over all the country, if the future of the alternating-current, single-phase motor depended upon the adoption of a lower frequency.

I find myself repeating the advice given by Mr. Wilgus, to the effect that the electrification of our steam roads calls for cool, unprejudiced, common-sense engineering. Like him I believe that the cause is injured by too strong enthusiasm for any one type of apparatus, and the best showing can only be secured by considering the type of apparatus best suited for the particular needs of the road in question as determined after a very careful unbiased investigation of the local requirements.

C. P. Steinmetz: I wish to endorse the statement that we are not yet ready to standardize one type of railway motor, or one method of electrifying steam railways. We shall not be ready to do so for some time; perhaps never. I agree with Mr. Wilgus that each railway problem should be considered on its own merits. The proper method of solving the problem in hand should be to apply the standard that has been found satisfactory by extended experience, and not deviate therefrom except where it is absolutely necessary. As has already been said, the problem before us is to substitute electric motors for steam locomotives where the conditions of service have grown beyond the capacity of steam locomotives. Whether the alternating-current or the direct-current motor has the advantage is rather a secondary question; the main question should not be lost sight of in discussing conflicting claims for the one or the other type of motor. At present there is an alternating-current motor and a better direct-current motor, regardless of the contention that the alternating-current motor is equal to the direct-current motor; for at the same speed and same energy input there is saved in the direct-current motor the power lost in commutating, and that lost as hysteresis in the field. The heating is less, and consequently the efficiency is greater. Now since the mechanical output or capacity of the railway motor is controlled by the heating, the alternating-current motor on a direct-current circuit gives the same mechanical output at a lower temperature; with the same temperature it gives a larger output

There is a class of service where alternating-current motors are necessary—a long railway with infrequent and irregular service, and a considerable amount of fluctuating freight traffic—in short, conditions where synchronous converter sub-stations would show a poor load-factor. In such cases, direct-current operation appears impracticable, and here is the field for the alternating-current motor or the steam locomotive. Where there is a 4-track or a 6-track railway with traffic so heavy that the distance between trains is limited only by safe headway, the load on the converter sub-station is so nearly constant, the load-factor so great, the rapidity of acceleration required so considerable, and the maximum capacity of the motor so great that the advantage is decidely in favor of the direct-current motor. In such cases there is no excuse for using alternating-current motors.

I do not share the objections to the synchronous converter, and do not believe there is any gain in reliability in eliminating this link. It is an advantage in a system to eliminate some of the links, but what wants to be eliminated is the weakest link, and that is not the synchronous converter, but the motor. A synchronous converter is about the strongest link. However, between these two extremes there is a very wide field where either the alternating-current or the direct-current motor may be used, or rather where different engineers may be justified, impartially, in arriving at different conclusions; but what should be guarded against is the adoption of any one system which precludes one for ever from changing over to any other system. I refer specifically to the adoption of an arbitrary frequency. At present, after many years of work we have succeeded in eliminating all frequencies but the two now universally used—60 cycles and 25 cycles. At the present time all the heavy power of the country is transmitted at 25 cycles. Adhering to this standard frequency, it would not be so formidable a thing to use the alternating-current motor and then find that after all, the direct-current motor would be better. The alternating-current motor could be used for outlying side branches of a railroad and the main line be operated with direct-current; or, inversely, a start could be made with direct current and later changed to alternating current, provided the interchangeability of the system be not lost sight of. Herein lies the harm of radically changing the frequency. Compelling one to adopt a frequency of 15 cycles brings about a very serious condition; it means giving up the possibility of securing the benefit of interchangeability with the large amount of power now available at 25 cycles. In brief, 15-cycles would be an odd system, as odd as the 40-cycle system is to-day.

In regard to the 1200-volt,direct-current motor, my conclusion is that the commutation of this motor is so infinitely superior to the commutation of any alternating-current motor I ever. have seen—except one—that there is no comparison. As Mr Armstrong has stated, there has recently been developed one alternating-current motor operating on heavy overloads with absolutely sparkless commutation. It is just as good as the standard direct-current motor, or probably a little better.

Frank J. Sprague: Owing to the lateness of the hour, I cannot now reply to the various speakers, because I cannot deliver my views in sufficiently condensed form. I shall have something to say later in a written communication to be inserted in the PROCEEDINGS. I think possibly the paper has at least one merit, it bids fair to bring out some additional facts about the apparatus of both kinds. The fact remains that a good many millions of dollars have been invested on two great trunk-line systems, which will soon be in competitive operation, and there will be a comparison on these roads which none of us can gainsay.

W. S. Murray (by letter). Conscientiously I find little in Mr. Sprague's paper to discuss. This was my conclusion at the meeting; the same now. It seems to me that what is not wrong in Mr. Sprague's paper is not new. In passing, however, I cannot fail to record here my high sense of appreciation for Mr. Stillwell's and Mr. Storer's excellent contributions, not so much because they were refutations of Mr. Sprague's unalterable conclusions, but for the valuable data they contained concerning the real relations in design and practice between alternating-current and direct-current railway motors. Again, it is difficult to express the pleasure in noting the small per cent. increase in weight for equal capacity and the almost coincident curve of efficiency. These cases being the citations of the chief engineer of the railway department of one of our large manufacturing companies, and a consulting engineer who has shaped the duties of many railway motors.

It would be my wish that the smallest emphasis be placed on the efficiency of the alternating-current motor, even though its efficiency curve throughout its complete range of load were the equal of its direct-current brother. If efficiencies be considered, let us discuss the ratio of the pound of coal to the ton-mile. There is nothing electrical about this; it is within the comprehension of steam railway engineers (though it is a chain made up of electrical links); and if the ratio proves less for the alternating-current than for the direct-current system, then we have a real value that is of as much interest to the banker or director interested in the railroad as to the electrical engineer desiring its use. Would it not be better to consider the whole chain rather than one link? I welcome the new weights and the new efficiencies for their corrective (?) influences of the one-part-at-a-time man.

It was unfortunate that the photographs as originally shown in the advance copies of Mr. Sprague's paper were so poorly representative of the catenary construction. However, I am told these were the best the publication department of the Institute could produce on the very short notice they received. Those now published in the regular PROCEEDINGS are fairly representative.

T. J. Johnston (by letter): While I am quite willing to leave the discussion of the engineering features of Mr. Sprague's recent paper on methods of electric traction to professional engineers, it seems to contain (or perhaps to reiterate) an economic fallacy; namely, that the "financial factor" will determine whether a road shall be electrified, the implication being pretty plain that it, solely, will settle the question.

The process so graphically described by Mr. Sprague, by which our present enormous steam railway system was built up, is now going on before our eyes, with electric railways; that is, short lines of road are being built, cities are being connected, extensions are being made and eventually consolidated, until in many directions it is possible to take extended trips by electric lines. Awhile ago the writer rode in an electrically propelled sleeping car, the comfort of which may be imagined.

The growth thus initiated will not stop short of a sufficiently complete system of electric railways; the willingness of present railway managers, or even their ability, to transform the power side of their systems need not be considered at all. If these gentlemen are unable to raise the money, they will be left with their freight business, and their passengers will be taken from them, even as now the interurban roads take all of the local traffic that is worth while, leaving the more expensive and troublesome long-distance trains as a sort of white elephant on the hands of the steam road. It will not be many years before the large cities will wholly prohibit the steam locomotive, as the Congress has practically done in Washington.

It is truly a serious situation for the railway men, with their credit hampered by foolish legislation and equally foolish popular clamor; while their electric rivals obtain privileges which no one would grant to the steam road. The problem of finding the money, and, after the money is found, of finding the available working force is truly tremendous, yet it must be solved. It is as certain as anything can be that our people want and will have electric traction on an increasingly great scale, until practically all of our passenger traffic at least is so operated. Nor will they be content with the present methods of running trains. It is amusing to see how a steam railway man with a converted road on his hands throws away the advantage of electricity and insists on running his cars in trains every two hours or so, instead of splitting up the units and running one or two cars every few minutes; for example, the Atlantic Division of the Long Island Railroad, upon which the flexibility of electric service is, during the "non-rush hours," nearly thrown away.

Lewis B. Stillwell (by letter): The paper read by Mr. Henry St. Clair Putnam and the writer on January 25 and the paper read by Mr. Frank J. Sprague on May 21 bring out an interesting and apparently radical difference of opinion in respect to the question of choice of system for electric operation of trunk-line railways. In the former the opinion was expressed that alternating-current equipment is the only class of equipment deserving serious consideration in connection with the general problem of replacing the steam locomotive by the electric motor on trunk-line railways. In the latter it is asserted that "where equal permanence of installation is provided for and equal ultimate as well as average duty there is not on demonstrated facts a wide variation in the initial cost of plant". While the position taken by the author is less radical than it was in the oral discussion of the paper of January 25, he devotes a large part of the present paper to the presentation of facts and opinions which have led him to the conclusion that the proposed 1200-volt, direct-current system is superior to the single-phase, alternating-current system.

When conclusions radically different are reached in a matter of this kind, the explanation is usually found by examining the premises respectively assumed. In this case an examination of the paper of the evening and consideration of certain facts clearly brought out in the oral discussion go far to explain why its author has reached a conclusion differing so widely from the opinions expressed by Mr. Putnam and myself.

1. It appears that the author's conclusions have been based largely upon a radical misconception of the facts as to weight and performance of single-phase, alternating-current motors as compared with direct-current motors. His reasoning is based largely upon the idea that motors of the former type weigh about twice as much as those of the latter type. As has been clearly shown in the discussion by the designing engineers of our great manufacturing companies, the difference in weight of 25-cycle, single-phase, alternating-current motors and 550-volt, direct-current motors of equal output is, in general, much nearer 25% than 100%: while the difference between 15-cycle, single-phase motors and 550-volt, direct-current motors of from 100 to 400 h.p. is still less.

The author places great emphasis upon the question of comparative motor-weights. If his view of the controlling importance of this consideration be accepted, it would appear that the reduction in the assumed ratio of weight upon which his conclusion so largely depends from 2 to 1 to 5 to 4, or less, might involve a material modification of his conclusions regarding the relative values of the contrasted systems.

2. It is evident also from the paper that its author has failed to balance accurately the inherent differences between single-phase and direct-current motors. In the light of Mr. Storer's oral discussion of this phase of the paper, the majority of the assumed disadvantages of the former disappear

3. An apparent oversight may further explain how the author has arrived at his conclusion. I refer to the fact that his paper ignores the very important consideration that in general a protected third-rail cannot be located in any position upon the existing tracks of our railways which will not involve more or less interference with rolling stock equipment. The third-rail location adopted by the New York Central, for example, makes it impossible to operate over tracks thus equipped large steel coal cars of the type now so extensively used. The New York Central has met the situation by excluding from its tracks which have been fitted up with a third-rail certain classes of rolling stock. This special solution may be satisfactory in this instance, but in considering anything like a general electrification of trunk-line systems the interference of the third-rail with rolling stock constitutes a very strong argument in favor of overhead construction.

There is nothing in this paper, nor were any facts presented in its discussion, which justify a modification of the opinion which I have expressed to the effect that the alternating-current system is best adapted to trunk-line operation. The paper under discussion uses the 550-volt, direct-current motor in such comparison of alternating-current and direct-current motors as it presents but in comparing systems substitutes the 1200-volt, direct-current motor for that of 550-volts. This substitution is materially easier on paper than it would be found in dealing with actual equipment. As a matter of fact, the so-called 1200-volt, direct-current system to-day does not exist except on paper; and while there is no doubt that it can be developed into a working system the paper under discussion ignores difficulties in the way of its development and application more weighty than any which to-day stand in the way of the complete development of a 15-cycle, single-phase system.

The New York Central has equipped its terminal with direct-current apparatus operating at about 600 volts, and has done so for reasons which probably were valid at the time the decision was made. It is conceivable that other railways in equipping terminals may be led by local considerations to adopt the same system. In the light of the discussion of this paper, however, it is difficult to conceive circumstances under which engineers would be justified in advising the use of 1200-volt, direct-current equipment in the electrification of a terminal or short division of railways now using steam locomotives. The author of the paper has advised the New York Central to use 600-volt, direct-current equipment in electrifying its New York terminal. He intimates that if called upon to do so he would advise the Pennsylvania Railroad to use 1200-volt, direct-current apparatus for the equipment of its line between New York and Philadelphia. Were this division of the Pennsylvania system to be electrically equipped to-day, it would be done for reasons which a few years hence will apply with almost equal force to the company's lines between Philadelphia and Pittsburgh. The present state of the art as evidenced by the facts set forth in the discussion of this paper and of the paper presented on January 25 justifies the statement that for the electrification of even short divisions the 15-cycle, single-phase alternating-current system at the worst is not inferior to the 1200-volt, direct-current system. The comparative advantages of the former, of course, increase very rapidly with decrease in frequency of service. Under conditions of average steam railway service in the United States, which were the conditions discussed in the paper presented by Mr. Putnam and myself on January 25, the first cost and the annual cost of the 1200-volt, direct-current system as compared with the single-phase, alternating-current system practically prohibits the adoption of the former. In view of these facts it would seem that there is no place for the 1200-volt, direct-current system in connection with the electrification of any part of our trunk-line systems. The 600-volt, direct-current system will do the work satisfactorily in electrifying a terminal. Only the alternating-current system is applicable, as the author of this paper himself suggests, to " roads of considerable extent which operate an irregular and sparse traffic ". Between these two there is no sufficient reason to justify the introduction of a third-rail system which does not pretend to solve the general problem, which can be used only on tracks from which certain classes of rolling stock are excluded, and which inevitably would introduce additional complication and interference with the ultimate standardization of electric railway equipment.

Frank J. Sprague (by letter): The comments on my paper have been varied and interesting, sometimes illuminating, but again marked by more of criticism than candor, and offering less of proof than affirmation.

I did not attempt to solve the problem of electric operation of trunk line railways, but rather to set forth some general problems, and certain technical facts as I have found them by somewhat careful investigation.

I have been taught by a modicum of experience that the electrical engineer is apt to approach the larger problem of railway electrification with a superabundance of confidence, undiluted with practical and necessary experience in that particular field. It has seemed necessary to utter a warning against too great a measure of self-reliance, too positive prophecy, and to indicate some of the difficulties in the way of achievement.

I prefer to deal with facts, not theories; performances, not promises; and where these are at variance, it is essential that the differences should be pointed out. I am, for special reasons, probably more anxious than most members of this Institute that railway electrification shall prove acceptable and beneficial, and I welcome every advance, no matter through what channel, which can contribute one iota to that end. So long as equal results are attained, it hardly seems necessary to emphasize the fact that simplicity is a desideratum of the utmost consequence, and I should be glad to eliminate every piece of apparatus between a central station and a motor which does not prove essential to operation.

If I express some measure of disappointment, it is because of the fact that in spite of all the work done, and my own hopes as well, more has not already been accomplished in the single-phase, alternating-current motor development, and that neither it—nor for that matter what has been done with high-potential direct-current motors—warrants approaching the general railroad problem other than with diffidence and hope, and makes us doubly obligated to urge the utmost progress along whatever path may offer any advantage whatever.

Whatever my beliefs, I cannot but chafe at the slowness of advance, and the subordination of development on the one hand to a fixed ambition, and on the other hand to commercial catholicism. I doubt if any member of this Institute questions how quickly and radically I would demonstrate my own confidence in future possibilities if the companies which have borne my name had not been swallowed up in the sea of modern consolidation, instead of my now being obliged to content myself with academic pleas for intelligent expansion.

Quite possibly I have not fully understood the purport of Messrs. Stillwell and Putnam's interesting paper, but if so, then I have company in such misunderstanding. While it is true we are not in entire accord, we are not entirely in disagreement; for I note that Mr. Stillwell accepts historical facts, and is even tolerant of my generalities. We do disagree, it seems, in one important essential at least. He has "nailed his flag" to a 15-cycle mast, guyed by an overhead trolley wire, for trunk-line service. I have gently remonstrated, and being something of an agnostic, have said "I don't know"—venturing the opinion, with which I am quite sure in the end most practical railroad men will agree, to say nothing of a large body of the electrical engineering fraternity, that no present standard can be safely adopted to the exclusion of everything else. Such a decision would be not only a bar to evolution in the development of the application of electricity to railways, but a final expression of opinion that invention is at an end, and that the dicta of engineers can decide or change the inevitable exercise of individual thought, and curtail the activities of competitive manufacture.

Mr. Stillwell lays much stress upon the "conditions of average steam railway service in the United States." The average conditions, measured financially, do not, in my judgment, permit of electrification, which conclusion I have tried to make clear, and which is not altered even if I have not succeeded.

I feel particularly indebted to Messrs. Wilgus and Henderson, the former of whom, in his executive position, has had immediate charge of a great electrical development, and both men of wide practical railroad experience, for their common-sense and illuminating comments from the standpoint of the steam railroad man, because our tendency as electrical engineers is to discuss with too much detail the technique of our profession.

Now and then in our art, as in all others, some one not too closely face to face with technical problems coins a laconic phrase, which one instantly recognizes as expressing the truth in a nutshell, and as a crystallization of his own ideas on the subject, and then he wonders why nobody thought of it before. Such a phrase, and a particularly apt one, is that of Mr. Wilgus', "evolution, not revolution". It is the concrete description of the progress in the electric railway industry since its beginning, and it is expressive of what it will be in the future.

In studying different motors, it seemed wise to expand previous methods, and to adopt one capable of wide application. Inasmuch as it was impossible within the limits of a paper already too long to apply this method specifically to all makes and sizes of motors, I contented myself with selecting one especially typical example of direct-current and 25-cycle, alternating-current motors, supplementing the details of this comparison by some specific facts about other machines, namely, the smallest on regular interurban service, and the largest in present locomotive service, presumably a sufficiently wide range for illustration of certain facts, leaving the application of the specific method to any other case of interest to an engineer.

In comparing capacities, it is eminently proper that the *weight-efficiency* of electrical equipments should be based upon each of two conditions: first, the total weight of motors and any connecting device necessary to transmit the power of the motor to the axle, this weight, if the trunk frame forms a part of the motor, including such additional part as is necessary over and above that required for structural purposes; and secondly, the total amount of electrical apparatus as above determined, plus every device for collecting current or controlling the motors carried upon the car or locomotive.

Mr. Stillwell holds that I should compare motors of equal capacities, not of equal weights and dimensions, and states that since the weight-coefficients of all motors, of whatever make or type, increases with the size, there would not in such a comparison have been so great a disparity. Quite true, but the error of this reasoning is apparent if one reverses his proposal, and compares an alternating-current motor of a given physical dimension with a direct-current motor of larger physical dimensions and weight. What a disparity would then appear! I do not know that I am particularly surprised at the remonstrance which meets the actual comparisons made in the specific instance illustrated, for the method intelligently applied is sufficiently instructive for those who wish to know the facts to find further application. The meaning and the force of the comparisons will not be brushed aside by *ex-parte* statements of isolated and uncorrelated facts, or by such a criticism of specific motor weights and capacities as distinguished Messrs. Stillwell's and Storer's comments, somewhat unwarranted in view of my specific statement that the motors were "both standard modern machines".

In order to avoid any just criticism of the curves submitted, I selected not only standard modern machines of practically identical weight, but machines built by the same manufacturer, tested under like auspices and by identical methods, and by experts who had no thought that the machines would ever be compared in the matter I have shown. Not only are these machines of similar weight, but they are almost exactly of the same dimensions, of the largest practical size which should be put on a truck with a 33-in. wheel, and as large as should be used with a 36-in. wheel when running in the open on a standard railroad. Gear and transformer weights were, as stated, eliminated.

That an erroneous conclusion might be expressed in comments based upon a hasty and cursory perusal of a paper is understandable, but that it should be allowed to stand after opportunity to ascertain the facts suggests either great preoccupation.

or a hiatus in memory. It is a wise father who is not ashamed of an adopted child, and I cannot but regret that Mr. Stillwell has so long failed to recognize, in motor *X*, whose weight, as well as speeds and capacities throughout a thermal range varying from two-thirds of an hour to five hours were given with exactness, a machine for which he is largely responsible. Its characteristics are based upon the official technical reports of the General Electric Company, the builders of this G. E. 69 *B* type for the Interborough Rapid Transit Company, on Mr. Stillwell's general specifications, 418 of these machines now forming part of the equipment of that road. They are sometimes "rated at 200 h.p. at 300 amperes", but actually test to 241 h.p. with 75° rise of temperature, according to the standard practice of the American Institute of Electrical Engineers. Several hundred more of these motors are in use on the London underground railways, and 268 motors of similar frame, known as the G. E. 69 *C*, built for 50 volts higher normal operation, nearly 100 less revolutions at the one-hour rating, but developing, notwithstanding, 232 h.p. with like rise of temperature, are in use on the New York Central Railroad. Type *Y* is the G. E. A. 603 25-cycle, alternating-current motor, and illustrates the largest of this type of machines built for motor-car work.

Call these machines what one will, by any name which may smell more sweet, the comparisons are on identically the same basis, therefore absolutely proper; and in all fairness comparisons of any machines should be made with identically the same kind of data. When so made, Mr. Stillwell's pyramid may be inverted, and landed on its base where it belongs.

A similar direct-current motor when equipped with commutating poles weighs about 400 lb. more, but in view of a remarkable freedom from sparking it can with perfect impunity be steadily operated at an increase of potential which will much more than offset the increased weight. As an example of what can be done with this type of machine, I have seen a standard motor of 75 h.p. commutator capacity, temporarily fitted with commutating poles, operated with an increase of 80% in voltage, and develop over 250 h.p. without a sign of distress. Of course this is unusual, and ordinarily prohibitive on account of the speed of the machine, but it illustrates the possibilities of an improvement which I have so steadily urged, and which in now being adopted has so largely augmented the allowable working direct-current potentials. If Mr. Storer will compare on the thermal basis a quadruple motor equipment of this type with an equipment of 25-cycle, alternating-current motors of like permissible speeds and weights, the comparison will be somewhat instructive.

With regard to 15-cycle motors, I enumerated with a good deal of particularity certain advantages which they individually offered as compared with the 25-cycle motor, and especially the increase of capacity. I assume there is here little room for disagreement; but granting the full measure of these advantages, variable in the matter of capacity according to the nominal rating, and the ratio of load to that rating, it seems quite apparent that the increase in weight of the transformer will largely offset the saving in motor-weight capacity. Inasmuch as we are concerned not alone with motor weights, but with the total weight which must be carried by the individual drivers, and within allowed wheel-bases, this offsetting of the saving in weight in one part of the equipment by an increase in the other cannot be ignored; and the question properly arises whether the advantages are sufficient to warrant the adoption of the standard in spite of many well known objections.

It is a curious commentary upon the futility of prophecy, that within a month of the announcement of the necessity of a new standard, and within the hour of its repetition, the responsible technical engineers of a great manufacturing corporation voice, not only for themselves but for a great portion of the engineering world, their disapproval of its adoption, and in the same breath announce a radical advance in 25-cycle motor construction which maintains the merits of a higher frequency, and removes one of the reasons for lowering it.

Comparisons based upon motors designed, but not built, are essentially unsatisfactory, and of course they will be more or less at variance, depending upon the size and make of motors selected. The 15-cycle, single-phase, alternating-current motor is too new a machine to have any record behind it. In my paper I compared the weights of certain standard quadruple motor suburban equipments, designating the motors *A* and *B*, the former for 15 and the latter for 25 cycles, the weights being those officially given by the manufacturers. These motors were of competitive makes, the former being the Westinghouse and the latter the General Electric, but, as I stated, I did not deem the weights given as final. It will be therefore perhaps interesting to know that, eliminating the element of competitive manufacture, and comparing recently given official weights of 15- and 25-cycle equipments made by the former concern, there is an excess of total weight of a quadruple equipment of nominal 75 h.p. motors greater than that given in my paper.

Certain features of the New York Central and the New Haven machines have been given so frequently that it is unnecessary to refer to them further at the present moment, except to state that their weight-coefficients are very different, and much in favor of the former machines. When large 15-cycle alternating-current, and other types of direct-current locomotives are built, there will be an opportunity to make further comparisons on a like basis. It may be interesting to note here that the recent decision to adopt three-phase locomotives on the Cascade Tunnel was because of lack of guaranteed capacity of 15-cycle motors.

Mr. Stillwell says that I do not pay sufficient attention to the cost of the intermediate link between the generating station and the locomotives. I will endeavor to add some information bearing on this point.

The New Haven electrical equipment comprises 35 locomotives weighing 93.3 tons each, or a total of 3266 tons. with an aggregate capacity of 35,000 h.p. on the hour rating. Considering the individual capacity, the number of machines which will be under repairs, the time in the shop and other lay-overs, I believe that not over 23 of the New York Central machines would be required to do the work of the 35 New York, New Haven and Hartford ones. The New York Central locomotive weighs 95 tons, which will make a total of 2185 tons, with an aggregate capacity of 50,600 h.p. The difference in total weight is 1081 tons, and on an assumption of an average duty of even 200 miles per day there would be an excess of 216,200 daily locomotive ton-miles on the New Haven system. The difference in the cost of the above locomotives would ordinarily be about $400,000. The total distance from Stamford to the Grand Central Station is 33.48 miles, 21.45 miles comprising the single-phase section. As I have pointed out in my paper, the direct supply to the overhead line from the main station is but a special provision; it does not mark any wide application, for step-up and step-down transformers will be absolutely necessary as a general rule. Therefore, for comparison, we may assume on the New York, New Haven and Hartford the presence of those transformers. The introduction of synchronous converters in addition, assuming the same number of sub-stations, would add about $15 per kilowatt of normal capacity, so that the $400,000 differential in locomotive costs would provide for a synchronous converter addition of 26,667 kilowatts, which would have a temporary excess capacity of anywhere from 100 to 200%, according to the specifications of the engineer and the zeal of the manufacturers.

But this is not all. In a letter addressed to Mr. W. H. Newman, president of the New York Central, under date of Oct. 27, 1905, and published in the technical press in December of that year, in which the abandonment of the system then being introduced, and the adoption of the single-phase alternating-current system were urged, one of the principal reasons given was a great saving in cost of the working conductor system, which it was claimed would aggregate $9,000,000 between New York and Buffalo on the Central's line alone. The actual difference in the number and cost of equipments which would be required was ignored. The estimate per mile of road of a four-track line, with catenary construction from bridges over the tracks, and with operation at 6000 volts, exclusive of transformers, was given as $12,436. Some time afterward an estimate was published purporting to give the cost of the New Haven installation, which with additional provision of an extension of the bridges to cover six tracks instead of four, but not including the additional overhead work, was stated to be $27,000 per mile of road, although with operation at 11,000 volts. A careful analysis of actual construction makes this, according to Mr. Wilgus' statement, probably over $50,000 per mile, which I assume is exclusive of any lowering of tracks, clearing of right-of-way from trees, or work in connection with telegraph or telephone circuits. The cost of the working conductors of a third-rail system for four tracks, the protected under-contact rail being used, supplemented by a main conductor so that any of the tracks can be cut out, is much less than this.

Looking into the matter soberly, then, it would seem that in the first really comparative examples on a large scale, the cost of the working-conductor construction of the alternating current system as actually erected is considerably higher than that of the third-rail construction, when installed on a trunk-line railroad in operation, and also that the cost of equipment to do equal work is much higher, this latter difference alone being enough to pay for a great abundance of synchronous converter apparatus.

Just here, I may be permitted to suggest that it savors of trespass beyond the proper limits of a discussion of my paper when one assumes what my decision would be in the event of my opinion being asked as to the equipment of a trunk line division. Whenever such decision may be necessary, it seems reasonable to suppose that I shall be guided by the particular railroad problem under consideration, the real interests of my clients, and the then known or probable development in the art quite irrespective of what my decision might have been at some other time and under other conditions.

It seems necessary to emphasize the meaning of restricted capacity of equipment for any allowable truck dimensions and unit wheel-weights. I repeat that it is a matter of no vital concern that 20 or even 40 tons be added to the weight of a freight train with any given motor capacity, especially on low-grade roads; but it is of the utmost importance if either the same capacity can be got with fewer units, or if, on the other hand, the excess weight will give even 50% more continuous capacity. What is required in any locomotive is simplicity and capacity; simplicity, to avoid an acute attack of appendicitis when far from home, and capacity, to meet the inevitable overload demands which will be made upon it by the operating force and the exigencies of service. This latter quality has been the constant aim of every superintendent of motive power, every general manager, and every locomotive builder. Larger cylinders and boilers, increased tube and grate surfaces, and more capacious fire boxes—all demanding greater weight on wheels, continually opposed by the limitations of bridges, rails, and ballast, and disheartening to the engineer of maintenance and way.

Need there be any more eloquent and forceful, nay, vital plea for keeping down wheel-weights, both individual and as concentrated on bridge members, especially when running at high speeds, than the appalling number of rail breakages reported during the past winter, and the recent attack upon the sufficiency of rail-sections and the integrity of rail manufacture—all emphasized by the Carnegie company's report of 20 broken rails after a single trip of the Pennsylvania's 18-hour flyer to Chicago!

On the subject of costs, we should be somewhat chary in formulating conclusions based upon assumed prices for electrical apparatus. At a former meeting of the Institute, unit and differential prices were given for 15- and 25-cycle electric locomotives. Mr. Stillwell based his calcluations on $25,000 per locomotive for 25-cycle operation, with a possible reduction of $1,000 for 15-cycle equipments, this latter difference being enlarged to $5,000 per unit by Mr. Storer. Little reliance can be placed upon such figures when it is well known that for various causes, such as changes in price of labor and material, variation in types of motors and locomotive design, the use of alternating-current or direct-current apparatus, etc., the unit price of various locomotives within the last three years has varied, not $1,000 or $5,000, but over $25,000, and the actual capacity of the highest priced locomotives has been less than that of lower priced ones.

Mr. Storer has favored the discussion by several positive statements, and certain figures giving the apacities and efficiencies of various types and sizes of motors. As presented, these are interesting but not conclusive; I submit that it is impossible properly to discuss them unless sufficient data are given to analyze them on the thermal basis after the manner I have indicated. There is nothing mysterious about it; and if in addition to the thermal curves, there are submitted the detailed statements of the weights of apparatus which go on a car or locomotive, we will be in possession of that much needed information urged before the standardization committee of the Institute as essential to a full understanding of machine performance. Engineers need the facts, but they should be complete, not such selected ones as manufacturers are sometimes inclined to submit for digestion.

