DEPARTMENT OF COMMERCE

TECHNOLOGIC PAPERS

OF THE

BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 28

METHODS OF MAKING ELECTROLYSIS SURVEYS

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Bureau of Standards

ISSUED AUGUST 26, 1916

WASHINGTON
GOVERNMENT PRINTING OFFICE
1916

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By Burton McCollum and G. H. Ahlborn

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Part 1.—INTRODUCTION

I. DEFINITION AND SCOPE OF PAPER

The subject of electrolysis surveys deals with the various methods or types of measurement employed to determine the danger to underground pipes and cables and other structures due to the flow of stray electrical currents, the extent of damage already produced by them, and the proper mitigative measures that should be applied for reducing future trouble in particular cases. It is the purpose of this paper to discuss the methods of determining electrolysis conditions; of collecting data upon which the design of mitigating systems may be based, including a discussion of the measurements to be taken; the characteristics of the instruments best adapted to the requirements; the procedure to be followed; the recording and arrangement of the data; and to a certain extent the interpretation of the results. This discussion is based on the experience and observation of the engineers of the Bureau of Standards and others who have been engaged in this work, both in this country and abroad. It is hoped that the paper will enable those who are less familiar with this work to proceed more efficiently in carrying out a survey, avoiding certain errors and unnecessary measurements, and that it will assist materially in establishing a better understanding of the significance of the results obtained.

It should be emphasized here, however, that in general no two electrolysis surveys will be conducted in exactly the same way, so that it is not possible to lay down a definite and complete program. The procedure prescribed in this paper is intended to cover those measurements most frequently made and to describe methods that have been found suitable for making them. The kind and character of the readings taken, and to a certain extent the details of procedure to be followed will vary so much with individual conditions that much reliance must be placed on the judgment of the person conducting the tests. In fact, the proper procedure during a large part of the survey will depend in large measure on the results obtained in the preliminary tests. In general, therefore, it is important that investigation of electrolysis conditions be undertaken under the direction of a competent engineer very familiar with the method of procedure in securing test data as well as experienced in interpreting the results of such tests.

With the rapid growth in the extent of trolley lines and the traffic carried by them, and the agitation for the protection of underground piping systems and other underground structures against electrolysis, the importance of and interest in this subject have increased tremendously. The damage due to stray currents has followed so closely upon the construction and operation of trolley lines and is so generally a phenomenon accompanying the operation of such lines that it may be considered as a problem of street railway engineering. Only a few years after the introduction of electric railway systems in 1884, serious corrosion of pipes occurred in certain places and efforts were made to determine the cause and eliminate the trouble. Electrolysis from other causes than street railway stray currents is not unknown, but the instances are so infrequent and the damage so small as to deserve only a passing comment for the purpose of pointing out that some grounded circuits, of which the Edison three-wire system is the most common example, may do damage to sheaths or pipes even if only small differences of potential exist between the different grounded points.

II. PURPOSE OF ELECTROLYSIS SURVEYS

By means of proper measurements it is possible to determine with sufficient definiteness for most purposes the extent and location of the areas in which the pipes and other structures are in danger and the degree of seriousness of the trouble. The cause of the damage in progress, whether due to stray currents or natural corrosion by soil, cinders, or organic matter, can generally be ascertained, and in case of electrolytic corrosion the source of the current can generally be definitely determined. The various factors connected with the pipe systems, which tend to aggravate electrolytic damage, such as infrequent local discontinuity or high resistance in the pipe systems, unusually low-resistance soil or the use of certain methods of mitigation not adapted to existing conditions, may also be detected. Defects in the railway return systems which tend to give rise to electrolysis troubles, such as poor rail joints, infrequent cross bonds, insufficient conductance in the negative return, improper use of such conductance, or too long feeding distances, may be determined.

III. CLASSES OF SURVEYS

In the following discussion several classes of surveys are recognized. The first is what may be called a complete electrolysis survey, which is made not only for the purpose of determining the extent and location of the danger from electrolysis, but also with the view of determining the proper procedure to be followed for the permanent mitigation of the electrolysis trouble. The second embraces such surveys as would usually be made by a pipe or cable owning company solely for the purpose of determining whether existing conditions are satisfactory and differs from the former mainly in that most of the information with respect to the railway system is not required, and fewer electrical measurements are taken, the number and character of those obtained depending on the thoroughness with which the survey is to be carried out. A third class of survey, which needs little discussion, however, is one made to determine whether ordinances or regulations governing electrolysis conditions in a municipality are being complied with. Such surveys are usually made periodically, the periods usually varying from three months to a year. In general, in such surveys those quantities are measured which are specifically limited by the ordinances or regulations which are in effect in the locality in question. In this paper there is discussed the various types and classes of measurements and the general character of the information that should be sought in carrying out a complete electrolysis survey. No attempt has been made to outline briefer classes of surveys, since the data required for these will vary so much with individual circumstances that they will have to be determined by the engineer in charge of the work. The procedure, however, in obtaining the data which the plan of the survey calls for will not be materially affected by the omission of certain tests which would be called for by the complete survey.

Part 2.—PRELIMINARY DATA

I. DATA REGARDING PIPE AND CABLE SYSTEMS

In making electrolysis surveys a considerable amount of preliminary data are usually necessary. It is of first importance to gather all evidence regarding the character, extent, and location of known damage to underground structures. This evidence may usually be obtained from the companies operating the water, gas,

telephone, and other underground systems, but even though these companies can give no direct testimony as to injury of underground structures this does not always indicate that no damage exists. The data on the pipe and cable systems should include the location of the mains and railway tracks shown on a map. The type of joints used, and the kind of pipe material—for example, cast iron, steel, etc.—should be determined. Where current measurements are desired, the size and other data for definitely determining the cross section and conductivity of the pipe sections should be given for the particular sections on which current measurements are to be made.

II. DATA REGARDING RAILWAY SYSTEMS

As regards data on the railway system the following should be determined:

1. The character of the service, whether city, suburban, or interurban. This will have a bearing on the schedule, momentary variation in load on different lines, and load factor.

2. Physical data on railway systems, such as rail weights, types of bonds and joints used, and roadbed construction.

3. The practice of the railway company in regard to frequency of cross-bonding, bond maintenance, and bond testing.

4. Load curves are necessary for the interpretation of the data in order to reduce short-time readings to all-day or other average values. Where the load varies considerably in different sections of a power-house feeding area, it may be necessary to get the load curves on different feeders as well as the total power-house load curve.

5. Where a survey is made with the ultimate purpose of correcting electrolysis conditions by applying some method of mitigation, it will also be necessary to secure complete data on the magnitude and distribution of load, the generating and substation feeder systems, frequency of schedule, and probable future demands of traffic.

Much of the above data can be most conveniently shown on a map of the railway system which would include location of tracks and return feeders, weight of rails, and location of cars based on schedules and running speeds and the average current per car.

Part 3.—ELECTRICAL MEASUREMENTS

In discussing the electrical measurements required for a complete electrolysis survey they have been divided into three general classes, namely, voltage surveys, current surveys, and miscellaneous readings. In the ensuing discussion not only the methods and instruments best adapted to the work but the purpose of the measurements and the interpretation of the results will be dealt with.

I. VOLTAGE SURVEYS

The number and character of the potential readings required depend on the information wanted. As was pointed out in a preceding paragraph, the readings taken depend on the nature and thoroughness of the investigation to be made, and this is emphasized here because a number of potential measurements are described which, although often useful, would be unnecessary in many cases. For example, simple preliminary surveys to indicate where damage has occurred would hardly require extensive over-all potential measurements or measurements of potential gradients. On the other hand, if it is necessary to redesign the railway return to take care of electrolysis conditions, more complete observations of potential conditions are requisite, and in certain experimental work one finds it necessary to get data bearing on every phase of the problem. The voltage surveys are here divided into three main classes: (1) Over-all potential, (2) potential gradient, and (3) potential difference measurements. The latter term applies to potential measurements taken between different structures, such, for example, as between water pipes and lead cable systems, or between pipes and railway tracks.

1. OVER-ALL POTENTIAL MEASUREMENTS

(*A*) **Definition.**—The expression "over-all potential" is here applied to the difference of electrical potential existing between the point of lowest potential in any feeding district and the points of approximately highest potential on or near the various branches of the railway system. They thus reveal the maximum differences of potential which exist in the earth or in the rails, which are the immediate sources of the stray current. A power house has a feeding area at all points of which the ground and rails are positive to the negative bus bar, which is almost universally the grounded or return side. The difference of potential between the

negative busses of two stations and a point on the tracks is the algebraic sum of the potential drops between that point and the negative busses of the two stations, making it possible that either station bus may be positive to the other. For the same reason the over-all potential between any bus and a point in another power-house area consists of two or more components of different signs and the bus may even be positive to that point. However, the concentration of current as it approaches a power house with the usual type of return system—that is, designed with converging and a constantly decreasing number of tracks and the current itself constantly increasing—produces large potential gradients in close proximity to the station and all of the busses are therefore negative to a very large per cent of all the railway area. The tendency for leakage from the rails, which is one of the fundamental factors, under average conditions is determined in large degree by the maximum differences of potential existing between points within any feeding area rather than between points lying in different feeding districts.

(*B*) **Importance of Over-All Potential Measurements.**—The importance generally attached to over-all potential measurements as an indication of electrolysis conditions is indicated by the fact that all laws and regulations that have thus far been adopted for reducing electrolysis troubles have recommended the limitation of the over-all potential drops to some definite and relatively low value. Such limitation has been required or recommended in regulations in effect in Great Britain, in various cities on the Continent, and in a number of cities in America.

In all laws and regulations that have up to the present time been adopted, so far as we are aware, the over-all potentials and potential gradients have been specified as those taken between various points on the railway tracks. This is true of the various European ordinances as well as those adopted in this country, and such limits have proven quite successful, particularly in Europe, in relieving the electrolysis troubles. There is much to be said, however, in favor of limiting potential drops in the earth or on pipe networks rather than on the railway tracks. Such voltages afford the most accurate criterion of all as to the actual danger of underground structures and would also prove more advantageous to the railway companies, since if potential drops in the earth or on the pipes are made the subject of limitation, higher voltages could be allowed on those tracks having a high resistance to earth.

Under this plan low voltages in the tracks would be required only where most needed, and railway companies would be encouraged to so construct the track as to give a high-leakage resistance to ground. If, however, the voltage drop in the track is limited by regulations, any construction of roadbed that would reduce leakage would increase the current flowing on the track, thereby increasing the voltage drop and thus increasing the difficulty and cost of complying with the regulations. On the other hand, if the voltage drop on the pipes is made the basis of the regulation, the railway companies would profit by any construction which tends to reduce the leakage instead of suffering by it, as in the case where voltage drops in the tracks are limited. If this plan were adopted, it would be necessary to prescribe lower voltage limits than would be applicable to tracks in order to secure the same freedom from electrolysis.

Over-all potential measurements, when interpreted in the light of other conditions to be discussed later, afford a valuable index of electrolysis conditions generally. The over-all potential is also a quantity which lends itself to easy and ready determination. In cases of reported damage these measurements reveal whether the railway systems are seriously at fault, and what lines or sections are most concerned. When taken in conjunction with certain load data they permit the calculation of the negative power losses, and they also yield valuable information bearing on the desirability of rearranging the feeding areas. When studied with due regard to the character and location of the railway lines and power houses and the distribution of the loads, the probability of too high a current density in the return, local high resistance in the return, or too great feeding distances can be determined. It seems desirable, therefore, in most cases that the over-all potential measurements be the first step in a complete electrolysis survey.

(*C*) **Instrument Leads for Taking Over-All Potential Measurements.**—Since the points between which the potential is to be observed are quite widely separated, the problem of bringing lead wires from these points to the voltmeter is one of considerable importance. For spans of 1000 feet or less, leads on the ground may be used, but the consideration of such measurements more properly belongs to the discussion of potential gradients. Lines may be strung on poles or on the trolley span wires and be used for this purpose solely. This may be done when it is desired to get continuous records for long periods of time, probably at points

which represent the maximum over-all potentials and where records are required by ordinance or needed as evidence, and in some cases it may be found more economical than renting telephone wires. For temporary use, however, as when surveys are made only at infrequent intervals, the use of telephone lines which are already in place is most convenient, there often being idle pairs which are especially suited to the purpose. They usually extend to every part of a city, and by trunking through the various exchanges any two points may be connected to the voltmeter. Since the over-all potentials seldom exceed from 10 to 30 volts the telephone cables are in no danger from voltage breakdown. We have never experienced any disturbance of the telephone service

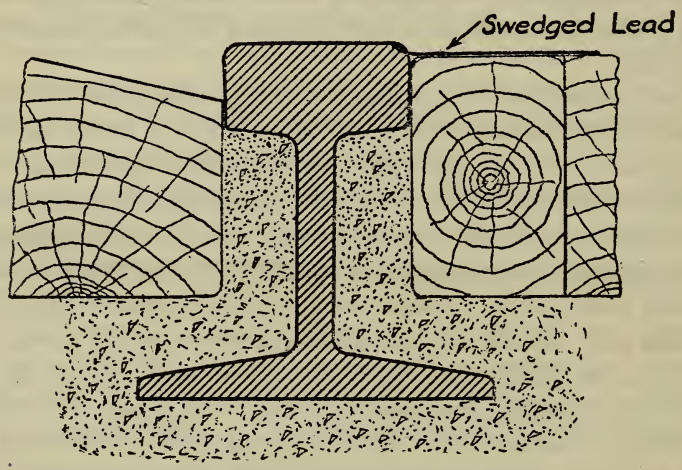

FIG. 1.—*Method of making permanent connection to rail*

due to the use of these wires either from noises in parallel lines or damage to the circuits. When the number of idle pairs available for over-all voltage measurements in a certain district is limited the pairs may be split, using one wire to connect to each point. Where plenty of idle pairs are available, however, it is best to connect the two wires in parallel, thereby reducing the resistance of the leads, which in long lines may become considerable.

The point of lowest potential on the rails or pipes in any powerhouse area is the logical place for connecting the lead from the negative terminal of the instrument. This will usually be the point on the rails nearest the negative bus, but this is not necessarily so, especially when insulated negative feeders are used. Since the other points will usually be compared to this most negative one, the contact and connection to the latter should be

made quite permanent in character by one of the methods described below.

To reach the rails at outlying points, a connection must be made between the rail and the lead wires. If only a short-time reading with an indicating instrument is desired, a workman may make contact during the reading, but if a longer record of voltage conditions is necessary, or if the reading is to be frequently repeated, a lead protected from traffic must be permanently attached to the rail. The leads may be buried in the surface of unpaved streets, or laid upon asphalt blocks or brick pavement, and a board nailed over them to protect them from traffic.

(*D*) **Terminal Connections for Over-All Potential Measurements.**—Methods of making connection of the lead wires to rails are of great importance, and careful attention to this detail will

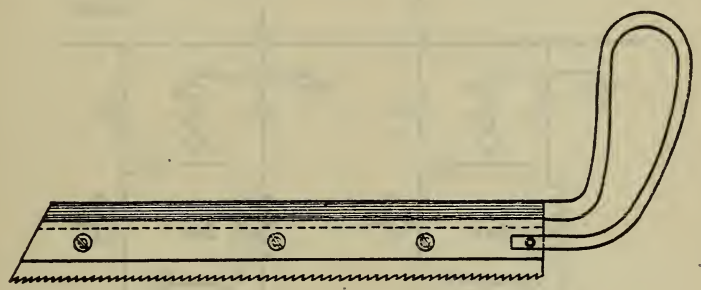

FIG. 2.—*Special hack saw for slotting rails and pipes for making swedged connections*

save much trouble from errors in readings or broken connections. Holding a wire on a bright spot on the rail is feasible, but is tiresome for the assistant, and the contact is rather uncertain at best. A file with a soldered lead may be held on the rail when a contact for a short time only is desired, but a much more certain contact is obtained by swedging a wire into a slot in the outside of the rail head where it is out of the way of cars. Such a connection (see Fig. 1) can be made so quickly and has been proven by experience to be so strong and durable that it is recommended even for temporary work. The usual hack-saw frame does not permit making a slot in such a small space, and a special saw frame made of steel, as shown in Fig. 2, is very convenient for this work and also in making connections to pipes, mentioned later under the discussion of current measurements. Magnets have been used, but experience has shown that the electrical connection is not as reliable as in the case of a swedged joint.

In order to make contacts on the ground or pipe systems it is preferable to use fire hydrants or gas or water service-pipe connections where these are available, but in case they are not available, several driven pipes connected in parallel will furnish a reasonably low-resistance ground with less danger from galvanic potentials than if one pipe is used. The metallic connections to water or gas mains furnish very low-resistance contacts, and the potential differences on these systems are more directly comparable with the danger of such systems than the measurement on the ground with small-area contacts. Where the potential differences in the ground are small it may be necessary to use nonpolarizable electrodes, such as described later, in order to obviate the galvanic electromotive forces.

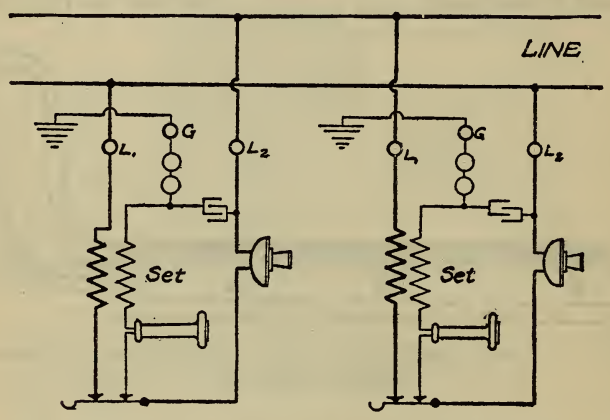

FIG. 3.—*Diagram of a common type of two-party circuit which can be used for securing temporary ground connections*

The contact in the ground or to the rail may be made before the test, and when using idle lines the lead to ground or rail can be permanently connected to the telephone wire so that a workman need not be sent to each point when making measurements, all connections being made in the telephone central stations. Such permanent connections should be made whenever possible, as they will greatly reduce the time and labor required in testing. Temporary grounds, such as single-driven ground rods, are undesirable because of the uncertain and high-contact resistance which is likely to exist. There are many good grounds on a telephone system which are tested for resistance and are required by company regulations to be below a certain value, frequently 70 ohms. These grounds are placed at terminal boxes and at certain types of telephone instruments—for example, prepayment telephones

FIG. 4.—*Arrangement of connections for measuring over-all potentials*

and some party-line telephones. Fig. 3 shows the connections of one type of two-party circuit, and by tracing them it is seen that with the receiver off the hook a connection exists between the ground and both sides of the line through certain resistances.

(*E*) **Procedure in Making Over-All Potential Measurements.**—(*a*) PRELIMINARY PLANS.—In instituting an over-all potential survey in a city it is first necessary to determine the location of the points between which potentials are to be observed. As a rule, not only maximum potentials should be measured but leads should also be run, as described above, to a good many intermediate points to permit taking potential gradient measurements, as described later.

By consulting a railway positive feeder map a list of power stations and their extreme feeding points can be made. If a complete set of readings from remote feeding points is desired, special lines to these points may be run or leased from the telephone company. With the above list of points to be reached the telephone officials can prepare a table showing the terminal boxes, pair and cable numbers, including trunk cables, which are necessary to make complete circuits between one of the telephone central offices or other point where the measuring instruments are placed and the power house and feeding ends. A large city map mounted on a board, as shown in Fig. 4, showing railway lines and having binding posts with connections on the back to the terminal room and on the front for the instruments will expedite the work and insure greater certainty of correct connections, especially where measurements are to be repeated. The wire running from any point on the street is connected to the back of a binding post piercing the map at the corresponding point. After the correct connection of wires has been verified one can readily connect a voltmeter between the wires leading to any points in the city without danger of error.

Readings are first made between the negative points in each power-station area in order to determine the point of lowest potential in the city. Measurement can then be made from this low point to all other points selected and between any two points as desired.

(*b*) METHODS OF MAKING TEMPORARY CONNECTIONS.—Where for any reason permanent connections to tracks can not be made as explained above, temporary connections become necessary, and these require considerable time and expense for labor. For

instance, in case a temporary potential terminal on the rails is desired, a workman must go to the point, run a double wire from the two sides of the pair in a near-by terminal box, and make contact on the rail. With the common telephone the workman can report when ready and receive instructions over the same wires used in the potential test. If the terminal-box grounds are used a workman must go to each point and make such connection. A ground on a lead-cable sheath should be avoided as it may carry current from some distant point with a very different potential.

When a workman is not required at the point at the time of observation, as when telephone instrument grounds are used or other connections installed previous to the tests, the measurements may be taken efficiently and quickly. The ground at coin box or prepayment telephones may be made use of by placing a coin in the slot, thus completing the circuit between the ground and the line. Certain two-party lines, which have a ground at each instrument and where the selective ringing is done over opposite sides of the line and ground return circuit, may be used when the receiver is taken off the hook. It is necessary in any case to ring the telephone at the point desired and ask the party to place a coin in the slot or to leave the receiver off the hook for a short time.

