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GROUND CONNECTIONS FOR ELECTRICAL SYSTEMS

BY

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Bureau of Standards

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1898
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By O. S. Peters

CONTENTS

	Page
I. Introduction.....	5
1. Terminology.....	7
2. Purpose of ground connections.....	7
II. Resistance of ground connections.....	7
1. Contact resistance between metal and earth.....	8
2. Total resistance of a ground connection.....	10
3. Distribution of resistance in the earth about a metallic body....	12
4. Formula for the resistance of a ground connection.....	13
III. Uses and service conditions of ground connections.....	14
1. Low-voltage, alternating-current circuits.....	15
(a) Causes of leaks in transformer insulation.....	15
(b) Causes of accidental contacts or connections between wires.....	16
(c) Current and potential relations in low-voltage circuits due to contact with high-voltage circuits.....	17
(d) Point of attachment of ground wires to single-phase low- voltage circuits.....	24
(e) Point of attachment of ground wires to polyphase low- voltage circuits.....	26
(f) Effect of resistance in ground connections for low-voltage circuits.....	32
2. Direct-current distribution systems.....	33
(a) Two-wire systems.....	33
(b) Three-wire systems.....	34
3. Detectors of accidental grounds.....	37
(a) Two-wire, direct-current distribution systems.....	37
(b) Three-wire, direct-current systems.....	38
(c) Low-voltage, alternating-current systems.....	39
4. Machine frames.....	41
(a) Insulated frames.....	42
(b) Ground connections for frames.....	45
5. Conducting bodies inclosing or near electrical circuits.....	46
(a) Danger from accidental contact between metallic bodies and electrical circuits.....	46
(b) Danger from contact with electrical circuit and metallic body at the same time.....	48
(c) Railway power-house switchboard frames.....	50
(d) Interior fixtures.....	51
(e) Grounding in large buildings.....	52
6. High-voltage transmission and distribution systems.....	53

III.—Uses and service conditions of ground connections—Continued	Page
7. Electrical systems under construction or repair.....	55
(a) Danger to workmen from atmospheric electricity.....	55
(b) Danger through leakage from neighboring lines.....	57
8. Lightning arresters and overhead ground wires.....	58
(a) Danger from improper use of a ground connection for a lightning arrester.....	58
(b) Effect of resistance in the ground connection.....	60
9. Lightning rods.....	61
10. Meter systems, signal systems, and auxiliary ground connections for testing purposes.....	64
IV. Different forms of ground connections and electrical characteristics of each.....	65
1. Driven pipes.....	65
(a) Variation of resistance with depth.....	66
(b) Variation of resistance between two driven pipes with depth and distance apart.....	69
(c) Variation of resistance of two or more pipes in parallel with distance apart and depth.....	72
(d) Variation of resistance with contact area.....	78
2. Plates.....	80
(a) Variation of resistance with depth.....	80
(b) Variation of resistance with area of plate.....	81
(c) Resistance of two plates in parallel.....	82
(d) Plates on edge v. plates laid flat.....	84
3. Strips.....	85
(a) Variation of resistance with length.....	87
(b) Variation of resistance with depth.....	89
4. Patented grounding devices.....	91
5. Water pipes.....	92
(a) Resistance of water-pipe ground connections.....	93
(b) Electrolysis by alternating current.....	96
(c) Electrolysis by direct current.....	98
(d) Heating of pipes by flow of current.....	99
(e) Extent of danger to employees of the water utility.....	100
6. Multiple ground connections.....	101
(a) Direct-current systems.....	102
(b) Alternating-current systems.....	103
(c) Common ground wire.....	105
7. Variation of resistance of ground connections with seasons.....	106
(a) Temperature effects.....	107
(b) Moisture effects.....	108
(c) Experimental results.....	109
8. Increasing the conductance of ground connections.....	113
(a) Effects of salt.....	114
(b) Effects of coke.....	121
9. Dissipation of energy by ground connections.....	124
10. Potential gradients.....	130
V. Mechanical construction of ground connections.....	137
1. Driven pipes.....	137
2. Plates.....	140
3. Strips.....	141
4. Water pipes.....	141
5. Ground wires.....	143