Reference to the relative torques attained by continuous and intermittent currents is unfortunate, for if there is any characteristic of single-phase operation which is particularly noticeable, it is the slow acceleration of cars equipped with such motors; in other words, the lack of motor torque with equal gear reductions. The reasons are too well known to waste time discussing them. Mr. Steinmetz very aptly puts the case in a nutshell when he states that no matter how good a single-phase alternating-current motor is, when put on a continuous-current circuit it is a better motor, and it then becomes possible to re-design a machine to get more capacity out of a given weight, or less weight and less cost of construction for a given capacity. Possibly the self-repairing characteristic of the motors referred to by Mr. Storer may be explained by the fact that, weakened by an alternating current, they broke down when put on to a grounded circuit, and when put on to a lower potential metallic circuit they managed to function.

It .s a new theory in mechanics that reduced clearances and allowable wear of working parts is preferable to ample latitude in these matters. With regard to gears, it is quite possible that on the motors with which he is acquainted the same gear-pitch is used on slow-speed direct-current motors and high-speed single-phase motors. It might occur to one that permissible strength of parts in one case is sacrificed to the manufacturing requirements of the other.

I confess to a stenographic error in the matter of the minimum number of poles on single-phase motors. Of course, most people know that four instead of eight poles are used on certain sizes of motors; but there are other manufacturers, and 14-pole machines have been proposed.

It is quite true that locomotives are not intended to stand still: Mr. Storer remarks that they are intended to move. Undoubtedly, but it is likewise necessary to start a train, or perhaps hold one on a grade, and there are times when a machine, if a part of the equipment fails, may be called upon to stand very considerable periods of steady pulling without actually turning, and certainly great overloads. A little greater familiarity with practical railroading would perhaps show him instances in which locomotives are really not intended always to go, but sometimes actually stand still and push, and keep on pushing. A case in point is the operation of freight trains on long up-grades, where the helper locomotive, well back from the head of the train, is frequently called upon, when the leading locomotive pulls up on signal, to hold the train with full head of steam against slackened draw-bars, and to prevent it being pulled in two when the leader starts again.

It will not do lightly to dismiss the New York Central type of machine from further discussion, or possible notice, by remarking that there is but one single installation of this type. That is quite true, but it happens to be the largest electric locomotive installation in the world, and this particular group of machines is now probably doing more work than all other electric locomotives of trunk-line size which have been built in the United States in the last twenty years. It is, therefore, a machine which must be seriously reckoned with.

Mr. Scott seems to favor alternating-current braking by return of energy to the line, and even claims it to be more effective than direct-current braking on a closed circuit. His present attitude on the subject is a reversal of position assumed but a short time ago by his associates; but this is in accord with the change of heart on multiple-unit operation and commutating-pole railway motors.

In referring to the discussion of Mr. Carter's paper before the Institution of Electrical Engineers, I did not state it as a fact, or my opinion, that there is 10% lower electrical efficiency in a single-phase motor as compared with the direct-current current motor, but quoted Mr. W. M. Mordey, a well known advocate of single-phase apparatus, and for the purpose simply of illustrating the fallacy of assuming that the location of the excess loss, no matter how much, is a matter of indifference.

Of course, as Mr. Scott says, by varying the voltage taps on a transformer, the speed with any given torque can be reduced below that corresponding to the maximum working potential. I might add that the capacity is reduced in the same ratio, and there would be little effect upon the comparison of weight-coefficients.

A paper presented at a Special Meeting of the American Institute of Electrical Engineers, Chicago, Ill., May 24, 1907.

RELATIVE MERITS OF THREE-PHASE AND ONE-PHASE TRANSFORMERS

BY H. W. TOBEY

During the last few years there has been a gradually increasing tendency in this country toward the use of three-phase transformers on three-phase circuits instead of groups of three, or in some cases two, one-phase units. It is the purpose of this paper to outline briefly these two systems, and to point out as far as possible the important features of both, with their advantages and limitations.

In this country, particularly, there is a strong feeling among many engineers in favor of single units. This feeling is probably due in part to the fact that if one transformer in a group gives trouble it can be readily removed and replaced by a reserve transformer or if no reserve is at hand the load can be carried by the remaining two, if delta connected; whereas if one phase of a three-phase transformer gives out the entire transformer is rendered useless. Where the plant is small, this feeling is more or less justified on account of the fact that an extra three-phase transformer, because of the additional expense, would be out of the question, whereas the cost of an extra one-phase transformer would not be serious.

Where the plant is fairly large, the saving in cost introduced by installing three-phase units makes possible the providing of an extra transformer for reserve. Moreover, if no reserve is available it is possible, in the case of shell-type transformers at least, to take an injured phase out of commission and operate the remaining two phases in open delta until the necessary repairs can be made. This is done by means of an arrangement recently announced, in which both primary and secondary windings of the injured phase are cut out and short circuited on themselves. As mentioned, this method applies only to shell-type transformers connected delta primary and secondary.

From the foregoing, it would seem that as far as reliability is concerned the two systems are about equal.

As to initial cost, the three-phase transformer has a distinct advantage. Not only is it possible to utilize the iron in the magnetic circuit to better advantage, but a saving is also possible in the cost of the containing tank, inasmuch as only one is required instead of three. All things considered, the cost of a three-phase transformer may be taken as about 85% of that of three of the one-phase type—total capacity, frequency, and voltage being the same of course in both cases.

In addition to the initial cost, there is also a saving in material and labor incurred in connecting up the transformer for service. With the three-phase type, all interconnections between phases are made within the containing tank or case, thus leaving but three high-tension and an equal number of low-tension terminals with which to connect outside lines. For installation, therefore, the total amount of cable required is less, the connections are simpler, and consequent danger of error less with the three-phase transformer than with several one-phase transformers. The expense of isolating compartments is also much reduced, it being customary in many plants to provide a separate berth for each unit.

While general appearance is not necessarily a controlling feature in a transformer building, it is nevertheless to be considered, and here again the three-phase transformer with its simple connections would look neater and more symmetrical than would three one-phase units.

Floor space and height are features which in stations of limited area require careful consideration. In these regards the three-phase transformer has distinct advantages, as a saving of at least 30% can be attained in floor space. and usually its height is somewhat less than that of the one-phase unit.

As regards regulation, neither system can claim an advantage. Both regulate equally well on balanced and unbalanced loads, whether these are inductive or non-inductive.

In some plants the question of limited facilities for handling would be a deciding factor. Here then the choice would be in favor of one-phase units, on account of their decreased weight and dimensions.

For extremely large three-phase units it is probable that some system of forced-oil circulation would be adopted, as by this means the large coils and extremely large mass of iron necessary to form the magnetic circuit may be cooled without difficulty.

In small transformers suitable for pole suspension, the advantages of the three-phase transformer are emphasized in appearance and reduction in weight.

In general, the two systems may be summed up as follows: where the plant is of small or medium size, the facilities for handling limited, and the floor space not an important feature, groups of one-phase transformers would, without doubt, be adopted. For large plants, however, having ample facilities for handling, and particularly where floor space is a question of importance, the three-phase type would be most suitable.

A paper presented at a Special Meeting of the American Institute of Electrical Engineers, Chicago, Ill., May 24, 1907.

RELATIVE ADVANTAGES OF ONE-PHASE AND THREE-PHASE TRANSFORMERS

BY JOHN S. PECK

In considering the relative advantages of three-phase and one-phase transformers, it will be assumed at the outset that the three-phase transformer is to be compared with a group of three one-phase transformers whose aggregate output is the same as that of one three-phase transformer; for it will be admitted at once that a comparison between one one-phase transformer and one three-phase transformer of the same output would be all in favor of the one-phase transformer. On this assumption, the advantages of the three-phase transformer over the one-phase group are as follows:

1 Lower cost.
2 Higher efficiency.
3 Less floor space and less weight.
4 Simplification in outside wiring.
5 Reduced transportation charges and reduced cost of installation.

The disadvantages are:

1 Greater cost of spare units.
2 Greater derangement of service in the event of breakdown.
3 Greater cost of repair.
4 Reduced capacity obtainable in self-cooling units.
5 Greater difficulties in bringing out taps for a large number of voltages.

The various advantages and disadvantages enumerated above will be considered in sequence.

ADVANTAGES

1 *Lower Cost*—A three-phase transformer should always be cheaper to manufacture than three one-phase transformers of the same total output; for, by combining one-phase units into a three-phase unit, there results a considerable saving in active material due to the magnetic phase relations. Also, there is only one containing case, one set of end-frames, one cooling system, etc., to be provided for the three-phase unit.

The labor is also less, not only on account of there being less active material to handle—one case, one set of end frames, etc.—but because the unit as a whole is larger, and there is always less labor cost in manufacturing one large unit than there is in manufacturing several small units for the same total output.

2 *Higher Efficiency*—Since there is less active material in the three-phase transformer than in the one-phase group, the loss at the same densities will be less, and therefore the efficiencies higher, consequently the total radiating surface required may be less.

3 *Less Floor Space and Less Weight*—This follows from a consideration of 1 and 2.

4 *Simplification in Outside Wiring*—The star or delta connecttions of a three-phase transformer are simply and easily made inside the case, for as a rule only three high-tension and three low-tension leads are brought out; whereas with three one-phase transformers at least six high-tension and six low-tension leads are brought out and the transformers interconnected by suitable wiring.

5 *Reduced Transportation Charges and Reduced Cost of Installation*—The lighter weight and less bulk of the three-phase transformer will, in general, result in reduced transportation charges especially where shipment is made by water. This advantage is open to question, however, when there are long wagon hauls over mountain roads, with poor facilities for handling heavy machinery. In this case it may be cheaper to transport a greater weight and bulk in small units; but in general the transportation charges should be considerably in favor of the three-phase transformer.

It should also be noted that in many foreign countries duties are charged according to the weight of material, but whether duties are charged according to weight or price, the advantages are with the three phase transformer.

In general, it will be cheaper to install one large unit than three small ones. This is particularly true where the transformer must be dried out on the site by heating or by a vacuum process.

DISADVANTAGES

1 *Greater Cost of Spare Unit.*—It is obvious that any three-phase unit having three times the capacity of a one-phase unit will cost considerably more. This may be of some importance where there is but one three-phase unit, but it will be found that in many cases the cost of two three-phase transformers with a total capacity of 200% will be but little more than that of four one-phase transformers having a total output of 133%. Where there are several similar three-phase units, it will be found that the reduced first cost of adopting three-phase units will more than pay the difference in cost between the three-phase and the one-phase spare unit. In addition, there is the advantage that the three-phase spare unit will have three times the capacity of the one-phase spare unit.

It should be noted, however, that, with a three-phase or one-phase core-type transformer, there is much less need of carrying a complete spare unit than with the shell-type one-phase or three-phase transformer. This is on account of the very simple construction of the core-type transformer, and the ease with which it may be repaired. The top-yoke is built up in one solid piece and bolted down with butt joints to the three vertical cores. Thus it is necessary in case of repairs to loosen only a few nuts, remove the top yoke, slide off the damaged coils, and replace them with new ones; bolt down the yoke and replace the transformer in position. Should the laminations be welded together, it might be necessary to do considerable filing, but in general there is less chance of burning the laminations than with the shell type of construction. With a supply of spare coils, any ordinary burn-out should be repaired in a very few hours. On the Continent, it is quite customary to use core-type three-phase transformers with only coils as spares even for very important work; for it has been found in actual practice that repairs can be made in but little more time than is required to replace one transformer by another.

With the present standard shell-type of construction, a much longer time is required for repairs, on account of the fact that the laminations must be removed and replaced a few at a time. The repair of a three-phase shell-type transformer is so serious an undertaking that it would probably seldom be attempted on the site but the transformer would be returned to the manufacturer.

2 *Greater Derangement of Service in the Event of Breakdown*—When three one-phase transformers are connected in delta on both high- and low-tension windings, one of the three may fail and be cut out, and the remaining ones will continue to carry about two-thirds the total load without overheating. With the star connnection on either winding, this cannot be done. A three-phase core-type transformer cannot be operated with a short-circuit on any phase. The three-phase shell-type transformer may be operated, however, with a short-circuit on one phase provided both windings are in delta; but, while this may be used as a temporary expedient for carrying partial loads, the whole transformer must be removed eventually for repairs.

In any event, whether core- or shell-type transformers are used, there will be probably a somewhat greater delay in substituting a three-phase spare unit than in substituting a one-phase spare unit.

3 *Greater Cost of Repair*—With three one-phase units it is probable that in the event of breakdown in one, it will be cut out before the others are damaged. With a three-phase unit, where the phases are so near together, there is the possibility that a breakdown in one-phase may damage one or both of the others. In such event, there are two or three phases instead of one to repair; but in any event the repair of a three-phase transformer will be in general more expensive than the repair of a one-phase transformer of the same type.

4 *Reduced Capacity Obtainable in Self-Cooling Three-Phase Units*—In some cases it is highly desirable to use only self-cooling transformers. 1500 kw. is approximately the maximum size of a three-phase transformer that, with present methods of construction, can be made self-cooling. A group of three one-phase self-cooling transformers can be built with an output of two or three times this amount. Thus, if an output greater than 1500 kw. is required, it will be necessary to use two three-phase transformers, a more expensive arrangement than three single-phase transformers. It is very seldom, however, that an output greater than 1500 kw. is required from a self-cooling transformer. When artificial cooling is permissible, the three-phase transformer may be built for any desired capacity.

5 *Greater Difficulties in Bringing out Taps for a Large Number of Voltages*—The increased difficulty in arranging the three-phase transformer for a large number of different voltages might in some cases prevent its use, but such cases will be of very rare occurrence and need scarcely be considered.

To sum up, it may be said that the three-phase transformer has certain real and positive advantages over the one-phase type, while its disadvantages are chiefly those which result in the event of breakdown—an abnormal condition which occurs at rarer and rarer intervals as the art of transformer design and manufacture improves. It is the writer's belief that, as on the Continent, the three-phase transformer has already superseded the one-phase in most cases so in America and Great Britain the use of the three-phase transformer will show a very rapid increase within the next few years.

It is also the writer's opinion that a three-phase core-type transformer having as good or better performance than the shell type can be built for less money. This, together with the fact that the core type can be repaired so readily, makes it more desirable than the shell type.

In the above discussion, the three-phase transformer has been compared with three one-phase transformers, but it is possible to use two one-phase transformers with the V or T connection for three-phase working; and, by placing the two in the same case, a considerable saving in cost over three separate transformers may be effected. On account of the phase relations of the currents, however, the capacity of each transformer must be 15% greater than half the capacity of the three-phase transformer, with a corresponding increase in cost and losses.

There is another serious objection to this arrangement, for on account of the out-of-phase relation of voltage and current the voltage across the three phases will not remain in balance as the load comes on.

It is also open to very serious doubt whether this transformer can be built as cheaply as can the three-phase core type. The writer does not believe that this type will ever come into very general use.

Discussion on "Relative Merits of Three-Phase and One-Phase Transformers," at Chicago, Ill., May 24, 1907.

Peter Junkersfeld (by letter): A decision as to the use of three one-phase transformers or one three-phase transformer should take into consideration all local conditions. The five disadvantages enumerated by Mr. Peck will in some cases be so great as to prohibit the use of three-phase transformers; in other cases these disadvantages may be negligible.

In a small system, or in any system in which the total number of units are few, the " greater cost of spare units " and " greater derangement of service " often throws the balance in favor of three one-phase transformers. However, the troubles with, or breakdowns of, three-phase transformers have perhaps been less than is generally supposed.

The Chicago Edison Company had in service on May 1, 1907, about 42,000 kw. of three-phase transformers, which type it has installed exclusively in connection with synchronous converters during the past six years. The one-phase transformers installed previously for converters aggregate about 8,000 kw. The company also has in service as step-up and step-down transformers for generators or lines a total capacity of about 6000 kw.

In reviewing the ten years' experience in which the one-phase transformer capacity has grown to 14,000 kw., and the six years' experience in which the three-phase transformer capacity has increased to thirty-two units varying in size from 550 to 2200 kw. and aggregating 42,000 kw., we have found that the total number of " troubles " where transformers have been taken out of service have been less with the three-phase than with the one-phase transformers. In fact, there was only one case worthy of notice with three-phase transformers, and even in this the damage was not serious. The one-phase transformers varied in size from 100 to 500 kw., some oil-cooled and some air-blast.

A fruitful source of transformer troubles are the taps for various voltages and the wiring inside the top of the transformer. The above mentioned three-phase transformers were not adopted until the system was so well developed that a great multiplicity of taps was no longer necessary. This, with the particular attention paid to the wiring inside the top of transformer, accounts partly for the few troubles with the three-phase transformers. The latter also embody all of the latest developments in transformer design known, having been in service little more than six years, while some of the one-phase transformers have been in service for a much longer period and are thus of earlier design.

In small and often uncertain undertakings, and in pioneering or extraordinary extension work, there are cases where three-phase transformers should not be used. The advantages of three-phase transformers are, however, so great and the results obtained are so good, both in this country and in Europe, that the use of three-phase transformers merits the most careful consideration in every case. The undertaking that is small to-day may become large to-morrow, and the growth or change in condition usually makes the situation more favorable for the three-phase transformers.

R. F. Schuchardt: Our experience has been of such a nature as fully to justify the decision made six years ago to adopt the three-phase transformers in our converter sub-stations. Where the installation is connected to an overhead line, or where the units are small in number, the situation is, of course, different. I refer to an installation such as ours where the system is very large and has underground transmission lines throughout. The disadvantages enumerated by Mr. Peck almost entirely disappear in such a system. Taking them individually:

" Greater cost of spare unit ". An individual unit being only a very small portion of the total installation, the expense is comparatively small and the saving due to use of three-phase transformers will more than offset this.

" Greater derangement of service in the event of breakdown " and " Greater cost of repair ". The transformer breaks down so seldom that one can very well afford to take the risk, especially in view of the advantages.

" Reduced capacity obtainable in self-cooling three-phase units ". Units of this kind are not generally used self-cooling. A blower system is usually installed in order to get greater capacity out of the apparatus.

" Greater difficulties in bringing out taps for a large number of voltages ". As Mr. Junkersfeld has said, the transformers are now so well standardized that a large number of taps are not required. We do not even avail ourselves of the advantage to be obtained, in case of part breakdown, by having the delta connection on both primary and secondary. We connect the secondaries in star and then join the star points together and to the neutral of the three wire direct-current system. The converters thus also serve as balancers.

C. W. Stone: Most of the discussion seems to be based upon the larger size units. I think that we ought to consider the small unit for pole work. I think this is one of the places where three-phase transformers are particularly well adapted. On poles we are always crowded for space, and that is where we need the smallest unit that we can get for the maximum output. That means the three-phase transformer.

Another point, which has not been mentioned at all, is the underground circuit in manholes. I do not think there is any place more crowded or any place that gives more trouble than the apparatus installed in the manhole. Therefore the three-phase transformer is particularly good in that place because the connections are so much simpler, and the trouble in the manholes comes principally from a poorly made connection. In a three-phase transformer there are fewer of them and therefore less chance of poor work.

In large size units in large stations the question is not so much the question of cost of spare unit as it is the question of the design of the station. Frequently transformers are left until the last thing. The transformers and the switchboards are always left until after the station is designed, and then we have to tuck them away in some corner. Therefore the question is reliability. The extra cost of spare apparatus, etc., does not come into the question at all. It is a question how much we can get in the smallest possible space. There again we have the three-phase unit. As far as reliability is concerned and the cost of repairs, I think Mr. Schuchardt and Mr. Junkersfeld pointed that out very well. The total percentage of breakdowns and the total necessity for repairing is so small that I do not think it ought to come into the question at all. The three-phase transformers do not burn out any more than the single-phase. In fact, the burn-outs are so few that we can disregard them entirely.

There was a question in Mr. Peck's paper about operating the three-phase transformer with a Y-connected secondary, stating that with the delta connection we could operate with one phase cut out and operate the other two on open delta. This is also being done in many places with the Y connection using the ground return where the system is grounded. This has happened in a number of cases where three-phase units are installed and one of the lines has broken down and with a grounded neutral all the rotary apparatus and similar apparatus has gone on operating, and the sub-station man hasn't known that the main line was out until it was reported from outside.

Walter S. Moody: It is pleasant to find Mr. Peck such a thorough convert to the advantages of the three-phase transformer. It is to be regretted, however, that America had to lose so able an engineer before European practice convinced him of the wide range of usefulness of the three-phase transformer.

It was quite natural that American practice with its strong appreciation of the desirability of simplification and standardization of design and construction should for a long time have neglected the saving in cost, simplicity, etc., resulting from the use of three-phase transformers, by using single-phase transformers exclusively. As the volume of transformers manufactured increased, however, the force of these considerations largely disappeared, due to the fact that larger transformer makers had such a large output that the cost of manufacturing a given capacity of both single- and three-phase transformers would not be appreciably greater than making the same capacity of single-phase transformers only. One not acquainted with the facts might conclude from remarks in Mr. Peck's paper that three-phase transformers have been in use in this country but a very short time, and had been produced in very small quantities. While undoubtedly American desire for simplicity and interchangeability retarded more than it should the use of the three-phase transformers, I have strongly advocated their use for six or seven years, and have been responsible for the design and building of some 450,000 kw. ranging in size from five to 7500-kw. units.

Mr. Peck's paper puts the advantages and disadvantages most clearly, in my opinion, and in all important respects, most accurately. There are one or two minor points in connection with the relative advantages of the core- or shell-type construction as applied to three-phase transformers on which I should differ slightly. First, with reference to the ease with which repairs may be made on the core type, I think the European practice of a removable yoke is sufficiently objectionable to offset its advantages. Bolts in a transformer core are always a source of danger, in that the insulation around them may become charred or otherwise damaged, thereby greatly increasing the eddy-current losses. The butt-joint between the yoke and the rest of the core can only be satisfactorily made if the surfaces that are to come in contact are milled or otherwise finished to a true surface. If the surfaces are not finished, or even if they are, the eddy current between the sheets in the two parts of the core may readily be sufficient to cause the welding together of the laminations that Mr. Peck mentions. Some manufacturers use thin sheets of paper between the two parts of the core to avoid this, but the thinnest paper results in a material increase in magnetizing current.

The labor involved in removing the yoke, if it be interleaved with the rest of the structure, is not so great as might be supposed. I have seen such a yoke on a 500-kw. transformer removed and returned to position in fifty minutes. This is certainly not a long time compared with the other necessary operations, including the removal of the transformer from the tank and the exchange of coils.

As one of the disadvantages of the three-phase transformer, Mr. Peck mentions the likelihood of a burn-out in one phase being communicated to adjoining phases. This is quite likely to happen in case of a bad short-circuit in the core-type construction, but I have never known it to happen in the shell type, as the large body of iron between the phases protects the copper in different phases, except the portion that projects beyond the cores, and at these points it is easy to put in a fire-proof barrier. Consequently, the somewhat greater ease with which the core type may be repaired is largely offset by the fact that the damage is likely to be less restricted in its extent than in the shell type.

I agree with Mr. Peck regarding those crosses between a single-phase and a three-phase transformer which consist of two single-phase transformers in one case connected open delta or **T.**

While the T-connected sets have a limited field of usefulness, because they only admit of returning current to the neutral of the system, yet they are neither single nor three-phase, and like most compromises, are undesirable in many ways.

W. B. Jackson: One point has not been brought out which is certainly an important reason for our not having adopted the three-phase transformer in America. It has not been many years since the operator or the person in charge of an electric transmission plant, in a district where serious and destructive lightning troubles were encountered, held his breath during every lightning storm and he usually has had experiences where one single-phase transformer has gone out of business and the two remaining have saved the day without disturbing his service.

There is a statement in Mr. Peck's paper to the effect that for important work single three-phase transformers are used in Europe. I question whether, for what we would consider important power work, we should be willing, even with the present design of transformers, to use a transformer without some reserve. With the present improved transformer design, we have arrived at a time when the question of reserve is not so important as it was a few years ago, and when it may be policy in some cases to use a single transformer without reserve in cases where the service is not very important. But if we assume a condition where the light and power for a town, a small town if you please, is being supplied from the transformer the service demands a reserve. The same is true of a mining camp, especially so if hoists and mills are being supplied with power, and so it goes with most classes of service. One must have an arrangement by which a portion of the apparatus may be taken out of service and still the service will go on.

We all appreciate the tendency that the prevailing opinion has to change one's ideas on subjects, and I wonder how much the opinion of a person who changes his abode from America to the Continent will change. I remember, five years ago, discussing with a prominent engineer of Austria the relative advantages of using three-phase transformers for transmission work as compared with single-phase transformers. He was unwilling to be convinced that there was a single reason for the use of single-phase as against three-phase transformers until I took up the matter of the lightning conditions as they exist in America. He was then willing to admit that there might be cases where single-phase transformers would work into a power transmission scheme with advantage. The feeling of this engineer seemed fairly to represent the opinions of most European engineers.

P. M. Lincoln: There is one objection to the three-phase transformer that has not yet been brought out. I refer to the matter of leads. In very high voltage transformers, say 60,000 volts and above, it is one of the most difficult elements of the design to bring out the leads properly, and where it is a question of bringing out three leads for 60,000 volts instead of one, as is the case with a grounded neutral Y transformer, or two, as is the case with a single-phase transformer to work in delta, I believe the difference is quite considerable, and that the difficulty of bringing out those three leads in the case of the three-phase transformer as against the one or two leads in the case of the single-phase transformer is a question to be taken carefully into consideration. That objection applies only to the very high voltages. Even with two leads brought out, practically all the available space is taken up by those two leads.

If we have three transformers connected in delta it is possible, as we all know, to go ahead and do business on the two remaining in. However, when that occurs, either there must be an interruption to the service in order to cut out the damaged transformer (if it be damaged) or else we must have automatic apparatus such as reverse-current relays or something of that kind to cut out the damaged piece of apparatus automatically. Now reverse-current relays theoretically can be so constructed as to do that all right, cut out that damaged piece of apparatus and let the other two go on and do business. However, the experience that I have had with reverse-current relays and such apparatus would lead me to be rather doubtful whether in actual practice such a scheme will work satisfactorily. When we get a short-circuit on these high-tension lines, with the tremendous amount of power behind them and synchronous apparatus on the ends of the line, there are surges and other effects going on in that system which we do not know very much about.

C. W. Stone: About bringing out the high-tension leads from very high tension transformers. I think there is a decided difficulty in bringing out the leads of a high-tension transformer. I think there again the three-phase transformer comes in, because we only bring out three leads as against six in three single-phase transformers, and wherever we pass through a case there is a weak point. We have six weak points on three single-phase transformers and only three weak points on the three-phase.

P. M. Lincoln: That applies when the transformers are connected in delta. On the very high tension lines we have the middle of the star grounded and that makes it necessary to bring out only one high-tension lead from each transformer. The other lead can be connected right to the case inside.

C. W. Stone: I meant to confine my remark to the delta connection.

Edward A. Wagner: It seems to be the concensus of opinion that the three-phase transformer is the proper thing, based I believe on the assumption that the secondary load is three-phase distribution to a three-phase motor. In this country the practice of a good many stations is to have three-phase generators, and distribute mixed loads; that is, motors and light; and where they distribute for light the distribution is frequently scattered so that it would not pay to put in a three-phase transformer to furnish the light. In such cases the single-phase transformer is far more desirable, because the extra copper required for running the secondary lines would more than offset the advantages of the three-phase transformer. I think, then, that in taking up the question of preference of three phase over single phase, it is acknowledged that the three-phase transformer is more efficient than three single-phase transformers combined, but there are other cases where the condition of operation may possibly determine the necessity of installing single-phase transformers.

A. H. Pikler: Mr. Moody says that the disadvantage of the core-type transformers with butt-joints is that the insulation around the bolts might get damaged. That may be so, but not if the transformer is properly made.

As to the increase of eddy currents due to the milling of the adjoining surfaces. The decreasing of the eddy currents is done, not by interposing a sheet of paper between the yoke and between the legs, as Mr. Moody suggests, but by interposing paper between the sheets of the yoke, or between those of the leg. As to the increase of the magnetizing current, it seems to me that the magnetizing current in a shell-type transformer, other things being equal, is a good deal higher than in a core-type transformer where the surfaces are carefully milled, because the magnetic reluctance in a shell-type transformer on account of the flux, the lines of force, traveling from one plate to the one above, and so on, or from one plate to the adjoining plate in the same plane through an air-gap, is much greater than in a core-type transformer with butt-joints. It seems to me that the core-type transformer with the butt-joints is a great advantage to the customer, because it enables him to repair a transformer in a very short time. For instance, such a transformer even above 400 or 500 kw., if a coil is damaged, may be repaired in four or five hours, whereas in a shell-type transformer one has to pull out every single sheet of the core, then take the coils out, repair the coil, and then build up again the core by single sheets. This causes great delay in repairing. It takes probably two or three days, and with large units repairs cannot be made at the station at all; the units have to be returned to the factory. Whether it is butt-joint or not, I believe that the proper construction for a high-tension transformer is the core type, because in a core-type transformer one can separate very easily and conveniently, either by insulation or by oil ducts, the high- and low-tension windings, whereas in shell-type transformers, both the high and low-tension coils necessarily must be supported by one support, and on that support the creeping surface cannot be made large enough to allow a good insulation. It is necessary to put very heavy insulation between the coils and core, between or over the high-tension and low-tension coils. The disadvantage of this is that, if there is good insulation, there is retained within the coil also the heat which cannot radiate, whereas between the high- and low-tension coils in a core-type transformer there is always circulation through the open duct around the coils. This is not the case with the shell-type transformer. In the shell-type transformer coil there are quite sharp corners on the top and bottom of the coil and at the same point there is the support of the coils. From this it can be seen that at the very point where the construction is mechanically the weakest, it is also weakest electrically, and it is also weak from the point of heating.

E. N. Lake: Irrespective of minute details of manufacture, I think we would probably all agree upon the use of three-phase transformers if we confined that use to distributing systems consisting of a large number of sub-stations interconnected by means of underground circuits. But in the matter of the use of these transformers for interurban railway conditions in which there is a string of sub-stations, any one of which is quite essential to the operation of the road, the danger of interruption to the service would be materially greater in the case of a three-phase transformer than with three single-phase transformers. I have in mind a road some 35 or 36 miles in length, which depends for its operation upon three sub-stations. These sub-stations are equipped with three single-phase transformers, each operating a single converter. One spare transformer was provided, making a total of ten transformers for the system. During lightning or other disturbances upon the system, when some of these transformers went out, it was possible to operate with only 60% of the transformer equipment in service; that is to say, with four out of the ten transformers out of service, the road could still operate. I think that those who are interested in the operation of such roads, where there are not the advantages of the interconnected system and not the protection against lightning of the underground distribution, will hesitate to recommend the three-phase transformers.