(*c*) Avoidance and Correction of Errors.—When a series of readings has been obtained certain corrections may have to be applied. The most obvious is that for resistance of leads in series with the instrument. If the resistance of the instrument is high, the external resistance will be a small per cent of the total and since the value of the external resistance is sometimes uncertain, it is desirable to keep it as low as possible. The resistance in the telephone central stations is reduced to a very small value by avoiding running the circuits through the switchboard. The resistance of the lines may be definitely determined. It is common practice to use No. 19 copper in trunk cables, which has a resistance of 88 ohms per loop mile, or 44 ohms per wire per mile, or 22 ohms per mile paralleled. The other cables have No. 22 wire which has twice the resistance of the trunk pairs. If special lines are erected for the survey, they will be heavier to provide mechanical strength, and in this case the size and length will be definitely known. Since the leads will seldom exceed 10 miles in length, the resistance will not exceed 300 ohms or 1 per cent of a 30 000-ohm instrument. This is not a very important correction on observations of a potential which may vary from zero to 200

per cent of the average value, and can be neglected. Special indicating instruments having ranges of about 15 volts and a resistance of the order of 30 000 ohms can readily be obtained. When, however, an ordinary Model 1 Weston portable voltmeter of 15-volt range is used the resistance would be about 1500 ohms, in which case the error due to 10-mile leads would be about 20 per cent and would require correction. The resistance of the contact when connection is made direct to rail would, in practically all cases, be only a fraction of an ohm. The greatest resistance is found when a telephone instrument ground is used, since by referring to Fig. 3 it will be seen that in this case the bell coils (varying in the different types of telephones from 500 to 2500 ohms), one side of a mutual inductance and receiver are directly in series while an inductance and the transmitter parallel each other and are in series with the circuit. This requires that an appreciable correction be applied when ground connections are made through such circuits. When a recording instrument is used the external resistance will probably be a considerable percentage of the total resistance, since these instruments usually have a lower current sensibility and resistance than the best indicating instruments. Where pairs of wires are used the resistance can be measured by making a loop and the correction calculated or the instrument may be calibrated on each circuit, by means of a special indicating instrument of very high resistance. The latter is generally desirable as a check and is generally more accurate owing to the possibility of unknown resistances in the circuit.

In making connections in the telephone central stations, the switchboard equipment, plugs, jacks, etc., might be used and thereby expedite the work, but the resistance and uncertainty of sleeve contacts, coils, etc., and the possible introduction of the operating potential are sufficient reasons for avoiding the station circuits by connecting directly to the incoming and outgoing wires on the terminal frames. The accidental impression of the telephone operating potential must be guarded against, since it is very possible for this to occur and thus render all readings worthless. An examination of the circuits, or a careful examination of results, usually will reveal the presence of such an extraneous potential, if any exists. The telephone potential is usually as large or larger than most over-all potential drops and is practically steady, and for this reason can easily be distinguished from the railway voltage.

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(*d*) General Procedure.—While making over-all potential measurements, as well as in all other electrolysis tests described later in this paper, it is advisable wherever practicable to arrange to have the test data worked up and tabulated, and preferably laid out on maps as the work proceeds. In this way it is possible to keep in close touch with the progress of the work; and by making a study of the preliminary data before the work is finished it is often possible to modify the original plans in such a way as to obtain more complete and accurate data regarding electrolysis conditions. It has a further advantage in that it will bring to light any apparent inconsistencies in the readings at various points in time so that these can be checked and the uncertainties eliminated.

In over-all potential measurements, as well as all other electrical measurements made in connection with electrolysis surveys, it is desirable to take the readings at each point over as long a time as circumstances will permit. The variability of such readings, due to the fluctuating character of railway loads, is usually such that readings taken over a period of a few minutes only may give a very misleading impression as to the conditions which actually exist. This is particularly true where infrequent car schedules prevail. On a line on which the 15-minute schedule is maintained it will be found that certain of the readings, such, for example, as potential-difference measurements between pipes and rails, will vary periodically between wide limits, depending on the condition of the cars. Periods of several minutes may elapse during which the reading will be very small, and this will be succeeded by a short period of a few minutes' duration during which the readings may be several times greater. Obviously, it is important in such cases to continue readings throughout a complete load cycle. Care should be taken that the period is either substantially one-load cycle or an exact multiple of a load cycle. It will be apparent that if the reading is taken, say, over one and one-half load cycles, the reading may include either two hollows and one peak of the voltage curve or two peaks and one hollow, and in the latter case the average value will appear much larger than in the former case. Very large errors often result in this way, so that care should be taken to minimize such errors by determining the period of the load cycle before determining upon the length of time over which the reading is to be taken. Of course if the load cycle is short, so that the reading can be continued over a con-

siderable number of cycles, the error due to this cause will be negligible.

Wherever conditions will permit it is desirable to continue the readings at any point for a period of about one hour, and in the case of very infrequent schedule, as on certain interurban lines, even a longer period should be adopted. Even then it will be necessary, if accurate conclusions are to be reached, to reduce these readings to some equivalent average values for a longer period, such as a day or longer. This matter is discussed in some detail in a later section of this paper dealing with interpretation of electrolysis surveys.

2. POTENTIAL GRADIENT MEASUREMENTS

(*A*) **Definition of Term.**—A potential gradient is the rate of change of potential along a conductor. It is generally expressed in volts per thousand feet, but this is intended to convey the idea of the rate per thousand feet at any point and not that 1000 feet is the exact length to be employed. Under the head of potential gradients will be included all potential measurements between two points on the tracks or between two points in the earth over distances materially less than the extremes of the power-house feeding area. In using the term "gradient" it must be borne in mind that the rate of change of voltage may not be regular, as, for example, if high-resistance joints or other irregularities in resistance of the circuit are encountered.

(*B*) **Measurement of Potential Gradients in Tracks.**—Potential gradient measurements are usually made in the railway tracks but sometimes also on the pipe systems in the earth. The same method of making contact with rails, the same types but slightly lower ranges of instruments, and often the same kind of leads as those described under over-all potential measurements may be used in obtaining potential gradients in the rails. The procedure will often be different, however, because the distances are generally shorter and may be spanned in a more convenient or economical manner than by the use of telephone wires. The points to be reached must be selected and a decision made as to the type of leads best suited to reach these locations. If spans are quite long, such as several thousand feet, telephone or pilot wires may be used, as in over-all potential tests, and in that case there would be no difference in procedure from that described above for making over-all potential measurements. If the dis-

tances over which the over-all potential measurements are to be made are two or three thousand feet or greater, it will be much better to use telephone lines. When, however, it is desired to measure gradients between many points a thousand feet or less apart it will generally be easier to run a short span of wire directly between the points between which the gradient is to be measured, as described later.

The apparatus necessary in making rail gradient measurements includes voltmeters, leads, and suitable contact terminals. Since the gradient often ranges from a fraction of 1 volt to 20 volts or more per 1000 feet multiple range instruments are necessary. Instruments giving ranges from 1 to 50 volts are not unlikely to be required. It is practicable to secure instruments of suitable ranges so that they can be used in both the over-all potential and potential-gradient measurements as well as for many other tests. Such instruments are described later in this report. The telephone lines used as leads and the rail contacts have already been discussed, but in measurements of shorter spans of 1000 feet or less a length of wire on a special reel and equipped with a crank and brake will expedite the work. The wire can be paid out from the reel along the side of the street and raised above crossings where traffic would cut the wires or insulation. The kind of wire is important, the most suitable being flexible No. 12 or 14 gauge copper wire with good rubber insulation impregnated to resist moisture. Solid wire is so easily broken by traffic or in handling that it should not be used, and a flexible wire is recommended. For measurements made in this way portability and ruggedness in the voltmeters are more important than when the measurements are made at some central point with the aid of telephone wires.

The contact terminals used will depend on whether the measurement is to be made between the points on a track or pipe system or between the points in the earth. For making measurements between points on the tracks or on a pipe system or other metallic structure any metallic terminals held firmly against the rail or pipe, or a wire swedged in the slot after the manner described above under over-all potential measurements may be used.

(*C*) **Measurement of Potential Gradients in the Earth.**—(*a*) Need of Making Earth-Gradient Measurements.—Measurements of potential gradients in the earth are useful in showing the general conditions in a railway feeding area, but more especially in

determining local conditions. The desirability of a general earth survey may be questioned, since the potential gradients on the rails or on pipe systems are such excellent indications of conditions and are much more easily obtained and more accurately measured. However, special situations may arise where potential measurements between various points in the earth are necessary, and they are useful for many purposes. The presence and direction and approximate magnitude of large transverse currents which enter one side of the intercepting main and produce damage upon leaving may thus be revealed. High-resistance joints of an underground main may be located more rapidly by gradient measurements in the earth above the pipe than by excavations. A formerly common street-railway practice of placing large ground plates as distributors or collectors of the return current in moist earth has not been entirely abandoned. This is objectionable, although its continuance in some cases may be unintentional. Gradients radiating from such terminals may be traced by a series of earth-gradient measurements. The gradients are greater close to the electrode, and thus the existence and location of such grounds can be determined. Buried pipe lines or other conductors of uncertain locations which are discharging current into the earth may be located by gradient measurements, there being usually a reversal or abrupt change in the gradient when the buried conductor is crossed.

(*b*) Instruments for Earth-Gradient Measurements.—The procedure, and especially the equipment for earth-gradient measurements, differs from those used for measuring rail gradients. Three sources of error are encountered in these measurements which are not met with in rail-gradient measurements, namely, electrode potential drop, galvanic potential differences at the electrodes, and polarization potentials. Since the values of the gradients are often small, a comparatively long span and an instrument of high sensitivity is necessary. In a number of surveys made by the Bureau of Standards a span of 500 feet was used and gradients great enough to overshadow small galvanic potential differences were obtained. The range of the voltmeter used should extend from a few millivolts to about 10 volts for most purposes. In order to eliminate errors due to the resistance in the earth near the contact terminals it is generally necessary to use an instrument of very high current and volt sensitivity, so that a high resistance can be connected in series with the instru-

ment sufficient to make the resistance of the earth contacts practically negligible. An instrument having a resistance of from 2500 to 3000 ohms per volt requiring from 0.4 to 0.3 of a milliampere for full-scale deflection is desirable for this work. A portable voltmeter of this kind can be readily obtained from instrument manufacturers. A portable galvanometer having a current sensitivity of 0.5 microampere per centimeter and having a high resistance in series has been used very satisfactorily for this and for other measurements mentioned later. This instrument is made by Leeds & Northrup Co., does not require extreme care in handling, and has proven very rugged in use. It has been mounted on a surveyor's tripod, which makes a very convenient arrangement for leveling and making observations. The use of a potentiometer for this work is not recommended, since this equipment is heavy and delicate and requires a zero setting, and hence is not well suited for field work where rapidly varying voltages are usually encountered.

(*c*) Leads and Terminals for Earth-Gradient Measurements.—The leads used in making earth-gradient measurements should be thoroughly insulated throughout their length. The contacts or electrodes are the most vital part of the equipment and special attention must be given to these in order to eliminate errors due to galvanic action and polarization. If iron rods are driven into ordinary soil, galvanic potential differences of from 0.01 to 0.1 volt will often be indicated, while the same rods in soil mixed with coke or cinders or affected by local surface seepage from city streets will produce voltages of half a volt or more. To eliminate these galvanic potentials, nonpolarizable electrodes have been devised and described by a number of investigators. One type which the Bureau of Standards has found most satisfactory is shown in Fig. 5. It consists of an electrode of copper immersed in a copper-sulphate solution contained in a cement cup. Another type consists of an iron tube containing a solution of ferric chloride, the lower end of the tube being closed with a porous substance such as a compressed sponge. The outside of the tube should be insulated so that electrical contact with the earth is made only through the moist sponge. The resistance between this copper-sulphate terminal and ground will seldom exceed 250 ohms except in exceedingly dry soils, and in such cases a little water poured into the holes around the electrode will suffice to reduce this resistance to a point where it will not materially affect the reading of a high-sensitivity portable voltmeter.

When two electrodes of this kind are used troubles from polarization at the electrodes are eliminated. These terminals are used by driving an opening in the earth with a bar and filling this with water to a level sufficient to cover the electrode and inserting the latter. The lead wires are then connected to the voltmeter or other indicating instrument used, and the reading taken.

Where it is desired to take a potential reading between a lead cable sheath or an iron pipe and a point in the earth, such an elec-

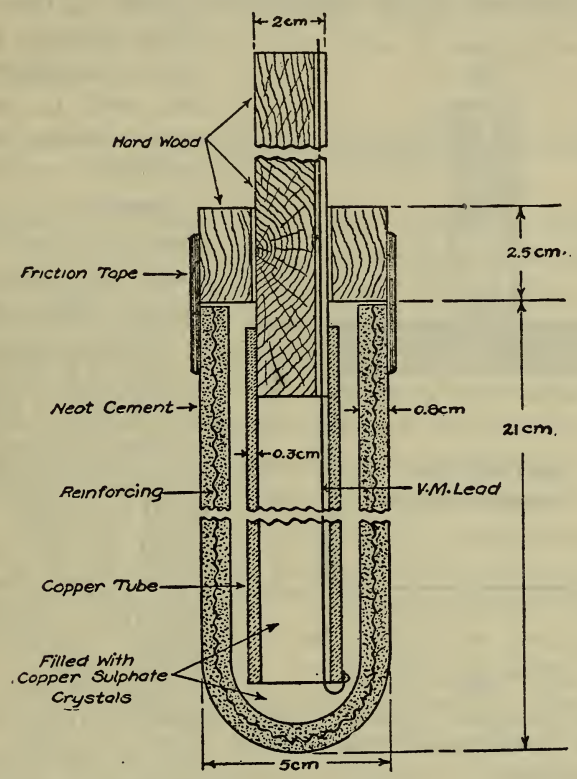

FIG. 5.—*Nonpolarizable electrode suitable for making contacts with earth*

trode should not be used for the earth terminal, since a battery effect would be obtained due to the dissimilar character of the electrodes. If the potential difference is to be taken between lead cables and the earth, a lead electrode should be used. Potential-difference measurements between iron pipes and a point in the earth are likely to be unreliable because of the presence of more or less iron oxide on the surface of the pipes which may affect the polarization potential. Where it is desired to measure a potential gradient in a direction at right angles to the pipe and

close to the same, it is better to use two nonpolarizable electrodes, one very close to the pipe and the other a little farther away. If the potential is high enough to be at all serious, it will be practicable to measure the potential drop over a foot or so in length which would answer the purpose very well.

(*D*) **Measurement of Potential Gradients in Concrete.**—It has been shown by numerous laboratory experiments that under certain conditions flow of electric current through reinforced concrete will produce certain deleterious effects at the electrodes. These effects, although quite uncommon in practice, need to be guarded against under certain unfavorable conditions, and it sometimes becomes necessary to make measurements of potential gradients in different parts of a concrete structure. To do this it is best wherever practicable to make measurements between different parts of the reinforcing material or other embedded metal in the concrete, where these are not metallically connected together. Where such terminals are not available, however, it may be necessary to measure potential differences between two points in the plain concrete. In this case, as in the soil, an electrolyte serves as a conductor in the concrete, and the same sources of error are encountered as in making potential-gradient measurements in the earth. In particular, the resistance in the concrete near the electrodes will often be much greater, especially where the concrete is above grade, and hence fairly dry. Since openings in the concrete are not easily made and the length over which measurements are taken is short, different contacts and a greater sensitivity in the instrument are necessary. Only a portable galvanometer can be used for this work. A suitable contact, shown in Fig. 6, consists of a copper cup with a piston which forces the

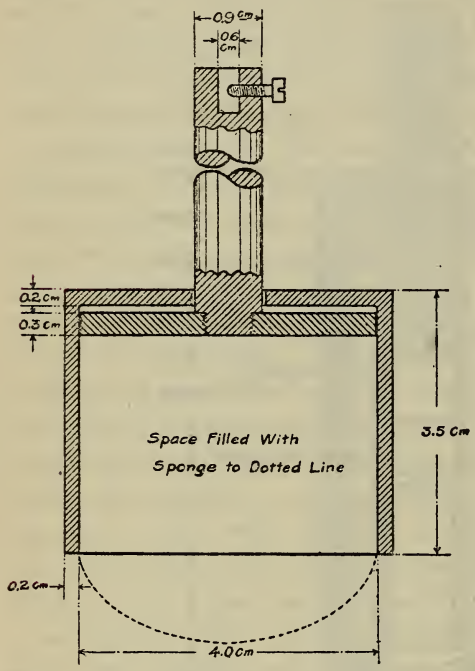

Fig. 6.—*Nonpolarizable electrode especially adapted for making contact with walls of concrete structures*

sponge saturated with copper-sulphate solution against the concrete surface. The contact resistance varies with the moisture content in the concrete and with a sensitive portable galvanometer, such as described under earth-gradient measurements. The resistance of the circuit can be of the order of several hundred thousand ohms, so that the resistance of the concrete near the contacts will be negligible in practically all cases. When testing between ordinary reinforcing material and a point in the concrete, an iron electrode in a solution of calcium hydroxide should be used. It can be made up in the same form as the copper electrode described above.

3. MEASUREMENTS OF POTENTIAL DIFFERENCES BETWEEN PIPES, RAILS, AND OTHER CONDUCTORS

(*A*) **Definition of Term.**—The term "potential difference" is here used in reference to voltage measurements between various systems of conductors. For example, between pipes and rails, lead sheaths and rails, lead sheaths and ground, and a number of other combinations. The distinction made between gradients and potential differences is that gradients are values obtained between two points on a single conductor, while potential differences are measured between two different conductors.

(*B*) **Purpose of Potential-Difference Measurements.**—Potential-difference measurements are probably the measurements most commonly made in electrolysis surveys and are justly given great importance, for when interpreted with due consideration to other circumstances they afford a valuable index to local electrolysis conditions. Some ordinances specify the maximum potential differences which will be permitted. However, a low potential difference does not always indicate a safe condition, nor does a high potential difference necessarily indicate a condition of danger. The possibility of a low or high resistance path must be considered in interpreting such data. Nevertheless, a considerable number of potential-difference measurements should be made in electrolysis surveys, since when properly interpreted they assist materially in determining electrolysis conditions.

(*C*) **Number and Location of Measurements.**—Potential-difference measurements should be made at selected points between fire hydrants and tracks, lead cable sheaths and tracks, lead cables, and any accessible pipe systems, and in many cases between different pipe systems occupying the same territory. These measurements should be made throughout a large part of the

railway feeding area, including many points in the neutral and negative areas as well as in the regions where the buried metal structures are, in general, positive to the railway tracks. This is necessary because there are many places where certain or all of the pipe and cable systems may be negative to railway tracks, but some of them may be more strongly negative than others, and consequently set up a condition of danger to the latter. This is particularly apt to be true where excessive pipe drainage is used for the purpose of reducing the potential differences in the positive areas.

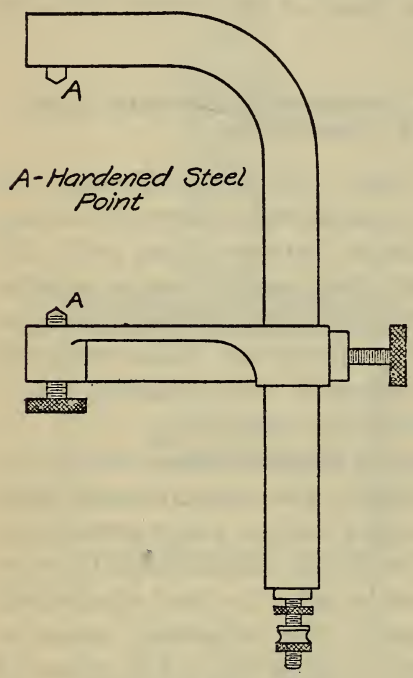

Fig. 7.—*Special clamp for attaching voltmeter leads*

(*D*) **Equipment for Potential-Difference Measurements.**—In case potential-difference measurements are to be taken between metallic conductors the current sensitivity of the voltmeter is not important, since spans or leads are usually short. The ranges necessary do not differ greatly from those required for over-all potential measurements, although the readings are, in general, somewhat lower and the same instruments are practically always used. In the potential-difference measurements, however, a zero-center instrument is very desirable, since a large proportion of these measurements will show frequent reversals.

Since the objects between which potential-difference measurements are made are usually close together, short leads are usually all that are required, and for contact the wire swedged in a sawed slot, as described above, under over-all potential measurements may be used. Use may also be made of a "C" clamp, or better, a special clamp after the design shown in Fig. 7. The clamp has a large spread of jaw, hardened points, and a place for attaching wire. In cases where the contact point is to be held in during measurement it should have a good insulating handle designed to prevent the hand getting in contact with the metal during meas-

urement, as the values may often be so low that an extraneous potential of small proportion might invalidate the reading. When measuring potential differences between points in the soil the nonpolarizable electrodes, such as described under potential gradient measurements, must be used in the electrolytic conductors.

II. CURRENT MEASUREMENTS

1. DEFINITION AND IMPORTANCE OF CURRENT MEASUREMENTS

Under the head of current measurements are included all observations of current flow obtained by ammeter readings or by a potential drop on a conductor, the resistance of which is approximately known. They include also measurements of the leakage of current from pipes or cables into the earth. The amount of current carried by underground structures is often so closely related to the total extent of the damage produced that a knowledge of its magnitude is often very desirable. There are a variety of conductors in which it is at times necessary to measure the current, including copper feeders, railway rails, cast-iron, wrought-iron, steel, and lead pipe, lead cable sheaths, reinforced concrete structures, and occasionally in portions of the soil.

2. MEASUREMENT OF CURRENT IN FEEDERS AND RAILS

(*A*) **Need for Measuring Current in Feeders and Rails.**—Measurement of current in feeders and rails is not necessary where it is desired merely to determine the degree of danger which exists to underground structures. When, however, it is desired to design a system of mitigation with a view of reducing the leakage of stray currents into the underground structures, it is necessary to secure complete data regarding the magnitude and distribution of the railway loads, not only in positive feeders, but in the negative feeders and tracks also. Measurement of current in tracks is also useful because such measurements when properly made and interpreted often give a good idea as to the proportion of the total railway load that is leaking off into the earth. They also show at what points return feeders should be connected to the tracks in order to take off the current without permitting unduly large voltage drops in the track return. They further show the approximate amount of current that needs to be taken off at each point, and hence the size of the feeder that would be required. Such measurements are often of value also in esti-

mating the losses in the negative return; and by measuring currents in different rails of a track, local bad bonding will be revealed by unequal distribution of currents between the different rails of the track. In fact, the quickest and most reliable way to get a good idea of the general condition of the track bonding is to test for equality of distribution of current in the rails at numerous points.

(*B*) **Methods of Measurement.**—(*a*) DIRECT MEASUREMENT WITH AMMETER OR SHUNT.—An ammeter or shunt inserted in the feeder or rail circuit is the most accurate method of obtaining current measurements, but it is often the case that feeders, particularly negative feeders, are not provided with ammeters, and it is usually difficult and often impracticable to insert them. In such cases a potential-drop measurement on a portion of the cable or rail, together with data concerning the cross-section and resistivity of the conductor, form the basis of a much more convenient and sufficiently accurate method of measuring. An instrument well suited for current measurements in all metallic conductors is an indicating or recording millivoltmeter of 10, 100, or 1,000 millivolt range. The lower ranges of the recorder described elsewhere in this paper for other purposes are well adapted for this work. A high current sensitivity is not essential, since we have here a low-resistance circuit and good contacts with no galvanic effects. Suitable terminals for connecting the instrument leads to rail are shown in the accompanying illustrations. Fig. 8 shows a contact point *a* with a long handle *b*, and flexible cord *c*, the slack of which can be taken up in the hooks *d*. Fig. 9 shows a rail spanner that has proven very convenient for measuring current in rails with indicating instruments. The spanner is a frame carrying two hardened points or portions of hack-saw blades at a fixed distance apart, preferably about 4 feet, and insulated from each other. A handle is provided for convenient application to rails on which it is designed to be used. It is made of aluminum, thin brass, and wood, is very light, and is made with a screwed handle so that it can be taken down and packed in a small space. This rail spanner has been found light and convenient enough so that one observer can handle it and an indicating voltmeter and get rapid and accurate results. Where a recorder is to be used for taking measurements during a period of considerable length, swedge connections to the rail, like those described above under over-all potential measurements, should be

used. The data concerning the resistance of the conductor can be obtained by an electrical calibration at each point or by a calculation from the cross section and specific resistance of such conductors. The latter is much more convenient, and is accurate enough for most practical purposes, and is quite generally used. Where high accuracy is sought, however, a calibration is necessary, and various methods for making a calibration are described below.

(*b*) Calculation of Current from Voltage Readings.—In the case of copper cables the cross section and specific resistance

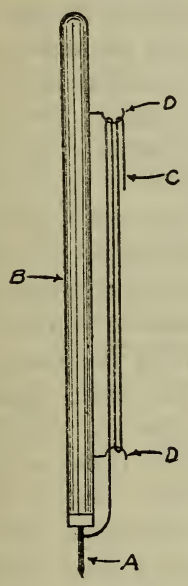

Fig. 8.—*Contact point with insulating handle*

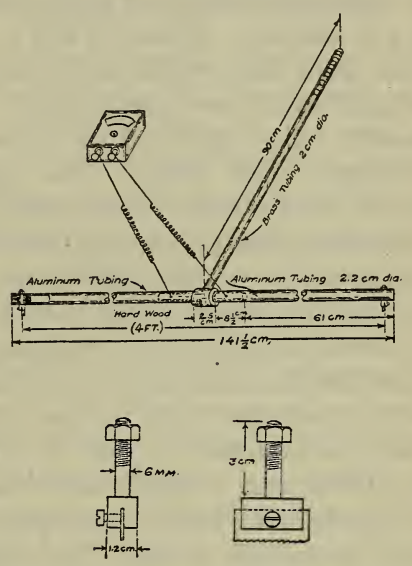

Fig. 9.—*Rail spanner for making contacts on a short length of rail*

are known so accurately that a calculation based on this data is sufficient for all purposes of electrolysis surveys. For example, taking the resistivity of copper at 10.7 ohms per mil-foot, if a 1 000 000 circular mil-cable has a drop of 6 millivolts on a 5-foot length the current will be given by the equation

$$I = \frac{E}{R} = \frac{0.006}{5} \times \frac{1\,000\,000}{10.7} = 112 \text{ amperes.}$$

This value would generally be correct within a few per cent, since all the values entering into the calculation are known or can be measured with an accuracy of at least 1 per cent. If the cable carries sufficient load to make it perceptibly hot and a high

accuracy is desired, an allowance must be made for temperature coefficient of copper. When rails are the conductors, neither the cross section nor the resistivity are so accurately known as in the case of copper, since rails vary widely in weight, composition, and heat treatment. The composition and heat treatment of steels affect resistivity so decidedly that variations of from 9 to 20 microhms per centimeter cube occur. Modern practice is tending toward greater uniformity of carbon and manganese content, and also toward harder steel with higher resistivity. It is desired, where convenient, that the conductivity of sample sections of the rail be determined for each particular installation in case high accuracy is desired. In lieu of this a very close estimate can be arrived at from the composition or the exact conductivity for the product as given by the manufacturer. Tests made by the Bureau of Standards on a number of rails show considerable variation in both resistance and weight. One specimen of T rail having A. S. C. E. section rated at 80 pounds per yard was actually 15 per cent lighter than this weight, and its resistance was 0.0002975 ohm per pound-foot. Two specimens of rail, one 95-pound tram rail and one 112-pound trilby, had resistivities of 0.00028 and 0.000315 ohm per pound-foot, respectively, giving the same average as the first and a maximum variation of 9 per cent. Resistivities varying between 0.000275 and 0.00035 ohm per pound-foot have been encountered in rails in service, but these represent rather extreme and unusual variations. If the value of 0.0003 ohm per pound-foot (which corresponds to over eleven times the resistivity of copper) is used, the results can in most cases be depended upon to within 10 per cent, which is usually close enough when we consider the highly variable character of the terms to be measured. As an example of a method of calculation, using the values of the various quantities in terms of the units commonly obtained in observation, we take the following example. If the potential drop in the rail is E volts per yard, and the weight of the rail W pounds per yard, the current in the rail I, in amperes, will be given by the equation:

$$I = \frac{EW}{0.0003 \times 3}$$

3. MEASUREMENT OF CURRENTS IN PIPES AND CABLE SHEATHS

(*A*) **Purpose of Measurements.**—The measurement of current flow in pipes and lead cable sheaths and other buried structures is important for a number of reasons. Large currents in the

pipes are accompanied by the danger of corrosion on the positive side of high-resistance joints which may occur at many points throughout the pipe network, particularly in cast-iron mains. Also heavy currents set up high potential gradients in the pipes and thereby tend to produce large potential differences between neighboring pipe systems, causing the one of higher potential to discharge current into the one of lower potential, resulting in injury to the former. Further, when heavy currents are flowing in pipes there arises a danger from arcing at points where the pipe line and its connection are opened for any reason. This danger is particularly great in the case of gas pipes where an arc might ignite escaping gas. There is also a danger of arcing where two pipes of different potential make momentary mechanical contact. Cases have also been brought to our attention in which lead cable sheaths had been overheated, and even water service pipes and their connections had been heated to a red heat.

In order to guard against these and other dangers it is important to keep the current flow in pipes at as low a value as practicable, and hence the importance of making current measurements in buried pipes in many instances. Furthermore, the relative magnitude of the current flow in pipe systems at given points both before and after the installation of electrolysis mitigation measures offers a valuable index to the effectiveness of the measures adopted. Such measurements are also useful in many cases in determining the source of stray current. A recording meter measuring the current flow in a pipe at the same time that a measurement is being made of the railway load supplying the district from which the pipe collects its current will often afford, through a similarity of the records, definite evidence regarding the sources of the stray current. Such measurements are particularly useful where two or more railway lines operate in the same vicinity.

(*B*) **Selection of Points of Measurements.**—It is very important in making current measurements in pipes to select carefully the points at which the measurements are to be made. Points of representative and of maximum current flow are usually desired in making such observations, and since tests are rather expensive, requiring excavations in the case of pipes, careful selection of locations is necessary. In the case of a street railway line paralleled by a pipe line the maximum current will occur at the point where the pipe is neutral to the rails, but this ideally simple condition does not exist in city networks, and the greater concentra-

tion of current usually occurs within the positive area. Current measurements should usually be made in mains which extend in the general direction of the potential gradients in the earth. These are, in general, toward the supply station and can be readily determined in any particular case. By consulting a map of the pipe networks, including both gas and water systems, the pipes most likely to be carrying current are usually quite evident. Mains running more or less at right angles to the direction of current flow in the earth serve as equalizing busses, which distribute the current among the radiating mains leading into the power-house area. This distribution, however, is disturbed by high-resistance joints, especially in cast-iron mains, and the selection of the particular main or set of mains carrying the maximum current is usually difficult. Where only a few mains extend in a direction away from the power house, measurements of current can readily be made in all of them. Otherwise, a representative number should be chosen for current measurements from which an estimate of the total current sufficient for most purposes can usually be had. In any event the exact value of the total current flow is not so important as the order of magnitude of the current, the source whence it comes, and the secondary effects on other underground systems to which it may give rise.

(*C*) **Methods of Measuring Current Flow in Pipes.**—Three general classes of methods of measuring current flow in pipes and other metallic structures have been used. The first of these, and the one used in the great majority of cases, is the ordinary drop of potential method, in which the millivolt drop on a measured length of pipe is taken and the current calculated from the millivolt drop and the resistance of that portion of the pipe over which the potential drop was measured. Complete tables giving the resistance per unit length and much other data regarding all of the common sizes and kinds of pipe used in practice are given in Table 1 below.

The second class of methods comprises all those in which an auxiliary or derived circuit is used to shunt out all or any portion of the current in a section of the pipe on which the millivolt drop is being measured, the current being shunted out being measured by an ammeter, and its percentage of the total determined from the percentage drop in the millivoltmeter reading on the section from which the current is shunted. These methods have taken various forms and are described later under the head of "Divided

circuit methods." In most cases a battery is used in this auxiliary circuit. The third method consists in the use of what is known as a direct-current ratio relay in a manner somewhat analagous to the use of a current transformer in alternating-current instruments.

These last two methods are chiefly useful for calibrating a section of pipe in order to eliminate in some measure the uncertainties arising from the use of the tables. They are desirable, however, only in cases where high accuracy is sought, such, for example, as when securing evidence to be presented in court, or where it is desired to measure the leakage of currents from a given section of pipe by an accurate measurement of the current at two points, the difference between which measurements would give the values sought. In such cases extreme accuracy is necessary, and it is not safe to assume a value for the resistance of the pipe. These different methods of measuring current flow in pipes are described in detail below.

(*a*) Drop of Potential Method.—This method, which as stated above consists merely in connecting potential terminals to a section of pipe a few feet apart and measuring the millivolt drop and calculating the current from the voltage drop and the resistance of the section as determined from the accompanying tables, is very widely used, and it is accurate enough for most purposes. Its great simplicity especially adapts it to work of this kind. The accuracy of the method depends chiefly on the character of the current flow and the knowledge of the resistance of the pipe. It will appear from the data presented below in connection with the pipe tables that the resistance of the pipe can practically always be depended upon to be within 10 per cent of the value given in the table and usually much closer than this. Further, the currents usually found on underground pipes fluctuate between very wide limits, so that when readings are taken with an indicating instrument it is usually quite impossible to determine the average value of the readings with an accuracy as good as 10 per cent. Even with a recording instrument an accuracy of 10 per cent is often quite difficult to obtain, particularly where a 24-hour record on an ordinary circular chart is used. It is evident, therefore, that it is hardly worth while in most cases to use a more complicated method in order to eliminate the possible error due to the assumed resistance of the pipe when errors from other sources are likely to be much larger.

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The data on pipes and cable sheaths obtained in the study of this method of measurement are summarized in two sets of tables. In the first set of tables are shown the dimensions and weights of the various kinds and classes of pipe and lead sheaths. This set of tables is not needed in ordinary electrolysis survey work for obtaining values of current in pipe, but is given here for the purpose of showing the degree of variation to be expected in practice in pipes from different manufacturers, and hence the probable accuracy of the results obtained by the drop of potential method. The working tables to which reference must be made for reducing the millivolt reading to amperes constitute the second set of tables. These tables are derived in part from the first set of tables and contain the card size of the pipe, the weight in pounds per foot, the resistance in microhms per foot of length, and the current corresponding to 1 millivolt drop on 1 foot of length. In Table 1, showing the variations of the dimensions and properties of pipe from different manufacturers, the first column gives the laboratory number, the second column the card diameter, the third column the card weight in pounds per foot, the fourth column the observed weight, and the fifth column the per cent variation from the card weight. Then follow in order the specific gravity, measured resistance per foot of length, resistance per pound-foot, resistance per centimeter cube, and finally the percentage variation of each individual measured resistance from the mean of all the values in this section of the table.

Wrought-iron Pipes—In Table 1, section A, on wrought-iron pipe, will be found test data on 86 test specimens from different manufacturers, all the pipe being of standard weight, with diameters ranging from ¼ inch to 6 inches. The last 32 specimens are the product of one manufacturer and are included in this table because they are sold as wrought-iron pipe, although the resistance measurements indicate a higher resistivity than that of the steel pipe tested. Considering all of the pipes in this section of the table, the variations in weight per foot from the card weight show the pipe to be as frequently over as under weight, the average variation being 2.5 per cent. It will be noted that this variation is much greater in the case of the small pipes of one-half inch or less diameter. The average specific gravity of these specimens was 7.59.

In the resistance data it will be noted that the last 32 specimens referred to above have a resistivity of 14.39 ohms per centimeter

cube as compared with 12.78 and 12.97 for the two other groups; that is, it is higher than the steel, which was found to average 13.56 ohms per centimeter cube. This, of course, greatly increases the variation from the average, and this variation has an average of 4.77 per cent from the mean of the entire set. The average resistance of the entire set per pound-foot is 209.3 microhms.

Steel Pipe—There are 64 specimens of steel pipe from two manufacturers, the data on which are shown in section B of Table 1. Ten of these are boiler tube, on which no per cent of card weight is made, but since practically the same material is used in manufacturing as in the other pipe, the resistance of all specimens are included in the average. The weight variations are somewhat less than in the preceding table, even the small sizes checking very closely, and the average variation from the mean is 2.3 per cent. The resistance is 215.8 microhms per pound-foot and 13.56 microhms per centimeter cube, the value for copper being 1.59 ohms per centimeter cube, and the average variation from the mean is 2.3 per cent, the greatest single difference being 5.2 per cent.

Cast-Iron Pipe.—In section C of Table 1 are given data on 22 specimens of class B cast-iron pipe from two different manufacturers. The diameters range from 3 to 6 inches. The cast-iron pipe industry is quite different from the wrought-iron or steel industry, there being many small companies in the field and the uniformity of the product would not be expected to be as great as in the case of iron or steel pipe. It will be seen from the table that the average resistance per pound-foot is 1227 microhms and the resistance per centimeter cube 84.8 microhms. From these averages certain individual specimens vary as much as from 16 per cent low to 22 per cent high, and the arithmetical average of all the variations from the mean is 9.4. It was observed that internal diameter and wall thickness of these cast-iron pipes were on the average greater than the card values. The card weight shown in Table 1 is not that listed in the standard cast-iron pipe tables, because that weight includes the bell. In these tables the weight per foot is based on the card dimensions and the unit weight 0.264 pound per cubic inch, which figure is used by the manufacturers.

American Ingot Iron.—Thirteen specimens of American ingot iron pipe were received and the data are shown in section D of Table 1. No comparison of weights is made, since the dimensions

were not standard. The average resistance of 177.3 microhms per pound-foot, or 11 microhms per centimeter cube, indicates a much purer grade of metal than the wrought iron or steel discussed above.

Lead Pipe.—In section F of Table 1 are shown measurements on 27 specimens of lead pipe from one manufacturer, the sizes ranging from ¼ inch to 2 inches. A class was not specified in the specimens received, so they were rated in the class to which their weights most nearly corresponded. This would perhaps tend to reduce somewhat the variation in the results, especially since there are eight classes within the range, from very heavy to very light pipe. But lead works very easily, and is so homogeneous that a good uniformity of product might be expected, and an average variation from the mean of 3.9 per cent and an extreme of 10.2 per cent are probably as great as would usually be found in practice. It will be seen that in most cases the specimens were lighter than the card weight. The resistance data show the very decided homogeneity of commercial lead, the average resistance being 419.5 ohms per pound-foot and 21.12 per centimeter cube, and the average variation from the mean is only 0.5 per cent, while the maximum variations are between +2.1 and −1.4 per cent. The average value here given is about 10 per cent greater than generally given for commercial lead, but chemical analysis did not reveal any appreciable amounts of tin or antimony.

Lead Cable Sheaths.—Only a few specimens of lead cable sheaths, and these from one manufacturer, were tested. The practice as to size and thickness and chemical composition varies so much from time to time that any figures that might be obtained would be of little value, except where the composition is definitely known. The figures given in section G of Table 1 were those supplied by the manufacturer.

Copper Steel.—Several grades of copper steel pipe were tested and the results are shown in section E of Table 1. In this table the last column gives the kind of steel and the percentage of copper for the different grades. The specimens tested of a given grade were all uniform but there is considerable variation between the different grades.

In Table 2 there is summarized the resistance of the pipe in ohms per foot for the various sizes and kinds and also the number of amperes corresponding to a drop of 1 millivolt per foot, so that the voltmeter reading needs to be multiplied only by a constant

factor for any given kind and size of pipe. In the use of this table it is necessary to take the millivolt drop E on a portion of the pipe of length L in feet and then refer to the last column under the particular kind and class of pipe used and multiply the figure there found by the ratio of the observed voltage to the length in feet. For example, supposing we are measuring the current flow in a 10-inch cast-iron pipe of class B. Referring to Table 2 it will be seen that for this class a current corresponding to 1 millivolt drop on 1 foot is 42.4 amperes. If we are measuring over a length of, say, 8 feet and the observed millivolt drop is 3 millivolts, the current flow in the pipe will be $I = 42.4 \times 3/8 = 15.9$ amperes.

In using this method it is necessary first to make an excavation at the point where the measurements are to be taken and attach two leads to the pipe, preferably as far apart as practicable without including a joint in the pipe. These connections can be made in any one of a variety of ways, such as by drilling a hole in the pipe and screwing in a plug to which a lead has been soldered. This is all right for a thick-walled pipe, especially cast iron. For thin-walled pipe, however, it has been the practice of the Bureau of Standards to use the swedged connection such as described previously for making connections to rails in over-all potential measurements. If it is desired to use these connections for future measurements, the leads should be brought underground to a point inside the curb and there terminated in an ordinary service box or other suitable receptacle so that they will be protected from traffic but be readily accessible for repeating the measurements at any future time. If it is desired to use these leads for making measurements over a period of several months or longer, it is important to protect the junctions between the wires and the pipes from corrosion by painting them over with a heavy asphalt paint or other suitable protecting agency. The observation of potential can best be made with a millivoltmeter of high-volt sensitivity. A zero center instrument having a range of 10 millivolts on either side of the zero is usually sufficient where the current density in the pipes is relatively high. In many cases, however, where the current is small and the pipe relatively large, and especially in the case of wrought-iron or steel mains in which the resistivity of the pipe is low, a higher sensitivity instrument is often necessary. In such cases a portable galvanometer may be used. Where the currents are large enough to give a reading of 1 millivolt or more over the section spanned by the potential terminals an ordinary recording instrument can be used.

(*b*) Divided-Circuit Methods.—Divided-circuit methods in various forms have been used by a number of investigators for many years. Probably the first to use them was Prof. Adams, of Columbus, more than 15 years ago, and it has been used by a number of other investigators. Credit for having first published a detailed description of the applications of various forms of this method and the procedure for the measurement of current in pipes by them is due to Carl Hering, whose paper was published in the Transactions of the American Institute of Electrical Engineers for June, 1912. The following description of the principle of the method is taken from Hering's paper:

The fundamental principle is as follows: Let *P*, Fig. 10, be a part of an underground pipe which has been uncovered and through which an unknown current *I* is flowing as shown. At first let it be supposed that this current is steady, and of course a direct current. Let *D* be a sensitive galvanometer, millivoltmeter, or any other form of detector of small difference of potential, connected as shown; there should

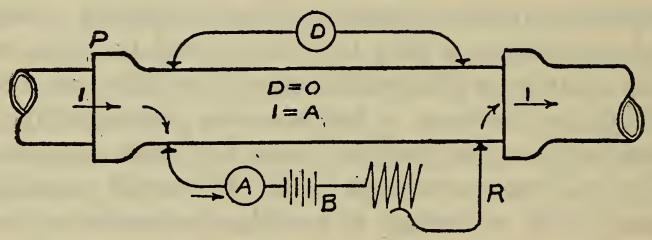

Fig. 10.—*Arrangement of connections fvr Hering's method of calibrating pipe sections*

preferably be no variable resistance like an unbonded pipe joint between the two contact points. Let *A* be an ammeter, *B* a few cells of accumulators, and *R* an adjustable resistance; the shunt circuit containing them is connected, as shown, anywhere outside of the points of application of the voltage detector, the farther away the better—they may even be on the other side of a joint.

To find the current flowing in the pipe adjust the resistance *R* until *D* reads zero; then there will no longer be any current flowing in the shunted part of the pipe, hence the reading of the ammeter will give the current *I* in the pipe. The current may be said to have been sucked out of the pipe by the battery, and made to flow through the ammeter, where it can be measured; as far as the current in that short section is concerned the pipe circuit has in effect been electrically cut in two as though an insulating joint had been introduced.