H. B. Gear: With regard to the use of three-phase transformers for pole work suggested by Mr. Stone, in view of the possibility of using the open delta system for such installations, the use of small three-phase transformers does not seem to be especially advantageous. The saving thus made by the use of two single-phase transformers instead of three is about equivalent to the saving made in manufacturing cost by installing three cores in one case. Furthermore, so far at least as one company is concerned, the prices quoted for the three-phase units thus far show no saving whatever over the cost of three single-phase units.

As to the larger units, say over 25 horse-power, where it is customary to use three one-phase transformers, where they are mounted on a pole the disposition of the weight is rather more easily effected where there are three single units than with one unit. A 60- or 75- or 90-kw. unit, which would be required for a good many three-phase installations in Chicago, is a very awkward thing as a single unit to set on a pole, unless a platform of some sort be set to one side, or a separate pole set and a platform put between them, whereas three 20- or 30-kilowatt units can be installed on ordinary hangers by using double arms of a little extra strength, without any platform construction and at less expense of erection.

As to the use of underground three-phase units, the advantages cited by Mr. Stone are undoubted in that the number of joints in the manhole is reduced, but there is the quite material disadvantage that a three-phase unit of 60 or 75 kw. is so large that special manhole covers must be provided to get the apparatus in and out of the manhole, whereas, with the single-phase units, either of them which may be damaged can be taken in or out through an ordinary size manhole cover.

Perhaps the most serious objection, however, to the use of three-phase units in a large distributing system is the fact that a full equipment of another type of apparatus must be carried in stock. To a company which is installing and removing every day a considerable number of transformers for both lighting and power purposes, the question of keeping a full quota of all sizes in stock is a matter of great importance. Most central stations have, therefore, found it preferable to use the same kind of transformers for both lighting and power, as they can thus carry a line of three or four of each size in stock and are prepared for any three-phase power installation or for any lighting installation at any time.

A. H. Pikler: I notice that the matter of regulation has not been taken up at all in the comparison between single-phase and three-phase transformers. The regulation of a single-phase transformer is better than that of a three-phase transformer. The regulation depends, especially in the case of power transformers, where the load has a power-factor less than unity, mostly upon the reactance of the transformer. In a core-type transformer the reactance depends upon the length of the leg over which the coils are distributed, the relative distance between the coils, and finally the thickness of the coils. In a shell-type transformer it depends on the dimensions of the coils and the number of subdivisions between the primary and the secondary coils. If we make three single-phase transformers into one three-phase transformer, then, in a core type, we have to use a shorter core and thicker coils, consequently the reactance of the transformer will be greater. In a shell type when combining three single-phase transformers into one three-phase transformer, we have to crowd the coils together, and make them thicker, allowing less intermingling between primary and secondary coils, else the magnetic circuit will grow too big, the weight of iron too great, and the magnetizing current excessive. So from this we can see that the reactance in both cases is greater and the regulation of three-phase transformers compared with single-phase is worse.

Edward A. Wagner: I do not agree with Mr. Pikler on that score. The combining of three single-phase transformers into one common unit or on one common magnetic circuit does not affect the reactance of those coils, because the reactance of the coils due to the leakage in the iron is negligible. The internal reactance of the coils is proportional to the area of the path between primary and secondary and inversely as the length. Combining them on a magnetic structure so as to get a multiphase magnetic path does not affect the reactance of each separate coil, and it should not, therefore, affect the regulation, since the regulation is due entirely to the combination of the resistance and the reactance of both primary and secondary coils.

A. H. Pikler: I did not say that the combined flux affects the primary and secondary coils of the reactance at all. I took one single-phase transformer alone and one three-phase transformer alone, a single-phase transformer of one-third of the capacity of the three-phase and the three-phase transformer the aggregate capacity of three single-phase transformers. If you know what are the factors in determining the reactance of a transformer, it is obvious that in a single-phase transformer those factors are more favorable for a smaller reactance than in a three-phase transformer. The combined flux has absolutely nothing to do with it.

Edward A. Wagner: As I understand Mr. Pikler, his comparison is on the basis of, say, 300 kw. capacity. He makes the statement that if we have a 300-kw. three-phase transformer, and on the other hand three 100-kw. single-phase transformers, that the single-phase transformers connected delta or **Y**, whichever way he pleases, will give better regulation than the 300 kw., three-phase transformer. Now the only difference between the three single-phase transformers and the one three-phase transformer is that the three-phase transformer has the same number of coils combined on a smaller core, and since the core-loss is proportional to the weight, we gain greater efficiency in total output. But as far as reactance of the coils and the resistance and the weight of copper in the outfit, there is no difference between the three single-phase transformers and the one three phase transformer, because the reactance of the coils is the same in either case.

A. S. McAllister (by letter): Mr. Peck says:

On account of the phase relations of the currents, the capacity of each (V-connected or T-connected) transformer must be 15 per cent. greater than half the capacity of the three-phase transformer, with a corresponding increase in cost and losses. There is another serious objection to this (either the T or V) arrangement, for on account of the out-of-phase relation of voltage and current the voltage across the three phases will not remain balanced as the load comes on.

The author's remarks are true when applied to the V-connection, but they must be somewhat modified when dealing with the T-connection. When two transformers are T-connected on both their primary and secondary sides, one of the transformers must be designed for 15.5 per cent. more volt-amperes than one-half the rating of the equivalent three-phase transformer, but the other transformer is subjected to exactly one-half of the volt-amperes of the three-phase transformer. If the voltage between the phase leads is E, and the current per lead I, the three-phase transformer must be designed for 1.732 $I\,E$; one of the T-connected transformers would be designed for $I\,E$ and the other for 0.866 $E\,I$.

Two transformers with T-connected primaries and secondaries will transform three-phase power from one voltage to another without voltage distortion equally as well as will two similar transformers used to change power from two-phase to three-phase; even for unbalanced loads the transformation will be satisfactory, provided only that the transformer with the larger volt-ampere rating be constructed with its primary and secondary coils well interspaced.

W. F. Lamme (by letter): The strongest argument against using three-phase instead of single-phase transformers is the one of accident to the transformer, but when the installation of transformers becomes very large so that the number of reserve transformers becomes large this argument of accident decreases.

Transformers as built to-day by responsible manufacturers are quite reliable, and the chances of breakdowns are, or can be made, remote. In the case of three-phase transformers this reliability can be increased by the use of more careful design and construction and higher insulation tests, and the customer can still get his three-phase transformer at less than three single-phase transformers will cost him, and the risk of a shut-down in the two cases due to accident to the transformer may be considered as equal.

K. C. Randall (by letter): For quite small units up to approximately 100 kw., or even larger, where interruption may be tolerated, the three-phase unit will doubtless show up well. Where the units are larger and isolated, and especially where continuity of operation is of prime importance, three single-phase units will probably show better in three-phase work. As sizes of 1000 kw. and larger are approached, the three-phase units again come to the front, especially as to installation costs.

As to handling when the station is new, during the course of construction provisions may be made for lifting nearly any size unit which it may seem desirable to install; therefore, the choice of the single-phase unit is not necessarily an essential consideration. If a large growth of power business is contemplated, and if at first it is desirable to install but one or two of the future six or eight units, it may be advisable to use the three-phase units irrespective of their size.

If the station be an old one, it will probably be desirable to adhere to the already selected type of unit, unless the original choice has been subject to improvements, which would warrant the selection of different units. This would mean two different types within the same station, or upon the same system, and probably sacrifice the interchangeable feature.

The failure of a three-phase transformer or of one of a group of single-phase transformers is about of equal significance in its bearing upon a shutdown. In either case, if operation is delta-delta, switches may be so arranged that the transformer on the faulty phase may be cut out, the remaining two transformers operating in *V* to carry a portion of the load. This applies equally well to the single-phase or three-phase units. Shell-type transformers are here contemplated. A failure in any phase of a core-type will put the transformer out of service, unless the faulty phase can be opened and isolated. If operation were star on either end, then operation could not be continued until the unit was repaired or replaced. The cost of the three single-phase units with a spare unit may be called 400%; and the cost of two equivalent three-phase units 500%. The cost of two groups of single-phase units; that is, six transformers, will be 600%. As a matter of fact, it is doubtful if the two three-phase units will actually cost any more than the four single-phase units when they are finally installed, wired up, water-piping completed, and ready for operation, the single-phase units being arranged so that any three may operate in a bank, and the three-phase units being arranged to operate singly or in parallel, as may be desirable. It should not be lost sight of that the three-phase units have a capacity of 200%, while the three single-phase units have a capacity of but 100%, it being impracticable to use the fourth transformer to advantage with the delta-connected group. However, the four transformers may be connected in open delta, two on each leg, so that a capacity of 13% higher with the same heating effect in the transformers, is obtained. The gain in capacity is in general obtained at the expense of regulation, it being well known that transformers, operating in " *V* " or open delta, do not give equal regulation on the three legs of the three-phase circuit.

It would then appear that for good size units, say 1500 to 2000 kw., in stations where considerable power is to be used and a continual growth of business is expected, it will frequently be advisable to employ three-phase units rather than single-phase, as in this way complete new units may be installed one at a time to much better advantage than if single-phase units were used in groups of three. The three-phase unit being the heaviest, it will generally be more difficult to handle, particularly in the case of old stations where crane facilities are very limited; yet it still may seem advisable to install the three-phase unit, making a special effort for this purpose. Side tracks are now generally found near stations, so that the transportation matter is pretty well taken care of.

There is a tendency to ship transformers unassembled, as is done with large generators. If this is done the disadvantage of the additional weight of three-phase over single-phase units is small, and it will only require the attention of an experienced man for a number of days to put together the three-phase units on the premises rather than at the manufacturer's works.

D. L. Huntington (by letter): For nearly four years the company with which I am connected has been purchasing three-phase transformers for nearly every installation of 150 kw. or more, and is using transformers of this kind in sizes from 150 kw. to 2200 kw. These transformers have been installed on 60,000-volt lines, star-connected with grounded neutral. Under these circumstances there would be practically no advantage in case of breakdown by the use of three one-phase transformers, as the latter could not be used to obtain temporary service.

On all remaining points the three-phase transformer has a distinct advantage; namely, first cost, convenience, simplicity of wiring, space occupied, piping and general expense of drying out, filling with oil, and installing. If the large quantities of oil used in transformers be considered a serious fire-risk, the one-phase installation will be much more of a risk than the three-phase on account of the larger quantity of oil required.

Mr. Peck says that with the core-type one- or three-phase transformers there is much less need of providing spare capacity than if the shell type is used. I wish that our experience would bear out this conclusion; but unfortunately we have had all our transformer troubles with core type and none with shell type. I will of course admit that in case of a burn-out the core type is much more readily repaired; but in that very fact lies the reason of its inferiority as against trouble, for the looseness of construction, which so readily admits of the removal of coils is the cause of most of its failures, so far as our experience goes.

A paper presented at a Special Meeting of the American Institute of Electrical Engineers, Chicago, Ill., May 24, 1907.

FORCED-OIL AND FORCED-WATER CIRCULATION FOR COOLING OIL-INSULATED TRANSFORMERS

BY C. C. CHESNEY

With the increased demand for large individual transformers, and for installations of large aggregate capacity, the relative merits of forced-oil and forced-water circulation for the cooling of oil-insulated transformers have been recently receiving the special attention of transformer designers.

The method of cooling transformers by means of forced-water circulation has been in use a number of years, and is too well known to require any more than a very general description. The essential feature is a cooling coil of pipe composed of a number of turns of iron, brass, or copper pipe placed in the oil in the upper part of the containing tank, and generally above and around the ends of the transformer windings. Through this coil is circulated the necessary cooling water, the heat being transferred from the winding and core to the pipe-coils by the natural circulation of the oil from the heated parts of the transformer to the cooler pipe-coil.

The more recent methods of cooling transformers by forced-oil circulation does away entirely with any internal cooling coils, but makes necessary external auxiliary cooling apparatus. The lower part of the windings of the transformer is enclosed in a metal box containing suitable directing plates, and this box is connected to the oil inlet by a vertical pipe raised to the top of the tank and passing through the cover. The outlet pipe has its opening somewhat above the top of the windings, thereby insuring a safe oil level. Oil under a slight pressure is introduced through the inlet pipe, and in passing through the transformer the oil is brought into intimate contact with the various windings and laminations by means of ducts and directing plates. After leaving the transformer, the oil flows through an external cooling system containing a surface condenser and strainer, and an oil pump, the latter providing the pressure needed to keep the oil moving at a proper rate through the entire system. An additional pump is provided to circulate water through the condenser. Sufficient water is usually circulated through the condenser to give a 10° cent. rise to the water temperature, and the rate of oil-flow is usually adjusted to approximately twice that of the water. The organization of the entire cooling system is shown in Fig. 1.

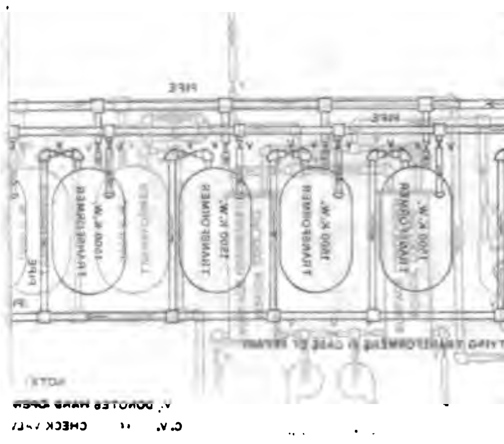
To offset the additional cost which this auxiliary cooling apparatus represents, there is a less first cost of the transformer proper, due to the markedly more efficient cooling which the positive circulation of the oil insures, and to the prevention of any local heating, in pockets, etc. The density in both copper and iron can be increased for the same temperature rise, which means less material used in the design of the transformer. In addition, since there is no cooling coil, the tank can be reduced in height, and less oil will be needed to fill it.

The total saving in the transformer proper will vary from 15 to 25%, depending upon the size of the transformer. The reduced height of the transformer is, however, particularly welcomed on the score of shipment. With forced-water circulation the designer is handicapped, in the larger sizes, by being limited to a height of approximately 11 feet; this being the maximum height that can be safely shipped on any of the American railroads. By the use of forced-oil apparatus, however, the capacity of the transformer which can be shipped completely assembled is materially increased. On the other hand, as against the gain in head-room the total floor space required will be greater, on account of the additional floor space required for the auxiliary cooling apparatus.

If a comparison of the total cost of the transformers installed is taken, the balance in favor of the forced-oil system appears for the large installations of 4000 to 5000 kw. when composed of individual transformer units of not less than 1200 to 1500 kw. While forced-oil circulation is undoubtedly out of the qestion for smaller plants and smaller units, it merits for the large power plants the most careful consideration of any engineer.

RCULA-
AT

should
d. It
denser
neces-
floor
neces-
is not
l they
Also
ooling
using
s not,
there
narily
rmer.
h the
of the
This
uently
built
order
ck is
with
neces-



COOLING OIL-INSULATED TRANSFORMERS

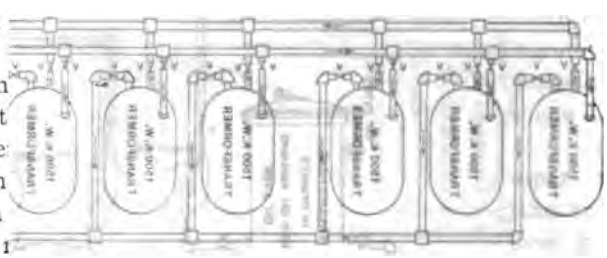
Fig. 1

there-
mping
That
most
, and
, low-
ce as

speak
men-
it is
ating
water
there

ler it
than
ture;
water,
five

with
and (
flows
conde
the p
throu
to cir
usuall
to th
adjus
organ
To
appa
prope
positi
local
iron
mean
addit
in he
Th
from
The
welcc
tion
limit
maxi
can
the c
assen
again
be gr
the a
If
insta
appe
comp
to 15
of th
the l



FORCED-OIL CIRCULATION FOR

Discussion on "Forced-Oil and Forced-Water Circulation for Cooling Oil-Insulated Transformers," at Chicago, May 24, 1907

C. W. Stone: Mr. Chesney points out one thing that should be considered in two ways; the extra floor space required. It is true that if one considers the space taken by the condenser outfit for cooling the oil and the extra pumping apparatus necessary, more floor space may be required, but that extra floor space can usually be found in most stations. The space necessary for the cooling apparatus, the pump and condenser, is not so great as the space occupied by the transformer, and they can usually be put away in some corner in the station. Also in several cases I have found it advisable to install this cooling coil, not in a part of the station but, say, in the tail-race, using the water from the turbine to do the cooling. There is not, therefore, the complication of extra pumping facilities; there would be one set of pumps similar to those that are ordinarily used for forced water circulation in a water-cooled transformer.

Another important thing to consider in connection with the forced oil-cooling of transformers is head-room. Most of the attention given in this paper is on the score of shipment. This is a serious matter only in the very largest size; but frequently in the design of a water-power station where the station is built right on the rock, considerable excavating is necessary in order to provide transformer compartments; and where the rock is solid, the expense is considerable, and if one can dispense witb any head room at all it is well worth saving, even if it is necessary to incur the expense of extra pumping facilities.

It is also true that the oil is under moderate pressure; therefore very little trouble should be experienced from the pumping outfit with forced oil circulation and separate cooling. That is, the troubles experienced are not nearly as serious as in most central stations where the oil has to be pumped anyway, and frequently at much higher pressure. An ordinary small, low-pressure, motor-driven pump is about as simple a device as can be put in a station.

W. S. Moody: One little detail that Mr. Stone did not speak of in connection with forced-oil designs is perhaps worth mentioning; namely, the incidental advantage attained when it is possible to locate the cooler in the tail-race of a generating station. Here, having practically an infinite quantity of water compared with what is actually needed for the cooling, there is no perceptible rise in temperature of the water.

When the water for cooling is pumped through the cooler it is hardly ever practicable to use a larger quantity of water than that which will be raised about 10 degrees in temperature; consequently the average temperature of the cooling water, when the cooler is in the tail-race, can be considered as five degrees less than when water is pumped through the cooler, The result is either a reduction of five degrees in the actual temperature of the transformer under full load, or the possibility of using a cheaper transformer having the same actual temperature as one cooled by artificially circulated water.

A. Henry Pikler: The idea of cooling transformers in this way is not recent. The reason for the increasing use of this method of cooling is due to the development of very large units, which require special devices for keeping the temperature within the proper limits.

The dissipation of heat in transformers with forced oil circulation is primarily due to convection and not to conduction or radiation. Consequently the speed with which the oil is forced through is of vital importance; the greater the speed up to a certain limit, the better the cooling and therefore the smaller the apparatus for a certain given rise in temperature. Therefore the statement: "The total saving in the transformer proper will vary from 15 to 25% depending upon the size of the transformer," has very little value unless the speed be given.

As in all apparatus which has forced cooling, so with this one—the danger arises in the case of breakdown of the cooling arrangement. The density in the copper and the iron, and consequently the heat generated, is higher in this than in transformers cooled by other means. If the cooling arrangement gets out of order, the former kind of transformer can be operated without forced cooling for fewer hours than the latter; this is certainly a disadvantage in the former system.

W. B. Jackson: There seems to be one advantage here which has not been pointed out. In this system of water cooling transformers the possibilities of trouble from leaking water pipes may be entirely eliminated; in other words, instead of there being pressure tending to force the water into the oil it is entirely practicable so to arrange the system that the water will be drawn through the cooling coils in such a way that the old danger of water getting into the oil and in that way short-circuiting the transformers, is entirely overcome.

W. S. Moody: I was just referring to this particular possibility of trouble. As soon as the idea of using the forced-oil method of cooling occurred to us, this source of danger naturally presented itself as something necessary to guard against. We do so by simply arranging that the water and oil pressures in the cooler be such that the leakage will be in the direction from the oil to the water, so that if there is any little leak the result is simply a little loss in oil. There is no possibility of water leaking in the other direction.

P. M. Lincoln: There is one disadvantage that occurs to me and one which no one has yet mentioned, and one which the oil transformer designer realizes more than anything else; namely, that oil is the hardest stuff there is to keep where it belongs; and the more piping, etc. there is to convey this oil around the more danger there is of getting leaks and a condition which might be best designated by the term "sloppy". That is, I think, one real objection to the scheme of having forced oil circulation rather than the present. It is undoubtedly cheaper; that is to say, there are bound to be less materials used with a properly designed oil circulation than if the oil is allowed to circulate itself, and efficiency can be improved for the reason that with a more efficient means of carrying off the heat there is bound to be an improvement in efficiency. As against that there is this condition of having a greater tendency to leakage and having an auxiliary apparatus which the modern operator, if my experience leads me to judge aright, tends to avoid rather than to court.

S. M. Kintner (by letter): Mr. Chesney treats only briefly a subject about which a great many interesting things can be said. In his brevity he has left at least one point that needs to be qualified. He says: "The density of both copper and iron can be increased for the same temperature, etc." The above is true for the higher frequencies only so far as change in density in the iron is concerned. It is not the loss and consequent temperature in the iron that prevents a greater magnetic density for the lower frequencies, but it is the increased magnetizing currents that would follow working at any greater magnetic intensity.

There are several characteristics of oil that must be borne in mind for a thorough appreciation of the various methods employed in cooling oil-insulated transformers.

The oil is an extremely poor conductor of heat. I have repeatedly noted temperature differences of 60° cent. in a column of oil only 6 in. tall. The heat was of course applied at the top of the oil column. The above condition is one that existed after several hours' operation so as to insure a final balance of temperature conditions.

The oil carries heat by convection currents only and consequently has a tendency to pass upward only. This makes it extremely important to see to it that no dead oil pockets exist in the transformer, as otherwise a hot spot of 50 degrees or 60 degrees cent. excess might exist locally in the windings.

The oil film heated by contact with the hot coil tends to rise along that face. This oil film is very thin and exceedingly difficult to measure. Temperature measurements taken by thermometer laid alongside of the coil face will give an incorrect reading, unless specially guarded against the oil flow. Temperature differences of five or six degrees have been noted within one-eighth of an inch of the coil face when explored with a point thermo-couple.

Oil acts simply as a heat ferry in taking the heat from the inside of the transformer to the place where it can deliver this excess heat to a dissipating body. It is, therefore, evident that large "docking facilities" are very essential in order to prevent congestion of traffic of the little heat ferries; that is to say, ample contact area between the oil and the source of heat and again between the oil and the dissipating body is required.

All the above points should be given thorough consideration in the development of the various systems of transformer cooling. The following brief discussion gives the principal points involved in the best known methods of cooling.

Self-cooling, oil-insulated transformers. Self-cooling transformers give up their heat to the surrounding air and the improvements in these, in so far as cooling is concerned, have been improving the facilities of the oil for loading and unloading the heat. The unloading facilities have been improved by using corrugated cases, by using cast iron ribs and pins, by using larger tanks (particularly taller ones as the top of a transformer tank is by far the most effective radiator to the air on account of its higher temperature above air) and lastly by using tubes, containing a certain proportion of volatile liquids that will vaporize on being heated slightly, and consequently keep the tubes at almost uniform temperature throughout their entire length.

All of the above devices have sought to get more contact area of heated air with tank or body which is to deliver the heat to the air, and to get more oil contact surface with the tank or as equivalent.

Forced water-cooled transformers. As the speed with which the oil moves is directly dependent upon the temperature difference of the oil, it is evident that more rapid oil movements will be obtained in the water-cooled transformer with its chilling water coils near the top of the tank than in the self-cooler. The increase in oil speed is a very desirable thing, as it sweeps out the oil vent ducts in the transformer and keeps them supplied with fresh cold oil. The speed of oil movement is dependent upon the temperature difference between the hot oil and the cold oil in which it is immersed. This speed can never exceed a certain maximum because of permissible temperature differences being limited to fairly small values, possibly not more than 20 degrees cent. should be allowed. It is evident therefore, that this method of cooling reaches its limits from the lack of sufficient speed of oil movement.

There have been some instances of cooling in which the transformer tank was immersed in running water. This is but a modification of the above method and has given satisfactory service in a number of places.

Care must be exercised in using these methods to prevent leaks of water into the oil, as a trifling amount of water will cause serious damage.

Moisture will sometimes condense on the surface of the water-cooling pipes at the points where they enter the transformer; this is caused by their temperature being lower than that of the surrounding air and is readily prevented by lagging the pipe so as to prevent its coming in contact with the air inside the transformer tank.

Frequent inspection of the water coils is necessary to make sure they are not collecting sediment on the inside that would prevent water flow.

Forced-oil circulation transformer cooling. This method, which involves the drawing off the hot oil from the top of the transformer tank and the cooling of the oil before it is returned, has its principal advantage in the increased rate of oil movement that is possible.

It has an additional advantage in that the cold oil can be delivered directly in the transformer against the copper and iron.

It is possible with this method of cooling to increase the rating of the transformers from 15 to 30 per cent., depending

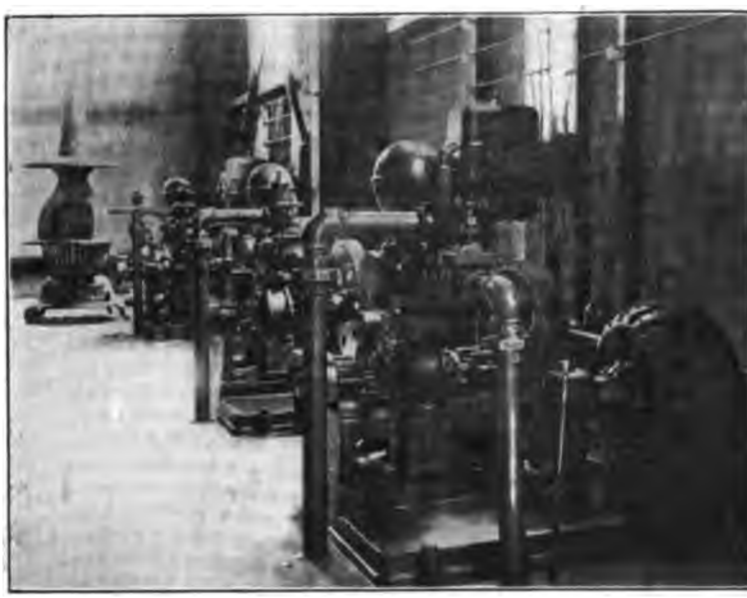


Fig. 1.

upon conditions involved in individual cases. A fairly accurate idea can be obtained of the amount of cooling possible with this method if the figure 9 gallon-degree-min. per kilowatt is taken. From 25 to 30 degrees of cooling is possible if sufficient radiator capacity can be obtained. There is no difficulty in getting this if the radiators are immersed in cool running water.

Figs. 1, 2, and 3 illustrate an installation of the above kind at DeCew Falls, near St. Catherines, Ontario. In this plant, five 2500-kw. oil-insulated transformers are each provided with a forced-oil cooling system. In this installation each transformer has an independent cooling system which is in no way connected to the others save in the source of electric supply of the individual motors.

Rotary pumps driven by induction motors, all arranged on the same sub-base as shown in Fig. 1, circulate the oil at the rate of approximately 90 gallons per minute. The oil is drawn from the top of the tank by a pipe which enters the tank through the cover and dips down into the oil to a depth of approximately eight inches below the surface. The oil after passing through the pump passes to the cooling coils. Fig. 2 is a view of one of the coils taken as it was being lowered into position in the

FIG. 2.

tail-race of the plant. The oil, after passing through this coil where its temperature is lowered to within a few degrees of that of the water, is delivered directly against the bottom of the copper coils of the transformer. The bottom of the transformer is partly closed so as to force the large part of the cold oil to pass upward through the transformers. The rest of the oil passes up around the outside of the iron and assists in carrying away the heat due to the iron loss.

A check-valve is placed in the pipe at the inlet to provide against possible danger of draining all the oil in the event of the cooling coils being torn away by ice or drift in the tail-race.

The pressure of the oil is always in excess of that of the water, and consequently a leak would cause a loss of oil but no inflow of water. A very small oil leak is readily noticeable in the water, so that the system seems amply safeguarded both as regards safety of operation of the transformers and against loss of oil.

Fig. 3 shows several of the cooling coils in position. This view was taken at a low-water period during the time of erection.

These cooling coils have been in service about a year and a half and have given very good service. No trouble has been experienced with leaks in the coils or with troubles from driftwood or ice. No difficulty has been experienced in starting

Fig. 3.

the cold oil after standing idle for hours in the low temperatures that exist in Canada.

It is possible to use a single pump for installations of this kind in place of the more expensive arrangement shown in the views above, provided this pump draws its hot oil from a common tank which fills from overflow outlets in the various transformers. An arrangement of this kind makes a safe operating condition though hardly as satisfactory as the individual pumps.

There are some places, where water is not available, where the circulation of the oil through radiators which dissipate their heat to the air will be found the best available. This air cooling can be assisted by fans directed against the radiators.

A. H. Babcock (by letter): Some expensive experiences with cracked or punctured water coils in high-potential transformers caused me, several years ago, to discuss with the manufacturers, the oil-circulation cooling method. At that time there had not been reported sufficient troubles of this kind to make the matter of enough importance to force the factories away from a manufacturing standard method.

In making the installation, it is suggested that in addition to the reversed connection of the water circulating pumps, as shown in the author's sketch, the condensers be placed in such position relative to the oil piping that, with all pumps stopped, the oil pipes in the condensers will be under a static head. Under no conditions should it be possible for the water to rise into the oil-circulating pipes.

To avoid condensation within the transformer case, the oil should not be cooled below the temperature of the air in the case. A pair of thermometers, one in the air of the transformer case, the other in the oil, provided with contacts within their bores, and connected bridge fashion, could be used to give an alarm when the temperature of the oil falls too low. Similar thermometers with a single pair of contacts have been used on the Pacific coast for several years, to signal excessive oil temperatures.

It is suggested further that a system of air cooling the oil be developed for use in arid regions where water is difficult to obtain.

Broadly considered, in my opinion the disadvantages named by the author are of small importance compared with the obvious advantages.

M. C. Canfield (by letter): It seems to me that some of the advantages incidental to the forced-oil circulation system have been overlooked in the paper under discussion. In the forced-water circulation type, there is occasionally trouble from sweating of the water pipes at the top of the transformer case, and many transformers are built with heat-insulating coatings on the upper portion of the cooling pipes where they are above the oil. This sweating is, of course, due to the great difference of temperature between the air in the top of the transformer case and the water pipes. This difficulty does not occur in the forced-oil circulation system.