If *D* is a galvanometer with proportionate deflections, instead of a mere detector, then by taking a deflection immediately after the shunt circuit has been opened a reading proportionate to the drop of voltage for that current will be obtained. The instrument *D* is thereby calibrated to read the pipe currents directly and can be used for this purpose thereafter; the test with the battery current is therefore merely of the nature of a preliminary calibration, and need be carried out only once for each station.

A number of modifications of this method are described in Hering's paper. The chief advantage claimed for this method as

compared with plain drop of potential method described above is that it eliminates the uncertainty of the resistance of the pipe and therefore gives greater accuracy. It is very doubtful, however, whether the complication of the additional apparatus is justified except in special cases. As previously stated, the resistance of the pipe can be definitely determined from the tables with an accuracy of about 10 per cent, and the extremely variable current that is usually found on pipes can hardly be averaged with greater precision than this. Moreover, since the millivolt drop being measured in any practical case is usually very small (generally less than 1 millivolt), quite appreciable errors would be introduced due to thermoelectromotive forces in the millivoltmeter circuit itself. A difference of 3° or 4° in the temperature of the junctions would produce errors amounting to several per cent or larger, and this difference might readily occur, especially in gas pipes when the pipes are excavated and one terminal is more or less damp and others relatively dry. Further, the temperature coefficient of iron pipe, particularly wrought iron or low carbon steel, is very high, and seasonal changes in temperature of the pipe will produce variations of 5 to 10 per cent in the resistance. It appears, therefore, that accurate calibration of the pipe is very rarely justified in view of the complications of the apparatus required for this purpose.

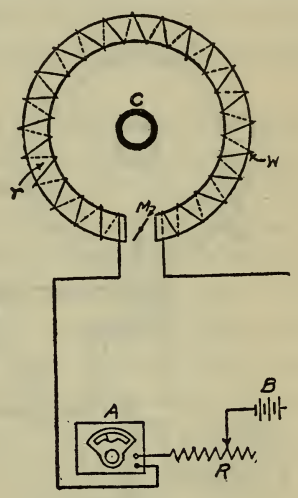

FIG. 11.—*Diagram of D. C. ratio relay*

(*c*). USE OF THE DIRECT-CURRENT RATIO RELAY.—The use of the direct-current ratio relay for measuring current in conductors which can not be opened for the insertion of ammeters or shunts has only recently been employed. The ratio relay permits the measurement of variable continuous currents of any magnitude by means of a small capacity D. C. ammeter. In its fundamental principle of operation the relay consists of a split iron ring *r*, shown in Fig. 11, which is slipped over the conductor *C*, the current in which is to be measured. The iron ring need not be laminated, and it carries a secondary winding *W* consisting of a large number of turns of fine wire in series with a low-voltage battery *B*, a variable resistance *R*, and a direct-current ammeter *A*.

In the gap between the poles of the split ring is placed a small electromagnet M. Current in the conductor C sets up a magnetic flux in the iron, which may be neutralized by a current in the auxiliary winding W from the battery B. When this neutralization occurs, as indicated by the small electromagnet, the ampere turns of C and W are equal and the current in C is read on the ammeter A, the reading being multiplied by the ratio of the turns W to the turns C, which latter in the case of the pipe is unity. This ratio relay is manufactured in two forms, in one of which the secondary is made to follow automatically the fluctuations of the line current C. In the other form, known as the D. C. line current-testing set, the current in the secondary is controlled by the observer. A complete circuit diagram for the automatic instrument is shown in Fig. 12. In this form any magnetism due to unequal primary and secondary ampere turn causes a deflection of the electromagnet M, which in moving will open or close a relay contact K. If the primary ampere turns are in excess K closes, the relay P is energized, and its plunger presses against the action of a spring, a small carbon pile rheostat R causing the secondary current to increase until the secondary ampere turns are slightly in excess, when the contact K opens. When the current in the relay D is kept at K the plunger of the relay P recoils. The resistance of the carbon pile R, whose plates are immersed in oil, increases, and the secondary current falls until the contact at K closes again. Thus there is maintained in the secondary circuit a pulsating current, the average value of whose ampere turns is exactly equal to the ampere turns of the conductor C. The principle of operation is thus quite similar to that of the Tirrill regulator.

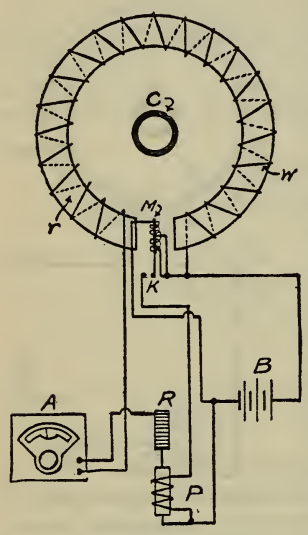

Fig. 12.—*Circuit diagram of automatic D. C. ratio relay*

As these instruments are made commercially two iron cores are provided in connection with the current ratio relay. One is large enough to encircle a conductor up to about 3½ inches diameter, and the other large enough to encircle a conductor up to about 15 inches in diameter. This core is hinged so that it can be placed

around pipes of large diameter. Larger sizes can be provided, if desired.

In order to measure the current in any conductor such as a pipe line, relay, or bus bars, open the hinge core and close it around the conductor. Insert the contact plug so that the current enters the core from the side marked with a cross. After that press the button on the left-hand side of the instrument box and the ammeter will at once show the current flowing in the conductor. Should the direction of the current be unknown, insert the plug either way and if no reading is obtained reverse the plug, whereupon the current flowing in the conductor will be indicated. This instrument will measure current from about 2 per cent of its full rated load up to 100 per cent of the rated load. It can be secured for any desired maximum rating.

The instrument just described, which is automatic in its operation, is most convenient for the measurement of rapidly fluctuating currents such as usually found on pipe systems. It is practicable, however, to use a simpler form known as the d. c. line current-testing set. This differs from the ratio relay in so far as it does not work automatically, but the rheostat which regulates the secondary current to balance the primary magnetizing force is operated by hand. A signal lamp is provided showing when the ampere turns in the secondary coil are in excess of those of the primary, and this instrument can be used very well where the changes of current are not too rapid and where only approximate results are desired. The nonautomatic instrument is simpler in construction, cheaper, and considerably lighter in weight than the automatic relay, and it would often be useful for purposes of electrolysis measurements. This instrument can be used for making current measurements of from about 10 amperes up to any higher value, although the accuracy on a 10-ampere setting would not be very great. This instrument is considerably more convenient to use than the divided-circuit method described above and should prove quite useful where for any reason it might be necessary to get a more accurate measurement of the current than is practicable with the ordinary drop of potential method. It can also be used in connection with the drop of potential method for the purpose of calibrating the pipe; that is, for measuring the resistance of any particular portion of it. This apparatus is manufactured by the Weston Electro-Mechanical Co., of Oakland, Cal.

(*D*) **Current Leakage Measurements.**—It is often desirable to measure the amount of current which is leaking off from a pipe within any given area in order to get an idea as to the general average rate of corrosion within this area. In general, three methods of measuring the intensity of leakage current are available, namely, (1) by differential current measurements—that is, by measuring the current flow in the pipe at both ends of the section within which the leakage is to be determined and taking the difference between the readings as the total leakage within the section in question—(2) by the use of the Haber earth current collector; and (3) by the measurement of polarization potentials.

(*a*) Differential Current Measurements.—The first of these methods can be used advantageously where the section under investigation offers a large area for leakage and where conditions are such that the total leakage of current is large. In this case an accurate measurement of the current flow at the two ends of the section can usually be made to yield a fairly accurate value of the total leakage sought. In work of this kind, however, it is not sufficiently accurate to use the drop of potential method of measuring current, but either some form of the divided circuit method described above, or a d. c. ratio set should be used. The latter is, in general, to be preferred, because of its greater convenience and high accuracy. In making measurements of leakage currents by this method it is necessary to make sure that there are no branches in the pipe or other metallic connections by which current may be carried away from the pipe within the section under examination.

(*b*) Use of the Haber Earth Ammeter.—The Bureau of Standards has experimented with a number of modified forms of this apparatus, the various modifications used being designed to reduce to a minimum the errors accompanying its use. The type that we have found most satisfactory consists of a plate of glass or mica inside of an insulating tube, the inside diameter of which about equals the diameter of the insulating plate, and in our work we have generally used a diameter of 10 cm. (4 inches) and a length of about 10 cm. also. On either side of the insulating plate is placed a thin copper disk from which insulated leads are brought out to connect to a milliammeter. On the outside of the copper plates are placed thin layers of some porous material saturated with strong copper-sulphate solution to prevent polarization. For this purpose one or two heavy sheets of blotting paper

soaked in a saturated solution of copper sulphate has been found very desirable. Outside of these layers of blotting paper the insulating tube is filled in with earth taken from the excavation in which the current is to be collected. It is very important that the earth be packed into the collector as soon as taken from the excavation so that the moisture content will be the same as that in the earth which is to be filled in around the collector; otherwise, the resistivity of the earth in the collector may be greater or less than that of the earth surrounding the collector, in which case the instrument will read in error. In practically all cases we have found that because of the high conductivity of the copper plates and the strong copper-sulphate solution on either side of them, the density of current inside the collector is greater than in the region surrounding it, so that there is a general tendency for the ammeter connected to the leads to read too high, and we have had to overcome this by putting a proper amount of resistance in series with the ammeter. The amount required varies according to the design of the collector and the relative resistivity of the earth inside the collector and that surrounding, and it should be determined for each particular design of collector and for the average conditions under which it is used.

The errors due to the above cause, however, are generally rather small compared to other sources of error, chief of which is the unequal distribution of current discharge from pipe surfaces in actual practice. We have found that the current discharge over any considerable portion of a pipe surface is very nonuniformly distributed, and a current collector placed at one point of a line might show a very heavy current discharge from the pipe, but when moved a foot or two away might show practically no current. For this reason we regard the earth collector as of very little value except for very special kinds of electrolysis survey work, and we rarely use it where the object of the survey is merely to determine the general electrolysis conditions existing in any particular case.

(*c*) Polarization Potential Measurements.—A method that has been proposed for determining the intensity of leakage current on the surface of the pipe at any point is that of measuring the polarization potential at the surface of the pipe. This method has been used to some extent abroad, but has found practically no application in this country.

The polarization voltage at the surface of an electrode is *the change in voltage between an electrolyte and electrode immersed therein*

due to the flow of electric current to or from the electrode. In a great many electrolytes, including some soils, this change in voltage, or the polarization potential, soon reaches a steady state after the application of a current, and the magnitude of the polarization potential is nearly proportional to the intensity of the current flowing. Under such conditions if the potential difference between a pipe and an electrode buried in the soil adjacent thereto be measured at a time of the day when no current is flowing from or to the pipe and again at a time when there is current flowing to or from the pipe, the sign and magnitude of the change of voltage will give a fair idea as to the intensity of the current discharge at the point under consideration. However, in many electrolytes and in certain soils the polarization potential is not by any means proportional to the intensity of the current flowing, so that unless extraordinary care is exercised the results of polarization potential measurements may be decidedly misleading. The variations that may be expected under certain conditions are discussed in another publication of the Bureau of Standards.[1]

The method of polarization potential measurement has the further disadvantage which is common to the use of the Haber earth ammeter as mentioned above, namely, that even if conditions are such as to make the measurement a correct one, it gives only a local value of the current leakage and a very large number of such measurements would have to be made in order that any adequate idea regarding the rate of damage on the pipe could be determined. Further, this method requires two measurements, one of which must be made when it is known that substantially no current is flowing so that it is often quite inconvenient to use.

It will appear from the foregoing that measurements of leakage currents are usually unsatisfactory, not only because of the difficulty of making accurate measurements but because, owing to the irregular and uncertain character of the distribution of the leakage, the measurements when made are of doubtful value.

III. MISCELLANEOUS MEASUREMENTS

1. LOCATION AND TESTING OF HIGH-RESISTANCE JOINTS IN PIPES

In making electrolysis surveys it not infrequently becomes necessary to determine whether or not there are any considerable number of high-resistance joints in certain portions of the pipe system. For example, if it is contemplated to install a pipe-

[1] McCollum and Logan, Technologic Paper No. 26, this bureau.

drainage system on a large cast-iron main, this should not be done until it has been definitely determined that there are no high-resistance joints in that portion of the line in which heavy currents would be caused to flow by the pipe drainage. Also in case it is not definitely known that heavy currents are flowing in any important main it may often be desirable to determine whether or not there are any high-resistance joints, since the presence of such joints in a main carrying heavy current is likely to give rise to serious corrosion on the positive side of the joint. If such joints are found, it is important either to prevent the current from flowing in the pipe or else to bond over the joint so as to minimize the trouble as far as practicable.

High-resistance joints in pipes are most conveniently located by means of potential gradient measurements along the pipes. It is generally best to begin by taking potential difference measurements between accessible points a considerable distance apart, such, for example, as between adjoining fire hydrants or between service connections 100 feet or more apart. Wherever such connections are not readily available, it is entirely feasible to drive holes in the ground above the pipe with a bar or auger and insert in these holes nonpolarizable electrodes, such as described in the previous part of this paper, and measure the potential difference between them after the manner already outlined. It is unnecessary that these holes should be drilled down to the surface of the pipe, but if the holes terminate anywhere within a foot or two of the pipe, they would generally suffice. It is not therefore necessary to locate the pipe with great precision. Measurements are taken between points thus located throughout the length of the pipe that is to be explored, and if there are any resistance joints in the pipe it will be found that the potential-drop readings at certain places will be larger than others, it being assumed of course that potential readings are taken at each point for a sufficiently long period to get a fair average value. The time required will vary from two or three minutes to half an hour according to whether the schedule is frequent or infrequent or whether the current in the pipe is being affected by the cars in a large territory or only by those on a single portion of the line. After going over the line in this way, taking potential-difference measurements between points a considerable distance apart, those sections which show high readings are then explored in more detail in a similar manner by placing the electrodes closer together, and in this

way the location of the high-resistance joint can be definitely determined.

When the location of the joint has been determined it is usually sufficient to measure the drop of potential across the joint and also determine approximately the conductivity of the soil in the vicinity, and from this it can be determined with sufficient accuracy whether the pipe is in serious danger at that point. If the earth resistance is low—such as, for example, a few hundred ohms per centimeter cube—then a drop of potential of 0.1 volt across an ordinary joint should be considered serious; but if the resistance of the earth is very high under average moisture conditions—say, 10 or 15 thousand ohms per centimeter cube or more—a potential drop of several tenths of a volt on a heavy cast-iron main will usually be permissible, although in the case of a wrought iron or steel main a considerably lower value should be maintained. If it is desired to measure the actual resistance of the joint in terms of a given length of pipe, this can be done very conveniently by means of the principle of the Wheatstone bridge, as shown in Fig. 13, in application to rail joints. Here the joint being tested forms one arm of the bridge and a measured length of the pipe a second arm, and two resistances M and N serve as the other two sides of the bridge. The current in the pipe suffices for the test current. It is only necessary to adjust M and N so that the galvanometer or millivoltmeter reads zero, and then the resistance of the joint in terms of a known length of pipe can be determined from the bridge setting.

2. TRACK TESTING

(*A*) **Kinds and Character of Track Tests.**—The need for making electrical tests on railway tracks is, in general, twofold. First, to locate the cause of any bad electrolysis conditions that may have been previously encountered; and, second, to serve as a guide for the systematic maintenance of track bonding and return feeders, and in some instances to determine the need for additional feeders. The track tests usually consist either in measuring the current density in the tracks at various points or in testing the condition of the bonding of the joints and the cross-bonding between tracks. Measurement of current in the tracks is made only when it is desired to find out whether or not additional return feeders are required to prevent excessive track drop even on a well-bonded track. These current measurements are made by the drop of potential method the same as described above for

determining the current flow in pipes or by means of the direct-current ratio relay, also described above. The most frequent measurements, however, are the tests of the bonds and cross bonds.

(*B*) **Methods of Testing Bonds.**—There are three methods in use for testing the condition of track bonds as follows:

(*a*) Examination by Inspection.—This method of testing bonds by simple inspection is one which had much greater vogue in the past than at the present time, but it is unfortunately, even now, too frequently depended upon. It consists usually in going along the track and making superficial inspection of the bonds, and if they appear to be mechanically good, the assumption is made that bonding is in satisfactory condition. Not infrequently this inspection is not made except when snow is on the track with a temperature not much below freezing, in which case the man goes

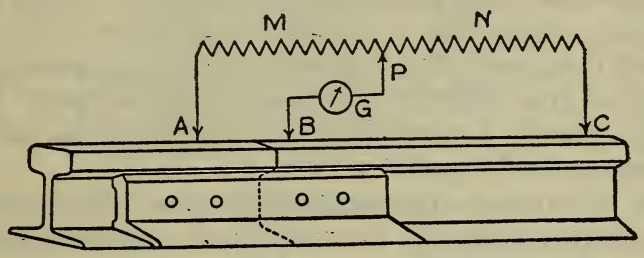

Fig. 13.—*Diagram of circuits in portable bond tester*

along the track and wherever the snow is found to be melting adjacent to a bond the joint is listed for rebonding. This crude method of bond testing can not be too severely condemned. A joint that appears to be mechanically perfect may have a high electrical resistance, due to corroded contacts, which corrosion may not be evident through superficial inspection, and joints may have a sufficiently high resistance to increase the total track resistance several fold without generating sufficient heat to melt snow around the joint. Any examination of bonds by simple inspection should, in general, be regarded as a very poor makeshift and some more accurate method should be used wherever practicable.

(*b*) Use of Portable Bond Testers.—There are in use at the present time a number of portable bond testers operating on the principle of the slide wire bridge, a portable millivoltmeter being used to determine when the bridge is balanced. The principle of operation is essentially similar to that shown in Fig. 13, for the

measurement of the resistance of a high-resistance joint in the pipe. These instruments indicate the resistance of the joint in terms of the resistance of a definite length of rail. One man can operate a testing set of this kind when necessary, although a man with a helper to handle the contact terminals can work somewhat more conveniently and more rapidly. This method of testing, while somewhat slow and tedious, is in most cases about the most economical method of testing bonds.

(*c*) Bond Testing by Means of Special Test Car.—A method that has been used to a considerable extent during the last few years for testing bonds of railway lines is what is known as the "autographic method." This method is like that of the portable bond tester above described and is based on the comparison of the potential drop across a certain length of rail, including the joint with that across an equal length of adjacent solid rail. The two readings are taken and autographically recorded within a fraction of a second; during this short time the variation of the current in the rail is so small that it generally can be neglected, so that the potential drop will be proportional to the resistance. Should, however, a change of current occur, it is shown on the record and due allowance can be made.

General description.—The complete recorder consists of the following principal parts: (1) Recording table, containing necessary measuring, recording, and locating devices, also controlling apparatus for a motor generator set and storage battery; (2) motor generator set consisting of a 600-volt motor directly connected to a low-voltage direct-current generator capable of supplying a local testing current of approximately 500 amperes; (3) storage battery supplying the energy for the spark and auxiliary circuits and the motor which drives the roll of paper on which the record is made; (4) test truck maintaining the necessary contact brushes, interrupter for spark circuit, and contactor for paper drive motor.

The three first mentioned are installed in the temporary test car and the test truck is attached to the car. On high-speed roads where the operation of the test truck would be inconvenient the brushes are mounted on the temporary test car. The measuring instruments are Weston millivoltmeters, one for each rail, provided with a special wire scale which connects with a spark coil. A wire is leading from each division of the scale to the spark cone; the record passes between this spark cone and a bar connected to the spark coil. For each discharge of the spark coil the current pierces the chart at a place corresponding to a position of the

millivoltmeter handle; the discharges are so frequent that every move of the handle is recorded. By means of an electric motor connected with a contactor on a wheel on the test truck the chart is moved proportionally to the distance traveled by the truck.

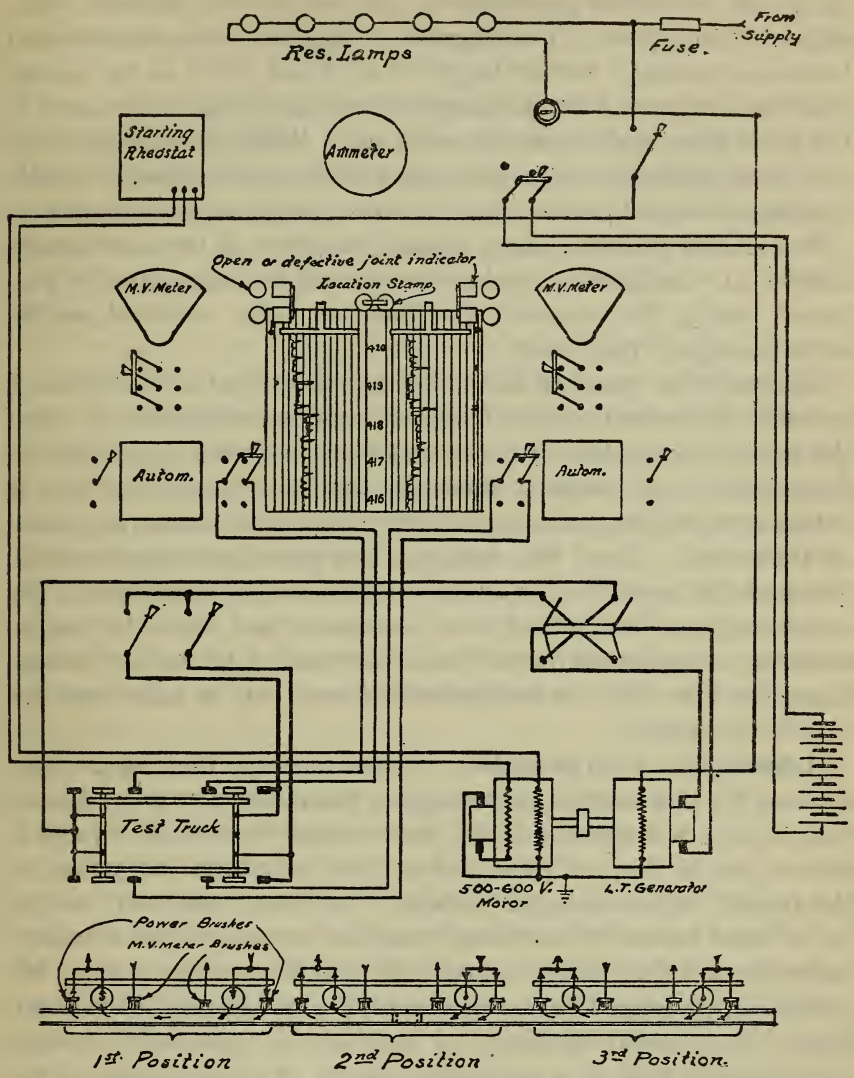

FIG. 14.—*Diagram of external connections of test car*

One inch of record represents 64 feet of track. The diagram in Fig. 14 shows the external connections of the recorder. The local testing current is conveyed to and from the rail by means of the contact brushes, and in a similar manner the connection of the

millivoltmeter is brought in contact with the rail. In order to eliminate thermoelectromotive forces the brushes are of steel similar to the rail.