Any leakage which may occur in the cooling coils of a water-circulation transformer, results in the escape of water into the transformer case, and consequently, into the oil. In the case of the forced-oil circulation it is a simple matter to keep the oil at a higher pressure than the water, so that any leakage which may occur will be a leakage of oil into the water, and not vice versa.

Mr. Chesney refers to the possible reduction in height of transformer obtained by the use of forced-oil circulation, but suggests that the total floor space required will be increased because of the space required for the cooling apparatus.

In the case of the transformer with forced-water circulation, the transformer-case must be of a size to contain the transformer, and to provide ample space around it for the circulation of the cooling oil. This space must be large, to provide for the descending currents of cooled oil, and as the pressures acting to produce such currents are very small, being due to differences in specific gravity of the oil only, the currents are slow and require much space.

In the case of the forced-oil circulation the situation is completely altered, as it is only necessary to provide for the flow of oil in one direction within the transformer, the flow in the opposite direction taking place through the piping of the cooling system. It is desirable to make the transformer case fit quite closely around the transformer, in order to throw the oil current against the transformer as much as possible. It would therefore seem possible materially to reduce the floor space occupied by a transformer equipped for forced oil-circulation. This reduction of floor space should materially offset the space occupied by the auxiliary cooling apparatus, especially with large installations.

G. Percy Cole (by letter): Occasions may arise in very large installations where it would certainly be good engineering to adopt transformers cooled by forced-oil circulation, but, taking everything into consideration, these instances are exceedingly rare, and it will usually be found that the water-cooled type will fulfil the requirements satisfactorily in spite of its slightly increased size.

The water-cooled type appeals more favorably to engineers for the following reasons:

1. Because it has passed the experimental stage, and proved its reliability, even in the very largest units at present installed.

2. The simplicity of the cooling system. The majority of power houses, where very large units are installed, are hydroelectric, and in such cases the water required for cooling costs next to nothing; the piping being reduced to a minimum, since a gravity system will replace pumps in a great many cases.

3. Less liability for the oil to take up moisture. We hear of extremely few instances where trouble has resulted from cooling coils leaking. The adoption of cooling coils of seamless copper tubing, and the great care bestowed by manufacturers in building and installing this tubing have resulted in almost absolute freedom from the trouble of water getting into the oil from the cooling system.

With the adoption of very large units and high voltages (60,000 to 80,000 volts) it is absolutely necessary that the oil surrounding the coils be kept free from moisture. Where oil has to be circulated through the transformer, out through piping, through large cooling systems and pumps external to the transformer, there is much greater danger of getting water into the oil than with water-cooled transformers. Even if a gravity water-cooled system cannot be employed, and pumps have to be used, water circulation shows up more favorably even if only taking into account the amount of liquid circulated; for since oil has a specific heat of approximately half that of water, it is quite evident that at least twice the number of gallons per minute for the same cooling effect would have to be circulated if oil circulation were adopted than if water-cooled had been used instead.

D. L. Huntington (by letter): The advantages which forced oil would have over forced water appear to me as follows:

1. The movement of the oil, being guided specially to those portions of the windings or core which most need cooling, should be much more effective than with forced water, and for this reason higher efficiencies and longer life should be had for a given combination of copper and iron; or the equivalent of a larger output with the same efficiency and life.

2. In large or comparatively large installations there would probably be a saving in first cost; but on small installations this is very doubtful.

3. Where clean water is not obtainable for forced-water transformer coils the gradual clogging up of the coils is inevitable, and I know of no effective means of cleaning them thoroughly. Under such conditions the forced oil method becomes almost necessary where the installation is to consist of large units otherwise the use of smaller units of the self-cooled type would be the only practical resource, and that a very expensive one, not only in the transformers, but in the buildings and wiring.

4. In case the forced-water type of cooling coils are used which enter and leave the top of the transformer, there is danger of freezing if the transformer is temporarily out of use, and the only practical plan which we have been able to find is to blow the coils out with compressed air. The forced-oil system would be easy to drain of water on such occasions. This advantage would not apply to those forced-water transformers with bottom inlet and outlets, upon which I have for some time insisted, and which are of course readily drained.

Disadvantages

1. For the forced-oil system some measure of attendance, comparatively regular and frequent, would be absolutely necessary. This would mean a greatly added expense in many plants, such as our'sfor instance, where we have numerous sub-stations of from 150 to 1500 kw. capacity in a mining country, where the only attendance now required is for a few minutes once a day.

2. With forced-water transformers it is usually possible to obtain water of steady flow and under the required pressure at small expense, and the cooling is therefore very simple, and consequently, very reliable. The forced-oil system is much more complicated and cumbersome and much more likely to get out of order, and, to assure reliability equal to the forced-water system, a considerable part of the circulating apparatus should be in duplicate.

3. My experience is that in case of a burn-out in a high-tension transformer the oil usually becomes so carbonized as to be unfit to use again until it has been carefully filtered. In such a plan as that shown in Mr. Chesney's paper, the pumps would immediately distribute this carbonized oil to all the uninjured transformers, a really serious matter. A similar effect would be had if a water leak developed. As an insulator, all the oil would, to some extent, deteriorate, and would all have to be dried With the other system the oil of one transformer only would probably have to be treated.

4. To remove these objections to some extent, forced-oil coolers could be installed for groups of transformers. This only lessens the objection, however, and adds materially to first cost and operating cost.

5. Furthermore, if any moisture is carried into the oil in the forced-oil plan, the oil carries it to the plates in the transformer where it will be most likely to do harm, whereas moisture may accumulate in appreciable quantity in the bottom of a forced-water transformer without doing damage.

Generally speaking, unless the objections regarding spreading of damaged oil through the undamaged transformers can be overcome in some simpler manner than by having a separate cooling plant for each unit, I think the advantages of the forced-oil system are distinctly over-shadowed by its disadvantages. Perhaps some ingenious and simple method may be devised to shut off the oil circulation automatically from a damaged transformer. Then, in that case, there are many installations where the size is of some moment, in which the forced oil cooling will be distinctly the best to adopt.

W. F. Lamme (by letter): There are certain cases in which it is better to cool the oil in the transformer through circulating oil through cooling coils in water than by circulating water through cooling coils in oil. In a water power plant an abundance of cool water is always at hand for cooling purposes, and there seems no good reason why these cooling facilities should not be taken full advantage of. If ample cooling coils are placed in this water, and oil from the transformers is circulated through coils in this water, the cooling effect is better than if this water is passed through cooling coils in the transformers. Besides, the type of pipes through which the oil is circulated can be made and installed by any good pipe fitter and can be made as extensive as the operation may demand, whereas, in the case of the ordinary internal coils these coils are made by the manufacturers to suit the case and core of the transformer and are difficult to increase or modify.

In the case of oil circulation the pressure is applied to the oil and not to the water. This lessens the liability of water getting into the oil due to this cooling apparatus. We know that many cases of accident have been due to leaky coils in the case of water-cooled transformers.

Since external circulation permits larger cooling facilities of course oil circulation can be made to give much more reserve capacity where the same core and case are used. This is a very important matter in plants having a high peak load.

In warm, dry climates, such as the San Joaquin and Sacramento valleys of California during the dry season of mid-summer, it has been demonstrated that external circulation of oil cooled by water dripping over the cooling pipes in the open air has a very marked advantage over water circulation through internal cooling coils. We have no definite figures on hand showing these advantages, but a simple observation makes it evident that the advantage exists.

Wm. McClellan (by letter): In discussing this question it must be assumed that all mechanical features would be worked out so as to be thoroughly reliable. The expense of either system will vary according to the details and size of the installation, and in cases where there is a large number of transformers a considerable difference in the cost of the two systems might be found.

From his present point of view, the writer would be rather disinclined to favor the adoption of a forced-oil system. Such a system does certainly increase the risk of getting small amounts of moisture in the oil, and it is well known from recent experiments how much damage a very small amount of moisture can do in transformer oil.

In the forced-water type it is possible to keep all joints, except those which are brazed, entirely outside of the transformer case so that there is no risk from water except in case of a serious accident. The circulation of oil in the forced-water transformer is very uniform and takes place very quietly. The result is that moisture which accumulates gradually is very likely to be found at the bottom of the transformer and is undisturbed by the oil circulation; this would probably not accumulate to as great a degree in the forced-oil transformer.

One point in favor of the forced-oil transformer is the ease with which it permits of oil treatment. It looks very much as voltages increase as if we might come to the time when regular treatment of transformer oil would be imperative. In case of the forced-water transformer, this means removing it from the line, taking out the transformer oil, giving it some sort of a drying and purifying treatment, and then returning it to the transformer With the forced-oil circulation it would be entirely unnecessary to take the transformer off the bus bars since the oil could be treated at some point in the circulating system without affecting the operation of the station.

This will be all the more important should we ever arrive at the sub-station with all the transformers out of doors. As it is, with high tension transformers inside of buildings, there is some risk in removing oil from the transformers and allowing them to stand even for a few hours without oil if the cover must be taken off for any reason. It is very remarkable how quickly the insulation resistance of high-tension transformers will change gradually under these conditions.

A. L. Mudge (by letter): The extent to which forced-oil circulation for transformers comes into use will depend largely on the manufacturing companies. If they can quote materially lower prices per kilowatt, while making the same guarantees, it looks as if forced-oil circulation would almost entirely displace forced-water circulation for large installations. If there is little or no reduction in price, the water-circulation type has the advantage on account of greater simplicity of piping and connections, as no condensers, etc., will be needed. There will be less oil in the power house, and therefore, less fire-risk. In case of fire, if the oil has to be quickly drawn off from one transformer, it is necessary to open only one valve on a transformer using the water-circulation system, while in the oil-circulation system at least three valves have to be operated.

However, a material reduction in first cost in the case of large installations would probably offset the slightly greater complexity of the oil-circulation system. In most plants the oil reservoir could be located above the level of the transformers, thus doing away with one of the oil pumps.

Calvert Townley (by letter): To dissipate a given amount of heat requires a given quantity of water at a given temperature-difference from that of the part to be cooled. The nearer the point at which this water can be applied to the heated material the more efficient it will be as a cooling agent. Therefore, where water is expensive or limited in supply the method of cooling by circulating it in pipes within the transformer case uses the water in its most efficient manner and has a material advantage, However, where water is plentiful and inexpensive the method of forced oil circulation permits the use of larger quantities of water, producing a much greater cooling effect.

The first instance where oil was circulated for the purpose of cooling transformers, and with which I am personally familiar occurred in the Farmington River Power Company's station, near Hartford, Connecticut, in 1896. A number of step-up transformers of 150 to 200 kw. capacity each, self-cooling, were found to be heating abnormally. As a remedy the transformer cases were tapped and a 60-ft. pipe connected thereto, which pipe, wound in coil, was immersed in the tail race. A small circulating pump, belted from a convenient shaft, forced the oil through this pipe, and the result, at a negligible expense and no inconvenience, was an immediate reduction of temperature, so that the transformers worked well inside the normal margin of safety.

It will be noted that for water power installations the oil circulating plan becomes extremely simple and very inexpensive, as, where the tail race or other stream is available, no power-house floor space is needed for the cooling equipment.

There is a further advantage, that, whereas in transformers cooled by water forced through a pipe inside the transformer cases any leak in such pipe permits the escape of water into the transformer oil, thereby endangering the life of the transformer itself, with the forced circulation of oil such leak only lets oil escape into the surrounding water, and the transformer itself is in no danger of injury.

A paper presented at a Special Meeting of the American Institute of Electrical Engineers, Chicago, Ill., May 24, 1907.

ENCLOSED STATION WIRING

BY F. O. BLACKWELL

In the design of a power station, the wiring is often given but scant consideration, and is fitted into such spaces as may

Fig. 1

be left over and not available for other purposes. In reality, a safe system of station wiring is as important as reliable machinery and should be given thorough consideration in making the plans of the building. Power houses have frequently been shut down by animals getting across the conductors and by materials accidentally coming in contact with them. Men working about a building may be killed or injured seriously by exposed electrical connections. Once started, it is impos-

FIG. 2.

sible to say how much damage an arc will do with open wiring. In every case the service is likely to be interrupted.

In the power house of a few years ago, when the amount of power was relatively small, a short-circuit was not a serious matter; but to-day, with 50,000 or 100,000 h.p. concentrated in one plant, a much higher standard of station wiring is called for.

FIG. 3

With a large amount of power, the destructive ability of an arc is enormously increased, and the use of high potentials has made it possible for arcs, once started, to jump almost any distance if not confined.

The direct loss of income is large, but this is nothing to the indirect loss due to the depreciation in the selling value of the power output, caused by loss of public confidence in the reliability of the service.

The attached photographs will give some idea of high-potential arcs, although none of them has any great amount of power back of it, or is of as high potential as is now generally used.

Figs. 1 and 2 show arcs on a 40,000-volt 2,000-kw. system which, in a light breeze, jumped some 40 ft

Fig. 4

Fig. 3 illustrates a 30,000-volt air-switch opening with no load except the charging current of the line.

The metal vapor from an arc, even after the current has been interrupted, will often short-circuit conductors at a distance from the point where the arc started. Wires of high-potential circuits which are as far apart as it is possible to have them inside of a building, may be affected by arcs between low-potential conductors beneath them.

Lightning striking in the neighborhood of a transmission line has been known to cause a short-circuit after the discharge was over, due to the path of hot gas floating across the wires.

In order to prevent the occurrence of short-circuits, and to localize the damage should an arc start from any cause, the following elementary principles should be observed:

1. The system of connection should be as simple as will give the necessary control over the station.

Fig. 5

2. The conductors should follow the shortest and most direct line from generator to transmission line.

3. Each conductor should be surrounded and separated from every other by a continuous fire-proof barrier.

4. The circuits should be as far apart as possible.

Enclosed wiring has already become the accepted practice in important low-tension plants of from 2,000 to 15,000 volts, but is not used as generally for higher potential where the writer believes it is much more important.

Low-potential insulated cables, drawn through ducts or enclosed by split-tile or pipe coverings, are safe provided care is used to cover the cable joints at the manholes, as a cable-joint is a frequent source of trouble.

A single-cable tunnel, or duct system with common manholes through which all the cables in a plant run the length of a building is often employed, in which, if anything goes wrong with one cable, the entire power house is disabled. Accidents of this kind might be avoided by keeping the cables from each unit in a conduit at a distance from other circuits, and laying out the wiring so that each generator can be operated as if it were in a separate power station.

Where bare conductors are used on account of many connections, or where the potential is too high for insulated cables, the wires should be enclosed by substantial walls or barriers of brick, concrete, tile, or stone with only such openings as are necessary to get at insulators or connections. Covers should be provided for all openings.

A good example of enclosed wiring for 13,000 and 60,000 volts is shown in Figs. 4 and 5. These photographs are from the Toronto and Niagara Power Company's transformer house at Toronto.

Discussion on "Enclosed Station Wiring," at Chicago, Ill., May 24, 1907

C. W. Stone: I notice that Mr. Blackwell speaks of the connections being simple. I think this is a very serious matter and one that is not given the consideration it warrants. We try to make a system flexible by putting in all sorts of tie connections; then in order to save space and save cost we put in knife-switches. By putting in the knife-switches we court just what we are trying to avoid. The knife-switch may be opened by mistake. If it is opened under load by mistake there is a big arc, which may be whipped across and involve all the adjacent apparatus. Therefore, if possible, I think we should always try to keep each individual circuit entirely distinct, with no tie, and if ties are used we should use enclosed switches; that is, all switches in the form of knife-switches must be put in between barriers in order to confine the arc.

From Mr. Blackwell's paper it is quite evident the arc cannot be confined, if an arc at low voltage will jump forty feet. He also speaks of putting in barriers between the conductors. This is a very serious point with high-tension apparatus. If barriers are put between them, jumping distances are shortened and therefore the barriers must be put farther apart. This makes it almost prohibitive to install bus-bars in a bus-bar compartment, because the bus-bar compartment becomes as large as the station in order to allow safe jumping distances.

One other thing in connection with the keeping apart of the high-tension conductors, and that is the point where they are brought together in order to put in potential transformers. Potential transformers are connected across between phases, therefore resulting in a tie directly across between phases through a small device. This small device must be isolated and separated in such a way that if an arc forms or an arc jumps across the terminals it will not communicate between the phase wires. This means that each lead has to go through some brick barrier or soapstone barrier or through an insulator, which is bad at very high potentials. Then the current transformer is also used, a very serious thing with high potentials. It therefore would seem good practice to eliminate all secondary devices whatever from the high-potential side, installing all instruments on the low-potential side, running directly from the transformer, say, or the switch to the line, with nothing whatever connected to it.

L. C. Marburg: What Mr. Stone has said regarding simplicity of wiring connections cannot be endorsed too strongly. There is a tendency towards introducing flexibility to such an extent that the complications necessary to obtain it form a weaker point in the system than the original arrangement, the failure of which it is intended to take care of. In other words, while providing for an emergency occurring, say once in three years, we may be introducing the danger of a breakdown once a month.

With regard to enclosed wiring for 60,000 volts, Mr. Stone's remarks also appeal to me. Compartments for such high voltages become too large to be practicable, and it would seem that open work if properly designed, for example the type of installation adopted at the Ontario Power Company's plant at Niagara Falls, offers as much reliability as can be obtained. If wires are separated a sufficient distance so that an arc cannot hold, the installation is about as safe as it can be made. For voltages not higher than 30,000, bus-bar compartments and barriers between compartments and oil-switches have become the standard practice, at least as far as generating stations are concerned, but it would seem as if in many cases, wires were enclosed more than advisable. What is wanted are brick or concrete barriers between all bus-bars and between all switch connections, and as little brick or concrete work as possible should be introduced outside of this, so as to leave all wires and insulators visible and easily reached. For example, a bus-bar compartment may consist of one main vertical wall in the rear and a number of horizontal concrete slabs supported in front by means of small concrete columns. The bus-bars are placed in the horizontal compartments formed by these slabs, and switch connections are carried through the rear wall to switches located above or below these compartments, barriers being placed between the individual leads. This arrangement leaves all wires and insulators visible throughout, and seems superior to closed compartments and closed vertical risers between compartments and switches, as any leakage will be readily detected and as all insulators can easily be cleaned.

Instrument transformers on the high-tension side are of course undesirable, but, if the station contains a high-tension bus-bar with several independent outgoing lines needing protection, they cannot be done away with entirely.

P. M. Lincoln: Mr. Blackwell summarizes his paper thus:

1. "The system of connection should be as simple as will give the necessary control over the station". I think that all electrical engineers will agree with him there.

2. "The conductors should follow the shortest and most direct line from generator to transmission line". That, again, I think is a point where unanimous decision will be made.

Concerning the third, the vote will be by no means unanimous.

3. "Each conductor should be surrounded and separated from every other by a continuous fire-proof barrier".

I think the vote of the large majority would be "no" rather than "yes" to that, for the reason that the principal advantage of enclosing bus-bars, wires, etc., is to prevent a destructive arc from forming between those bus-bars, etc. Now the higher the voltage of a station, the less destructive become the arcs. With 2000 volts I presume there is about the maximum destruction that can possibly be got; at least I have had occasion to believe that from seeing what a 2000-volt arc will do with a very large amount of power behind it. I believe thoroughly, judging from my own experience, that 2000-volt bus-bars for any very large amount of power should be enclosed, by all means; but for the same amount of power at 60,000 volts or at 40,000 volts I do not believe the same thing holds. The destructiveness of an arc is in proportion to the volume of current and goes up with some power of that volume which I do not know—the square, at least, probably much higher—and, as I said before, the higher the voltage the less the amount of current available for producing destruction. That is one very good reason for omitting these fire-proof barriers at some point as the voltage of an installation goes up.

Another obvious and very good reason for omitting those barriers is the difficulty of obtaining insulation as the voltage goes up. Any material available for barriers must be considered as dead ground on these high voltages.

For these two reasons, therefore, I believe that there will be by no means unanimous assent to this statement in Mr. Blackwell's paper.

4. "The circuits should be as far apart as possible".

This will be assented to, I believe, by the majority of engineers. This statement is in contradiction to a certain extent to his third, because introducing fire-proof barriers practically means separating the wires double the distance that would be necessary without the use of fire-proof barriers. There is no fire-proof material that can be treated as an insulator at 60,000 volts and above; that is, no fire-proof material that is available for use as barriers that can be treated as an insulator at 60,000 volts and above.

E. N. Lake: I might give an example of how this problem was worked out in a small synchronous-converter sub-station designed for operation at a potential of 25,000 volts. I shall endeavor to show by a sketch the arrangement of the circuits and apparatus.

The transmission line wires were carried from the pole line to a cross-arm built into the parapet of the sub-station, thus making a design which was distinctly a part of the building structure. From this point the line wires went directly into the lightning-arrester tower. This tower was divided by a concrete floor into two stories, as shown. The back portion of the tower was further divided by vertical barriers running from the floor line of the lower story to the roof of the second story. These barriers were of brick four inches in thickness, built into both floors and the roof, thus giving the barriers a rigid lateral support. In the upper part of the structure the lightning-arresters were installed. Below the lightning-arresters the current transformers were located. Below the second floor the bus-bar chambers were located, which, instead of being arranged open on top were with closed top of concrete construction open below. In the lower story, or switch room were located the

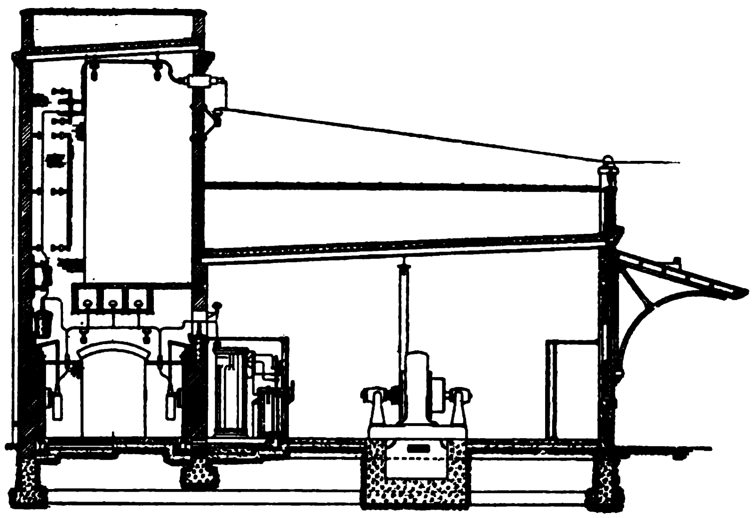


FIG. 1.

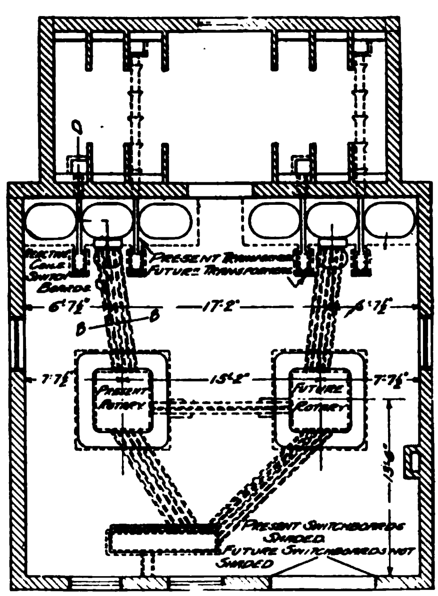


FIG. 2.

oil-switches. The barriers which extended from floor to roof formed the barriers between the oil-switch compartments.

The transmission line was so situated that it was convenient to bring the wires in directly to a lightning arrester tower located at the back of the station. The switch on one side controlled an incoming or outgoing line and the switch on the opposite side operated as an individual rotary switch. At the division wall between the switch room and the rotary room there was an arched opening in the wall for the location of the potential transformers. This construction in general accomplished the end which Mr. Blackwell has brought out in his paper, viz.: that throughout the sub-station from the point where the high-tension wires enter the disconnecting-switches on the lightning-arresters to the point where they entered the top of the step-down transformers, every foot of that distance, the phase wires were separated by fire-proof barriers.

L. C. Marburg: When sub-stations are taken into consideration, the main arguments advanced in favor of enclosing leads in compartments do not hold. If twenty or thirty miles of transmission lines are introduced, the individual wires of which cannot be separated by barriers there seems little use in separating these wires so carefully in a sub-station at the end of the line. If the building is fire-proof, a momentary arc that cannot hold cannot be considered very dangerous, particularly in view of the large resistance introduced by the transmission line between the generating station and the short-circuit. Compartment work in every 200- or 300-kw. synchronous converter station would involve considerable expense.

J. D. Jamieson: It has been my fortune to see some of the extremes in high-tension work, represented in one case of barriers carried to an excessive degree of refinement, and in another case, where the potential was within 10,000 volts of the first, with no attempt to provide barriers between the conductors. The second case I cite bears out the remarks just made about the inadvisability of providing barriers for extremely high potential. This course might be advisable from the standpoint of normal operation, or might take care of any possible rises in potential which might be occasioned, but there is another phase of the matter with which a large central station has to deal: that is, accidental contact. With a 60,000- or 50,000-volt system of a capacity of perhaps 60,000 kw. and a reasonable number of distributing circuits, every precaution has to be taken against accidental contact, and I think if a large station were put up in the fashion mentioned, without barriers, that we would find with a working construction force of 50 to 100 men there would be quite a lot of trouble due to the absence of barriers.

With regard to the addition of knife-switches to the system, it has always been the endeavor of the company with which I am connected to do away with the knife-switches to the extent of putting disconnecting points in a circuit in enclosed partitions; that is, disconnecting-switches, which are necessary in series with oil-switches, are put in the same compartment

On the higher potentials it is not possible to get oil-switches which are equipped with disconnecting appliances. Therefore we are forced to install knife-switches outside the oil-switch, which call for additional barriers. In some cases we go further than to provide barriers, we provide the barriers and then insulate the conductors inside the barriers. This practice has been pronounced superfluous by some, but we have had instances of the worth of such construction. There have been cases where an enormous flow of current, due to the accidental interruption of the circuit, had caused the conductors inside the barriers to be dislodged, and to rest upon the concrete shelves. In that case we found that the addition of insulation to the conductors prevented a very serious disaster. I think that barriers should be used in all cases, and further, that although there is no fire-proof material that is an absolute insulator, the effect of the short-circuit is greatly decreased even though the arc holds between the conductor and the barrier.

Fay Woodmansee: We all agree, I think, that the station wiring must be as simple as possible, and then after that the question of separating depends entirely, I believe, upon the voltage, the capacity, and also as to whether the station is a generating station or whether it is a sub-station located at the end of a line. In a sub-station located at the end of a line, I think the same as Mr. Marburg does; after a number of miles of line that has been unprotected, why in the station separate the wires from each other by barriers? In the station there is less liability for anything to get across the wires, because the wires are placed close to the ceiling. There it is almost possible for any material to get over them to cause a short-circuit and shutdown. Consequently the additional expense is not warranted, I believe, in barriers between poles of lightning-arresters, or anything which may cause an arc in its operation. But in the power house proper, where the question of keeping the potential on the bus-bars is very important and there are a number of men working in the station, I believe that the bus-bars should be separated from each other by some fire-proof barrier, as much to protect the life of the people who may be working in the building as to make the service safe. I think in a good many cases our stations are made much more complicated than they should be.

The question of running leads from bus-bars I think is a very important point to consider. It is oftentimes easier to insulate the bus-bars and run them lengthwise of the station and thus cut down to a minimum the number of feet of cable required. These cables can be run and protected in such a way that it is practically impossible to cause trouble.

P. M. Lincoln: I am thoroughly in accord with what Mr. Woodmansee has said with regard to the protection of life in the station. I think that is absolutely the first requisite that should be taken into consideration in making a switching layout. However, I do not believe that that element compels us to enclose each bus-bar or each wire in a fire-proof barrier. In fact, my own opinion is that the modern tendency is rather toward doing away with all buildings than putting buildings around every individual wire and piece of apparatus in a station. I think the time is coming when the bus-bars, transformers, switches, and practically everything else of that kind will be put out in the weather, and a building put around only the apparatus that it is absolutely necessary to cover, such as instruments and things of that character.

E. N. Lake: I cannot quite bring myself to agree with Mr. Woodmansee or with Mr. Lincoln in regard to justifying the additional expense of barriers. In a given case, where barriers were used in a fire-proof sub-station constructed of brick, concrete, and steel, the additional cost for the introduction of the barriers was probably twenty-five or may be fifty cents per kilowatt. It seems to me that such additional expense is fully justified in the matter of safeguarding life. I think that the protection of life is one of the most important things that we have to consider, it is in fact *the* most important thing to consider in designing stations for higher potentials.

P. B. Woodworth: Will Mr. Lincoln please explain how he is going to safeguard life when he has his wires out in the open with no house around them at all?

P. M. Lincoln: The space up in the air is very easy to obtain. All there is to be done is to put the station out of reach. An ordinary transmission line is not considered dangerous; it is out of reach. Exactly the same thing can be done with a sub-station. It seems to me that, if it is logical to put fire-proof barriers around the individual wires in a sub-station, it is just as logical to run those fire-proof barriers clear back to the generating station. That reduces the fire-proof barrier proposition to an absurdity.

E. N. Lake: If I were going to carry the transmission line wires from the sub-station back to the generating station in such a location that it was possible for the men in their daily work to come in contact with them, I would most certainly put the barriers all the way from the sub-station to the power house.

W. B. Jackson: Doesn't that reach the actual kernel of the matter? Namely, where it is possible for the wires to be touched by the employees in the regular performance of their duties, the wires must be protected by the fire-proof compartments or by separating walls of some kind, but as soon as the wires are carried out of that zone then let them be free. That is getting to be common practice, especially so in plants on the Pacific coast, and it seems to be the logical way to arrange high-tension wiring.

P. M. Lincoln: I think there is no disagreement on that point, that the most essential thing in putting in a sub-station must be to protect life, but I do not agree that putting fire-proof barriers around the wires is the only way to do that. Keep them up out of the way, where they can not be touched by the man in the regular discharge of his duties. That is one way. There are other ways, such as putting ground wires under them or around them, as Mr. Stone has suggested. I think, however, on the essentials there has been no disagreement, no very material difference of opinion among us.

Dugald C. Jackson: Your suggestion that the future sub-station will be out in the air reminds me of the stations of certain of the Western plants. They have step-down sub-stations, not converter sub-stations which require attendance, but step-down sub-stations, where the building consists practically of a light wooden framework with corrugated iron over it, and the line that passes over it drops down through the roof through suitable terminals, and the wiring is run to the transformers through ordinary fibre conduit, using the usual linen covered wire. That makes a sub-station that approaches the limit of simplicity. It is almost the equivalent of having the whole thing out of doors as perhaps it is even cheaper than to erect the structure on an elevated platform, and it also does this, which I think perhaps is likely to militate against Mr. Lincoln's proposal to put everything outdoors; it protects the transformer terminals and such switching terminals as are needed from the beating of the weather,—the sleet and rain and that kind of thing that one is bound to meet and which these terminals practically need to be protected from.

Edwin W. Olds: When you call upon me to speak upon the subjects that have been so interesting to-day, you are calling upon one who, while old in years, and in name, is very young in that part of the business. We are just putting in our first single-phase alternating-current direct-current car equipments. Electrical engineering is somewhat out of my line, but is very interesting, and some of the points that have come up have appealed to me in a practical way. I am not a technical man in any sense of the word. What little knowledge I have has been pounded into me in the good old way.

I have noticed in our direct-current operation in Milwaukee that in certain sections of the city where there are a great many telephone and other wires it is very seldom that any of our cars are struck by lightning; but in other sections where the telephone and electric light wires are not so plentiful, there is trouble with our cars. From my standpoint, this is quite conclusive evidence that a grounded conductor is of a great deal of importance, for, if it will protect our direct-current feeders and trolley lines, why should it not protect the higher potential wires that are so much more apt to be disturbed by the lightning.

Bertrand P. Rowe (by letter): In following the development of systems of station wiring in connection with switchboard installations, we begin with the single generator and the primitive system of open wiring carried on porcelain knobs, which was undoubtedly borrowed from the earlier experience of the telegraph companies, As the fire hazard from poor electrical wiring became more universally recognized, insurance companies from time to time insisted on better spacings, better insulation, and absence of combustible material. The sizes of generating plants have increased, and the amounts of power that have been concentrated on single sets of conductors or bus-bars have reached such proportions that the old-time methods would not suffice for their installation. With this new set of conditions, the underwriters have not meddled. They have found that the owners of generating stations are building fire-proof plants with concrete floors, and structural iron and masonry walls, and they have no regulations to offer regarding the installation of these heavy capacities beyond what are already in vogue for those of lighter capacity. Their fire-risks in such plants are small, and they are interested more in applying their rules to the wiring of factories and dwellings where there is a fire-risk.

The designers of electrical power stations, however, have found that with increased capacities at higher voltages there exists the danger of serious damages and shutdowns, due to arcs starting between conductors, being fed from conducting gases from vaporized copper with the power of large generating units concentrated behind them.

With low-tension systems, from 125 to 250 volts, this danger did not exist, even with thousands of amperes in bus-bar capacity, fed from storage-batteries, because the voltage was too low to maintain anything but a short arc. Difficulties of this sort have been noticeable in plants of from 2000 volts and upwards, principally because 2200 volts is the lowest high-tension voltage at which large amounts of power are concentrated.

In order to prevent arcs between conductors in smaller installations, the conductors were insulated. The practice in these larger installations is to use bare copper bus-bars, and insulate them by air-spaces, inclosed in fire-proof cells. All cable connections are likewise carried in cells, as well as all apparatus liable to cause an arc.

The practice of isolating the conductors has been followed in all modern heavy capacity plants up to and including 15,000 volts. The reason for the practice will be well exemplified if one starts out to design open-link fuse-blocks. It will be seen that a fuse for 250-volt service may be constructed very easily which will carry normally 2000 or 3000 amperes, and rupture the circuit on an overload of 25% without difficulty.

Now if one starts to design 500-volt fuses, he will find that a fuse to blow at 1200 amperes is a pretty difficult problem, and with plenty of power behind it, the fuse-block will be hard to construct which will not be destroyed by the arc. The rupturing of the established arc will be quite a difficult thing without careful study and design.

Now if one goes a step further and tries to design a 2200-volt fuse-block one will get into difficulty when the capacity gets above 300 or 400 amperes. And likewise one will find it difficult to design a successful 3300-volt fuse-block for a larger circuit than 200 amperes.

It follows, then, very readily that, as the voltage rises, heavy capacity currents become more difficult to break; they maintain themselves vigorously, destroying all material which may intervene. The tendency, therefore, in all modern installations, is to suppress all high-voltage arcs by eliminating as much as possible the air-break switching devices, and by using oil-switches, and placing barriers between conductors.

What the station engineer is doing for his own protection, is heartily seconded by the Board of Fire Underwriters, who are leaving the problem alone because not so vitally interested. And the problem is undoubtedly being handled generally in a much more satisfactory way than they themselves would feel free to demand.

Some time ago the underwriters inspected the plant of the Ontario Power Company at Niagara Falls, which has all of the low-tension conductors and switching devices in fireproof cells. The writer was much impressed by being told by these inspectors that they had only one recommendation to make regarding that entire installation, which was that a fire hydrant be placed at each corner of the building. They stated that the modern construction was ahead of anything they had seen at that time in the way of fire-proofing.

In the selection of barriers, the engineer is limited at present because the ideal commercial barrier does not exist. The common practice is to separate all conductors from each other and from grounds, using such distances that concrete or brick barriers may be used with safety. At high voltages, these substances must be considered as grounds, since they absorb moisture, and this makes necessary much wider spacings than if the barriers were of insulating material. Soapstone, while a little better than these, is still an absorbent material, unless impregnated. Porcelain is too dear, and glass will not stand an arc. Asbestos lumber and transite make admirable fire-proof barriers but are poor insulators.

Probably the nearest perfect barrier would be an impregnated material like soapstone, and this is of course expensive. No cheap insulating barrier being known, the common practice is to support all conductors on suitable insulators and rely on the grounded barriers for fire-proofing. The best practice assumes that all insulated cables are subject to deterioration, and unless they are protected by lead coverings with suitable end-bells, they are invariably as well supported on insulators as a bare cable should be. This insures permanency.

For installations of voltages above 15,000, the cellular construction is not so prevalent. But the subject for high-tension wiring for these voltages deserves great attention, because, as stated by Mr. Blackwell, this part of the installation usually gets scant attention when the building is designed. The very best modern practice is to lay out this system of wiring in advance and design the building to suit.

The writer does not agree with Mr. Blackwell that the use of barriers and fire-proofing for very high tension wiring is at present more important than for wiring whose potential is from 2000 to 15,000 volts, for the reason that at the very high voltages now employed the sizes of conductors are very small. They will usually burn away instead of maintaining a fierce arc, such as might be expected if heavy masses of copper are short-circuited. The practice of most station designers seems to sustain this view of the case.

One of the reasons why the use of barriers and cells for conductors has not been more extensively carried to higher voltages is because the generating voltages now deemed practical are all below 16,000 volts. Whenever the manufacturers are ready to put commercial generators on the market to generate current at 20,000 volts, this construction will be seen adopted universally for that voltage where heavy capacities are used. There are even now some cases where large quantities of power are to be distributed at 33,000 and 45,000 volts, and the cellular construction is advisable because of the heavy capacities that are carried on the bus-bars.

In the writer's opinion the use of the barriers and cells, such as are common with the lower voltages, are an unnecessary refinement in a majority of cases. In almost every plant operating at pressures of 45,000 volts and upward, the potential of the transmission system is raised to such a value that, with a given line-loss, the size of conductor can be made as small as mechanical considerations will warrant, to save expense in the transmission line. So long as this practice obtains, and unless large amounts of power are concentrated on high-tension bus-bars by banking the step-up transformers, there will seldom be large masses of copper in the high-tension system to maintain an arc. In fact the condition where heavy conductors may be required on the high-tension system of 45,000 volts or more, can be, and usually is avoided, by feeding separate banks of transformers into their own transmission lines, with a relay bus-bar of small capacity to enable circuits to be transferred from one bank of transformers to another in case of trouble.

In a modern power station, using oil circuit-breakers, if the idea of barriers between all high-tension conductors, irrespective of capacity, were logically carried out, it would be more necessary to require these barriers between the wires on the transmission line where the conditions of atmosphere and moisture are more conductive to short-circuits, than to require them in a properly wired power station where they are enclosed and dry and as well separated as they are on the poles. Where air-break switching devices are used, however, fire-proof barriers are certainly necessary if there are conductors near enough to the arc to cause any apprehension.

Another argument against the use of barriers between very high-tension conductors in power stations is the increased size of station often required if the idea is carried out properly, owing to our inability to obtain a satisfactory insulating barrier. As stated previously, all known barriers, except those of glass or porcelain, must be considered as grounds for high-voltage circuits, and glass and porcelain barriers are not practicable because of brittleness and expense. Therefore, we are forced to use grounded barriers, and the introduction of these barriers between the high-tension conductors in a station compels us to space our conductors much farther apart than they are for the transmission line, to provide sufficient insulation distance. It will be found that to install these barriers properly, a larger amount of room and expensive construction will be required than is usually warranted.

The most practical way to handle the problem is to confine all apparatus which is liable to arc, and separate the conductors by suitable air-spaces, using insulated conductors for the sake of safety. A time may come when reliable insulating material may be obtained in the form of fire-proof tubes through which these conductors may be carried, and which will be sufficient insulation to allow closer spacing of conductors. In such a case the saving in space in a power station will be justification for using them.

The writer believes thoroughly in providing an insulating covering for all high-tension conductors carried in air in the interior of a power station as a safeguard against accidents due to accidental contacts. While it is preposterous to think that cables carrying 60,000 to 88,000 volts can be insulated for safe handling, yet the writer believes that they should be as well insulated as possible to prevent workmen from being killed by contact with poles or other implements.

In addition to this the wires should be marked with danger signals and warnings to remind the unwary. These precautions may save loss of life and bills of damages which are usually awarded against power companies who are found guilty of carrying their deadly current on bare conductors where workmen may be near enough to be shocked.

It may be possible to insulate the conductors with some of the special tubing now on the market, with some form of impregnated oiled muslin next to the cable so that there is scarcely any danger to the cables, by preventing possible arcs. The writer believes that the best and most conservative practice in most cases will be to try to provide such arc insulation as this, and then support the entire insulated cable on insulators with good free air spacings between all adjacent conductors and to ground.

Stephen Q. Hayes (by letter): The writer agrees with three of the principles enumerated, but does not believe that in stations where voltages of 33,000 and upward are obtained by means of step-up transformers "each conductor should be surrounded and separated from every other by a continuous fire-proof barrier", and for the following reasons:

First, the violence of an arc and the destructive effect of a short circuit seem to depend more on the amount of current than power available, or for the same amount of power would diminish with increase in voltage.

Secondly, the short-circuit current available on the secondary side of a transformer is less than that which would be supplied by a generator wound for the same voltage and connected directly to the bus-bars. The use of the transformers introduces a cushioning effect.

Thirdly, as the fire-proof barriers offer a more or less perfect ground for high-voltage circuits, the striking distance from wire to ground has to be greatly reduced over what could be obtained with open wiring in the same space.

Fourthly, the use of enclosed bus-bars and wiring ordinarily necessitates several floors or galleries and a more expensive building and more costly structures than the open wiring.

Fifthly, it is more difficult to inspect and repair bus-bars, wiring, disconnecting-switches, lightning-arresters, etc., that are boxed in masonry compartments and only visible and accessible by the removal of doors than if everything is in plain sight. Incipient trouble will be noticed far sooner with open wiring than with enclosed and inspection will be more frequent and thorough if the station attendant in a few minutes' walk can see everything, than if he had to remove several hundred doors and visit two or three floors to examine the condition of the apparatus.

As Mr. Blackwell refers particularly to the Toronto & Niagara Power Company's transformer house at Toronto as a typical example of the enclosed wiring and bus-bars, it might be stated that at the time of a recent visit to that station in February, the static discharge apparently from the 60,000-volt wiring and bus-bars could be heard all over the building. This trouble may have been remedied since that time, but is one far more likely to be met with in a system of enclosed wiring than in a system of open wiring such as that of the Ontario Power Company's Plant at Niagara Falls.

C. W. Hutton (by letter): The enclosed station for the higher potentials has not, as stated by the author, been given the attention which it appears its importance demands. Cable insulation for potentials of 50,000 volts and upwards seems out of the question and the only alternative seems to be the use of long bus-bar ducts with the conductors mounted on suitable insulating supports, (the ordinary line insulator being the most common practice). The arrangement of the apparatus which would seem most simple and satisfactory would be to set the transformers in a straight line and in groups. A moderately heavy brick wall should be built immediately back of the transformers with openings suitably arranged for the passage of the high-potential wires from the transformers, which should be set with their high-potential sides next to the wall. Suitable open-air disconnecting switches should be interposed between the transformers and the openings in the wall and be mounted upon the brick wall immediately above the transformers. Three bus-bar ducts (considering that three phase working is to be used), preferably of tiling on account of its many desirable features, each having a section of approximately 2 ft. 4 in. by 2 ft. 6 in. high should be arranged one above the other immediately back of the brick wall, the bottom of the lower duct being approximately level with the tops of the transformers.

Sectional bus-bars and line oil-switches should be arranged in tile compartments immediately back of the bus-bar ducts, the bottom of the compartments being on a level with the bottom of the lower bus-bar duct. Suitable hand-operated oil-switches for plants of from 10,000 to 15,000 kilowatts can now be made up in three-pole units at a cost of about $175.00, including the remote-control apparatus, so that the liberal use of oil-switches is not prohibitive on account of expense.

One of these three-pole units can be very conveniently installed in a space of 5 by 5 by 10 ft. long. From the oil-switches used for the individual line circuits, the lines pass through suitable wall openings to the outdoor disconnecting switches mounted on poles immediately adjoining the building, thence to the transmission lines. Remembering that all oil-switches have open-air disconnecting switches on both sides, it will be seen that it is never necessary to open the air-switches under load. Practice has shown the above arrangement to work out very simply in construction and highly effective in operation.

The low-potential station wiring at any voltage from 15,000 down has been so well standardized that time will not be taken to discuss it.

Wm. McClellan (by letter): There is little doubt that the enclosed wiring is much more desirable in power stations and sub-stations when the voltage is less than say 20,000. Above this voltage, engineers would do well to favor conditions which will permit of open wiring as much as possible. It is a note-worthy fact that, for the same power, as the voltage increases, the arc, although capable of jumping over longer distances, becomes in itself less destructive. It may also be noted that about the only time an arc can start in a properly designed installation is where open switching is done. So far as bus-bars, tap connections, and apparatus terminals are concerned, there is no danger whatever in open wiring. The remedy then is to make use of oil switches. It is usually found that for very high voltages the amount of space required and the cost of complete installation would be far greater for the enclosed wiring than for the ordinary open type. It is quite apparent that the trend of design for very high voltage sub-stations is towards an inclosure as small as possible. The writer's conception of the future very high voltage sub-station, or step-up portion of a power house installation, is a small switching compartment enclosing the control switches and meters, with transformers and remote controlled oil-switch all out of doors. Under these circumstances the lightning arrester is about the only place at which it would be possible for an arc to start. As this will probably be out of doors anyway, it does not affect the general question. Should we be so fortunate as to get all that the electrolytic arrester seems to promise, we should have no trouble here.

L. A. Herdt (by letter): Large hydroelectric plants of recent design, operating under high voltages and developing large amounts of power, show so much variety in the arrangement of the electrical apparatus as to suggest wide differences of opinion among the designing engineers as to what is considered necessary and advisable to guard against the spread of arcs and to protect the apparatus from trouble if it exists in one part of the plant.

In some cases the isolation of the high-tension apparatus and conductors is carried out in such a way that each conductor is surrounded and separated from every other by incombustible walls and barriers. Transformers are placed in pits and isolated from one another by heavy masonry fire walls. On the other hand, in one of the largest hydroelectric plants of this country, the high-tension bus-bars and disconnecting-switches are placed in an open room without any intervening sections or barriers; the transformers are walled in, but in groups of three.

In another installation of considerable size the transformers will be found all placed together in one room, the high-tension wiring is open without barriers of any kind; considerable distance is allowed between the conductors and this has, so far, afforded sufficient protection.

The writer, however, agrees with Mr. Blackwell that high-tension apparatus and conductors require to be guarded against the spread of arcs, and should be protected from fire spreading from adjoining apparatus or from external sources. This protection is best secured by fire-proof barriers, but the extent of this protection and the expenditure thus incurred should bear some relation to the amount of power generated and the revenue to be derived from the sale of the power. The writer is of the opinion that when there exists a number of high-tension transmission lines carrying large amounts of power, each transmission line, with its high-tension switches, bus-bars, lightning-arresters, and transformers forming one unit, should be separated altogether by fire walls and the like from the apparatus belonging to another similar set. The high-tension bus-bars common to all the different units should be constructed with great care, and whether placed in continuous fire-proof barriers or not they should be provided with disconnecting- and tie-switches, so that each unit could be operated as a separate plant or could be coupled with the others when found advisable.

A paper presented at a special meeting of the American Institute of Electrical Engineers, Chicago, Ill., May 24, 1907

POTENTIAL STRESSES AS AFFECTED BY OVERHEAD GROUNDED CONDUCTORS.

BY R. P. JACKSON.

This paper is a theoretical investigation of the potential gradients and the equipotential surfaces about grounded conductors suspended in the air, and also about metallic towers for supporting transmission lines. It is obvious that equipotential surfaces surround all conducting material subject to static strain, but the position of these surfaces and the gradient of change at different points are usually difficult to determine.

An example is furnished in the overhead grounded wire sometimes used as a protection for a transmission line against lightning. Such a wire placed above a transmission line serves two purposes: first, it interposes a grounded conductor between the sky and the transmission line, and tends to relieve the line from direct strokes (the effectiveness of the grounded wire for this purpose will probably depend largely on its size and the frequency with which it is grounded); secondly, a much more frequent condition, however, is the stress due to induced potential between the transmission wire and ground. If we make an assumption which seems reasonable that there is a potential stress between a cloud and the ground, and that the distribution of this stress is nearly uniform, at least in the vicinity of the earth's surface; that is, that the potential due to the cloud is proportional to the height above the ground, and the potential gradient is, therefore, approximately a straight line near the ground, it is possible to determine in what way this gradient will be altered by the presence of a grounded conductor some distance above the earth.

The potential at a point near an indefinitely long cylinder remote from other conductors is proportional to the logarithm of its distance from the centre of the cylinder. If the potential at the point also tends to be proportional to its distance above the ground, its resultant potential will be the algebraic sum of the two. Obviously, the surface of the ground is itself an equipotential surface; for if it were not, current would flow from the points of high to those of low potential, and it would immediately become an equipotential surface. This fact, that the earth is conducting, cannot be represented mathematically, so it is necessary to assume an image of a charged object the same distance below the earth's surface as the real object is above. and that its charge is always of opposite sign. The surface of the earth then becomes of uniform potential without assuming that it is conducting. The equation for potential of a point near a grounded wire then becomes

$$C\,H\text{--}K \log \frac{R}{r} = P \qquad (1)$$

where H is the distance of the point above the ground, C and K are constants, and R and r are distances of the point from the image and the wire respectively. P is then the potential of the point taken. By taking the point on the surface of the grounded conductor, H, R, r, and P become known. The constant, C, is determined by the assumed gradient, so the constant K may then be determined, and if logarithms to the base 10 are used, will include the proper modulus.

In Fig. 1 a 0.5-in. wire 50 ft. above the ground has been assumed. The gradient is taken at two per foot, so that if the wire were not there the potential at the point where it has been assumed would be 100. This is convenient so that values deduced may also be used as per cent. ratios. The equation becomes approximately

$$2\,H - 30 \log \frac{R}{r} = P \ (2).$$

All the curves of Fig. 1 are calculated from this equation.

It may be seen that at no point directly beneath the grounded conductor is the potential greater than 52. Curve G becomes the gradient instead of N. The meaning of this is that a transmission wire placed, say 5 ft. below the grounded wire, would, when there was a charged cloud overhead, have a potential of about 55% of that which would exist if there were no grounded wire tending to cause a charge to leak from ground to the transmission line. Again, after the cloud has discharged, there would be only 55% as great a potential on the wire, and consequently only 55% as great a charge to escape suddenly to ground. In other words, the curves do not indicate that complete protection is obtainable from a single wire, but that under certain conditions a material reduction of static stress will occur. The amount of this reduction is dependent on the

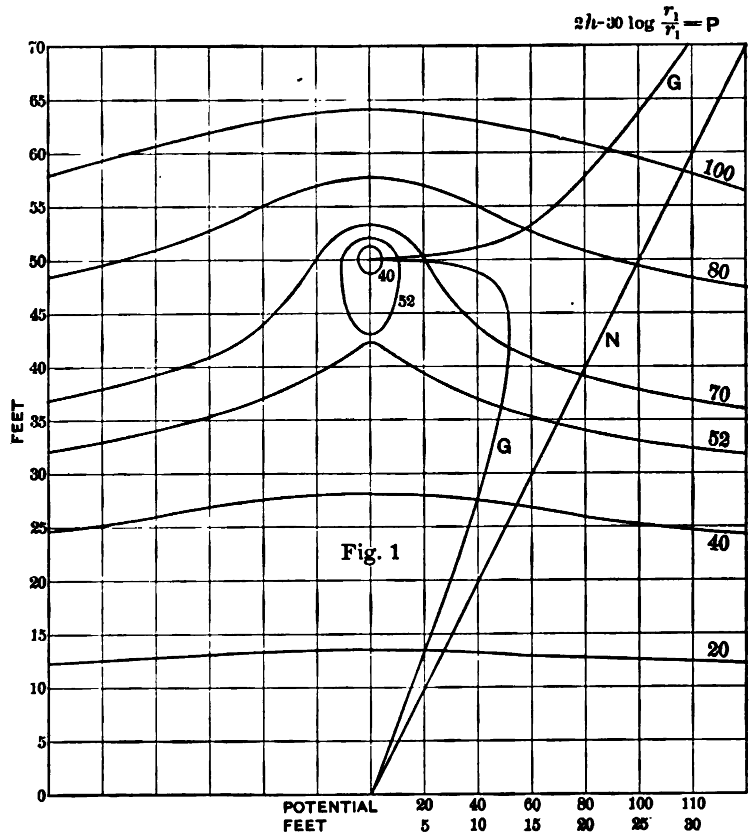


Fig. 1

relative positions of the transmission line and the grounded conductor.

The equation given for a single conductor may easily be elaborated to cover any number of conductors of various sizes, distances apart, and height above ground. By taking the point for which the potential is determined by equation (2) on the different wires in succession, as many equations will be obtained as there are constants, so all may be determined.

The equation for two wires, 10 ft. apart, 50 ft. high, and 0.5 in. in diameter, becomes

$$2\,H\text{–}23\ log\ \frac{RR}{rr} = P.$$

Fig. 2 shows the corresponding curves. It will, of course, be true that the protected area is considerably larger. Fig. 3 shows the assumed gradient, a straight line reaching a value of 100 at a

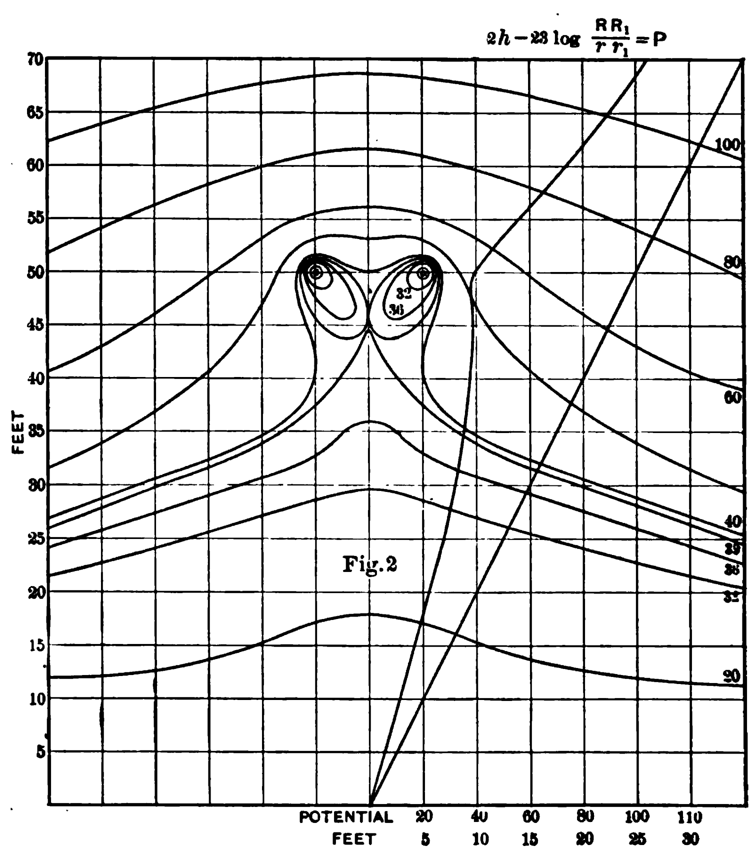
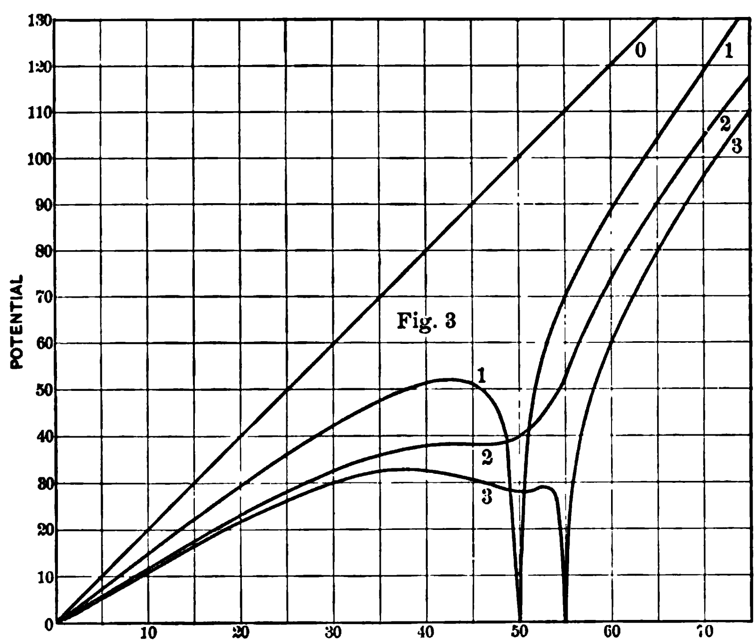


Fig. 2

height of 50 ft., and also shows the gradients on a medial plane for one 0.5-in. wire, 50 ft. high, two 0.5-in. wires, 10 ft. apart, and 50 ft. high, and the same plus another wire between them and 5 ft. higher. Curve 1 being for one wire, Curve 2 for two wires, and Curve 3 for the three wires, respectively. If a number of wires were arranged either in a horizontal plane or cylindrically with the concave side towards the earth, there would be a large area of low potential covered, which would probably be a comparatively safe location for a transmission line.

The above deductions are based on the assumption that the transmission wires are completely insulated, both from the ground and from the other parts of the circuit not affected by the cloud potential. Insulated uncharged conductors of small dimensions in the direction of the static stress have no appreciable effect on the static field about them. The above is a condition, however, that would be practically impossible on a real transmission line, since it is reasonably certain that either



the insulators will leak sufficiently soon to supply the small charge necessary to relieve the potential stress, or such charges will be supplied through a grounded neutral, if there be one, or by the capacity of the remainder of the circuit not affected by the cloud potential. In any case the gradually developed stress due to the cloud will be relieved by charges appearing on the transmission wires, but when the cloud suddenly discharges by a lightning flash, the charges on the line wires escape suddenly either lengthwise on the wires and into power stations, or over insulators at the points where the stress is greatest.

By the fundamental principle of the conservation of energy, the potential stress which will cause a charge to appear on a wire will be reproduced in the opposite direction by that charge, if the original stress be removed. This also holds good when a grounded wire is placed above a transmission line, so although curves of Figs. 1, 2, and 3 are calculated on the basis of perfectly insulated line wires, they hold equally good for an actual

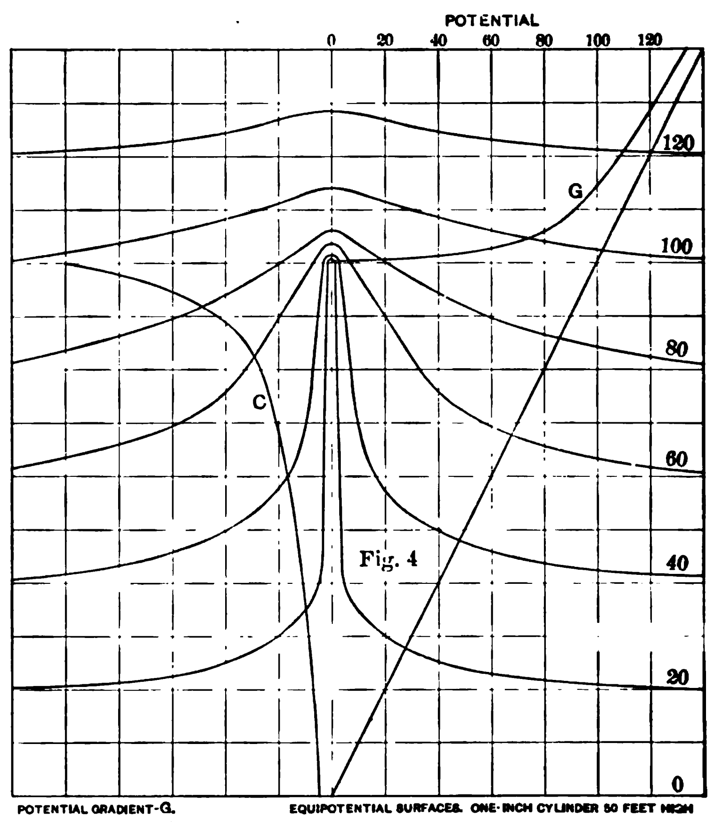


Fig. 4

transmission line where charges could readily find their way to the parts of the line under stress by the paths previously mentioned. This can be proved mathematically, independently of the principle of conservation of energy referred to above.

If the line were so insulated that only a partial charge could leak to the transmission wires, the primary stresses would be reduced somewhat, but the grounded wire would still have the same beneficial effect.