Method of Operation.—When the test truck is moving along the track the successive positions of the brushes will be those indicated at the bottom of the diagram. The first shows the potential brushes spanning a certain length of solid rail, while in the second position they span an equal length of rail, including a joint, and in the third they again span the solid rail. While the brushes have had these positions every movement of the millivoltmeter needle has been recorded on the chart by means of the electric sparks.

Should the potential drop exceed the limit of the instrument, which is 110 millivolts, the instrument will be automatically protected during the overload, this incident being recorded on the extreme edge of the record.

Although the speed of the paper is proportional to the distance traveled, it is usual to take frequent locations of landmarks along the route in order that more exact locations of bad joints may be determined. At frequent intervals the local testing current is withdrawn and the amount and direction of the rail current noted on the record. From the change in the potential drop the direction and the amount of traction current can be determined. By connecting one instrument as a voltmeter and the other as an ammeter a continuous record can be obtained of the trolley voltage along the line and the transmission losses can be calculated for any desired point.

Advantages of Autographic Test.—Among the advantages claimed for this method of testing are the following: (1) A special test current is employed in the joints under test, so that there is always ample drop of potential to give a definite indication on the record; this avoids the difficulty frequently met with in the use of bond testers of insufficient traction current to give a definite indication on the testing instrument, which may give rise to frequent and prolonged delays on the part of the tester; (2) it eliminates the personal element; (3) it gives an autographic record which can be filed as a permanent record of the condition of the track at the time of test; (4) a large amount of track can be covered in a short time, so that a test of the entire road can be quickly made at any particular period.

The cost of testing bonds by this method depends upon the locality and local conditions, but in general it is somewhat greater

than the cost of manual testing with the usual portable bond tester. This apparatus is manufactured and operated by the Maintenance Improvement Co. (Inc.), 14 Church Street, New York City. A number of railway companies have designed and used test cars of various descriptions for the testing of rail bonds, but the detailed description of these is beyond the scope of this paper.

Practice regarding the maintenance of track bonds varies considerably, and different companies permit widely varying resistance in bonds before considering them in need of replacement. In the majority of cases, however, a joint which has a resistance greater than 6 to 10 feet of rail is regarded as defective. This subject is discussed in detail in another publication of the Bureau of Standards.[2]

(*d*) Testing of Cross Bonds.—In addition to testing the joint bonds above referred to it is important also to test periodically the condition of cross bonds. This can best be done by means of a low-reading voltmeter having a range not exceeding about 1 volt, the method being to go along the track and at frequent intervals measure the potential difference between the two rails of the single track and also between the tracks of the double-track line. It is permissible, as a rule, to have considerably higher potential drops between rails and tracks than would be allowed on a single joint, but in general, the drop of potential between rails in any particular location should not be greater than about 0.1 volt.

(*e*) Periodic Testing of Bonds.—It is highly desirable for the purpose of permanently maintaining good electrolysis conditions to adopt the practice of testing periodically all bonds and cross bonds on a railway system. If the track is once placed in good condition and the roadbed is, in general, of substantial construction so as to prevent excessive mechanical strains on the joint due to passing traffic, the testing of bonds about once a year will probably be sufficient under most conditions. Where, however, the joints are known to be deteriorating rapidly and particularly where the roadbed is such as to allow considerable movement of the joints under the weight of traffic, much more frequent bond testing will be necessary if the track is to be maintained at all times in reasonably good condition.

[2] E. R. Shepard, Modern Practice in the Construction and Maintenance of Rail Joints and Bonds in Electric Railways, Technologic Paper No. 62, this Bureau.

3. MEASUREMENT OF EARTH RESISTANCE

In connection with any extensive electrolysis survey it will, in general, be desirable to take a considerable number of samples of earth from widely scattered points throughout the area under investigation and measure the resistivity of these samples. This data is often desirable to assist in the interpretation of the electrical tests made in connection with the survey, since if the earth resistance is, in general, very high it will be safe to permit higher potential drops between various points of the pipe networks than would be safe if the earth resistance were found to be, in general, comparatively low. The methods for measuring earth resistance and the conditions under which tests should be made are set forth in detail in another publication of the Bureau of Standards.[3]

4. MEASUREMENT OF LEAKAGE RESISTANCE BETWEEN RAILWAY TRACKS AND EARTH

(*A*) **Importance of Tests.**—The determination of the average resistance of the leakage path between railway tracks and surrounding earth is often very desirable, particularly where it is necessary to determine what over-all potential drops may safely be permitted in the track return. It will be evident that if the resistance of the leakage paths is very high it will be safe to allow higher potential drops on the track than if the leakage resistance be low, although the voltage drop which may be considered safe is not directly proportional to the average resistance of the leakage path. The relation between these is discussed in detail in another publication of the Bureau of Standards.[4]

(*B*) **Method of Testing.**—The Bureau of Standards has given considerable attention to tests of this character and still has the subject under investigation. A considerable number of tests on various types of roadbeds have been made, during the course of which two methods have been found satisfactory. One of these methods consists of inserting insulating joints in the track at two points distant 1000 feet or more apart and bonding around these with a heavy bond designed to be conveniently opened at any time for testing. The test is made at night when no traffic is on the line, the shunt around the insulating joint being opened and then a low-voltage battery applied between the isolated section of track and a suitable earthed terminal giving a very low resistance to ground. For this purpose the railway track on either side of

[3] McCollum and Logan, Technologic Paper, No. 26, this Bureau.
[4] McCollum and Logan, Technologic Paper, No. 63, this Bureau.

the isolated section can be used. These tracks have substantially the potential of a point on the earth quite remote from the track section under test. When this connection is made the current flowing from the battery to the isolated section of track must practically all pass off through the track roadbed in this section, the leakage around the insulating joints being very small compared to the total leakage through the roadbed of the section under test; and this current is measured simultaneously with the potential difference between the track and a second earth terminal which should preferably be remote both from the isolated track section under test and from the earth terminal which is carrying the cur-

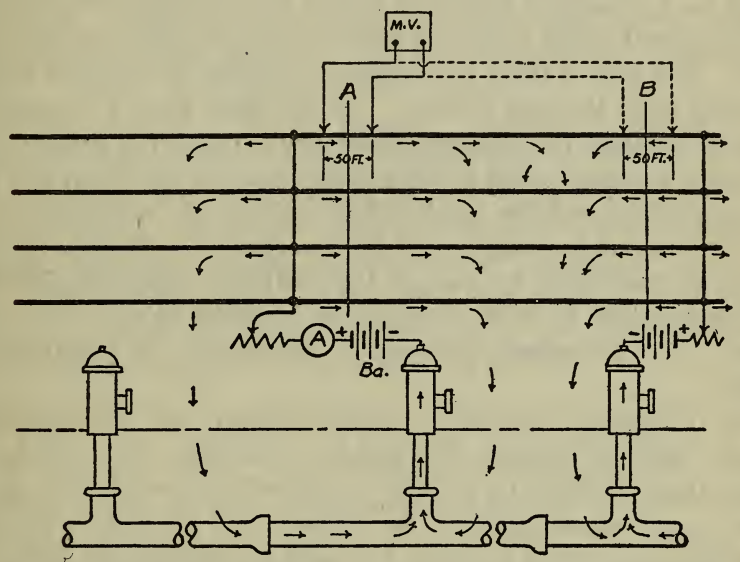

FIG. 15.—*Diagram of connections between a double-track railway line and adjoining pipe syestem, for measuring leakage resistances of a section of roadbed*

rent of the battery. The resistance of the leakage path between the isolated track section and ground is then calculated from the ammeter and voltmeter readings.

The second method of testing which has given satisfactory results in some cases eliminates the necessity of inserting insulating joints in the track, a procedure which is often quite difficult, especially where cross bonds or space bars are frequently used, In this method two batteries are required and the arrangement is shown in Fig. 15. The batteries are stationed from one to several thousand feet apart and connected as in the preceding test, one terminal being connected to track and the other to an earthed terminal some distance away. It is desirable to connect the

positive terminal of both batteries to the track and the negative terminal to earth, since this represents the polarity existing in practice where a current is leaking from the track into the earth. From an examination of the figure it will be seen that a great deal of current flowing from each battery will flow off in the directions away from the section under test, as indicated by the arrows, but a certain amount, corresponding to the total leakage of the current on the section between the batteries, will flow into this section. If now we measure the millivolt drop on a short length of the rails at the points *A* and *B*, just inside the points at which the batteries are connected to the tracks, we can calculate from this millivolt drop on a measured length of rail of known weight the approximate current which is flowing into the section under test from each end. The sum of these two currents will then be the total leakage current from the test section. At the same time a voltmeter is used to measure the potential difference between the section under test and a remote point in the ground, as at *E;* and from this voltmeter reading and the total leakage current the resistance of the section can be calculated. If high accuracy is sought, the rails must be calibrated by one of the methods described above for calibrating pipe in order to secure an accurate value of the resistance. This refinement, however, is unnecessary in practically all cases.

A considerable number of measurements of this sort have shown that, in general, the leakage resistance of 1000 feet of single-track roadbed of ordinary type will be found to range between 0.3 ohm and about 6 to 8 ohms. In general, in concrete roadbeds and others in which the rails are thoroughly embedded in the earth the leakage resistance is quite low; whereas where the track is so constructed that the rails are entirely out of contact with the earth and the ties set on well-drained rock ballast, the leakage resistance is very high. It is obvious that, in view of this very wide range of roadbed resistance, it would be absurd to limit the permissible voltage drop in any section of track to the same value, regardless of its resistance. Hence it is important to determine the approximate roadbed resistance in various portions of a railway system before a strictly logical limitation of voltage drop could be prescribed. It is most important, and in general would be sufficient, to determine the leakage resistance of the tracks at a few points in the system in outlying regions where the current tends most to leak off the rails and also in the region near the power house where current is returning to rails, care being

taken to select representative types of construction. An experienced engineer can usually form a fairly accurate judgment regarding the leakage resistance of a railway roadbed by inspection of the line or by an examination of the specifications under which the road was constructed, so that where only a rough estimate is required an actual measurement of the leakage resistance is not necessary.

5. DETERMINATION OF THE CAUSE OF CORROSION

There is a very common impression extant that the final products of the corrosion of iron when due to stray currents are the black oxides, whereas in the case of self-corrosion the red oxide is produced. Numerous investigations have been made with a view to determining whether or not this is true to any appreciable extent. These investigations are described in some detail in Technologic Paper 25 of this Bureau. In these experiments it is shown that when iron corrodes, whether due to electrolysis from stray currents or to local galvanic action, the first product of corrosion is usually the hydroxide of iron or some other soluble salt of iron, depending on the constituents of the electrolyte in the soil. When these come in contact with the oxygen usually prevalent in soil waters an insoluble precipitate of iron oxide is formed. If the rate of corrosion is relatively rapid and the concentration of oxygen relatively low, the tendency will be to form ferrous oxides, and there may, therefore, be expected a predominance of the black magnetic deposit often mistakenly called graphite. If, on the other hand, the rate of corrosion is relatively low and there is an abundant supply of oxygen in the soil water, the tendency will be for the ferric or red oxide to predominate. In most soils the amount of oxygen that can come in contact with the dissolved iron salt is usually quite limited, so that where the corrosion is very rapid there will be a definite tendency toward the formation of the black oxide. As a rule, especially in severe cases of electrolytic corrosion, the corrosion takes place much more rapidly than in the case of soil corrosion, so that, in general, we would expect the black oxide to result from corrosion due to this cause, whereas in the majority of cases, due to the slowness with which self-corrosion proceeds, we would expect a predominance of red oxide. This rule is by no means infallible, however, because electrolytic corrosion sometimes takes place more slowly where the current discharged from the pipes is very small, and further special cases arise in which self-corrosion proceeds with great ra-

pidity, as, for example, in certain acid soils or in soils in which cinders, furnace slag, or other foreign materials exist which may form galvanic couples when in contact with iron. In such cases the end products of self-corrosion may be black oxides and appear identical in every respect to the end products of electrolytic corrosion. It is therefore impossible to tell with certainty from the examination of a corroded pipe whether or not the corrosion has been caused by stray currents. Nevertheless, wherever a large preponderance of the black or magnetic oxide exists it may usually be regarded as a good indication that the rate of corrosion has been so great as to make it probable that stray currents have been largely responsible, unless corrosion tests under the same conditions which exist locally show that self-corrosion can take place with great rapidity. At the present time the only certain way of determining whether or not stray currents are causing corrosion in a particular case is to make proper electrolytic tests to determine whether the pipes are actually discharging current into the earth. In a case where serious corrosion has been caused by stray currents, and the cause of the stray currents later removed, the only way of determining whether the previous corrosion was caused by stray currents or by local influences is to make actual corrosion tests in the soil under the same average conditions of moisture and using the same kind of iron as was previously found corroded. In the absence of a test of this kind it is not possible at the present time to fix with certainty the cause of the damage.

6. DETERMINATION OF THE SOURCE OF STRAY CURRENTS

Cases frequently arise in practice where it can be easily established that pipes or other underground structures in a given locality are being damaged by stray currents, but the question arises as to the source of the stray current which is causing the trouble. This question arises frequently where two or more electric railway systems operate with grounded return in the same or near-by districts. There are, in general, two ways of determining the source of the stray current under such conditions. One method consists essentially in connecting voltmeters, preferably recording voltmeters, between the pipes or other structures which are discharging current into the earth and some other structure into which the currents are being discharged, which latter may be an auxiliary earth terminal if desired, and then shutting down momentarily first one and then another of the

railway power houses and determining the effect of this on the reading of the voltmeter. In case the shutting down of one railway system makes practically no difference in the voltmeter reading, while the shutting down of the other results in marked reduction of the reading of the instrument, it indicates quite definitely that current from the second system is the one giving rise to the trouble.

Another method which may often avoid the necessity of shutting down the power houses even temporarily consists in connecting one recording voltmeter in a suitable manner to the pipe structure, as described above, and connecting other recording voltmeters between the railway tracks and earth in all those sections of track which are known to be strongly positive to earth, and therefore discharging current into the earth. These instruments are allowed to run for a considerable period, preferably for several hours, and the shape of the curves giving the potential-difference readings at different points on the railway system are compared with the shape of the voltage curve obtained in the underground structure under investigation. If the potential difference between the injured pipe and the earth varies widely and in a substantially similar manner, as potential difference between the tracks and earth in any particular section of the railway system, it affords a definite indication that it is the leakage of the current from this section that is giving rise to most of the damage. Sometimes it will be found that the damage in a given locality is caused chiefly by the leakage from a single railway line or section of line, in which case the investigation is considerably simplified. More frequently, however, the corrosion at any point may be affected simultaneously by the leakage of current from a number of railway lines. Usually an examination of the local system will show which lines are likely to be affecting the district under investigation, and where two or more lines appear to be thus involved it is necessary to combine the readings of potential difference between tracks and earth of all of these lines, thus giving a composite leakage curve, which is to be compared with the curve of potential difference on the pipe structure under investigation. As a rule, it will be found that enough disturbing influences are at work so that the potential-difference curves will not be of exactly the same shape, but it is usually possible to show whether or not they tend, in general, to increase or decrease simultaneously, and in the majority of cases the source of the greater part of the stray current can be definitely determined in this way.

7. LOCATING CONCEALED METALLIC CONNECTIONS

During the course of electrolysis surveys it is frequently necessary to locate concealed metallic conductors such as buried cross bonds in the tracks, metallic connections between the pipes and railway negative return, or even to determine the exact location of pipes themselves where such location is only approximately known. The most frequent and difficult case encountered is the location of unknown metallic connections between pipes and railway return. To locate these with a minimum of time and effort three classes of measurements are generally made.

(1) Potential-difference measurements between the pipes and railway tracks are made, and where these are much smaller than would be expected from over-all potentials and potential gradients which have been found to prevail throughout most of the railway area, it indicates a strong probability of the existence somewhere of metallic connections between the pipes and railway negative return. These may not, however, be directly between the pipes and tracks, so that potential-difference measurements made at various points along the track will not reveal even the approximate location of such connections. Their existence having been established with considerable probability by the potential-difference measurements, the next step is to measure potential differences between fire hydrants or, in the case of gas systems, between gas-service connections several hundred feet or so apart. The first such measurement will show in which direction the current is flowing in the main to which the hydrants or services are connected, and then the tester should proceed along the main in the direction in which the current is flowing and take a similar reading a few hundred feet farther on. In general, it will be found that the current will be flowing from all directions toward the point at which the metallic connection sought is made to the pipe, so that if the tester continually proceeds in the direction of current flow, he will ultimately come to a point at which the direction of current flow is reversed, and in a very short time he can almost always locate the connection within 200 or 300 feet. It can often be much more closely located by measuring potential differences between adjacent house services, it being possible in this way usually to locate the connection within 30 or 40 feet. This, however, is not close enough to make it economical to find by it excavation, but an exact location can now be determined by the use of a special exploring coil similar to that used by telephone com-

panies for locating crosses in telephone circuits. The principle of this is shown in Fig. 16. In this figure let *A* and *B* represent a railway and pipe system which are connected at some point by the buried metallic conductor *C*, the location of which it is desired to find. A special high-frequency buzzer or other interrupting device *D* is connected between the two pipe systems at any convenient point, a battery being in series with the interrupter. This can be made to send an intermittent current between the systems *A* and *B*, a portion of which will return by way of the metallic connection *C*. An exploring coil connected to a telephone receiver, if carried along the surface of the earth in the vicinity of the pipes *A* or *B*, will give a sound in the telephone receiver when brought near the buried conductor on which the intermittent current is flowing, due to the electromagnetic induction in the exploring coil. If the plane of this coil is parallel to the direction of

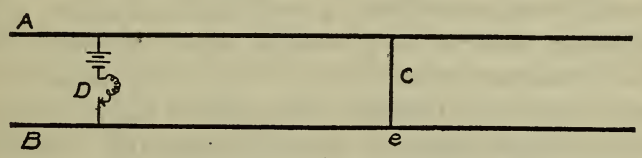

FIG. 16.—*Diagram of connection for locating concealed connection between buried metallic structures*

the conductor *B*, for instance, the intensity of the sound will be a maximum. If now the tester holds the telephone to his ear and proceeds along the pipe *B*, always keeping in such position that the intensity of the note in the receiver is a maximum, he will follow the course of the pipe system until he comes to the point *E* at which the metallic connection is attached, and as he proceeds farther there will be a sudden diminution in the sound in the telephone receiver. By then moving at right angles in either direction he can soon pick up the course of the connection *C* and trace it across to the other pipe system *A*. The hidden connection can then be uncovered and removed if desired. By following this procedure it is usually possible to locate a hidden connection within two or three hours, although in some cases where very complicated underground networks exist there may be so many disturbing influences and parallel paths for the current to follow that the definite location of the desired cross connection may be extremely difficult.

8. EXAMINATION OF CONCRETE STRUCTURES

In making an examination of concrete buildings, bridges, or other structures that are reported to have been injured by or to be in danger from stray currents it should first be determined whether or not the structure is of plain or reinforced concrete. If the structure contains no reinforcing material, there is no necessity of making any further investigation, because it has been definitely established that electric currents exert no deleterious effect on nonreinforced concrete.[5] If the structure in question is found to contain reinforcing material, an inspection should first be made to see whether there are any external evidences of injury of such character as may result in some cases from the discharge of current from reinforcing material into the concrete.

The existence of electric current in any particular structure can be determined by measuring potential drops between selected points on the structure spaced a considerable distance apart. If the reinforcing material is accessible, the instrument terminals should be connected directly to it, but if the terminals of the instrument have to be directly connected on the concrete, a nonpolarizable terminal similar to that described above in this report should be used. It is important in making such measurements to bear in mind that with sufficiently delicate instruments a potential difference will be indicated between any two points selected at random on a building or any other conducting structure; but the existence of such potential differences should not be accepted as evidence that any serious stray currents are flowing. If such readings are found to be of the order of magnitude of a few millivolts they should not be regarded as of any consequence. Where, however, readings of a few tenths of a volt or more between points comparatively close together are found, the source of these had best be determined.

In general, there are three possible sources from which stray electric currents may get into a building or other structure. First, from a private power plant within the building; second, through leaks from light or power mains which enter the building; and third, from stray currents from electric railway lines. It can readily be determined which of these possible sources may be giving rise to stray currents in any particular case by connecting a voltmeter between points in the building which exhibit appre-

[5] Technologic Paper No. 18, this Bureau.

ciable potential differences and momentarily shutting down the private plant or cutting off the outside source of electrical power. If the stray current comes from either of these sources, there will be sudden changes in the voltmeter reading when the sources of supply are shut off. If switching these sources on or off makes practically no difference in the voltmeter reading, steps should then be taken to see whether or not stray currents are entering the building on the grounded circuits of railway or other power lines. Where stray currents of this kind get into the building they usually enter or leave through water or gas pipes or cable sheaths which enter the building, or in rare cases through the bases of columns or foundations. It is a simple matter to determine whether or not currents are entering or leaving the building through any metallic pipes or cables which enter the building by merely taking potential-drop readings on a short length of such conductors; and the question as to whether currents are entering or leaving through columns of the building can be determined by similarly making potential-drop measurements on a suitable length of the column near its base. If the current is found to be entering the building through pipes or cables, substantially the same amount of current may be found to be leaving through other pipes or cables at other points, in which case it would usually be improbable that any serious danger would be set up. Where, however, more current flows into the building on metallic structures than is flowing out on similar metallic structures the difference might be expected to be leaving the building through the columns and foundations, in which case some damage might result; and in such cases the simplest and most obvious remedy would be to insert insulating joints in the pipes or cables which are conveying current into the structure.

In making such investigations it should be constantly borne in mind that ordinary concrete is an excellent preventive of corrosion of embedded iron, not only as regards self-corrosion, but also as regards electrolytic corrosion, and unless the potential differences between various parts of the building are of considerable magnitude no fears should be felt regarding the safety of the structure. In particular, great care should be exercised not to be misled by the presence of inevitable galvanic differences of potential which can be found in practically every structure of this kind but which cause absolutely no harm.

Part 4.—INTERPRETATION OF RESULTS OF ELECTROLYSIS MEASUREMENTS

I. GENERAL CONSIDERATIONS

The interpretation of the results of electrolysis tests requires long experience and thorough familiarity with the subject of electrolysis from stray currents. No specific key to the interpretation of the test data can be given, but below are discussed some of the fundamental principles involved, as well as some of the difficulties encountered in making a correct interpretation of electrolysis survey data.

As a rule, no single set of readings such as over-all potential measurements or measurements of current flow in pipes can be interpreted by itself alone, but must be judged by a variety of other conditions. For instance, very high over-all potentials may at times be accompanied by, and in some measure caused by, high leakage resistance between track and ground. This resistance is sometimes so high that even very high over-all potentials would not cause sufficient current to leak from the tracks into the earth to give rise to any serious electrolysis conditions. On the other hand, where the leakage resistance between tracks and ground is very low, the current delivered to the track in outlying portions will readily leak off into the earth, thereby greatly reducing the current in the rails and correspondingly reducing the voltage drop in the track. As pointed out in another part of this report, different types of roadbeds commonly encountered in electric railway work exhibit widely different characteristics as to leakage resistance between tracks and rails, some showing a resistance many times greater than other types of construction. In some cases 50 per cent or more of the total current may return by way of the earth and pipes, thus giving rise to low over-all potential drops, whereas if all of the current was compelled to return by the rails, much higher over-all potentials would prevail, although electrolysis conditions would be decidedly better in the latter case. Hence, while high over-all potentials *under average conditions* indicate bad electrolysis conditions, nevertheless, under certain conditions where leakage resistance is very high, such would not be the case; and conversely low over-all potentials *may result from* very bad electrolysis conditions due to low leakage resistance between tracks and earth.

Similar considerations apply to potential-difference measurements between pipes and tracks. High values of leakage resistance tend, in general, to produce high potential differences, whereas if the leakage resistance is low, a much larger current may flow from pipe to tracks with even considerably smaller potential differences. Hence, potential-difference readings alone can not be accepted as an indication of the amount of current discharged, and before even approximate conclusions can be drawn from them some definite idea regarding the leakage resistance between pipes and tracks near the points of measurement must be obtained. This depends not alone on the character of the roadbed. The location of the pipes is an important factor in determining both the amount of leakage current and also the distribution of such leakage current. Further, because of the effect of location on pipes on the distribution of leakage current, it is not sufficient to determine the total amount of current which the pipes may be discharging, but it is important also to know where and how the current leaves the pipes. If a main parallel to a railway line is at all points 20 or 30 feet distant, the current discharge will generally be distributed over a large area, so that a considerable amount of current may be discharged from the pipes without serious corrosion developing at any point. On the other hand, if the pipe comes very close to the track at a few points, as, for instance, where the main or services cross directly under the track and within a few feet of the surface, the current discharge will be greatly concentrated at such points, thereby giving rise to very rapid deterioration of the pipe. Again, even though it may be determined that the current is not doing any injury to the pipes at the point at which it is leaving them, as, for example, where pipe drainage is installed and the current is practically all removed from the pipe through metallic connections, it can not be concluded that such currents are not doing any injury to the pipe system on which they may be flowing, since there are, as a rule, a considerable number of high-resistance joints in pipe systems, and these resistances may be high enough to cause considerable current to leak around the joint, thus giving rise to considerable corrosion on the positive side of the joint in many and unlooked-for places throughout the pipe system. In addition to these considerations it must be borne in mind that current flow on any one pipe system may injure not alone the pipe system on which the current is found, but it may be causing even greater injury on some other

pipe or cable system from which it may be discharging into the system in which it is actually measured. Therefore, where considerable amounts of current are found on any pipe system it is important to find out whether it is producing trouble in any other pipe system from which it may be drawn. This is particularly important in cases where pipe drainage is applied to one or more of the pipe systems in any given locality. Even if drainage is applied to all the systems, great care must be exercised not to drain one system more than another, as by so doing considerable injury to the systems of higher potential may be produced. For this reason it is desirable to measure potential differences between the different systems of underground structures occupying the same general locality, as pointed out in an earlier part of this paper.

It will be evident from the foregoing considerations that the very low potential differences in the positive areas which accompany most installations of pipe-drainage systems may induce a false sense of security unless due consideration is given to the secondary conditions which may be set up by the pipe-drainage connections.

II. THE USE OF REDUCTION FACTORS

In most cases it is not practicable to take readings of current and potentials at any point over a sufficiently long time to get a fair average value of the readings at that point. Such readings should always be taken as long as circumstances permit, but in making electrolysis surveys it is usually necessary to take a large number of readings scattered over a wide area so that each reading can be continued only for a comparatively short time. Such short-time readings can not, in general, be used directly as a basis for determining electrolysis conditions. The great variability of railway loads generally causes the readings to fluctuate decidedly from time to time and in order to interpret properly the results of the survey the readings must be reduced to some common basis as, for example, either the potential for average scheduled traffic, the all-day average, the operating-day average, the average for the maximum hour, or the maximum average value for any 10-minute period. Each of these bases has certain advantages and disadvantages depending partly on individual conditions; and the method of procedure will often differ, depending on the method to be followed in interpreting the results. All are affected by such

factors as rush or light days, unusual weather conditions, electric heaters in cold weather, morning and evening peak loads, and other causes; and these factors must be considered. Electrolytic damage is determined by average conditions over long periods, but danger from arcing and overheating are more closely related to maximum values. Since electrolytic damage is by far the most important because of its continual and universal occurrence, while only very rare cases of arcing and overheating have been observed, the average values over long periods give a much more accurate index of the seriousness of the trouble than any short-time readings.

The great unreliability of short-time readings for determining electrolysis conditions is especially noticeable when comparing the load curve of a line having a 5, 10, or 15 minute schedule with that of hourly interurban service, or when comparing that of a station having a 45 per cent load factor with one having a load factor of 10 per cent. Because of this great variation and uncertainty in short-time measurements and for the purposes of interpretation and comparison, it is desirable that all short-time readings be reduced to values for some representative period, preferably the all-day average.

(*A*) **Ten-Minute Basis.**—Some engineers prefer to determine directly the highest average value for a period of about 10 minutes and use this as an index to electrolysis conditions, while some even attach importance to momentary peak values. The maximum 10-minute potential is a peak load value and must be measured at the time of peak, it being too variable to derive from a value observed during another part of the day and corrected by means of the load curve, as suggested later for readings over longer periods. Reading the actual value with no correction from a load curve has the advantage of greater simplicity and is free from one source of error, due to the possibility of the load curve being different on the line measured from the load curve used in calculations, which would probably be that of the station supplying that line. On the other hand, the 10-minute value during peak load fluctuates between much wider limits than the average for a longer period and results from one day to another will lack concordance to a much greater extent than in case of readings taken over longer periods, due to the irregular and widely fluctuating character of the load.

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Numerous investigations have shown[6] that the actual amount of corrosion which takes place is much more nearly proportional to the average all-day load than it is to any short-time peak value. For this reason it is undesirable to place undue significance on high-peak values of voltage readings which are of short duration, provided the average value of such readings throughout the day is small. Voltage readings taken during such high-peak periods or during another hour of the day should be referred to the load curve for the district under consideration in order to determine the approximate value of the all-day average. Better still, as is pointed out above, the readings should be taken over a longer period of time where practicable.

Our experience in attempting to interpret results of surveys by means of short-time peak values has convinced us that not only is it open to objection on the ground that, even if accurately obtained, it is not a true index of the electrolysis situation, but the accurate determination of such peak values will generally require practically as much time as the taking of measurements over greater periods, such as an hour or longer. This is due to the fact that in order to make sure of getting the reading during the maximum 10-minute period of any particular day it will be necessary to continue the reading over a period of at least one-half hour and preferably longer, and further, owing to the variation of the 10-minute maximum from day to day, such readings would have to be repeated on a number of different days in order that either the highest maximum value, or the average maximum value, may be obtained.

(*B*) **Hour Basis.**—The average values of a reading taken over a period of one hour, either during peak load or for average scheduled traffic, or any time of day, gives values of sufficient length of time and reliability that they can usually be repeated from day to day with a fair degree of consistency. Some ordinances prescribe as a limiting value of voltage the average value for the maximum hour. Peak values of this duration usually occur at a fairly definite time each day so that one-hour readings during peak load can generally be determined with fair accuracy, and where measurements are being taken with a view to determine whether or not an ordinance of this character is being complied with, it would obviously be most logical to take the readings for an hour or somewhat longer during peak load. However, for

[6] Technologic Paper No. 25, this Bureau.

ordinary survey work designed to determine the actual danger which exists to the pipes the one-hour values have the same weakness, although to a lower extent, as the 10-minute maximum values possess in that they are not an accurate index to the magnitude of the danger from electrolysis. If, however, the load curve of the station or principal feeders supplying the district under consideration is at hand, a reading taken over a period of one hour during practically any time of the day will permit the ready determination of the average value throughout the entire day with sufficient accuracy for practically all purposes. In gen-

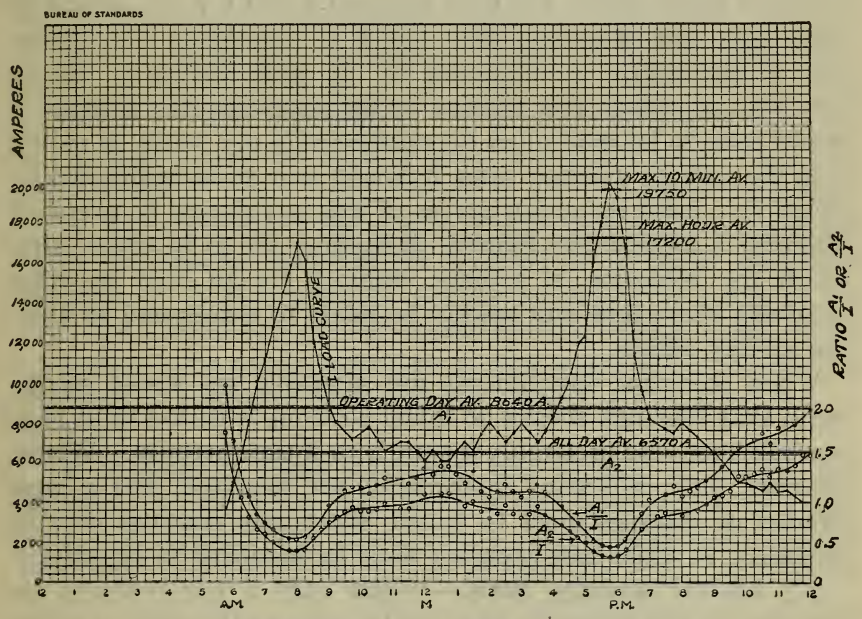

FIG. 17.—*Typical chart for correcting short-time readings to all-day or other average values*

eral, we would urge the taking of a large number of one-hour readings rather than a relatively small number of readings of a longer period, the one-hour readings being later reduced to average all-day values. The method of making this reduction is illustrated by curves in Fig. 17. In this figure curve I with the two high peaks is the load curve of a power station supplying a certain area under test. From this load curve either the operating-day average represented by the line A_1 can be determined, or the all-day or 24-hour average represented by the line A_2. If the reading at any point is taken during any particular hour of the day, its value reduced to the operating average would be the actual reading of the instrument multiplied by the ratio of the operating-

day average to the average ordinate of the load curve during the period when the reading was being taken. These ratios between the operating-day average and the actual value of the load are plotted in the curve marked $\frac{A_1}{I}$ and the ratios between the 24-hour average values and the actual load are plotted in the curve marked $\frac{A_2}{I}$. The ordinates of these curves for any hour can be used directly as the reduction factor to reduce an actual reading to an average for the day on either basis. For example, if the reading has been taken during the hour between 5 and 6 p. m., it will be very high, due to having been taken at practically the highest part of the load. By reference to the ratio curves it will be seen that to reduce this reading to the operating-day average it would have to be multiplied by substantially 0.5, while to reduce it to the 24-hour average value it would have to be multiplied by about ⅓. Load reduction curves of this sort should be prepared wherever a considerable number of readings are to be taken, after which the reduction of average readings for an hour or other relatively short time can readily be made to correspond to average all-day values.

When recording instruments are available we would recommend that readings always be taken covering a period of at least one-half hour, and preferably for one hour if time permits. Where, however, only indicating instruments are available and a large number of readings must be taken, short-time readings may be necessary, in which case accuracy must be sacrificed to expedition.

(*C*) **All-Day Average Basis.**—Where only a few readings are required, so that sufficient time can be given to the work, it is best to take all important readings over a period of a full day. In most cases, however, in making a complete electrolysis survey this can not be done, and readings have to be taken for a shorter period and reduced to the all-day values by the method described above.

III. EFFECT OF REVERSALS OF POLARITY

Throughout a large portion of every grounded railway return system it will be found that the potential differences between pipes and track frequently reverse in direction, the pipes becoming alternately positive and negative to earth with periods varying from a few seconds to several minutes or even longer; and special consideration has to be given to measurements in such places in

order that even an approximate estimate of their significance can be made. In general, four different classes of conditions have to be recognized in interpreting these measurements as follows:

(1) **Polarity of Pipes Always the Same.**—If the pipes are always of the same polarity, as, for example, always positive to surrounding structures, it is of course the arithmetical average value that should be used in judging the significance of the readings.

(2) **Polarity of Pipes Changing with Long Periods of Several Hours.**—If the pipes at any point are continuously positive for a period of several hours, and then of opposite polarity for a succeeding period of some hours, a condition which frequently exists in localities where a substation is operated during only a portion of the day, there will, in general, be very little protective effect due to the period when the pipe is negative to earth, and the actual corrosion is nearly indicated by the arithmetical average value of the voltage during the hours in which the pipe is positive to earth, this average of course being reduced to the 24-hour average basis. Thus, if a given pipe is found to be 4 volts positive to the tracks or other neighboring structure for a period of 12 hours, and either negative or at zero potential for the remaining 12 hours of the day, the actual amount of corrosion that would occur would undoubtedly be nearly equivalent to that which would result if the potential at the same point was maintained at 2 volts for the full 24 hours.

(3) **Polarity of Pipes Reversing with Periods of Only a Few Minutes.**—Under these conditions it has been shown by extensive experiments [7] that the corrosive process is in large measure reversible, and the actual amount of corrosion comes more nearly being proportional to the algebraic average of the applied potential than it is to the arithmetical average during the total time the pipe is positive. In all cases, therefore, where the polarity of the pipe is continuously reversing and the period of reversal does not exceed 5 or 10 minutes, the algebraic average should be used as the criterion of the importance of the reading.

(4) **Polarity of Pipes Reversing with Periods of from 15 Minutes to 1 Hour.**—Under these conditions neither the algebraic average nor the arithmetical average of the applied potential or current flow gives an accurate index of the amount of corrosion. For the shorter period the algebraic average comes more nearly being the best criterion, while as the period increases in length the arith-

[7] Technologic Paper No. 72, this Bureau.

metical average tends to give a better indication of the extent of the resulting corrosion. However, even where the period of reversal is as long as one hour the corrosive process is, under most conditions, to a considerable extent reversible and some allowance in interpreting the results should be made. The effect of the length of the period of reversal on corrosion is shown in the paper above referred to.

Part 5.—SELECTION OF INSTRUMENTS

In general, in making electrolysis surveys both indicating and recording instruments are required, the former being useful for taking very short-time readings of a preliminary nature that often assist materially in laying out a detailed plan for a comprehensive survey, and such instruments are also useful at times in certain kinds of measurements, such as measurements of current flow in large pipes where, because of the low value of the potential drop, recording instruments can not readily be obtained with sufficient sensitivity to record the values. Wherever it is practicable to use recording instruments, however, it is desirable to do so, since in this way readings can be taken over a greater length of time without unduly increasing the cost of the survey; and, moreover, a permanent record is obtained in which the personal element is eliminated.

On account of the variable and more or less irregular character of the readings, high accuracy in the measuring instruments is not required, but all instruments should be sufficiently rugged to yield moderate accuracy even under the severe handling such instruments must inevitably receive in field service.

In indicating instruments, which often have to be read quickly, owing to the highly variable character of the load, the scale should be so graduated that fractions of the numbered divisions can be quickly estimated without danger of error. This can be most easily and accurately done if the subdivisions are tenths of the numbered divisions. Since readings reverse frequently, zero-center instruments are usually desirable both in indicating and recording types. In many cases, especially in indicating instruments, it may be more convenient to have the zero a little to one side of the center so as to give a scale, such as -5, 0, $+10$ volts, or other ranges in the same proportion. This is desirable, owing to the fact that readings usually tend more strongly in one direction than in another, and in a scale of this kind a wider effective

range of the instrument is secured. For all purposes an instrument of very long period is desirable, since with rapidly fluctuating loads such an instrument can be more easily and accurately read, and it is the average values rather than momentary peaks that we desire to secure. When two instruments are to be read simultaneously it is important that they have identical periods, as otherwise phase displacements of the pointers may give rise to large errors. A long period is especially desirable in the case of recording instruments where, unless the period of the pointer be very long, the record will, on a rapidly fluctuating load, be so obscured that it will be practically impossible to determine the true average value of the reading over any desired period of time. We have frequently found it necessary to resort to special means to greatly increase the period of recording instruments. This has been done by shunting polarization cells of very large capacity around the moving coil of the instruments and having a certain amount of resistance in series with the instrument which, in many cases, can be the multiplier of the instrument. In this way periods of from 30 to 60 seconds have been obtained on Bristol recording instruments, and when such instruments are running on one-hour speed a smooth, distinct curve representing the algebraic average of the reading is obtained even with widely and rapidly fluctuating voltages. Although this result can be successfully achieved, the means for accomplishing it has not yet been developed beyond the experimental stage.

The volt sensitivity required of instruments is dependent on the range desired for each measurement, but it is often very important that the current sensitivity of the voltmeter should be high. High resistance is readily obtained in the better classes of instruments and should be sufficient to overshadow or permit an accurate correction for external resistance, such as long leads or soil contact resistance.

For an indicating instrument the Bureau of Standards has frequently used a special high-sensitivity voltmeter with a resistance of 2900 ohms per volt, and ranges of 5, 25, 50, and 100 volts have been found convenient and suitable for most voltage surveys in which an indicating instrument is needed. For recording instruments having a resistance of from 2 to 4 ohms in the lowest range, multipliers have been provided giving ranges of 0.005, 0.025, 0.1, 0.5, 2, 10, 50, and 150 volts. These ranges give a practically universal recording instrument for voltage and current survey work. The

lower ranges are used chiefly for current measurements by measuring the millivolt drop on a pipe or cable, the resistance of which is determined by calculation or from tables. Recording instruments for electrolysis work should always be of the dotting type, in order that they may have sufficient current sensitivity so that they may be given a high resistance in order to eliminate as far as practicable the necessity of correcting for the resistance of leads or contacts. Where such correction is found necessary it may conveniently be obtained by means of a very high resistance indicating instrument connected in parallel with the recorder. Where the necessary data are available the resistance of the circuit can be directly calculated, or in some cases it may be measured.

The Bureau of Standards has used in its survey work the Esterline dotting-type graphic recording voltmeter, and also the Bristol dotting-type smoke-chart recording voltmeter. Both of these instruments have been found very satisfactory for practically all purposes. The Esterline instrument has an advantage in certain cases, especially where readings are to be taken over a long period of time, because the ribbon-type record makes it practicable to run the chart at very high speed, and thus get greater detail over a long period without changing charts. Where records are to be taken over periods of one hour the Bristol instrument has some advantages. With this instrument running on the one-hour speed sufficient detail can be obtained for practically all purposes and the record at each point can be taken on a separate chart which greatly facilitates classification and filing of the records. The smoke-chart records have to be handled more carefully until after the record is taken and fixed, and this is in some cases a disadvantage. Figs. 18 and 19 show, respectively, typical Esterline and Bristol smoke-chart records.