It is obvious that to get the full benefit of the grounded conductors, they should be thoroughly and frequently connected to the ground, as their effectiveness consists in releasing their own charge at the moment of a lightning flash, and immediately receiving another of opposite sign from the ground. This latter charge is then of opposite sign to that which still remains on the transmission wires, and serves to reduce the potential of these wires.

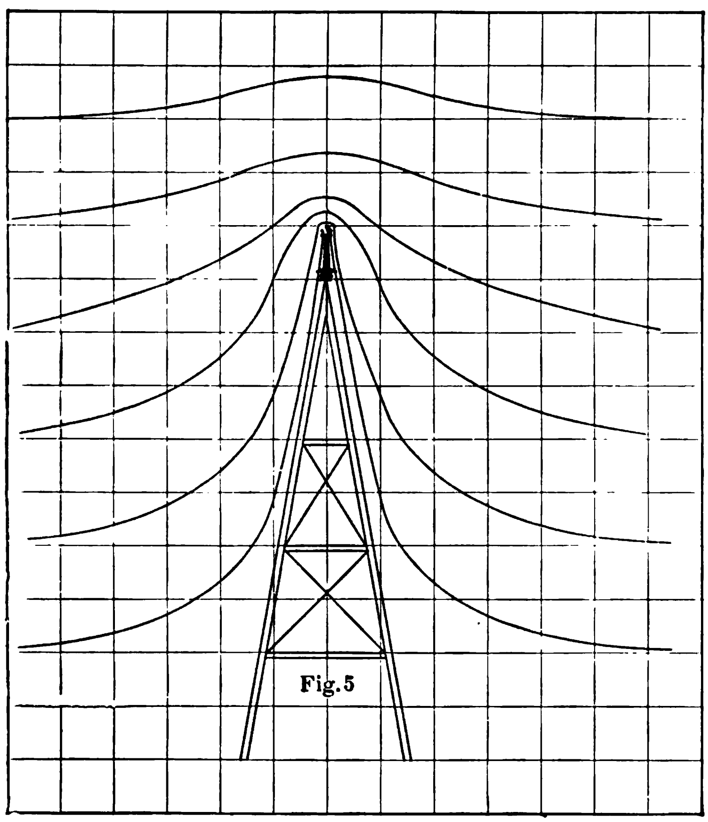


Fig. 5

It will be noted in Figs. 1 and 2, that the lines representing the equipotential surfaces are closely crowded together on the upper side of the grounded wire. This characteristic is much more marked in the case of a tower or spire projecting toward the sky. The potential of a point near such an object is much more difficult to calculate, so in Fig. 4, a 1-in. conducting vertical cylinder 50 ft. high was assumed, and the equipotential surfaces calculated. Curve *C* shows approximately the proportional charge at different points along the cylinder. Curve *G* shows the potential gradient from the top of the cylinder. It is seen that the charge density becomes relatively very great at the top of the pole or cylinder, and that the change of potential is very rapid for the first two or three feet above the top of the cylinder. This is a condition tending to produce leakage

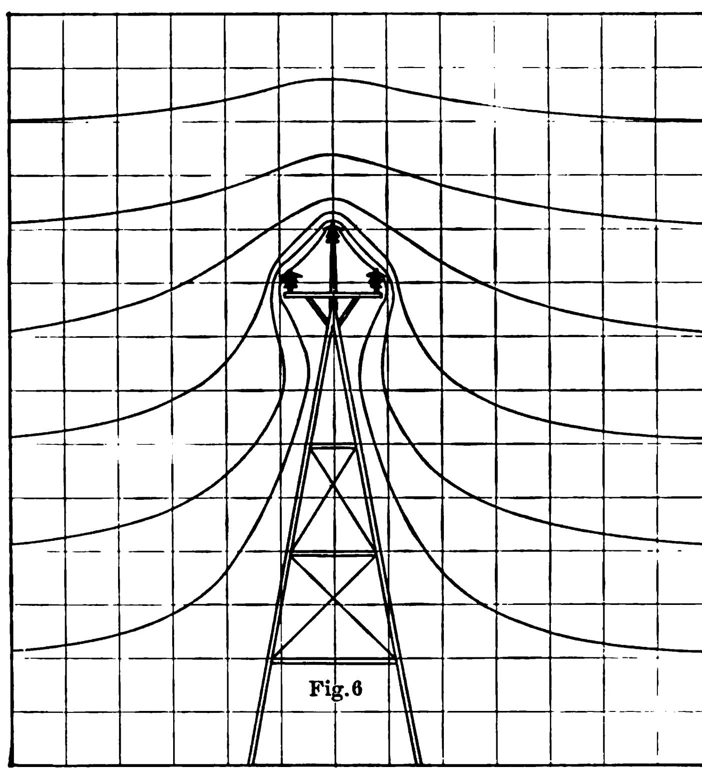


Fig. 6

into the atmosphere, or corona effect, such as the St. Elmo's light seen at times on mastheads of vessels.

Apparently, if an insulator were placed on the top of this cylinder, and a high-potential conductor were carried by this insulator, there might develop a conducting state in the atmosphere about this insulator that would cause it to flash over, especially if there were any sudden rise of potential on the conductor carried by the insulator. Fig. 5 shows one view of a metal tower under this condition, and Fig. 6 another view.

Fig. 7 shows the natural suggestion for relief. If the tower structure were carried higher, and the insulators and transmission wires suspended downwards, the desired result would be obtained without the additional shielding device shown in Fig. 7.

All the discussion given in this paper is, of course, pure theory, and if there were never any insulators broken, or other

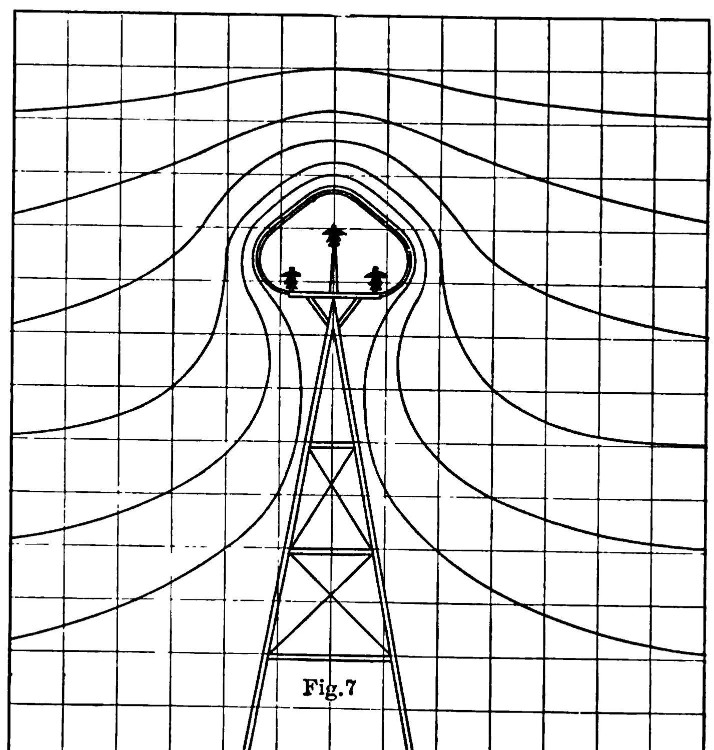


Fig. 7

trouble from lightning strains, it would have no practical value. Insulators are broken, however, especially those carried on metallic towers. So, while the information given in the curves does not indicate to any degree how much trouble can be eliminated by the devices discussed, there seem to be suggestions as to the most effective arrangement of such devices. If line insulators are subjected to frequent stresses of a value five times that which they will stand, a reduction of 50% would not avail much. If, however, the average of normal stresses to which they are subject are only 150% of the break-down value, a reduction of one-half in these stresses may eliminate a very large amount of trouble.

The general conclusions are as follows:

1. Properly placed and grounded conductors above a transmission line ought materially to reduce the electrostatic stresses to which the insulators will be subjected.

2. An insulator interposed between a high metallic structure and the sky, without a grounded conductor above the insulator to act as a shield, is exceptionally liable to break down.

Discussion on "Potential Stresses as Affected by Overhead Grounded Conductors," at Chicago, May 24, 1907

P. M. Lincoln: I consider Mr. Jackson's paper an interesting discussion of a very important topic. It is, as Mr. Jackson admits, purely a theoretical discussion of the amount of protection which may be expected from an overhead grounded wire. Many transmission line operators believe that this overhead grounded wire has no virtue; others believe that it has a great deal of virtue. I expect that there are representatives of both camps present and I hope the discussion will be complete.

Dugald C. Jackson: This paper relates to a subject that was discussed at the last Niagara Falls meeting of the Institute. It was there somewhat vigorously discussed on both sides. It seems to me that the art has progressed a good deal since that meeting, and the iron tower has become very much more important as a support for transmission lines than it was then. At that time one could consider, for the larger portion, at least of existing plants and perhaps the larger portion of plants then under construction, that the wires were erected upon wooden pole lines with wooden cross-arms, and that one could rely to some considerable degree upon the insulation of the wooden parts supporting the insulators. At the present time one must look upon the future transmission lines, and even the most important transmission lines of the present day as they are being built, as lines supported upon iron towers and therefore lines for which one can only rely upon the insulators themselves to give the insulation. It seems to me that the latter condition, as compared with the old wooden pole lines, makes this discussion of the overhead grounded protective wire quite a different matter. When we had the advantage of the wooden insulation to assist the overhead insulator, anything which brought the potential of the earth closer to the transmission line, as would be the case with the overhead grounded conductor, was inclined to increase the probability of a breakdown of the insulator, for the reason that it reduced the amount of added resistance to breakdown by reducing the length through the wood. I think that that effect has to a large degree been the effect that has led many people to object to the overhead grounded conductor, especially when added to the fact that the overhead grounded conductors were frequently put up very badly and caused trouble on account of their poor mechanical structure. However, even badly put up as they were of old, and notwithstanding the condition by which (with the wood pole line) the breakdown stress after the cloud discharge had occurred was increased on the insulators, the fact that the grounded conductor made a secondary circuit which in a certain extent abates the surges (as was pointed out, I think, by Mr. Steinmetz at the Niagara meeting I refer to), apparently gave the grounded conductor considerable value.

Now, when we come to the situation where the wooden insulation is out of the account, a reduction of perhaps 50 per cent. of the electrostatic stress on the insulator is well worth while, as Mr. R. P. Jackson points out. I doubt whether the reduction in the direct electrostatic stress produced by the grounded wire would be so great as 50 per cent., but if the reduction is as great as 25 per cent., which I have been able to convince myself it might be, I think it might be well worth obtaining in the case of a line built upon iron towers. Perhaps the reason that Mr. R. P. Jackson and myself differ as to the amount of reduction of the stress that comes about by a single overhead grounded wire lies in the fact that he has in his mathematical formulas taken no account of the disturbing influence of the metal line conductors themselves, while I have tried to do that, and when one takes three-phase wires six feet apart and puts a single grounded conductor a few feet above them, the influence is not nearly so great as one would imagine he would obtain from an examination of these equi-potential curves of Mr. R. P. Jackson's paper. This is by no means a criticism of Mr. R. P. Jackson's paper, which I think is a most suggestive paper and which comes at the very pertinent moment when the construction is changing from the old wood pole line construction to the preferable iron tower construction.

D. R. Scholes: I am hardly qualified to speak on this subject, so far as potential stresses are concerned, but I come in contact quite a good deal with the problem of the grounded conductor in building transmission-line towers, and it is interesting to learn how great the range of opinion is regarding the question. In some very long lines using steel towers no overhead grounded wire has been provided. This is true with regard to the lines of the Niagara, Lockport & Ontario Power Company. A certain amount of trouble has been reported with the top insulators in these lines, presumably due to the absence of the overhead grounded conductor. In some cases, one, two, or as many as three overhead grounded wires are provided for in the towers; in other cases there are guards placed over the insulators, or lightning-rods are provided, projecting considerably above the top of the insulator. In one installation now under construction in South Carolina, three overhead grounded wires are installed, placed in a sort of umbrella arrangement over the power wires, which seems to be the most extensive attempt at protection against lightning or static discharges by means of grounded wires that has yet been made.

The usual idea that occurs to the tower builder regarding the effectiveness of the overhead grounded wire is that if it is placed at such elevation that a plane passing through it and making an angle of 45 degrees with the horizontal lies above all the power wires, the power wires will be protected. Where this idea gets its foundation I do not know, but it comes to us very often, and we are often called upon to place the grounded conductor supports in this way. Almost without exception the towers that are now being built, to my knowledge, are provided with ground wire support in such way that if the ground wire is not strung at the outset it may be strung later, if developments indicate that it is needed.

H. C. Hoagland: My experience has been chiefly in Michigan where we have had trouble with lightning. We ran a grounded wire on the under side of the transmission wire, and then noticed that the lightning discharged down to the poles, splitting them. After putting on the ground-wire it practically eliminated that trouble. On the line from Jackson to Battle Creek two ground-wires were used on the top arm, one on each end of the arm, and that practically relieved the trouble in that case. In Illinois a part of the line is equipped with the ground-wire on top of the pole; that has only been in service about a month, but there has been no trouble on that line. On some of the other lines there has been serious trouble; they have been shut down four or five times in the last month. Arrangements are now making to put the ground wire on top of the poles as fast as it can be done. There is only one ground-wire, but on new construction perhaps it would be best to install two ground-wires.

P. M. Lincoln: I would like to ask Mr. Hoagland if his experience has demonstrated that the ground-wire is of positive value in preventing lightning discharges?

H. C. Hoagland: It has been demonstrated beyond any question of doubt in my mind that it is a great benefit even on the wooden poles, as in the Michigan case. We had several cases where four or five poles have been split into slivers. Putting on the ground wire did away with all that trouble.

R. P. Jackson: In regard to putting a lightning-rod on top of the tower. In some cases that feature results for good. Any conductor carried up above the insulator which the lightning may strike if it comes that way and which will also relieve the stress through the space, that is, the electrostatic stress through the atmosphere, will help matters, but it is not a complete relief. I have heard of cases where devices of this kind have been put up and a partial relief obtained, the number of broken insulators was much less, but that number could be still further decreased by putting up grounded lines which would prevent the transmission lines from accumulating such a static charge as they would otherwise. Of course if not released such charges will go to sub-stations and get into the generating stations and transmitting apparatus, but probably they will pass off at the next insulator. The greater the charge the greater the tendency to get off on a near-by insulator.

James Lyman: I was in Montana about a year ago and looked over some of the transmission lines, including the Madison River and the Big Hole transmission line. These transmission lines were put in about six or eight years ago. The Big Hole line is 15,000 volts, two three-phase transmission lines on one pole line. This line is about twenty miles long. It goes over a divide in the mountains where particularly severe discharges take place; these discharges are so severe that when the pole line was built the tops of nearly all the trees showed indications of having been struck. There was some hesitancy about building a pole line there, in fact all sorts of interruptions were expected. To guard against trouble, for three or four miles of this divide a barbed wire was run along the tops of the trees that had been struck by lightning; on each side of the pole line. Three barbed wires were also put on top of the pole line, one on the extreme ends of the upper cross-arm, which also carried one conductor of each of the two transmission lines, and one barbed wire on the top of the pole and grounded the wires at each pole. As an experiment, to see what the effect of these overhead grounded wires was, a small switch was put into each of the ground-wires, at the foot of the poles, so that all of them could be opened during a thunder storm. The lightning arresters were placed in the usual way at each end of the transmission line. The storm effects were watched soon after the transmission was put in, and the discharges of lightning could often be seen coming down to the barbed wire on the tops of the trees, also to the barbed wire on the tops of the pole line. The lightning-arresters were not particularly active; there was not very much going on, and for some six or eight months during the whole season there was no trouble. During one pretty severe storm, the switches on all the grounded wires were opened the entire length, so that the grounded wires were entirely disconnected from the ground, just during one storm. The lightning arresters discharged almost continuously, and there was anxiety lest some of the apparatus should be injured. It was not, however, during this storm, but it was a practical demonstration of the value of these overhead grounded wires. In the rebuilding of the Madison River transmission, which is about 50,000 volts pressure and about sixty miles long, it was planned to have a liberal size grounded wire, grounded every three or four poles, over the whole line, hoping thereby to get as good service there as that on the Big Hole line, which ran through a district where far more severe storms occurred.

From my experience the transmission lines which are protected by overhead grounded wires are more free from troubles than those which are not. Of course lightning-arresters also add greatly to the protection of the system, and I would recommend them in all cases.

P. B. Woodworth: Lightning protection brings to mind an experience I had with barbed wire. We had an equilateral distribution and it became necessary to put up some kind of protection. A single barbed wire was placed above the equilateral triangle. To specify barbed wire is one thing, and to actually put up a barbed wire is quite another thing. After we got it up it apparently worked well. But once—more than once, once in particular that I remember—the wire broke. Stranded barbed wire is usually wound on a reel. When that wire broke it wanted to get back on the reel, and it went round and round those three wires, time and time again, and one can imagine the situation when it became necessary to cut down a barbed wire so located.

W. L. Abbott: If I might be pardoned for introducing a reference to direct-current low-tension matters into this meeting, I will tell of an experience which we had in the Harrison St. power house of the Chicago Edison Company, which at that time supplied direct current only to an underground system.

During one particularly severe thunderstorm we noticed at every flash of lightning a flash at the commutator brushes, and at the instant of this discharge at the brushes the dynamo was so charged that the dynamo tenders would receive severe shocks if they were in contact with the machine, although ordinarily the machine could be handled without any discomfort whatever. During this storm several switchboard instruments grounded to their frames and burned out. We thought at the time that the lightning had struck a building in the city, followed our conductors to the power house, and had gone to ground through the iron framework of the building. We decided afterward, however, that the lightning had struck the iron smokestack of the power house and had finally found a ground by jumping from the framework of the building to the generators and switchboard apparatus, and then again to ground through the underground network.

W. B. Jackson: It has long been the feeling among a large portion of men operating electric transmission lines in regions where severe electrical disturbances occur that well installed grounded conductors when properly placed are a very material protection. Many have figured out reasons for this protective characteristic from a more or less practical standpoint. Mr. R. B. Jackson now presents a careful theoretical analysis of the situation as he sees it. This analysis, coupled with the practical results that appear to have been obtained by use of the grounded conductor, strengthens tremendously the argument in favor of the installation of this class of protection. To-day it seems there is very little that is being undertaken in practice in the field of alternating-current transmission of power that can not be greatly assisted by a careful consideration of the theory. In fact it almost seems that the old time condition is being reversed in these matters and that theory must now " blaze the trail " and practice finish the clearing. The old complaint that grounded conductors are more trouble than good is now a thing of the past, for it is entirely practicable to install properly located and grounded steel wires so that they will give much less trouble than the line they protect.

There is a fine opportunity for study upon electric lines affected by destructive electrical phenomena, by the use of the oscillograph. It would seem that such work when undertaken upon regularly operating lines should have something of the same zest as the photographing of the tiger in its native jungle. In fact it would seem that extreme persistence and patience and courageous endeavor, besides a good deal of experience, would be required to get oscillograph records of all of the phenomena involved. Mr. R. B. Jackson has evidently given this matter of grounded protective conductors careful study, but he has other things that must demand the greater part of his time, and the complete study of this subject is one that may worthily occupy the complete time and attention of careful investigators for an extended period.

This is a splendid subject to be taken up with the assistance of the large income of the Carnegie Institution of Washington, D. C., and one or more of the able scientists of that Institution might execute the work. I suggest that the American Institute of Electrical Engineers throw its influence toward such an end.

George Hayler (by letter): I am much interested in Mr. Jackson's paper. Mr. Jackson, while treating the problem simply from the theoretical standpoint, confirms absolutely our actual experience with high-tension lines.

We have been operating a power system about forty miles long, at 33,000 volts, 25 cycles, for something over two years, and this will be the third season for electrical disturbances.

The original lines were built in the form of an equilateral triangle, with the apex pointing upward, the ground-wire running the entire length of the system, and located about three feet below the cross-arms. This form of construction while exceedingly economical, is, in my opinion, the worst possible arrangement that could be devised. Virtually all of the interruptions to the service, caused by atmospheric disturbances, have resulted from the failure of the top insulators, showing beyond a doubt that the greatest potential strain occurs at that point.

The result in every case has been the same; that is, the top of the pole has burned off, down to the ground-wire. Last year we built five or six miles of line, using a new form of construction. The ground-wire on one line was placed on top of the pole and the conductors arranged on two cross-arms below. In the other case, the ground-wire was placed on one pin of the upper arm. There were numerous storms last season, and so far this year there have been four of more than usual severity. It may be only a fortunate coincidence, but the fact remains that none of these lines have ever caused us the slightest trouble, although we have ample evidence of severe lightning discharges along the route. About two weeks ago one of our employes saw the lightning actually strike a portion of this line about four pole lengths from No. 5 sub-station. The only damage was a punctured high-tension transformer terminal which caused a temporary short-circuit and threw out the circuit-breaker. I am thoroughly convinced that had this discharge taken place in the neighborhood of some of our old lines we should have undoubtedly lost a pole and suffered consequent interruption.

I am pretty thoroughly satisfied from my own experience that the grounded overhead conductor is the only practicable method of preventing insulator trouble due to severe atmospheric disturbances. I believe that the grounded conductor should be of a fairly large cross-section, not less than No. 4 gauge, and preferably stranded. It should be of the very best quality of annealed iron, thoroughly galvanized, and should be grounded at least on every other pole.

It will perhaps be of interest to tell that our type V arresters, as we now have them arranged, are working perfectly, and since their installation we have not lost five cents' worth of apparatus due to the failure of the protective devices. There is a slight tendency for the cylinders to weld together under a very severe discharge, but careful inspection will prevent any serious trouble arising from this cause, since it is our experience that very seldom do a sufficient number of cylinders weld together during one discharge to cause a breaking down of the arresters at normal potential.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

REPORT OF THE BOARD OF DIRECTORS FOR THE FISCAL YEAR ENDING APRIL 30, 1907.

The Board of Directors presents herewith for the information of the INSTITUTE a report of its work during the year, and of the various standing and special committees, also the financial standing of the organization.

The Annual Convention was held at Milwaukee, Wisconsin, May 28-31. The total registered attendance was 236. At this convention President Wheeler delivered his annual address upon the subject of Engineering Honor, and twenty professional papers were read and discussed, also the report of the Standardization Committee.

The Board of Directors has held nine monthly meetings during the year, and the Executive Committee one meeting.

In response to the invitation of the Institution of Electrical Engineers, a representative party from the American Institute of Electrical Engineers was organized to meet with European electrical engineers at London, June 24, 1906, and join with them as guests of the Institution in a circular tour through Great Britain. The Board of Directors was represented on this tour by President Wheeler, Past President Lieb, Manager C. O. Mailloux and the Secretary. There were in the party 23 Members and 12 guests from America, and 22 Members and 6 guests from foreign countries. An official banquet was given in honor of the visitors, at Hotel Cecil, June 25, at which about 500 guests were present. After devoting three days to various technical visits in London and vicinity, the party started June 28 on the circular tour, which included visits to Stratford, Rugby, Birmingham, Manchester, Liverpool, Glasgow, Edinburgh, Newcastle-on-Tyne, Leeds and Harrogate. This trip was made on a special train of dining coaches furnished by the London and Northwestern Railway. Every detail was successfully carried out, and the entire tour was not only instructive, but thorougly enjoyable in every respect.

Board of Examiners.—Ten meetings were held during the year, at which applications for election as Associates, enrolment as students, and transfer to the grade of Member have been reported to the Board of Directors as follows:

Recommended for election as Associates	944
Not recommended for election as Associates	4
Recommended for enrolment as students	459
Recommended for transfer to grade of Member	40
Not recommended for transfer to grade of Member	9
Reinstated to grade of Member	1
Held for further information	7
Total applications considered	**1,464**

Local Organization Committee.—This committee reports a present total of 33 local organizations included under the heads of Branches, University Branches and Student Meetings. The University of Illinois has been made a regular Branch by the Board, it having the requisite number of Members and Associates required by the By-laws. Student Meetings have also been authorized by the Board at the University of Maine and the Montana Agricultural College. A design for a student's pin has been authorized, and a supply ordered for sale. A conference with the Editing Committee led to an arrangement for the publication of meritorious original papers emanating from the Branches. There have been over two hundred Branch meetings held, with a total attendance of 16,500. At these meetings 137 original papers have been presented. Cornell shows an average attendance of 130, with a maximum of 225, Purdue an average of 100, with a maximum of 265, Wisconsin an average of 60, with a maximum of 175. All of the University Branches show that the enrolled Students are taking an active interest in the work. As soon as the revenue of the INSTITUTE will permit, it is the general belief that arrangements should be made for the systematic visitation of Branches by officers of the INSTITUTE and prominent engineers. There is a general call for some action of this kind which it is hoped would be productive in general good fellowship. The encouragement of the attendance of delegates from the Branches to the Annual Convention is also recommended by the committee.

The Engineers' Building.—During the past year, the permanent home of the INSTITUTE, occupied jointly with the American Institute of Mining Engineers and the American Society of Mechanical Engineers, has been finished and officially dedicated. Through the medium of the United Engineering Society, as a holding corporation, the American Institute of Electrical Engineers is the owner in perpetuity of one third of the property numbers 25, 27, 29, 31 and 33 West Thirty-ninth Street, being five city lots, valued at $540,000, purchased by members and friends of the societies, and the building thereon, erected at a cost of $1,050,000, which was the gift of Andrew Carnegie to the founder societies. The corner stone was laid by Mrs. Carnegie, May 8, 1906, when the structure was well advanced. The first INSTITUTE meeting was held in the Auditorium, January 25, 1907, and the offices of the INSTITUTE were occupied February 4, 1907. Inasmuch as the INSTITUTE has acquired a one-third interest in the Engineers' Building, the value of the equity therein has been included as an asset, and appears for the first time in the financial statement.

Building Fund Committee.—The last annual report of the Building Fund Committee stated that on April 30, 1906, the subscriptions had reached a total of $132,434.30 from 644 subscribers, and that $88,238.10 had been received and deposited in the Treasury of the INSTITUTE. The Committee reports that at the same date this year the number of subscribers to the fund had risen to 934; that the amount subscribed had reached $163,734.47, and that the amount actually collected and deposited had reached $124,829.17. It will be seen, therefore, that the new subscriptions during the year reached over $31,000, and that the cash collections during the year amounted to $36,591. The largest contributors during the year were Mr. George Westinghouse and the associated Westinghouse Companies; namely, the Westinghouse Electric and Manufacturing Company; the Westinghouse Air Brake Company; the Westinghouse Machine Company; Westinghouse, Church, Kerr Company; the Union Switch and Signal Company; the Nernst Lamp Company, and the Cooper Hewitt Electric Company. These interests subscribed the munificent sum of $50,000 toward the Building Fund of the three founder societies, and the INSTITUTE received one-third of this amount. The INSTITUTE also received one-third of a similar subscription of $3,500 made by the Allis-Chalmers Company. One of the most encouraging features of the work of the year was the large increase in subscriptions for moderate sums from individual members of the INSTITUTE, nearly 300 names being added to the list. It will be seen that barely $20,000 is now required to complete the amount that the INSTITUTE wishes to collect in order to meet its obligations in this respect, and it is believed that as there are still some 75 per cent. of the members who have not contributed to this fund this amount shall be pledged during the present year. At the same time, it may be pointed out that with nearly 1,000 subscribers to the fund, the Land and Building Committee is able to report a larger percentage of subscriptions from membership than has ever been secured before in this country in work of the same character in a technical society.

Standardization Committee.—A preliminary report prepared by this committee was presented at the Milwaukee Convention in 1906, where it was very thoroughly discussed, and referred back to the committee for further revision before being submitted to the membership.

The committee has held eleven meetings during the year, and the amended rules have been sent out to such members of the INSTITUTE as were believed to be especially interested in the work. A large number of suggestions have been received, many of which were incorporated in the tentative draft, and the rules are now practically in suitable form to be resubmitted for consideration at the Niagara Falls Convention.

Committee on Bibliography.—By the terms of the Wheeler Deed of Gift, dated May 17, 1901, conveying to the INSTITUTE the Latimer Clark library, a complete catalogue *raisonne* is to be published in the name of the INSTITUTE, reciting the condition of gift and explaining the features of interest of each book, for the convenience and information of members. The preparation of these entries, their verification, and chronological and subject classification, has been completed, and the work is now in the hands of the printer. Arrangements have been made with the Library of Congress and the British Museum for a careful comparative reading of the proofs, and Dr. Silvanus P. Thompson, Dr. G. Hellman and Paul F. Mottelay have also kindly consented to read them critically. The necessary care required to insure accuracy, and render the work authoritative and worthy of the INSTITUTE, involves a considerable amount of time, but it is hoped that the volume will be finished during the present year.

Committee on Papers.—This committee has endeavored to obtain theoretical and practical papers covering the principal branches of the art, and also to make the discussions more valuable, by inviting specialists to take part, after studying the papers in advance. Sixteen papers were presented at New York, and 21 are listed for the Annual Convention at Niagara Falls, in addition to topical discussions.

The committee recommends the preparation of rules and specifications for the guidance of authors in order that suitable cuts may be prepared for publication at a considerable reduction in cost.

The Editing Committee.—Immediately after its appointment, the attention of this committee was directed to the possibility of making the Proceedings a vehicle of information to the membership, of the general work of the INSTITUTE. A conference with the Local Organization Committee brought out the desirability of also including therein a larger proportion of meritorious papers originating through the Branch meetings. This work was undertaken beginning with the October 1906 issue, and many expressions of approval have reached the committee and the Secretary. The change has involved considerable additional labor and expense, but the result has not only been appreciated by the membership, but has made the Proceedings a still more valuable advertising medium.

John Fritz Medal.—On the occasion of the dedication of the Engineers' Building, April 17, 1907, this medal was presented to Alexander Graham Bell, Past-president of the Institute, in accordance with the decision of the John Fritz Medal Board of Award, upon which the INSTITUTE is represented.

Committee on Law.—The attention of this committee has been again devoted to a revision of the Constitution. The failure in the adoption of the draft submitted a year ago, led to the preparation of a revision embodying fewer changes, and the committee had the benefit of the advice of a majority of its members representing the interests of the Branches. The result was satisfactory in enlisting the enthusiastic support of the Branches, many of which made special efforts to induce their members to send in their votes, with such success that over 2,500 ballots have been received.