For indicating instruments we have found several types of Weston instruments very satisfactory, and the Weston model 45, which can be had with double scale and in practically any range, is very much used. Keystone instruments made in triple ranges are also much used and are particularly useful where a very wide range of values must be taken with the fewest possible number of instruments.

For work requiring extremely high current sensitivity, such as for use with nonpolarizable electrodes, or for measuring extremely small potential drops on heavy metallic structures, a portable galvanometer is very desirable. An instrument which we have

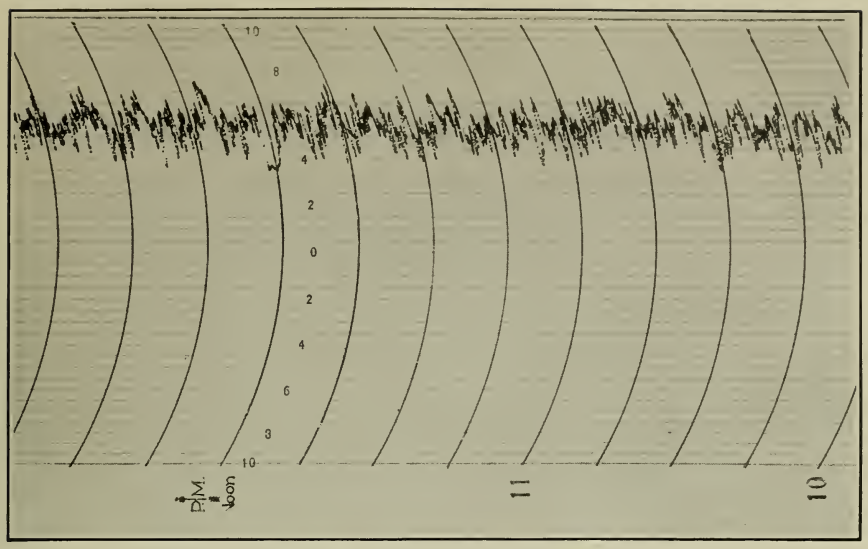

FIG. 18.—*Section of Esterline record*

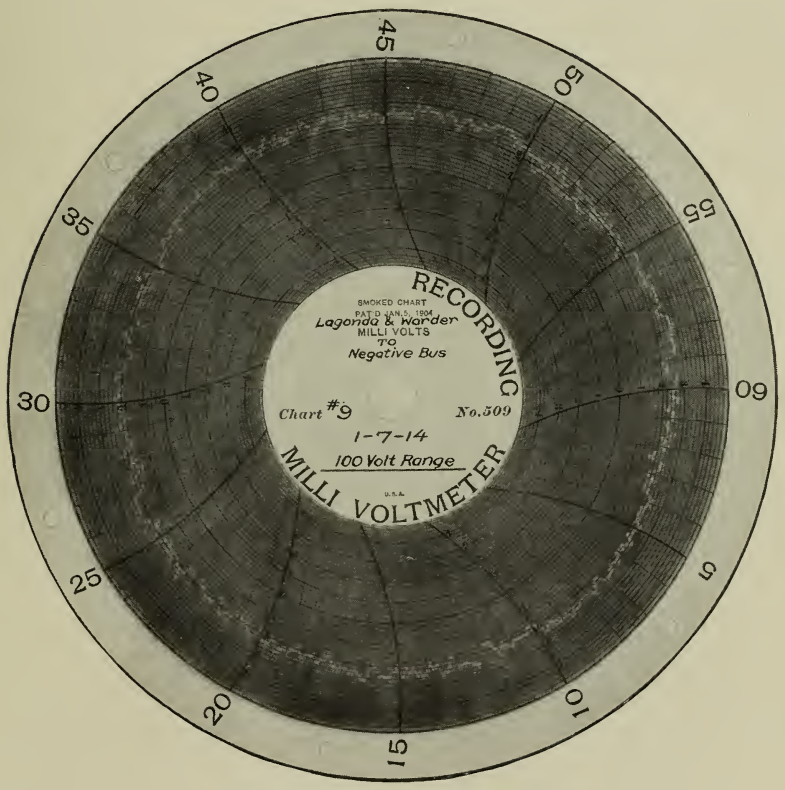

FIG. 19.—*Bristol smoke chart record*

used with much success for this work is a portable telescope galvanometer manufactured by Leeds & Northrup Co. The instruments of this type have a resistance of 225 ohms without multipliers, so that no special care need be exercised to secure very low resistance contacts on pipes such as is necessary with the ordinary millivoltmeters.

The telescope is mounted permanently with the instrument and the instrument possesses substantially the same degree of portability as ordinary portable voltmeters. In its use, however, considerably greater care is necessary in keeping the instrument level and we have found that the most convenient way to use it is to mount it on an ordinary surveyor's tripod. This not only facilitates leveling the instrument but brings it at an elevation where it can be conveniently read from a standing position. This instrument has a sensitivity of 20 megohms, and since its resistance is 225 ohms, as above stated, it would give a deflection of one scale division for about 1/88 of a millivolt.

For general electrolysis survey work we would recommend that one or more of all of the instruments mentioned above be available; and where very much work is to be done a considerable number of recorders will be found desirable both for reasons of economy and for expediting the tests.

Part 6.—NEED FOR SUPERVISION OF ELECTROLYSIS SURVEYS

It is well to emphasize here the desirability of having electrolysis surveys carried on under the direct supervision of a competent engineer thoroughly familiar with the subject of electrolysis from stray currents. The very great value of the properties generally exposed to possible danger from electrolysis is such as to make this question one of great importance. Further, the subject is a very complicated one, and not only are the sources of error in measurements and interpretation of results very great, but many of the measurements, unless studied and interpreted by one thoroughly familiar with the subject, may be so misleading as to destroy in large measure the value of the investigation.

While almost any one familiar with the use of electrical measuring instruments can carry out the details of the work, this should always be done under the supervision of an engineer who has had considerable experience in work of this kind, and where no local

engineer is available for supervising this work a competent consulting engineer should be employed. We can not too strongly urge upon the owners of underground utilities and railway companies the importance of considering this matter of electrolysis investigations in the light of a serious engineering problem and one which should not be dealt with by the more or less empirical and unscientific methods that have too often been followed in the past. It must be said, however, that there has in recent years been a marked tendency toward giving more careful and scientific study to this subject, and this has led to a marked betterment of electrolysis conditions in general throughout the country.

WASHINGTON, March 28, 1916.

APPENDIX—TABLES 1 AND 2

TABLE 1

Resistance and Other Data as to Pipes

Section A.—WROUGHT-IRON PIPE

Specimen No.	Card diameter (inches)	Weight (pounds per foot)		Variation from mean (per cent)	Specific gravity	Resistance			Variation from mean (per cent)
		Card	Observed			Microhms per foot	Microhms per pound-foot	Microhms per cubic centimeter	
B 1	0.25	0.42	0.387	− 7.8	.....	533.4	206.4	13.33	− 1.3
B 2	.25	.42	.411	− 2.1	7.579	477.9	196.4	12.56	− 6.1
B 3	.375	.56	.536	− 4.3	7.653	376.7	201.9	12.94	− 3.5
B 4	.375	.56	.546	− 2.5	.....	347.3	204.4	13.07	− 2.3
B 5	.50	.84	.858	+ 2.1	.....	234.5	201.2	12.81	− 3.8
B 6	.50	.84	.846	+ .7	7.549	232.0	196.3	12.58	− 6.2
B 7	.75	1.12	1.17	+ 3.5	.....	174.3	203.9	13.05	− 2.5
B 8	.75	1.12	1.11	− 1.8	7.615	185.0	205.3	13.18	− 1.9
B 9	1.00	1.67	1.76	+ 5.4	.....	115.9	204.0	13.09	− 2.5
B 10	1.00	1.67	1.74	+ 4.2	7.563	121.7	211.8	13.55	+ 1.2
B 11	1.25	2.25	2.23	− .9	7.670	87.08	193.7	12.09	− 7.4
B 12	1.25	2.25	2.21	− 1.8	.....	92.57	204.6	13.10	− 2.2
B 13	1.50	2.69	2.67	− .7	.....	72.66	194.0	12.42	− 7.3
B 14	1.50	2.69	2.82	+ 4.8	7.629	73.09	206.1	13.21	− 1.5
B 15	1.50	2.69	2.72	+ 1.1	.....	71.32	194.0	12.43	− 7.3
B 16	1.50	2.69	2.73	+ 1.5	.....	76.26	208.2	13.36	− .5
B 17	2.0	3.66	3.84	+ 4.9	7.659	50.35	193.3	12.39	− 7.6
B 18	2.0	3.66	3.71	+ 1.4	.....	52.24	193.8	12.45	− 7.4
B 19	2.5	5.77	5.86	+ 1.6	7.663	32.58	190.9	12.24	− 8.7
B 20	2.5	5.77	5.70	− 1.2	7.651	33.53	191.1	12.24	− 8.6
B 21	3.0	7.54	7.64	+ 1.3	.....	25.25	195.2	12.51	− 6.6
B 22	3.0	7.54	7.82	+ 3.7	.....	25.18	196.9	12.60	− 5.9
Y 1	3.75	.56	.494	−15.6	.....	424.1	209.6	13.44	+ .2
Y 2	.....	.....	.493	−12.0	.....	421.7	208.0	13.34	− .6
Y 3	.....	.....	.500	−10.7	7.578	413.4	206.8	13.26	− 1.1
Y 4	.50	.84	.821	− 2.3	.....	253.8	208.3	13.36	− .4
Y 5	.....	.....	.835	− .6	.....	251.1	209.6	13.44	+ .2
Y 6	.....	.....	.831	− 1.1	7.635	252.9	210.2	13.48	+ .5
Y 7	.75	1.12	1.13	− .9	.....	176.7	199.4	12.79	− 4.7
Y 8	.....	.....	1.12	0	.....	179.8	201.2	12.91	− 3.8
Y 9	.....	.....	1.12	0	7.643	179.2	201.5	12.92	− 3.7
Y 10	1.00	1.67	1.67	0	.....	119.8	200.2	12.84	− 4.3
Y 11	.....	.....	1.66	− .6	.....	119.3	198.5	12.73	− 5.1
Y 12	.....	.....	1.67	0	7.597	119.3	199.2	12.77	− 4.8
Y 13	1.25	2.25	2.30	+ 2.2	.....	90.42	208.2	13.35	− .5
Y 14	.....	.....	2.29	+ 1.8	.....	91.23	208.8	13.39	− .2
Y 15	.....	.....	2.29	+ 1.8	7.542	91.21	209.0	13.40	− .1
Y 16	1.50	2.69	2.64	− 1.9	.....	78.81	208.1	13.35	− .5
Y 17	.....	.....	2.65	− 1.5	.....	78.89	208.7	13.38	− .2
Y 18	.....	.....	2.68	− .4	7.608	77.67	208.1	13.34	− .5

TABLE 1—Continued

Resistance and Other Data as to Pipes—Continued

Section A.—WROUGHT-IRON PIPE—Continued

Specimen No.	Card diameter (inches)	Weight (pounds per foot)		Variation from mean (per cent)	Specific gravity	Resistance			Variation from mean (per cent)
		Card	Observed			Microhms per foot	Microhms per pound-foot	Microhms per cubic centimeter	
Y 19	2.00	3.66	3.48	− 4.9	.....	57.16	198.7	12.74	− 5.0
Y 20	.....	.....	3.46	− 5.5	.....	57.08	197.6	12.67	− 5.5
Y 21	.....	.....	3.51	− 4.1	7.582	56.32	197.6	12.67	− 5.5
Y 22	2.50	5.77	5.94	+ 2.9	.....	31.73	188.5	12.09	− 9.9
Y 23	.....	.....	5.94	+ 2.9	.....	32.49	191.7	12.37	− 8.4
Y 24	.....	.....	5.96	+ 3.3	7.671	32.70	194.9	12.50	− 6.8
Y 25	3.00	7.54	7.50	− .5	.....	26.09	195.7	12.55	− 6.5
Y 26	.....	.....	7.50	− .5	.....	26.49	198.7	12.74	− 5.0
Y 27	.....	.....	7.51	− .4	7.668	26.52	192.2	12.78	− 4.8
Y 28	3.50	9.05	8.72	− 3.6	.....	23.01	200.6	12.87	− 4.1
Y 29	4.00	10.72	10.6	− 1.1	.....	18.75	199.0	12.70	− 4.9
Y 30	4.50	12.49	12.9	+ 3.3	.....	15.61	201.9	12.95	− 3.5
Y 31	5.00	14.56	14.5	− .4	.....	14.14	205.7	13.19	− 1.7
Y 32	6.00	18.76	18.7	− .3	.....	10.61	198.1	12.71	− 5.3
R 1	.375	.56	.558	− .4	.....	416.2	232.1	15.00	10.9
R 2	.....	.....	.564	+ .7	.....	419.3	230.6	14.90	10.2
R 3	.....	.....	.572	+ 2.1	7.551	396.8	226.9	14.66	+ 8.5
R 4	.50	.84	.812	− 3.3	.....	265.9	216.0	13.95	+ 3.2
R 5	.....	.....	.815	− 3.0	.....	288.6	235.1	15.19	12.9
R 6	.....	.....	.817	− 2.7	7.509	265.9	217.2	14.03	3.8
R 7	.75	1.12	1.10	− 1.8	.....	216.5	238.3	15.40	13.9
R 8	.....	.....	1.10	− 1.8	.....	221.9	234.2	15.72	16.2
R 9	.....	.....	1.13	+ .9	7.441	206.0	233.7	15.10	11.2
R 10	1.0	1.67	1.68	+ .6	.....	127.2	213.0	13.76	+1.8
R 11	.....	.....	1.68	+ .6	.....	128.6	216.1	13.96	+3.3
R 12	.....	.....	1.67	0	7.589	124.5	208.4	13.46	− .08
R 13	1.25	2.25	2.25	0	.....	101.7	228.5	14.76	+9.2
R 14	.....	.....	2.28	+ 1.3	.....	106.4	242.0	15.64	15.7
R 15	.....	.....	2.32	+ 3.1	7.514	95.88	222.7	14.39	6.5
R 16	1.5	2.69	2.66	.....	.....	79.20	211.0	13.63	8.6
R 17	.....	.....	2.70	+ .4	.....	81.10	219.0	14.14	4.7
R 18	.....	.....	2.65	− 1.5	7.570	82.16	217.6	14.06	4.0
R 19	2.0	3.66	3.74	+ 2.2	.....	59.61	222.8	14.39	6.5
R 20	.....	.....	3.69	+ .8	.....	61.37	226.7	14.64	8.4
R 21	.....	.....	3.73	+ 1.9	7.584	60.08	224.5	14.47	7.3
R 22	2.5	5.77	5.87	+ 1.7	.....	37.10	217.7	14.06	3.4
R 23	.....	.....	5.86	+ 1.6	.....	37.37	219.0	14.15	4.7
R 24	.....	.....	5.84	+ 1.2	7.660	37.77	220.7	14.26	5.5
R 25	3.0	7.54	7.62	+ 1.1	.....	28.76	219.1	14.15	4.7
R 26	.....	.....	7.73	+ 2.5	.....	28.17	217.6	14.06	4.0
R 27	.....	.....	7.63	+ 1.2	7.602	28.58	218.0	14.09	4.2
R 28	3.5	9.05	8.90	− 1.7	.....	24.57	218.8	14.13	4.6
R 29	4.0	10.72	10.6	− 1.1	.....	20.27	215.4	13.91	3.0
R 30	4.5	12.49	12.6	− .9	.....	17.63	222.1	14.35	6.2
R 31	5.0	14.56	14.3	− 1.8	.....	14.99	214.4	13.85	2.5
R 32	6.0	18.76	18.4	− 1.9	.....	11.98	220.9	14.27	.....

TABLE 1—Continued

Resistance and Other Data as to Pipes—Continued

Section B.—STEEL PIPE, STANDARD WEIGHT

Specimen No.	Card diameter (inches)	Weight (pounds per foot)		Variation from mean (per cent)	Specific gravity	Resistance			Variation from mean (per cent)
		Card	Observed			Microhms per foot	Microhms per pound-foot	Microhms per cubic centimeter	
Y 33	0.25	0.42	0.420	0	.....	521.2	218.9	13.81	+1.4
Y 34	.25	.42	.425	+1.2	.....	517.4	219.9	13.87	+1.9
Y 35	.25	.42	.425	+1.2	.....	515.9	219.0	13.82	+1.4
Y 36	.375	.57	.556	−2.5	7.769	396.3	220.3	13.90	+2.0
Y 37	.375	.57	.556	−2.5	.....	403.9	224.7	14.17	+4.1
Y 38	.375	.57	.551	−3.3	.....	403.9	222.4	14.03	+3.0
Y 39	.50	.85	.796	6.5	7.754	261.6	208.2	13.13	−3.6
T 40	.50	.85	.799	−6.0	.....	261.1	208.7	13.16	−3.3
Y 41	.50	.85	.803	−5.5	.....	257.8	206.9	13.05	−4.2
Y 42	.75	1.13	1.11	−1.8	7.414	203.9	225.5	14.22	+4.4
Y 43	.75	1.13	1.10	−2.7	.....	206.5	227.1	14.33	+5.2
Y 44	.75	1.13	1.11	−1.8	.....	205.1	226.5	14.29	+4.9
Y 45	1.0	1.68	1.65	−1.8	7.706	132.3	218.3	13.77	+1.1
Y 46	1.0	1.68	1.64	−2.4	.....	133.0	217.5	13.72	+ .7
Y 47	1.0	1.68	1.66	−1.2	.....	131.8	218.5	13.78	+1.2
Y 48	1.25	2.27	2.22	−2.2	7.739	98.44	218.1	13.76	+1.0
Y 49	1.25	2.27	2.22	−2.2	.....	98.41	218.2	13.76	+1.1
Y 50	1.25	2.27	2.22	−2.2	.....	97.91	217.1	13.68	+ .6
Y 51	1.5	2.72	2.62	−3.7	7.804	84.84	222.2	14.02	+2.9
Y 52	1.5	2.72	2.62	−3.7	.....	84.43	221.5	13.97	+2.6
Y 53	1.5	2.72	2.62	−3.7	.....	84.78	222.4	14.03	+3.0
Y 54	2.0	3.65	3.44	−6.1	7.824	63.49	218.6	14.11	+1.3
Y 55	2.0	3.65	3.45	−5.8	.....	63.39	218.4	13.78	+1.2
Y 56	2.0	3.65	3.45	−5.8	.....	62.12	214.4	13.52	− .7
Y 57	2.5	5.79	5.88	+1.6	7.815	37.96	223.3	14.09	+3.4
Y 58	2.5	5.79	5.90	+1.9	.....	37.11	218.8	13.80	+1.3
Y 59	2.5	5.79	5.88	+1.6	.....	37.33	219.6	13.85	+1.7
Y 60	3.0	7.58	7.64	+ .8	7.843	28.02	214.0	13.50	− .9
Y 61	3.0	7.58	7.62	+ .5	.....	28.14	214.5	13.53	− .6
Y 62	3.0	7.58	7.65	+ .9	.....	28.20	215.7	13.61	.1
Y 63	3.5	9.11	9.02	−1.0	.....	23.93	215.8	13.62	0
Y 64	5.0	14.62	13.09	−4.9	.....	15.83	219.9	13.87	+1.9
Y 65	6.0	18.97	17.9	−5.6	.....	12.07	216.6	13.66	+ .3
N 23	.....	.....	2.46	.....	.....	85.0	209	13.07	−3.2
N 24	.....	.....	2.47	.....	.....	85.1	210	13.14	−2.7
N 25	.....	.....	2.47	.....	.....	84.2	208	12.98	−3.7
N 26	.....	.....	2.47	.....	7.83	84.8	209	13.08	−3.2
N 27	.....	.....	2.49	.....	.....	83.0	207	12.90	−4.1
N 28	1.25	2.27	2.17	−4.4	.....	95.8	208	12.98	−3.7
N 29	1.25	2.27	2.17	−4.4	7.79	96.4	209	13.09	−3.2
N 30	1.25	2.27	2.15	−5.3	.....	97.3	209	13.11	−3.2
N 31	.75	1.13	1.13	0	7.80	183.8	208	12.99	−3.7
N 32	.75	1.13	1.14	+ .9	.....	186.6	213	13.25	−1.3
N 33	.75	1.13	1.14	+ .9	.....	184.6	210	13.18	−2.7
N 34	.375	.57	.56	−1.8	7.76	399.0	223	13.86	+3.2
N 35	.375	.57	.56	−1.8	.....	394.0	221	13.92	+2.7
N 36	.375	.57	.57	0	.....	389.0	222	13.83	+2.8