High Tension Transmission.—A specia meeting was held in New York, March 22, under the auspices of this committee, at which introductions to discussions had been prepared. In addition to the oral discussion, a large number of written contributions were received from members in various parts of the world. The committee has arranged for another meeting at Chicago, May 24, and for a session at the Niagara Falls Convention. Arrangements were made for the publication in a single volume of the earlier work of this committee, the sale of which was very satisfactory, and a second edition is now being printed. The royalties received for these publications will practically cover the expenses of the committee, while the direct professional value of the information thus obtained and disseminated, is strong evidence of the benefits to be derived from the work of the INSTITUTE.

Increase of Membership.—This committee has been continuously occupied during the year in bringing to the attention of non-members actively engaged in electrical work, the increasing prestige of the INSTITUTE in order that its benefits and usefulness might be more generally appreciated. The results have been very gratifying, as shown by the number of candidates posted each month, reaching a total of about 1,200 during the period covered by the work of this committee. Since January 1, about 40 enrolled students have applied for election as Associates. The cost of carrying on the work of this committee is estimated at about one dollar for each application received.

Membership.—The total membership at the close of last year's report was 3870 classified as follows:

Honorary Members		2
Members		508
Associates		3360
Total May 1, 1906		3870
Elected prior to May 1, 1906, and since qualified		90
Elected May 1, 1906, to April 30, 1907, and qualified		751
Restored to Membership		1
		4712
Deduct—		
Total Deaths	22	
Total Resignations	40	
Dropped as delinquent	129	
		191
Total membership April 30, 1907		4521

The membership April 30, 1907, is classified as follows:

Honorary Members	2	
Members	536	
Associates	3983	
Total		4521

Associates Elected.—The Associates elected during the year, May 1, 1906, to April 30, 1907, and their present status is as follows:

Qualified and now Associates	751
Elections cancelled	2
Not qualified on April 30	196
Total elections	949

Resignations.—The following Members and Associates have resigned in good standing during the year:

Members.—A. E. Childs, P. Dawson.

Associates.—W. Ambler, F. F. Bahnson, S. R. Barton, G. R. Bott, W. F. Bouché, Orion Brooks, E. M. Burgess, H. S. Burroughs, E. L. Caldwell, F. R. Chambers, R. E. Cunningham, C. C. Curtis, W. H. Dopp, C. A. Fernald, George S. Gibbs, J. M. Gilmore, Phillip Hamlin, W. E. Hopton, C. E. Harthan, M. C. Hull, J. E. H. Hyde, J. E. Ives, P. H. Lombard, W. K. Leggett, Felix Levy, John Lind, W. W. Mason, Jr., J. A. L. Möller, G. E. McCarn, W. E. Moody, G. W. Nistle, F. R. School-field, A. V. Sedgwick, R. C. Shaal, Angus Sinclair, F. S. Stitt F. R. Spiller, C. H. Tyndall. Total, 40.

Deaths.—There have been during the year the following deaths:

Members.—A. V. Abbott, J. B. Cahoon, F. L. Freeman, Eugene Griffin, F. E. Jackson, J. E. Lloyd.

Associates.—C. A. Bragg, Louis Cassier, E. E. Davis, K. G. Gillberg, H. W. Goode, A. E. Hayes, W. C. Johnson, W. J. Johnston, B. E. Mercil, K. Okamota, C. F. Parker, C. L. Spier, A. H. H. Trott, F. Townsend, L. C. Whitehouse, W. A. Whittlesey. Total, 22.

Dropped as delinquent during the year, 129.

The average receipts and disbursements *per capita* for the past seven years, are shown in the following table:

RECEIPTS AND DISBURSEMENTS PER YEAR PER MEMBER.

During each fiscal year for the past seven years.

Year	1901	1902	1903	1904	1905	1906	1907
Membership, April 30th, each year	1260	1549	2230	3027	3460	3870	4521
RECEIPTS PER MEMBER:							
Entrance Fees	$0.61	$1.16	$1.59	$1.65	$0.83	$0.75	$0.90
Dues	8.61	10.06	9.01	9.33	9.30	9.47	8.95
Transactions, Sales, Advertising	1.03	1.54	1.79	2.11	1.70	2.15	1.81
Badges	.18	.26	.35	.39	.28	.27	.30
Interest	.12	.24	.21	.18	.21	.13	.25
	$10.55	$13.26	$12.95	$13.66	$12.32	$12.77	$12.21
DISBURSEMENTS PER MEMBER:							
Transactions	$2.83	$3.50	$4.67	$3.43	$3.77	$3.33	$2.83
Salaries	2.49	2.78	2.49	2.50	2.20	2.64	2.53
Meeting Expenses, incl. Branches	1.05	1.13	.87	1.16	.82	.68	.68
Housing	.94	.94	.65	.79	.75	.68	1.33
Library, incl. Rent and Salaries	.55	1.85	1.38	1.39	.81	.69	1.37
Postage	.46	.51	.69	.66	.66	.58	.59
Stationery and Miscel. Printing	.39	.53	.96	1.01	.70	.78	.85
General Expenses	.33	.59	.52	.45	.54	.29	.43
Badges	.16	.19	.27	.35	.25	.22	.29
Express	.15	.15	.15	.28	.22	.23	.28
Advertising						.36	.30
Office Fittings							.14
Total	$9.35	$12.17	$12.65	$12.02	$10.72	$10.48	$11.62
Credit Balance per Member	$1.20	$1.09	$0.30	$1.64	$1.60	$2.29	.59

LAND, BUILDING AND ENDOWMENT FUND.

RECEIPTS.		DISBURSEMENTS.	
Before appointment of Committee	$ 6,100.00	Paid United Engineering Society, acct. Contract	$ 8,000.00
Collected by Committee	123,361.67	Paid United Engineering Society, acct. Mortgage	9,000.00
Interest on balances	2,910.38	Paid United Engineering Society, acct. Interest	10,620.00
		Paid for Fittings and Furniture of Engineers' Building	3,924.04
		Expenses of Committee	4,681.94
		Balance in bank May 1, 1907	96,146.07
	$132,372.05		132,372.05

NOTE:—

Collected by Committee, as reported above	$123,361.67
Collected by Committee deposited since May 1	1,467.50
Total collected by Committee as per the Committee's report	124,829.17

NEW YORK, May 20, 1907.

DR. SAMUEL SHELDON,
President of the American Institute of Electrical Engineers.

Sir: Pursuant to the provisions of the Constitution, the Committee on Finance has during the year exercised supervision over the financial affairs of the INSTITUTE. It has considered all bills and approved for payment such as constituted a proper charge against the INSTITUTE.

It has considered and reported upon specific appropriations, and has made special reports upon various matters referred to it by the Board of Directors.

As provided by the Constitution, it has employed an expert accountant to audit and report upon the accounts of the INSTITUTE; and this report made by Messrs. Peirce, Gimson and Co., certified public accountants, has been approved by the Committee on Finance, and is transmitted herewith.

Very truly yours,
J. J. CARTY,
Chairman Committee on Finance.

GENERAL FINANCIAL STATEMENT.

MR. JOHN J. CARTY,
Chairman Committee on Finance.

Sir: In accordance with your instructions, we have audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30, 1907.

The results of this examination are presented in four exhibits, attached hereto, as follows:

Exhibit A. Balance sheet April 30, 1907.

Exhibit B. Receipts and disbursements for general purposes for year ended April 30, 1907.

Exhibit C. Receipts and donations for designated purposes, also expenditures on same for year ended April 30, 1907.

Exhibit D. Condensed cash statement.

We beg to present attached hereto our certificate to the aforesaid exhibits.

Yours very truly,
PEIRCE, GIMSON & CO.,
Certified Public Accountants.

MR. JOHN J. CARTY,
Chairman Committee on Finance.

DEAR *SIR*:

Having audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30, 1907, we hereby certify that the accompanying Balance Sheet is a true exhibit of its financial condition as of April 30, 1907, and that the accompanying statements of Cash Receipts and Disbursements are correct.

PEIRCE, GIMSON & CO.,
Certified Public Accountants.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

Balance Sheet April 30, 1907.

Exhibit A.

Assets.

Cash:		
Land, Building and Endowment fund	$96,146.07	
Carnegie (Library) fund	3,529.60	
General Library fund	237.00	
Compounded Membership fund and Interest	5,465.34	
*Mailloux fund	1,007.55	
International Electrical Congress of St. Louis, 1904, Library fund	2,140.10	
	$108,525.66	
*General cash in bank	17,624.24	
Secretary's petty cash on hand	500.00	
		$126,649 90
United States Government Bonds 3s, 1918	8,000.00	
Premium on Bonds	320.00	
		8,320.00
Equity in Societies Building (25 to 33 West 39th Street)	350,000.00	
One-third cost of land (25 to 33 West 39th Street)	180,000.00	
		530,000.00
Library volumes and fixtures	24,174.76	
Transactions	4,352.75	
Office furniture and fixtures	5,114.30	
Works of art, paintings, etc	2,300.00	
Badges	210.25	
		36,152.06
Accounts Receivable:		
Members for past dues	8,966.60	
Members for entrance fees	295.00	
	9,261.60	
Miscellaneous	145.60	
Subscriptions	24.90	
For advertising	1,661.47	
		11,093.57
United Engineering Society, assessment, advance payment May and June		2,222.22
Total Assets		714,437.75

* The Farmers' Loan and Trust Co. deposit account includes $7.55 of the Mailloux Fund.

Liabilities and Surplus.

Funds:		
Land, Building and Endowment Fund	$96,146.07	
Carnegie (Library) Fund	3,529.60	
General Library Fund	237.00	
Compounded Membership Fund and interest	5,465.34	
Mailloux Fund	1,007.55	
International Electrical Congress of St. Louis, 1904, Library Fund	2,140.10	
	$108,525.66	
Reserve fund (U. S. Govt. Bonds)	8,320.00	
Total		$116,845.66
United Engineering Society (for cost of land)		171,000.00
Total liabilities		$287,845.66
Surplus:		
In cash	$18,124.24	
In property and accounts receivable	408,467.85	
		426,592.09
Total liabilities and surplus		$714,437.75

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

Receipts and Disbursements for General Purposes for Year Ended April 30, 1907.

Exhibit B.

Receipts.

Entrance Fees	$4,075.00	
Current Dues	35,653.25	
Past Dues	2,310.00	
Advance Dues	219.00	
Students' Dues	2,256.00	
Transfer Fees	395.00	
Badges	1,367.50	
		$46,275.75
Sales, Transactions	915.07	
Subscriptions, Proceedings	661.98	
Advertising	5,597.35	
Binding	89.80	
Exchange	14.59	
Interest:		
U. S. Govt. Bonds	240.00	
Bank Balances	865.10	
Royalty	239.75	
Sundries (refund)	13.32	
Insurance Rebates	22.13	
Rent (sub-tenant)	250.00	
		8,909.09
Total		$55,184.84

Disbursements.

Stationery and Printing	$3,830.80	
Postage	2,669.83	
General Expenses	1,972.26	
Meeting Expenses	1,861.13	
Branch Meetings	1,196.96	
Badges	1,354.30	
Salaries	9,407.40	
Rent	2,645.04	
Office Furniture	652.39	
		$25,590.11
Proceedings—Transactions:		
Printing	6,624.79	
Salary	2,000.00	
Engraving	1,446.97	
Volumes	3,299.32	
Electrotyping	689.29	
Binding	704.79	
Express	1,272.76	
Advertising Commissions	1,380.00	
		$17,417.92
Library:		
Rent	1,475.04	
Librarian salaries	887.20	
Library Insurance	106.35	
Miscellaneous	395.66	
		2,864.25
United Engineering Society		6,666.66
Total		$52,538.94
Excess receipts over disbursements deposited in general fund		2,645.90
		$55,184.84

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

Receipts and Donations for Designated Purposes also Expenditures for Year Ended April 30, 1907.

Exhibit C.

Receipts.

Land, Building and Endowment fund, Donations, Interest, etc.	$37,062.46
Carnegie (Library) Fund, Interest	119.08
General Library Fund, Interest	7.08
Life Membership Fund	578.37
International Electrical Congress of St. Louis, 1904, Library Fund	73.04
Mailloux Fund, Interest	30.00
Total	$37,870.03

Expenditures.

Land, Building and Endowment Fund	$21,617.01
Carnegie (Library) Fund	541.85
General Library Fund	2.64
Mailloux Fund	23.20
Total Expenditures	$22,184.70
Deposited to credit of their respective fund accounts	15,685.33
Total	$37,870.03

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

CONDENSED CASH STATEMENT.

EXHIBIT D.

Cash on deposit April 30th, 1906	$107,818.67	
Secretary's petty cash April 30th, 1906	500.00	
	$108,318.67	
Receipts for general purposes, Exhibit " B "	55,184.84	
Receipts for designated purposes, Exhibit " C "	37,870.03	
		$201,373.54
Disbursements for general purposes, Exhibit " B "	$52,538.94	
Expenditures for designated purposes, Exhibit " C "	22,184.70	
		$74,723.64
Balance on hand April 30th, 1907		$126,649.90
On deposit for designated purposes, Exhibit " A "	$108,525.66	
On deposit for general purposes, Exhibit " A "	17,624.24	
Secretary's petty cash, Exhibit " A "	500.00	
		$126,649.90

PROPERTY ACQUIRED DURING THE YEAR.

(Reported as directed by the Constitution.)

Office Furniture and Fixtures	$4328.86
Library Books and Binding	500.00
Engineering Societies Building, Equity	350,000.00

All outstanding bills rendered prior to May 1st, 1907, have been paid.

Respectfully submitted for the Board of Directors.

RALPH W. POPE, *Secretary*.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

Report of Library Committee

In accordance with the provisions of the Constitution, we present the following report of the more important features of history of the Library of the Institute for the year ending April 30, 1907; the present condition of the several funds from which the support of the Library is directly derived; its present status as one of the associated libraries in the new Engineering Societies Building; and plans for the future.

Recent Slow Growth

During the past four years the overshadowing activity in securing by subscription the fund to purchase the land for the new building, and the labor attending its construction and equipment have naturally and properly occupied the minds and time of the active members of the Institute to an extent which has prevented such rapid progress of the Library as was recorded in the report of May 1, 1903.

It should, however, be noted that even under these unusual circumstances and amid these extraordinary calls upon the interest and resources of the members and friends of the Institute, the Library has in the past four years increased in number of volumes (not including duplicates) from 7727 to 10577, a gain of 2850 volumes; and in valuation of volumes from $16211.10 to $21726.47, a gain of $5515.37. This increase of over 35 per cent. in number of volumes is gratifying as indicating what may hereafter be accomplished now that the Library has a permanent fire-proof home, offers greatly increased conveniences, and is in other ways richly deserving of the cordial support of a rapidly growing number of members and friends of the Institute.

Gifts of Books

During the past year Mr. Edward D. Adams has once more illustrated the practical value of his support of the Institute Library by contributing a collection of about 200 scientific books, a list of which appeared in the October issue of the Proceedings.

Similarly, the McGraw Publishing Company has donated about 25 of its recent publications, which supply in part the serious need of the latest editions of electrical text-books, and new publications of the same character. The same Company has also turned over to the Institute a large collection of unbound electrical patents issued in this country during the past 15 or 20 years.

Another and very complete collection of United States electrical patents issued from the early years down to about 1904 has just been donated by Messrs. Dyer and Dyer. This will prove specially important in the equipment of the headquarters of some progressive Institute Branch.

The complete list of donors for the year is as follows:

ADAMS, E. D.
ALLEGEMEINE ELEKTRICITATS GESELLSCHAFT
ALLEN, W. F.
AMERICAN RAILWAY ASSOCIATION
CANFIELD, DR. JAMES W.
CARROLL, WM.
CARTY, J. J.
M. LE DIRECTEUR CONSERVATEUR NATUREL DES ARTS ET METIERS
CROCKER, F. B.
DUNBAR, JAMES W.
DYER AND DYER
L'ECLAIRAGE ELECTRIQUE
GERARD, LEON
GAUTHIER, VILARS
HAMACEK, ADOLPH F.
HAMMOND, ROBERT
INSTITUTION OF ELECTRICAL ENGINEERS
JENKS, W. J.
LIBRARY OF CONGRESS
MCGRAW PUBLISHING CO.
MARTIN, T. C.
MASS. BOARD OF GAS AND ELECTRIC LIGHT COMMISSIONERS
MULOCK, SIR WM.
NEW YORK CITY COMMISSION ON ELECTRIC LIGHT
PEDERSON, F. M.
PLASS, J.
RIES, E. E.
ROBERTSON, LESLIE S.
ROSENTHAL, S. W.
SHELDON, DR. SAMUEL
SHEPARDSON, PROF. GEO. D.
SOCIETY OF ARTS
SWENSON, BERNARD V.
TALBOTT, FRANK
TALTAVALL, T. R.
VAIL, J. H.
WARD, GEO. G.
WEAVER, WM. D.
WHEELER, SCHUYLERS.

STATISTICS OF LIBRARY, MAY 1, 1907.

Source	Titles	Volumes	Pamphlets	Valuation
Report of May 1, 1906	7400	10717	515	$22,069.31
PURCHASES:				
Carnegie Fund				
Donation Fund	7	18		22.45
Mailloux Fund	4	6		23.20
Institute Appropriation	3	6		26.00
Periodicals	25	58		116.00
GIFTS:				
Edward D. Adams	162	300		168.00
McGraw Publishing Co.	23	23		41.25
Miscellaneous	25	58	50	85.00
Gross Totals, May 1, 1907	7649	11183	565	$22,551.21
Duplicates	308	609		824.74
Net Totals, May 1, 1907	7341	10577	565	$21,726.47

In the following table of total valuation of the Library, May 1, 1907, the furniture and cases are those brought from the old offices at 95 Liberty street, no account being included of the new furniture, stacks, etc., provided as a part of the initial equipment of the Engineering Societies Building:

TOTAL VALUATION

Books	$22,551.21
Stacks	1,470.25
Furniture, catalogues, cases, etc.	208.28
	$24,229.74

The following tabulations give the state of the four funds from which the Library Committee is entitled to draw:

DONATIONS (GENERAL LIBRARY FUND)

Dr.		Cr.	
Balance May 1, 1906	$232.56	Purchase of books	$ 2.64
Interest May 1, 1907	7.08	Unexpended	237.00
	$239.64		$239.64

CARNEGIE FUND

Dr.		Cr.	
Balance May 1, 1906	$3952.37	Wheeler Bibliography	$ 541.85
Interest May 1, 1907	119.08	Unexpended	3529.60
	$4071.45		$4071.45

MAILLOUX ENDOWMENT FUND ($1,000)
(Proceeds for the maintenance of certain sets of periodical publications)

Dr.		Cr.	
Balance May 1, 1906	$ .75	Subscription	$23.20
Interest May 1, 1907	30.00	Unexpended	7.55
	$30.75		$30.75

INTERNATIONAL ELEC. CONGRESS OF ST. LOUIS, 1904, FUND ($2,140.10.)
(Proceeds for the purchase of international electrical literature)

Dr.		Cr.	
May 1, 1907	$42.54	Unexpended	$42.54

In conformity with Section 33 of the By-laws, this Committee submitted to the Board of Directors at its meeting of October last an estimate of requirements for the year commencing Nov. 1, 1906. The appropriation which resulted is stated below. Pursuant to Section 37, the expenses for the year commencing May 1, 1906, are stated on the other side of the account. This is in accordance with the method pursued in prior reports of this Committee although the actual unexpended balance of the present appropriation year, remaining after six months of operation to the credit of this Committee, with which to meet bills not yet received and the expenses of the coming six months beginning May 1, 1907, is $1582.14 instead of the amount represented by the apparently unexpended balance for the year ending April 30, found in the appended statement.

The charge for rent is calculated for the past year at the rate paid by the Library at the former quarters, from which removal took place about Feb. 1, 1907.

INSTITUTE APPROPRIATION ACCOUNT

Dr.		Cr.	
Appropriation for Maintenance for year ending October 31, 1907	$3363.00	Rent	$1475.04
		Insurance	106.35
		Salary, Librarian	713.20
		" Assistant	174.00
		Building	135.05
		Supplies	7.95
		Subscriptions	26.00
		Express and Postage	8.80
		Books	27.73
		Fixtures	73.08
		Miscellaneous	117.05
		Unexpended	498.75
	$3363.00		$3363.00

THE MOST URGENT NEED

is that of modern text-books to meet the everyday necessities of the patrons of the Library. Only a moderate percentage of the standard works of the past twenty-five years are now on our shelves. A notable opportunity is now presented to some member or friend of the Institute, or several acting together, to contribute a relatively moderate amount for this special object, which has never before assumed anything like its present importance; particularly in view of the fact that the use of this Library is now offered to the public and to nearly 10,000 members of the two founder societies which have now become associates of the Institute in the new headquarters, as will be explained more in detail at the end of this report.

BIBLIOGRAPHY OF THE WHEELER GIFT

The work of digesting the entire Wheeler Gift and preparing the Bibliography for the printer, which has been progressing for five years in the hands of Brother Potamian, is still going forward under the management of W. D. Weaver, who was appointed this year a special committee to complete the task to which he has given so much time and thought since Past-president Wheeler presented the collection to the Institute. Thus the loss which was felt in Mr. Weaver's resignation of leadership in Library affairs, after so many years of most painstaking labor, often at great personal inconvenience and always marked with characteristic grasp of detail and assumption of the entire load of committee responsibility, has been mitigated by his willingness to retain the direction of this important publication, for which funds were provided by Mr. Carnegie. Instead of being restricted to the 1400 members who formed the Institute in 1901, this octavo volume of probably 500 pages, affording annotations to all of the more important books and pamphlets in the collection, will be offered, during the coming fiscal year, to about 4500 members who make up the Institute of to-day; while many Libraries, scientists and engineers outside the Institute will doubtless secure copies at some reasonable price.

HISTORICAL MUSEUM

This is a new development naturally closely affiliated with the Library and merging into it by insensible degrees.

The first effective effort in this direction was made by Past-president

Wheeler shortly before his retirement from office last year, by enlisting the sympathetic coöperation of Mr. Edward D. Adams and then securing the adoption by the Board of Directors, of a general resolution, followed in January by a more specific authorization best expressed in the language of the resolutions then adopted:

"RESOLVED, That the Library Committee is hereby authorized to accept on behalf of the Institute, donations of original apparatus, models, photographs, manuscripts printed documents, and similar exhibits, suitable for a museum of historical electrical material; also to accept the loan of material of the same general character which cannot be secured by gift.

"RESOLVED, That each donation or loan accepted under the foregoing resolution shall be acknowledged by the Chairman of the Library Committee, specifying the articles received in sufficient detail to ensure subsequent identification, and reciting the conditions of gift or loan and acceptance."

The Board also appropriated $200 for the purchase of such cases, frames, etc., as might be desirable for making a start in this direction.

The first donation, by Mr. Adams, was an elaborate and costly model, some four feet in length, of the high-speed three-phase electric railway motor car which was operated on the Berlin-Zossen Railway, in 1903, at a speed of more than 150 kilometres per hour. Offers of early lamps, dynamos, regulators, etc., have been made by Messrs. James J. Wood of Fort Wayne, W. S. Andrews of Schenectady, A. J. Wurts of Pittsburg, Rudolph M. Hunter of Philadelphia, and a few others.

The Committee now invites correspondence regarding original relics, of the general character specified by the resolutions, which can be identified as genuine, and having a well-authenticated history; in other words, "first things" in electrical apparatus, pictures and manuscripts. It is not desired to secure models or papers simply because they are old. To adopt such a course would evidently result principally in establishing an electrical junk-shop. The purpose is to place the Museum at the outset on a high plane of excellence, by judicious selection of available material even though the collection grow slowly; by the exercise of special diligence in gathering and displaying information as to the detail of history which each exhibit represents; and by the provision of adequate protection during many years to come for each accepted article. Thus the conditions of security, permanency, and accessibility which invite contributions to the Library will equally encourage similar donations to the Museum.

Each article or group accepted will bear the name of the donor, and a careful registry will be kept of the conditions, if any, under which it has been contributed; to the end that the wishes of the donor regarding it may be kept in mind and respected by the Institute, in general accordance with the methods pursued in the case of articles donated to other corporate bodies, such as the Metropolitan Museum of Art.

SUB-COMMITTEES

The unusual number and importance of the tasks devolving upon this Committee this past year have been lightened by a division of labor indicated by the duties of four sub-committees, as follows:

(1) Purchase of furniture and floor covering for Institute offices: Edward Caldwell, Frank N. Waterman.

(2) Library subscriptions, purchases and donations: Edward Caldwell, C. A. Terry.

(3) Increased Library utility: Professor Charles F. Chandler, C. A. Terry.

(4) Historical Museum: F. N. Waterman, W. J. Jenks.

Much consideration has been and will be given to devising and putting into practice plans for enabling members at a distance, who cannot consult this Library in person, to secure many benefits from a liberal equipment and maintenance. It is proposed to offer facilities for getting certified excerpts from rare volumes, photographs of pages and diagrams, or translations from several foreign languages, all at a moderate charge; also to loan duplicate volumes under suitable restrictions. Correspondence is especially invited on this question of "increased Library utility."

Removal to Permanent Quarters

The completion and opening about January 1 of the new Engineering Societies Building, with its two spacious and convenient floors devoted respectively to reading room and stack room accommodations for the assembled libraries of the three founder societies, invited speedy removal from the extremely contracted and inadequate quarters at 95 Liberty street. This was accomplished in February without the loss or injury of a single volume belonging to the Institute Library. The transfer of the stacks to their permanent location necessitated entire rearrangement and a different system of mechanical support. Thus this transfer required much more time than the mere moving of the books, but everything was completed and the books carefully arranged early in April, and our section of the comfortable and well-lighted stack-room has been made fully available.

The Associated Libraries

Thus far this report has dealt with the Electrical Engineers' Library as an institution by itself. There remain to be considered its relations to its newly associated libraries, and changes in administration which are required in consequence.

The formal dedication of the building, April 16 and 17, found the three libraries of the founder societies occupying their permanent home in coöperative arrangement, offering to the student an aggregate of about 35,000 volumes at the outset, each section in charge of its own librarian, but open primarily to any one of the 15,000 members of all the separate societies, and incidentally to engineering readers generally, outside the fraternity.

The books of the Institute now occupy exclusively two sections or alcoves of the reading room, and also, jointly with the other societies, two other alcoves; thus displaying on the thirteenth floor about one-third of its volumes. The main body of the ancient treasures of the Wheeler Gift, Latimer-Clark Collection, is suitably and securely housed in glass-front wire-protected cases in the stack-room, a few of the most precious books being displayed to the visitor in locked show-cases, with explanatory cards across the open pages. It is the purpose of the Committee to increase the number of these valuable volumes thus shown, as soon as permanent show-cases can be made.

By authorization of the Board of Directors of each of the three founder societies, the chairmen of their respective Library Committees are empowered to meet in conference and jointly direct the mutual relations which now exist. Messrs. Raymond of the Mining Engineers, Suplee of the Mechanical Engineers, and the Chairman of this Committee have thus conferred and agreed upon several tentative conditions of coöperative action and rules of administration. Of these the following are of general interest:

"That no questions shall be decided by majority votes of the three representatives of the three societies, but that all decisions must be unanimous in order to become effective; dissent on the part of any one representative being sufficient to require a reference to the respective library committees, and ultimately if necessary, to the governing bodies of the respective societies, excepting as to matters regarding which the regular single representative is clothed with full powers.

"That for the present, all consideration of the question of a new organization for the administration of the three libraries, or of the appointment of any additional or general librarian, shall be postponed.

"That the present arrangement, under which the three present society librarians administer the three libraries, each under the supervision of her authorized society-representative, and in mutual coöperation as to matters of common interest or necessity, be continued.

"That the Reading Room be open on all week-days, from 9 a.m. to 5 p.m. Only members of the three founder societies, and others duly introduced by the Secretary or other authorized officer of one of the societies, will be permitted access to the alcoves or other spaces inside the rail.

"That for the protection and convenience of members, the Secretary of each society, will, upon application, issue to any member of his society in good standing a personal, non-transferable card, entitling him to the use of the libraries in the alcoves of the Reading Room. This card must be signed by the person receiving it, and surrendered at the desk at the time of its presentation. At every visit he must identify himself by signing his name in the registry.

"That non-members may, in the two outer alcoves, receive and consult books for which they call at the desk; or they may, on similar application to one of the secretaries, secure special cards admitting them to the inner alcoves under similar restrictions.

"The librarians shall have no discretion in the matter of allowing any catalogued pamphlet or volume to be taken from either of the libraries for any purpose, but shall decline to permit any such loan unless authorized in writing so to do by the Chairman of the Committee or the Secretary of the society to which the pamphlet or volume belongs. But a duplicate may be thus loaned at the discretion of the Librarian directly responsible."

Librarians and Special Services

The resignation of Miss Josephine T. Bragg after several years of service as Librarian, resulted in the engagement of Miss Jessie R. Hammett of Brooklyn, who began her work about the first of January and has made many friends by her diligence in personal effort to bring about the transfer of the Library with the least possible interruption of its availability, her enthusiasm in formulating new methods to adapt it to its new surroundings and increase its usefulness, and the readiness with which she has become acquainted with its frequenters and their necessities. Thus far an assistant, Miss Gladys Byrd, has been employed to expedite the completion of new arrangements.

The thanks of the Committee are due to Charles L. Clarke, one of our members, who has made valuable contributions to the plans for enlargement, radical rearrangement, and protection of the books during the transition period, and has served as secretary of the Committee and otherwise frequently assisted the members of the Committee, particularly in the work of furnishing the business offices of the Institute on the tenth floor, with which special duty the Committee was entrusted by the Board of Directors early in the present Institute year, in preparation for the occupancy which was fully accomplished shortly before the formal dedication.

Of the $4000 appropriated for these furnishings, the Committee expended $1195.81 for carpets, linoleum and other floor coverings, and $2614.41 for furniture of the office, reception, editorial, stenographers', and Board rooms; thus leaving a balance now standing unexpended of $189.78.

Respectfully submitted

The Library Committee
CHAS. F. CHANDLER
CHAS. A. TERRY
EDWARD CALDWELL
FRANK N. WATERMAN
W. J. JENKS, *Chairman*.

CONSTITUTION

OF THE

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

[*Incorporated March* 16, 1896.]

[*Adopted May* 13, 1884. *Amended December* 8, 1885, *September* 27, 1892, *May* 15, 1894, *March* 16, 1896, *May* 21, 1901, *and May* 21, 1907.]

ARTICLE I.