TABLE 1—Continued

Resistance and Other Data as to Pipes—Continued

Section B.—STEEL PIPE, STANDARD WEIGHT—Continued

Specimen No.	Card diameter (inches)	Weight (pounds per foot)		Variation from mean (per cent)	Specific gravity	Resistance			Variation from mean (per cent)
		Card	Observed			Microhms per foot	Microhms per pound-foot	Microhms per cubic centimeter	
N 37	.125	.24	.24	0	.....	934.0	224	13.77	+3.8
N 38	.125	.24	.23	−4.2	7.82	928.0	214	13.34	− .9
N 39	.125	.24	.23	−4.2	.....	926.0	213	13.45	−2.9
N 40	2.0	3.65	3.44	−6.0	.....	60.8	209	13.07	−3.2
N 41	2.0	3.65	3.45	−5.6	7.83	60.6	209	13.05	−3.2
N 42	2.0	3.65	3.48	−4.7	.....	60.2	209	13.07	−3.2
N 43	.....	.....	3.92	.....	.....	52.4	205	12.85	−5.1
N 44	.....	.....	3.84	.....	7.83	56.4	216	13.54	0
N 45	.....	.....	3.83	.....	.....	57.0	218	13.65	+1.0
N 46	.....	.....	3.92	.....	.....	52.6	206	12.91	−4.6
N 47	.....	.....	3.83	.....	.....	57.0	218	13.64	+1.0
N 48	3.5	9.11	10.18	.....	.....	20.9	213	13.29	−1.3
N 49	3.5	9.11	10.23	.....	.....	20.9	213	13.35	−1.3
N 50	3.5	9.11	10.23	.....	.....	20.8	212	13.29	−1.8
N 51	6.0	18.97	18.33	−3.4	.....	11.87	218	13.60	−1.0
N 52	6.0	18.97	18.38	−3.1	.....	11.81	217	13.56	+ .5
N 53	6.0	18.97	18.37	−3.2	.....	11.96	221	13.72	+2.4
Average	.....	.....	.....	2.3	.....	.....	215.8	13.56	2.3

Section C.—CAST-IRON PIPE, CLASS B

100	3.0	14.6	13.8	− 5.5	6.803	93.24	1287	89.48	+ 4.9
101	3.0	14.6	14.2	− 2.7	7.086	88.73	1259	86.68	+ 2.6
102	4.0	20.06	16.8	−16.2	7.070	72.09	1211	83.81	− 1.3
103	4.0	20.06	17.0	−15.2	7.056	73.17	1244	85.81	+ 1.4
104	6.0	31.14	27.5	−11.6	7.033	39.05	1074	74.15	−12.5
105	6.0	31.14	30.8	− 1.1	7.035	44.05	1357	93.85	+10.6
200	4.0	20.06	18.3	− 8.7	7.000	65.40	1198	82.71	− 2.4
201	4.0	20.06	16.8	−16.2	7.044	69.05	1160	80.32	− 5.5
202	4.0	20.06	18.0	−10.2	6.980	65.91	1186	81.90	− 3.3
203	4.0	20.06	17.3	−13.7	7.030	68.31	1182	81.75	− 3.7
204	4.0	20.06	20.7	+ 3.2	7.106	49.73	1029	71.35	−16.1
205	4.0	20.06	20.7	+ 3.2	7.087	55.04	1139	78.94	− 7.2
300	6.0	31.14	27.4	−12.0	7.102	38.25	1048	72.44	−14.6
301	6.0	31.14	28.4	− 7.8	7.085	38.59	1096	75.67	−10.7
302	6.0	31.14	27.8	−10.7	7.117	28.26	1063	73.42	−13.0
303	6.0	31.14	28.3	− 9.1	7.084	38.22	1082	74.64	−11.8
400	4.0	20.06	18.6	− 7.3	7.188	75.06	1396	96.75	+13.8
401	4.0	20.06	17.7	−11.7	7.019	74.84	1325	91.52	+ 8.0
402	4.0	20.06	19.0	− 5.3	7.227	69.60	1322	91.43	+ 7.9
500	6.0	31.14	27.8	−10.7	7.096	54.15	1505	104.1	+22.7
501	6.0	31.14	28.2	+ 9.4	7.065	51.10	1441	99.71	+17.4
502	6.0	31.14	28.2	+ 9.4	7.037	49.18	1387	95.79	+13.0
Average	.....	.....	.....	9.1	.....	.....	1227	84.83	9.3

TABLE 1—Continued

Resistance and Other Data as to Pipes—Continued

Section D.—INGOT IRON PIPE

Specimen No.	Card diameter (inches)	Weight (pounds per foot)		Variation from mean (per cent)	Specific gravity	Resistance			Variation from mean (per cent)
		Card	Observed			Microhms per foot	Microhms per pound-foot	Microhms per cubic centimeter	
A 1	2.0	Not standard	3.81	Not standard	.....	46.03	175.2	10.90	−1.2
A 2	2.0		3.83		.....	46.31	177.2	11.02	− .1
A 3	2.0		3.80		7.858	46.65	177.4	11.04	+ .1
A 4	2.5		4.66		.....	38.20	178.1	11.08	+ .4
A 5	2.5		4.69		.....	37.98	178.2	11.08	+ .5
A 6	2.5		4.71		7.837	37.69	177.7	11.05	+ .2
A 7	3.0		6.07		.....	29.54	179.2	11.14	+1.0
A 8	3.0		6.08		.....	29.20	177.6	11.05	+ .2
A 9	3.0		6.14		7.858	29.02	178.2	11.08	+ .5
A 10	3.5		6.61		.....	26.95	178.2	11.08	+ .5
A 11	3.5		6.64		.....	26.70	177.3	11.03	.....
A 12	3.5		6.63		.....	26.41	175.1	10.89	−1.3
A 13	4.5		12.28		.....	14.41	177.0	11.01	− .2
Average	.....	.....	.....	.....	7.851	.....	177.3	11.03	.5

Section E.—COPPER STEEL PIPE

11 [a]	2.0	Not standard	3.38	Not standard	7.810	78.4	265	16.57	+0.1
12 [a]	2.0		3.37		7.817	78.7	265	16.55	− .1
13 [a]	2.0		3.39		7.827	78.4	266	16.57	+ .1
21 [b]	1.5		2.48		7.819	94.9	236	14.71	+ .2
22 [b]	1.5		2.50		7.822	94.2	236	14.72	+ .3
23 [b]	1.5		2.52		7.809	93.0	234	14.62	− .4
31 [c]	2.0		3.53		7.845	61.3	217	13.45	+ .4
32 [c]	2.0		3.53		7.851	60.7	214	13.33	− .5
33 [c]	2.0		3.53		7.830	61.0	215	13.42	+ .1
41 [d]	2.0		3.45		7.861	72.0	248	15.42	+ .8
42 [d]	2.0		3.61		7.869	68.3	246	15.30	0
43 [d]	2.0		3.73		7.856	65.5	244	15.17	− .8

[a] Bessemer steel 1.00 per cent.
[b] Bessemer steel 0.35 per cent.
[c] Open-hearth steel 0.20 per cent.
[d] Seamless steel 3.25 per cent.

TABLE 1—Continued

Resistance and Other Data as to Pipes—Continued

Section F.—LEAD PIPE

Specimen No.	Card diameter (inches)	Weight (pounds per foot)		Variation from mean (per cent)	Specific gravity	Resistance			Variation from mean (per cent)
		Card	Observed			Microhms per foot	Microhms per pound-foot	Microhms per cubic centimeter	
L 1	0.25 (8 oz.)	0.5	0.456	− 8.8	.....	1093	499.0	21.45	+1.5
L 2	.25	.5	.456	− 8.8	.....	1101	501.9	21.57	+2.1
L 3	.25	.5	.459	− 8.2	.....	1062	487.6	20.96	− .8
L 4	.75 (AA)	3.5	3.564	+ 1.8	.....	137.8	491.1	21.11	− .1
L 5	.75 (AA)	3.5	3.576	+ 2.2	.....	136.4	487.9	20.93	− .7
L 6	.75 (AA)	3.5	3.576	+ 2.2	.....	136.9	489.5	21.05	− .4
L 7	.75 (AA)	3.5	3.495	− .1	.....	140.4	490.6	21.12	− .2
L 8	.75 (AA)	3.5	3.480	− .6	.....	139.9	486.9	20.92	− .9
L 9	.75 (AA)	3.5	3.477	− .7	.....	141.5	491.8	21.13	+ .1
L 10	1.00 (c)	2.5	2.419	− 3.3	.....	203.5	492.2	21.16	+ .1
L 11	1.00 (c)	2.5	2.422	− 3.1	.....	203.2	492.2	21.13	+ .1
L 12	1.00 (c)	2.5	2.429	− 2.8	.....	201.7	490.0	21.08	− .3
L 13	1.00 (AA)	4.75	4.766	+ .3	.....	102.2	487.0	20.92	− .9
L 14	1.00 (AA)	4.75	4.766	+ .3	.....	101.7	484.5	20.87	−1.4
L 15	1.00 (AA)	4.75	4.762	+ .3	.....	102.4	487.5	20.97	− .4
L 16	2.00 (c)	6.0	5.768	− 3.9	.....	84.70	488.6	21.00	− .6
L 17	2.00 (c)	6.0	5.772	− 3.8	.....	85.09	491.2	21.10	− .1
L 18	2.00 (c)	6.0	5.781	− 3.6	.....	84.94	491.3	21.12	.0
L 19	2.00 (AA)	9.0	8.888	− 1.2	.....	55.13	490.0	21.08	− .3
L 20	2.00 (AA)	9.0	8.926	− .8	.....	55.21	492.8	21.18	+ .3
L 21	2.00 (AA)	9.0	8.939	− .7	.....	55.23	493.7	21.20	+ .4
L 22	.25 (8 oz.)	.5	.452	− 9.6	.....	1093.0	493.6	21.21	+ .4
L 23	.25 (8 oz.)	.5	.449	−10.2	.....	1095.0	491.4	21.12	.0
L 24	.25 (8 oz.)	.5	.452	− 9.6	.....	1093.0	494.2	21.23	+ .6
L 25	.75 (c)	1.75	1.640	− 6.3	.....	302.8	496.7	21.32	+1.1
L 26	.75 (c)	1.75	1.650	− 5.7	.....	299.1	493.5	21.20	+ .4
L 27	.75 (c)	1.75	1.639	− 6.3	.....	301.0	493.2	21.20	+ .3
Average	.....	.....	.....	3.9	.....	.....	491.5	21.12	0.5

TABLE 2

Resistance and Current Data for Pipes

CAST-IRON PIPE

Nominal inside diameter (inches)	Weight (pounds per foot)	Resistance (microhms per foot)	Current for 1 mv on 1 foot (amperes)	Weight (pounds per foot)	Resistance (microhms per foot)	Current for 1 mv on 1 foot (amperes)
	A. W. W. A. standard, Class A			A. W. W. A. standard, Class B		
3	13.04	94.0	10.6	14.6	84.0	11.9
4	18.03	68.0	14.7	20.06	61.0	16.4
6	27.90	44.0	22.7	31.14	39.4	25.4
8	38.74	31.7	31.6	42.68	28.8	34.8
10	51.95	23.6	42.3	58.80	20.9	47.9
12	66.90	18.3	55.0	76.44	16.1	62.0
14	82.33	14.9	67.0	94.82	12.9	77.0
16	98.75	12.4	81.0	114.7	10.7	94.0
18	118.1	10.4	96.0	137.7	8.9	112.0
20	137.2	8.9	112.0	163.2	7.5	133.0
24	186.5	6.5	152.0	217.1	5.7	177.0
30	265.1	4.63	216.0	312.6	3.93	255.0
36	357.8	3.43	292.0	419.0	2.93	342.0
42	465.6	2.64	379.0	541.5	2.27	441.0
48	607.7	2.02	495.0	688.5	1.78	560.0
54	730.2	1.68	600.0	842.8	1.46	690.0
60	835.6	1.47	680.0	1012.0	1.21	820.0
72	1169.0	1.05	950.0	1416.0	.87	1150.0
84	1441.0	.85	1170.0	1860.0	.66	1520.0
	A. W. W. A. standard, Class C			A. W. W. A. standard, Class D		
3	15.47	79.0	12.6	16.37	75.0	13.3
4	21.27	58.0	17.3	22.83	54.0	18.6
6	32.93	37.3	26.8	35.30	34.8	28.8
8	47.97	25.6	39.1	51.16	24.0	41.7
10	65.66	18.7	54.0	71.54	17.2	58.0
12	85.26	14.4	70.0	93.59	13.1	76.0
14	108.0	11.4	88.0	119.1	10.3	97.0
16	133.3	9.2	109.0	147.5	8.3	120.0
18	162.4	7.6	132.0	178.4	6.9	145.0
20	190.9	6.4	156.0	212.4	5.8	173.0
24	257.7	4.76	210.0	286.2	4.29	233.0
30	367.5	3.34	300.0	421.4	2.91	343.0
36	499.8	2.46	407.0	580.7	2.11	473.0
42	656.6	1.87	540.0	762.0	1.61	620.0
48	833.0	1.47	680.0	960.4	1.28	780.0
54	1041.0	1.18	850.0	1227.0	1.0	1000.0
60	1220.0	1.01	990.0	1458.0	.84	1190.0
72	1744.0	.70	1420.0	.....	.....	.....

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TABLE 2—Continued

Resistance and Current Data for Pipes—Continued

CAST-IRON PIPE—Continued

Nominal inside diameter (inches)	Weight (pounds per foot)	Resistance (microhms per foot)	Current for 1 mv on 1 foot (amperes)	Weight (pounds per foot)	Resistance (microhms per foot)	Current for 1 mv on 1 foot (amperes)
	New England W. W. A. standard,[a] Class A			New England W. W. A. standard,[a] Class B		
4	14.89	82.0	12.1	.....	.....	.....
6	24.32	50.0	19.8	.....	.....	.....
8	35.58	34.5	29.0	.....	.....	.....
10	49.04	25.0	40.0	52.03	23.6	42.4
12	61.14	20.1	50.0	65.92	18.6	54.0
14	76.85	15.9	63.0	82.41	14.9	67.0
16	90.98	13.5	74.0	98.95	12.4	81.0
18	104.5	11.7	85.0	115.2	10.6	94.0
20	121.9	10.1	99.0	133.7	9.2	109.0
24	155.6	7.9	127.0	174.4	7.0	142.0
30	215.3	5.7	176.0	244.8	5.0	200.0
36	287.0	4.27	234.0	326.0	3.76	266.0
42	368.4	3.33	300.0	422.1	2.91	344.0
48	459.3	2.67	374.0	350.2	2.31	432.0
54	559.8	2.19	456.0	650.3	1.89	530.0
60	664.0	1.85	540.0	782.3	1.57	640.0
	New England W. W. A. standard,[a] Class C			New England W. W. A. standard,[a] Class D		
4	15.7	78.0	12.8	.....	.....	.....
6	26.72	45.9	21.8	.....	.....	.....
8	40.38	30.4	32.9	.....	.....	.....
10	54.99	22.3	444.8	57.94	21.2	47.2
12	70.67	17.4	58.0	75.39	16.3	61.0
14	87.97	14.0	72.0	94.85	12.9	77.0
16	106.9	11.5	87.0	114.8	10.7	93.0
18	127.4	9.6	104.0	138.0	8.9	112.0
20	147.6	8.3	120.0	161.4	7.6	132.0
24	196.3	6.2	160.0	215.3	5.7	175.0
30	277.7	4.42	226.0	307.3	3.99	250.0
36	373.3	3.29	304.0	412.3	2.97	336.0
42	481.1	2.55	392.0	538.9	2.28	439.0
48	608.0	2.02	495.0	678.9	1.81	550.0
54	749.5	1.64	610.0	839.9	1.46	680.0
60	911.5	1.35	740.0	1029.7	1.19	840.0
	A. G. I. standard gas					
4	17.3	71.0	14.1	.....	.....	.....
6	27.3	45.0	22.2	.....	.....	.....
8	38.0	32.3	30.9	.....	.....	.....
10	51.0	24.1	41.5	.....	.....	.....
12	67.0	18.3	55.0	.....	.....	.....
16	102.0	12.0	83.0	.....	.....	.....
20	139.0	8.8	113.0	.....	.....	.....
24	186.0	6.6	152.0	.....	.....	.....
30	256.0	4.79	209.0	.....	.....	.....
36	346.0	3.55	282.0	.....	.....	.....
42	453.0	2.71	369.0	.....	.....	.....
48	610.0	2.02	495.0	.....	.....	.....

[a] Specific resistance=1227. Microhms per pound-foot.

TABLE 2—Continued

Resistance and Current Data for Pipes—Continued

STEEL PIPE [a]

Nominal inside diameter (inches)	Weight (pounds per foot)	Resistance (microhms per foot)	Current for 1 mv on 1 foot (amperes)	Weight (pounds per foot)	Resistance (microhms per foot)	Current for 1 mv on 1 foot (amperes)
	Standard			Extra strong		
0.125	0.24	900.0	1.11	0.31	700.0	1.44
0.25	.42	510.0	1.95	.54	400.0	2.50
0.375	.57	379.0	2.64	.74	292.0	3.43
0.50	.85	254.0	3.94	1.09	198.0	5.0
0.75	1.13	191.0	5.2	1.47	147.0	6.8
1	1.68	129.0	7.8	2.17	100.0	10.1
1.25	2.27	95.0	10.5	3.00	72.0	13.9
1.50	2.72	79.0	12.6	3.63	60.0	16.8
2	3.65	59.0	16.9	5.02	43.0	23.3
2.50	5.79	37.3	26.8	7.66	28.2	35.5
3	7.58	28.5	35.1	10.25	21.1	47.5
3.50	9.11	23.7	42.2	12.51	17.3	58.0
4	10.79	20.0	50.0	14.98	14.4	69.0
4.50	12.54	17.2	58.0	17.61	12.3	82.0
5	14.62	14.8	68.0	20.78	10.4	96.0
6	18.97	11.4	88.0	28.57	7.6	132.0
7	23.54	9.2	109.0	38.05	5.7	176.0
8	24.70	8.7	114.0	43.39	4.98	201.0
8	28.55	7.6	132.0	.....	.....	.....
9	33.91	6.4	157.0	48.73	4.43	226.0
10	31.20	6.9	145.0	54.74	3.94	254.0
10	34.24	6.3	159.0	.....	.....	.....
10	40.48	5.3	188.0	.....	.....	.....
11	45.56	4.74	211.0	60.08	3.59	278.0
12	43.77	4.93	203.0	65.42	3.30	303.0
12	49.56	4.36	230.0	.....	.....	.....
13	54.57	3.96	253.0	72.09	3.00	334.0
14	58.57	3.69	271.0	77.43	2.79	359.0
15	62.58	3.45	290.0	82.77	2.61	383.0
WROUGHT-IRON PIPE [b]						
0.125	0.24	870.0	1.15	0.29	720.0	1.39
0.25	.42	498.0	2.01	.54	387.0	2.58
0.375	.56	374.0	2.68	.74	283.0	3.54
0.50	.84	249.0	4.02	1.09	192.0	5.2
0.75	1.12	187.0	5.4	1.39	150.0	6.6
1.0	1.67	125.0	8.0	2.17	96.0	10.4
1.25	2.25	93.0	10.8	3.00	70.0	14.3
1.50	2.69	78.0	12.9	3.63	58.0	17.4
2.0	3.66	57.0	17.5	5.02	41.7	24.0
2.50	5.77	36.3	27.6	7.67	27.3	36.7
3.0	7.54	27.8	36.0	10.25	20.4	49.0
3.50	9.05	23.1	43.3	12.47	16.8	60.0
4.0	10.72	19.5	51.0	14.97	14.0	72.0
4.50	12.49	16.8	60.0	18.22	11.5	87.0

[a] National Tube Co. tables, 1913. Specific resistance=215.8 microhms per pound-foot.
[b] Byers' table of weights. Specific resistance=209.3 microhms per pound-foot.

TABLE 2—Continued

Resistance and Current Data for Pipes—Continued

WROUGHT-IRON PIPE—Continued

Nominal inside diameter (inches)	Weight (pounds per foot)	Resistance (microhms per foot)	Current for 1 mv on 1 foot (amperes)	Weight (pounds per foot)	Resistance (microhms per foot)	Current for 1 mv on 1 foot (amperes)
5.0	14.56	14.4	70.0	20.54	10.2	98.0
6.0	18.76	11.2	90.0	28.58	7.3	137.0
7.0	23.41	8.9	112.0	37.67	5.6	180.0
8.0	25.00	8.4	120.0	43.00	4.87	206.0
8.0	28.34	7.4	136.0	.....	.....	.....
9.0	33.70	6.2	161.0	48.73	4.29	233.0
10.0	32.00	6.5	153.0	.....	.....	.....
10.0	35.00	6.0	167.0	.....	.....	.....
10.0	40.00	5.2	191.0	54.74	3.82	262.0
11.0	45.00	4.70	215.0	60.08	3.48	287.0
12.0	45.00	4.70	215.0	.....	.....	.....
12.0	49.00	4.27	234.0	65.42	3.20	313.0

LEAD PIPE

Specimen No.	Card diameter (inches)	Card weight (pounds per foot)	Resistance (microhms per foot)	Current for 1 mv drop per foot (amperes)
1	0.25	0.5	1093.0	0.915
2	.25	.5	1101.0	.908
3	.25	.5	1062.0	.942
4	.75 (AA)	3.5	137.8	7.257
5	.75 (AA)	3.5	136.4	7.332
6	.75 (AA)	3.5	136.9	7.305
7	.75 (AA)	3.5	140.4	7.123
8	.75 (AA)	3.5	139.9	7.148
9	.75 (AA)	3.5	141.5	7.067
10	1.00 (C)	2.5	203.5	4.914
11	1.00 (C)	2.5	203.2	4.921
12	1.00 (C)	2.5	201.7	4.958
13	1.00 (AA)	4.75	102.2	9.785
14	1.00 (AA)	4.75	101.7	9.833
15	1.00 (AA)	4.75	102.4	9.766
16	2.00 (C)	6.0	84.70	11.81
17	2.00 (C)	6.0	85.09	11.78
18	2.00 (C)	6.0	84.94	11.77
19	2.00 (AA)	9.0	55.13	18.14
20	2.00 (AA)	9.0	55.21	18.11
21	2.00 (AA)	9.0	55.23	18.11
22	.25	.5	1093.0	.915
23	.25	.5	1095.0	.913
24	.25	.5	1093.0	.915
25	.75 (C)	1.75	302.8	3.302
26	.75 (C)	1.75	299.1	3.343
27	.75 (C)	1.75	301.0	3.322