1. The name of this association is the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

2. Its objects shall be the advancement of the theory and practice of Electrical Engineering and of the allied Arts and Sciences and the maintenance of a high professional standing among its members. Among the means to this end shall be the holding of meetings for the reading and discussion of professional papers and the publication of such papers, discussions and communications as may seem expedient.

ARTICLE II.

MEMBERSHIP.

3. The membership of the INSTITUTE shall consist of Honorary Members, Members and Associates. Members and Associates shall be equally entitled to all the rights and privileges of the INSTITUTE, excepting that Members only shall be eligible to the offices of President and Vice-President, and shall be entitled to a diploma. Honorary Members shall be entitled to all the rights and privileges of the INSTITUTE, except the right to vote for officers and to hold office.

4. A Member shall be not less than twenty-seven years of age and shall be:

a. A Professional Electrical Engineer; or
b. A Professor of Electrical Engineering; or

c. A person who has done important original work of recognized value to electrical science; or

d. A person duly qualified as an engineer in an allied branch of engineering, and who, for a period of two years, has had responsible charge of electrical engineering work and whose professional record indicates that he is competent to design, as well as direct, electrical engineering works.

5. To be eligible to the grade of Member as a professional Electrical Engineer, the applicant shall have been in the active practice of his profession for at least five years; he shall have had responsible charge of work for at least two years, and shall be qualified to design as well as direct electrical engineering works. Graduation from a School of Engineering of recognized standing shall be considered the equivalent of one year's active practice.

6. To be eligible to the grade of Member as Professor of Electrical Engineering, the applicant shall have been in responsible charge of a course of Electrical Engineering at a college or technical school of recognized standing, for a period of at least two years.

7. An Associate shall be a person not less than twenty-one years of age who is interested in, or connected with, the study or application of electricity.

8. Honorary Members may be chosen from among those who have rendered acknowledged eminent service to electrical engineering or its allied sciences.

ARTICLE III.

ADMISSION, TRANSFER AND EXPULSION OF MEMBERS.

9. Honorary Members shall be proposed in writing by at least ten Members, and may be elected only by the unanimous vote of the Board of Directors, a ballot in writing to be forwarded by members absent from the Directors' meeting. The election of an Honorary Member shall be deemed invalid if an acceptance is not received within six months after the date of his election.

10. All applications for admission to the INSTITUTE shall be made for the grade of Associate, in a form prescribed by the Board of Directors, and shall refer to at least three (3) Members or Associates. In applying for admission to the INSTITUTE as Associate, any person may also apply at the same time for immediate transfer to the grade of Member Such

application for transfer may also be made at any time subsequent to election as Associate.

11. An application for transfer from the grade of Associate to that of Member shall be made in a form prescribed by the Board of Directors, and shall embody a full record of the general technical education of the candidate and of his professional career. It shall be signed by the applicant and shall refer to at least five Members who know him personally and are familiar with his work. Each of these references shall be requested by the Secretary to fill out a prescribed confidential form, to be addressed to the Board of Directors. No such applications for transfer shall be considered until at least five favorable replies have been received. The Board of Directors, or the Board of Examiners, in the event of failure of replies or receipt of unfavorable replies, may call upon the applicant to furnish additional names. Should an applicant for transfer certify that he is not personally known by five Members, the Board of Examiners may accept, for the deficiency, references to professional engineers of standing.

12. The reference to Members to whom an applicant is personally known may be waived in case of foreign applications; but the applicant shall in that case refer to at least two professional engineers of recognized standing.

13. The Secretary shall issue at stated intervals to each Member and Associate whose address is known, a list of new applications for admission to the INSTITUTE, with the request that the Members and Associates make written communication to the Board of Directors, in case of objection to any of the candidates named. The Board of Directors shall not act upon any name until at least twenty days after the date of issue of said list.

14. All elections as Associates, and transfers to the grade of Membership, shall be by vote of the Board of Directors; two negative votes shall exclude a candidate.

15. The Board of Directors may refuse to elect or transfer any applicant whose character, reputation or professional conduct would make him, in the opinion of the Board of Directors, an undesirable member.

16. A member of any grade in the INSTITUTE may resign his membership by a written communication to the Secretary, who shall present the same to the Board of Directors; whereupon, if all his dues and other indebtedness have been paid, as

provided in the Constitution and By-Laws, his resignation shall be accepted.

17. Upon the written request of ten or more Members or Associates that, for cause stated therein, a Member or Associate of the INSTITUTE be expelled, the Board of Directors shall consider the matter, and if there appears to be sufficient reason, shall advise the accused of the charges against him. He shall then have the right to present a written defence, and to appear in person or by duly authorized representative before a meeting of the Board of Directors, of which meeting he shall receive notice at least twenty days in advance. Not less than two months after such meeting, the Board of Directors shall finally consider the case, and if in the opinion of the Board of Directors a satisfactory defence has not been made, and the accused member has not in the meantime tendered his resignation, he shall be expelled.

ARTICLE IV.

DUES.

18. The entrance fee, payable on admission to the INSTITUTE shall be five (5) dollars. A fee of ten (10) dollars shall be paid on transfer to the grade of Member, which shall include the fee for a diploma.

19. The annual dues shall be fifteen (15) dollars for Members and ten (10) dollars for Associates.

20. Honorary Members shall be exempt from all payments.

21. Persons elected after any portion of the fiscal year shall have expired, shall pay dues pro rata for the unexpired quarters of that fiscal year.

22. A Member or Associate in good standing, by the single payment of two hundred (200) dollars, in addition to his entrance fee, shall become exempt from all future payments for dues or transfer fee. The money thus paid shall be invested as a special fund, to be known as the " Life Membership Fund," from which there shall be taken out and appropriated for the general expenses of the INSTITUTE each year until the death or resignation of said Member or Associate, the sum of ten (10) dollars. Upon the death or resignation of any such Member or Associate, the residue from said payment, including the interest thereon, remaining in the said fund, shall be transferred to the general fund of the INSTITUTE.

23. A Member or Associate who has been dropped as delinquent may be reinstated by the Board of Directors upon payment of all back dues, retaining his original date of election, and shall be entitled to a complete file of the published TRANSACTIONS corresponding with said payment, provided the same are available.

ARTICLE V.

OFFICERS.

24. The officers of the INSTITUTE shall be a President, six Vice-Presidents, twelve Managers, a Secretary, and a Treasurer, who shall hold office as follows:

25. The President, the Secretary, the Treasurer, for one year, the Vice-Presidents for two years, and the Managers for three years. The President, Vice-Presidents and Managers, shall not be eligible for immediate re-election to the same office. A Vice-President shall not be eligible for immediate election to the office of Manager. At each Annual Meeting, the President, three Vice-Presidents, four Managers, the Secretary and the Treasurer shall be elected in the manner prescribed below, and their terms of office shall commence on the first of August next succeeding their election.

26. The terms of the Officers elected at the Annual Meeting at which this constitution is adopted, shall begin on the fourth Friday in September following, instead of on the first of August, as provided in Section 25.

27. A vacancy in the office of President shall be filled by the senior Vice-President; a vacancy in the office of Vice-President shall be filled by the senior Manager. Seniority between officers of same rank and date of election shall be determined by the date of their election as Associates. All other vacancies shall be filled by the Board of Directors for the unexpired term. Such succession to office or appointment by the Board of Directors shall not render an officer ineligible for immediate election to the same office.

28. No officer shall receive, directly or indirectly, any salary, compensation or emolument from the INSTITUTE, either as such officer or in any other capacity, unless authorized by a vote of a majority of the entire Board of Directors.

29. No officer shall be interested, directly or indirectly, in any contract relating to the operations conducted by the

INSTITUTE, nor in any contract for furnishing supplies thereto, unless expressly authorized by the By-laws or by the unanimous vote of the members of the Board of Directors present at any meeting.

ARTICLE VI.

ELECTION OF OFFICERS.

30. During the first week in February of each year, the Secretary shall mail or deliver to each Member and Associate of the INSTITUTE, a list of all Members and Associates, together with a form showing the offices to be filled at the ensuing annual election in May, and containing the names of the incumbents and a copy of sections 30 and 31 of this Article, with the request that nominations be made for the various offices to be filled. These nominations shall not be signed, and shall be enclosed in an envelope, identified on the face by the name of the sender and mailed to the Secretary. To be considered, nominations must reach the Secretary prior to March first. The nomination ballots shall be counted and canvassed by the Committee of Tellers appointed as provided in Sections 34 and 35.

31. The Committee of Tellers shall submit to each member of the Board of Directors prior to the March meeting, a classified list of all nominations received, from which the Board of Directors shall prepare, during the month of March, a complete ticket, to be headed: "Directors' Nominees," containing the names of those whom the Board of Directors deem best suited for the offices falling vacant; provided that upon the request of two Directors at the meeting at which the "Directors' Nominees" ticket is prepared, the name of a second nominee for President shall be placed on the ticket, selected from the four names receiving the highest number of nomination votes for President, and provided further, that upon the request of two Directors at the same meeting, the names of one or more additional nominees for Vice-President, and upon like request, the names of one or more additional nominees for Manager shall be placed upon the ticket. The names on the Directors' Nominees ticket shall be listed in the order of the number of nomination votes received, beginning with the highest number. This ticket shall be printed on the same sheet with a second list, headed "General Proposal List," containing all the eligible names pro-

posed, and the number of votes cast for each; provided that no name shall appear which shall not have received at least three per cent. of the entire number of votes cast.

32. The voting for officers shall be restricted to the names of the " Directors' Nominees " and the names on the General Proposal List provided for in section 31 of this Article. This List, together with an envelope on which shall be printed the title of the INSTITUTE, the name and address of the Secretary and the words " Official Voting Envelope—Enclosing a Ballot Only," shall be mailed by the Secretary not later than the first day of April, to every Member and Associate, together with a copy of sections 32 and 33 of this Article; provided that any qualified Member or Associate not having a ballot and envelopes shall be entitled to obtain them from the Secretary at any time before the first day of May.

33. All names voted for shall be written, printed or otherwise marked on a single ticket or ballot, which shall be enclosed in a sealed, unmarked and unidentified inner envelope of any suitable character, which shall in turn be enclosed either in the " Official Voting Envelope " (received from the Secretary), or any other envelope, marked on its face, " Non-Official Voting Envelope—Enclosing a Ballot Only." The outer envelope of either class shall be identified by the name of the sender on its face, shall be sealed, and in order to be counted, shall reach the Secretary not later than the first day of May. The Secretary shall preserve, unopened, for ninety days, all ballots received after the first day of May.

34. The President, at the Directors' meeting to be held in February, shall appoint, subject to the approval of the Board of Directors, five Members or Associates, not members of the Board of Directors, to constitute the Committee of Tellers; should this Directors' meeting not be held, the President, previous to the twenty-first of February, shall appoint this Committee by letter to the Secretary, who shall notify the members thereof.

35. Any Member or Associate who shall deliver to the Secretary on or before the first day of March, a written petition signed by at least twenty Members or Associates, stating their desire that he be a member of the Committee of Tellers, shall also be a member of that Committee; provided that the aforesaid signatures shall not have appeared on another similar petition.

36. The Committee of Tellers shall meet at the office of the INSTITUTE as soon after the first day of May as possible, and shall receive, unopened, all ballots from the Secretary, who shall also make to it a written report of the number of ballots received on and before, and after, the first day of May. It shall forthwith proceed, in secret, to count the vote, and shall prepare and sign in duplicate a report of the results of the vote, which shall be sealed, and of which one copy shall forthwith be filed with the Secretary, and of which the other copy shall remain in possession of the Chairman of the Committee who shall hand this report to the presiding officer at the ensuing Annual Meeting. In the absence of this report by the Chairman of the Committee, the Secretary shall produce the duplicate copy, and hand the same to the presiding officer of the meeting. The presiding officer shall cause the report to be read, at the first session of the Annual Meeting and shall declare duly elected the eligible persons receiving the greatest number of votes for the respective offices.

ARTICLE VII.

MANAGEMENT. DUTIES OF OFFICERS AND COMMITTEES.

37. The affairs of the INSTITUTE shall be managed by a Board of Directors under this Constitution and the general provisions of the laws under which it is incorporated. The Board of Directors shall consist of the President, two Junior Past-Presidents, the Vice-Presidents, the Managers, the Secretary and the Treasurer.

38. The Board of Directors shall have such powers and duties as are prescribed by statute for a Board of Directors.

39. The Board of Directors shall direct the investment and care of the funds of the INSTITUTE, shall make appropriations for specific purposes, shall pass upon all applications for admission or for transfer, shall act upon all questions of expulsion of members, shall appoint all employees and fix their salaries, and in general shall direct the business of the INSTITUTE, either itself or through its officers and committees.

40. The Board of Directors shall prepare and adopt a series of By-laws which shall govern its procedure and that of the Committees, under this Constitution. Such By-laws shall be adopted or may be amended by a concurring vote of not less than twelve (12) members of the Board of Directors; provided,

that the text of a proposed By-law or amendment shall be furnished to each member of the Board of Directors at least ten days before the meeting at which a vote on the same will be taken.

41. The President shall have general supervision of the affairs of the INSTITUTE, under the direction of the Board of Directors. He shall preside at the meetings of the INSTITUTE, and of the Board of Directors at which he may be present, and shall be *ex-officio* member of all committees. He shall deliver an address at the Annual Convention. The Vice-Presidents, or in their absence, the Managers, in order of seniority, shall preside at meetings of the INSTITUTE and the Board of Directors in the absence of the President, and shall discharge his duties in case of a vacancy in the office. The President shall appoint the standing committees of the INSTITUTE. He may also appoint special committees from time to time.

42. The Secretary shall be the executive officer of the INSTITUTE under the direction of the President and the Board of Directors, He shall attend all meetings of the INSTITUTE and of the Board of Directors, and record the proceedings thereof. He shall collect and deposit, subject to the order of the Treasurer, all moneys due the INSTITUTE, reporting such deposit to the Treasurer, who shall receipt for the same. He shall personally certify the accuracy of bills or vouchers on which money is to be paid, and shall draw and countersign all checks, and these shall be signed by the Treasurer when such drafts are known to him to be proper, and duly authorized by the Finance Committee and in accordance with warrants executed by the Secretary. He shall have charge of the books and accounts of the INSTITUTE. He shall present annually to the Board of Directors a balance sheet, and from time to time shall furnish such statements as may be required. He shall conduct the correspondence of the INSTITUTE, and shall keep full records. He shall be in responsible charge, under the President and the Board of Directors, of all the property of the INSTITUTE. He shall, with the approval of the Board of Directors, employ such clerical force as may be necessary and shall be responsible for the work of all employees of the INSTITUTE. He shall perform such other duties as may be assigned to him. His entire time must be devoted to the affairs of the INSTITUTE, unless otherwise authorized by the Board of Directors. He

shall be paid a salary to be fixed by the vote of a majority of the entire Board of Directors.

43. The Treasurer and the Secretary shall invest such funds as may be ordered by the Board of Directors. They shall also pay bills when audited by the Finance Committee and approved by the Board of Directors. The Treasurer shall make an annual report and such other reports as may be prescribed

44. The Board of Directors may delegate any or all of its powers to an Executive Committee of seven members, consisting of the President, the Secretary, and the Treasurer, *ex-officio*, and four other members of the Board of Directors, which committee shall conduct the affairs of the Board of Directors between its meetings.

45. The Board of Directors or the Executive Committee (subject to the direction of the Board) may at any time authorize any officer, director, or other person to perform any acts or functions, which in the Constitution or By-laws may be prescribed to be performed by any specified officer or other person, whenever by reason of death, absence, disability or other cause, sufficient ground therefor shall appear to the Board or Executive Committee.

46. The Standing Committees to be appointed by the President as specified in section 41 shall be the following:

A Finance Committee of three members.

A Library Committee of five members.

A Meetings and Papers Committee of five members.

An Editing Committee of three members.

A Board of Examiners of five members.

A Sections Committee of five members.

A Standards Committee of nine members.

A Code Committee of seven members.

A Law Committee of five members.

The Board of Directors may appoint auxiliary members to any committee. The members of the Finance Committee shall all be members of the Board of Directors. All other standing committees shall include at least one member of the Board of Directors. All members of the Board of Examiners shall be Members of the INSTITUTE. All committees shall be directly responsible to the Board of Directors, and shall act under its directions. The Board of Directors may, at any time, at its own discretion, remove any or all members of any committee and appoint others. The terms of the members of all standing and special committees shall terminate at the close of the first meeting of the Board of Directors following the Annual Meeting.

47. All official communications of committees to the Board of Directors shall be made through the Secretary unless otherwise specially ordered by the Board of Directors.

48. In addition to the duties and powers hereinafter ascribed to committees, these committees shall perform such other duties, and shall have such other powers, as may be specified in the By-laws, or as may be delegated to them by the Board of Directors.

49. The Finance Committee shall have direct supervision of the financial affairs of the INSTITUTE. It may employ an expert accountant to assist in auditing the accounts. It shall approve all bills before payment, and shall make recommendations to the Board of Directors regarding the investment of moneys, and all specific appropriations. No payments other than for routine office expenses shall be made by the Secretary or Treasurer except upon the authorization of the Finance Committee.

50. The Library Committee shall have general supervision of the Library of the INSTITUTE. The committee shall make recommendations to the Board of Directors with reference to the Library, and shall direct expenditures for books or other articles for the same, of such sums as may be appropriated for these purposes.

51. The Meetings and Papers Committee shall arrange for the meetings of the INSTITUTE, and for the preparation and discussion of the papers to be presented before the INSTITUTE. The committee shall decide all questions regarding the acceptance or rejection of any paper submitted for presentation before the INSTITUTE, and all questions regarding the publication of papers presented before the INSTITUTE or any of its Sections.

52. The Editing Committee shall edit all discussions of the papers presented at any meeting of the INSTITUTE, and all communications in reference thereto, and shall decide all questions regarding the publication of discussions and communications in the PROCEEDINGS and TRANSACTIONS of the INSTITUTE or otherwise.

53. The Board of Examiners shall pass upon the qualifica-

tions of all applicants for election or for transfer, whose applications have been received by the Secretary, and which are in conformity with Sections 10, 11, and 12 of Article 3, and it shall report its findings to the Board of Directors for action.

54. The Sections Committee shall have the general supervision and management of the Sections and Branches of the INSTITUTE. The committee shall confer with the Sections and Branch officers, and it shall consider, investigate, and make reports and recommendations to the Board of Directors for action upon all matters regarding or involving the interests and the welfare of Sections and Branches, or the relations between these organizations and the INSTITUTE.

55. The Standards Committee shall consider and investigate all matters relating to units and standards appertaining to or applicable in electrical engineering and in the allied arts and sciences. The Committee shall make reports and recommendations to the Board of Directors for action thereon.

56. The Code Committee shall consider and investigate all matters relating to the formulation of rules for the protection of persons and property against fire and other hazards in connection with electrical installations and equipments, and shall confer with similar committees of other bodies regarding the same. The Committee shall make reports and recommendations to the Board of Directors for action thereon.

57. The Law Committee shall consider and investigate all matters relating to the Constitution and By-laws of the INSTITUTE, the duties and jurisdiction of its officers and committees, its legal status and responsibilities and like legal and cognate questions; also all other matters referred to it by the Board of Directors, the President or the Secretary. The Committee shall make reports and recommendations to the Board of Directors for action thereon. The Committee may consult legal and technical counsel with reference to any question before it.

58. The Board of Directors may, at its discretion, appoint Local Honorary Secretaries to represent the INSTITUTE in foreign countries. Such appointments shall be made for a period of two (2) years and may be renewed.

59. The following numbers shall constitute a quorum of the Board of Directors:

For all business prescribed by statute for a Board of Directors

—twelve members or such larger number as the statute may require.

For expulsion of Members—fifteen members.

For all other business—five members.

60. Unless otherwise specifically provided in this Constitution, the action of the Board of Directors shall, in all cases, be determined by the concurring vote of a majority of the members present, providing there exists the quorum required for the particular business.

ARTICLE VIII.

MEETINGS.

61. The Annual Meeting of the INSTITUTE shall be held in the city of New York, beginning on the second Friday in May, when a report of the proceedings of the INSTITUTE for the past fiscal year shall be furnished by the Board of Directors. This report shall be verified by the President, Treasurer and Secretary and approved by the Board of Directors. It shall show: the whole amount of real and personal property owned, where located, where and how invested; the amount and nature of the property acquired during the past fiscal year and the manner of its acquisition; the amount applied, appropriated or expended during the year, and the purposes, objects or persons to or for which such applications, appropriations or expenditures have been made; the names and places of residence of persons who have been admitted to membership in the INSTITUTE during such year; and all other facts bearing upon the status of the INSTITUTE. This report shall be filed with the records of the INSTITUTE and an abstract thereof entered in the minutes of the Annual Meeting. The reports of all officers and of the standing committees shall be presented at the Annual Meeting, and the vote for officers for the ensuing year shall then be announced. In addition to the above, professional papers and the discussions thereof arranged for by the Meetings and Papers Committee may be presented, and any other business may be brought before and transacted, at this meeting.

62. There shall be held outside of the city of New York not later than August first an Annual Convention of the INSTITUTE, for the presentation and discussion of professional papers, and for the transaction of other business not affecting the organization or policy of the INSTITUTE. All questions affecting the

organization or policy of the INSTITUTE may be brought up for discussion at this Convention, and may be referred by a majority vote to the Board of Directors, with recommendations. The time and place of such Convention shall be fixed by the Board of Directors.

63. Special meetings of the INSTITUTE for the transaction of business may be called by the Board of Directors at any time, by written notice stating the specific object thereof mailed to each Member and Associate at least thirty (30) days prior to the date of said meeting.

64. Other meetings of the INSTITUTE may be held at such times and places as the Board of Directors shall select, at which no business affecting the organization or policy of the INSTITUTE shall be transacted. Notice of all meetings specified in this Article of the Constitution shall be sent by mail, or otherwise, to all Members and Associates, at least ten days in advance.

ARTICLE IX.

INSTITUTE SECTIONS AND BRANCHES.

65. Whenever, in the judgment of the Board of Directors, a sufficient number of Members and Associates shall petition, in writing, these members may form, subject to the Constitution and all By-laws and regulations which may be hereafter prescribed by the Board of Directors a Section organization for the purpose of more effectually carrying out the aims of the INSTITUTE.

66. Any Member or Associate may become a member of such Section, but a Member or Associate shall be entitled to vote, or hold office, in one Section only.

67. The officers of each Section shall consist of a Chairman, a Secretary, and such other officers as each Section may find desirable. These officers shall be elected by the votes of the Members and Associates of that Section, in the manner provided in the Section By-laws. The election of any Member or Associate as a Section officer, shall not debar him from election or appointment to any other office in the INSTITUTE.

68. The Chairman of the Section shall perform the duties usually devolving upon the Chairman of any organization, and in addition shall be *ex-officio* a member of the Sections Committee of the INSTITUTE. He shall have the privilege

of appearing before the Board of Directors at any meeting, on giving due notice of his intention to do so, for the purpose of conference with the Board of Directors, in regard to any matters pertaining to the affairs of the INSTITUTE in his Section. The Chairman shall perform such other duties and shall have such other powers as may be delegated to him by the Board of Directors.

69. The Secretary shall report the Proceedings of the Section to the Secretary of the INSTITUTE; he shall, in general, discharge the duties of a Secretary both to the Section itself and in its relation to the INSTITUTE; he shall perform such other duties as may be prescribed in the Section By-laws, or in the By-laws of the INSTITUTE, or delegated to him by the Board of Directors.

70. Each Section may have the privilege of being represented at the Annual Convention, by an official delegate, who shall be the Chairman of that Section, or, in his absence or inability to attend, by an alternate delegate selected by the Section. The official delegate attending the Annual Convention may have his expenditures for transportation refunded by the INSTITUTE, as provided in the By-laws.

71. The Sections may hold meetings at such times and places as may be determined by their officers, for the purpose of carrying on their work.

72. Any Section may adopt for its own government such By-laws to be known as "Section By-laws" as it may find expedient, provided that no provision thereof shall be incompatible with the Constitution or the By-laws of the INSTITUTE.

73. University Branches may be formed and Student meetings may be held as provided in the By-laws.

74. Sections and Branches may be dissolved in the manner specified in the By-laws for failure to comply with the Constitution and By-laws of the INSTITUTE.

ARTICLE X.

GENERAL.

75. A quorum of the INSTITUTE at the Annual Meeting shall consist of not less than five per cent. of the total number of Members and Associates, present in person or by proxy. The same number shall constitute a quorum for the transaction of

business at the Annual Convention and at special meetings called as provided in section 63.

76. Every Member or Associate entitled to vote at any meeting may so vote by proxy, signed by the Member or Associate, and filed with the Secretary before the meeting at which it is to be voted. No proxy shall be valid after the expiration of eleven (11) months from the date of its execution, unless the Member or Associate executing it shall have specified therein the length of time it is to continue in force, which shall be for some limited period. Every proxy shall be revocable at the pleasure of the person executing it.

77. The Committee of Tellers named in Article VI., sections 34–35, shall be considered a proxy committee for the definite purpose of formally voting, at the annual election, letter ballots named in Article VI., sections 32–33, and canvassed by them as stated in section 36.

78. The fiscal year of the INSTITUTE shall terminate with the thirtieth day of April.

ARTICLE XI.

AMENDMENTS.

79. Amendments to this Constitution may be proposed by means of a petition signed by not less than one hundred (100) Members or Associates and received by the Secretary not later than February first; or by means of a Resolution adopted by the Board of Directors not later than February first. Such proposed amendment or amendments shall be submitted to legal counsel by the Board of Directors, and if, in the opinion of such counsel, they are in accordance with the laws under which the INSTITUTE is organized, a copy shall be mailed, with a letter ballot, to each Member and to each Associate, not less than sixty (60) days before the Annual Meeting.

80. Votes, to be considered, shall be received by the Secretary not later than one week before the Annual Meeting. The Secretary shall hand these votes unopened to the Committee of Tellers, which shall count such votes and make a sealed report to the Board of Directors in duplicate, of which one copy shall forthwith be filed with the Secretary, and of which the other copy shall remain in possession of the Chairman of the Committee, who shall hand this report to the presiding officer at the annual meeting. In the absence of this report by the

Chairman of the Committee the Secretary shall produce the duplicate copy and hand the same to the presiding officer of the meeting. The presiding officer shall then cause the report to be read. If the total vote be not less than thirty per cent. (30%) of the total membership of the INSTITUTE, and if seventy-five per cent. (75%) or more of all the Members and Associates voting shall declare themselves in favor of the proposed amendment or amendments, the same shall become a part of the Constitution.

81. Amendments shall take effect thirty (30) days after their adoption, but officers of the INSTITUTE at the time any amendment becomes effective shall continue in office until the end of the terms for which they were elected.

82. The Secretary shall print copies of the amendments as soon as practicable after adoption, and distribute the same to Members and Associates.

DISCUSSION ON "CONSTANTS OF CABLES AND MAGNETIC CONDUCTORS", AT SCHENECTADY, APRIL 25, 1907 (see p. 555)

W. A. Del Mar (by letter): Mr. Berg may well be surprised to find the great number of different formulas devised to express the inductance of a pair of parallel wires. The variety of formulas is remarkable, considering that a simple and accurate formula has been available in most of the standard mathematical treatises on electricity from Clerk Maxwell to Alex. Russel.

The inductance of a circuit is a measure of the magnetic

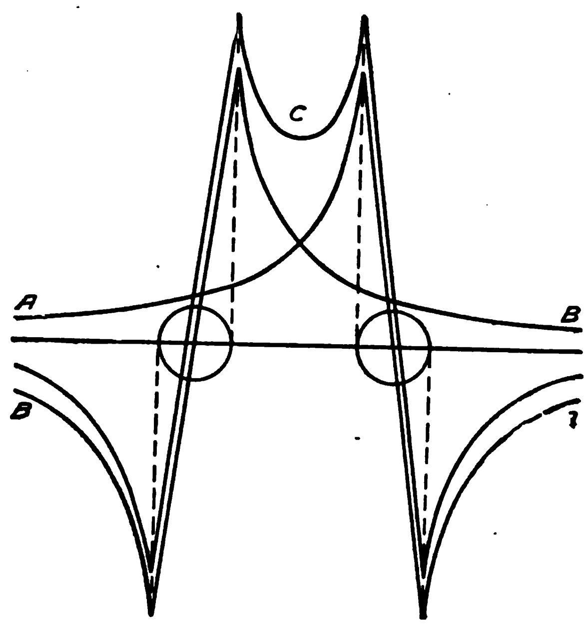


FIG. 1

energy associated with the current in it and is defined by the following well-known equation:

$$E = \frac{1}{2} L i^2$$

where E = energy in magnetic field interlinked with a circuit of inductance L carrying an unvarying current i. In the case of a circuit composed of two parallel wires, the size of which is negligible in comparison with their distance apart, the inductance is approximately equal to the total flux embraced by the circuit due to unit current therein.

In the paper under discussion this approximation is used as the basis of a formula which is apparently intended to be exact.

By a curious the coincidence, the exact formula is of the form given by Mr. Berg as an approximation; that is, it contains a term $\log \frac{2D}{d}$ instead of $\log \frac{D-r}{r}$ as given in the formula referred to above. Even using the approximation as a basis, the deductions given are not correct, owing to an error in the selection of the limits of integration.

When two conductors carrying currents in opposite directions are brought into proximity, the magnetic whirls around the conductors are squeezed together and the axes of the two whirls are pushed away from the axes of the conductors. In order to include the entire flux, the integration should, therefore, have been extended to the axes of the whirls, instead of merely between the axes of the two wires.

This is shown graphically in Fig. 1 in which the ordinates of the curves *A A* and *B B* represent the flux density around a pair of parallel wires, and the ordinates of the curve *C* show the resultant flux density due to the fields of the two wires. It will be noted that the curve of resultant flux density crosses the horizontal axis outside the axes of the wires, and the inductance will be the entire area between the resultant curve and the horizontal axis. The area of this curve expressed as a formula is cumbersome in the extreme and withal useless, because as stated above it is based on incorrect premises.

The equation defining inductance is stated above in terms of an unvarying current because the flux due to a varying current is not distributed in a condition of equilibrium, and is therefore not a definite quantity but depends upon the rate of the variation of the current. The flux due to unit current varying at any particular rate may be called the "effective inductance" at that rate.

INDEX.

BUSINESS OF THE INSTITUTE

PAPERS AND DISCUSSIONS

INDEX OF AUTHORS