	Page
VI. Inspection and testing.....	145
1. Inspection.....	145
2. Testing.....	146
(a) Ammeter-voltmeter method using three current terminals.....	148
(b) Ammeter-voltmeter method using two current terminals....	150
(c) Ammeter-voltmeter method using direct current.....	152
(d) Kohlrausch-bridge method.....	153
(e) Modification of Kohlrausch-bridge method.....	157
(f) Testing by lamp banks, fuses, and magnetos.....	159
(g) Single-voltmeter method.....	160
(h) Capacity to dissipate energy.....	161
(i) Potential gradient.....	162
(j) Low voltage v. high voltage in testing.....	163
(k) Auxiliary grounds for testing.....	166
(l) Leads, clamps, and other accessories to testing outfits.....	167
VII. Fire hazard and interference with service in grounding.....	169
1. Wiring.....	169
2. Gas pipes.....	171
3. Interference with service.....	172
VIII. Costs.....	173
IX. Bases for specifications.....	174
X. Field measurements of the resistance of artificial ground connections....	178
1. Method of measurement.....	192
2. Procedure in making tests.....	193
3. Summary of results.....	195
(a) Resistances by kinds of soil.....	195
(b) Resistances by types of grounds.....	196
(c) Average, minimum, and maximum resistances by cities....	198
(d) General practice in grounding secondary circuits.....	200
XI. Summary.....	203
Appendixes.....	210
Appendix I.—Summary of correspondence with electric companies on grounding.....	210
Appendix II.—Rules covering methods of protective grounding of circuits, equipment, and lightning arresters for stations, lines, and utilization equipment: Being section 9 of the National Electrical Safety Code.....	213
Appendix III.—Derivation of formula for the resistance of a ground connection.....	219
Appendix IV.—Bibliography.....	222

I. INTRODUCTION

Ground connections have come in recent years to play an increasingly important part in electrical systems of almost every kind. One of their chief functions is that of protecting persons against electrical dangers. Where depended upon for this purpose, they should be carefully made, because if they are poorly made, or inadequate for the purpose for which they are intended, loss of life or serious personal injury may result. Nevertheless, surprisingly little has been done to make generally known the

information available concerning ground connections in common use, and research on the subject has been limited. It is true, of course, that the desirability of grounding has been extensively discussed in its different phases; and although there still is some discussion as to the extent to which grounding should be carried, there is now fair agreement as to the parts of electrical systems which can be operated most advantageously when connected to earth.

With regard to the performance of ground connections under operating conditions, and the physical characteristics which they must possess to meet the requirements placed upon them, comparatively little has been written. As a result, information which is important to persons directly engaged in the safeguarding of life and property from electrical dangers by the use of ground connections is not readily obtainable. The consequences of this difficulty in obtaining information are evident in a more or less general lack of thoroughness and uniformity in the practice of grounding, and accidents due to inadequate ground connections not infrequently occur.

The object of this paper is to present the information now available concerning ground connections and their uses, and to supplement this information with new experimental evidence which, among other things, shows the necessity for basing specifications for ground connections upon their physical characteristics rather than upon arbitrary methods of construction as has been the custom to a large extent in the past. Considerable space is devoted to discussing the manner in which danger arises from ungrounded electrical systems, and also the desirability of grounding to avert such danger. The subject is taken up with special reference to the grounding rules of the National Electrical Safety Code¹ under the following main topics: (1) Resistance of ground connections; (2) their uses and service conditions; (3) different forms of ground connections and the electrical characteristics of each; (4) mechanical construction; (5) inspection and testing; (6) fire hazard and interference with service; (7) costs; (8) bases for specifications; and (9) field measurements of the resistance of ground connections.

With the object outlined above in view, a careful survey of the literature on grounding and ground connections has been made; considerable experimental work has been done in the laboratory and in the field, and correspondence and conferences had with

¹ See Appendix II.

representatives of corporations engaged in the generation and distribution of electrical energy. The results of this study will be taken up after referring to some of the terms used in the following discussion, and also stating briefly the purpose of a ground connection.

1. TERMINOLOGY

The terms "ground," "permanent ground," "ground connection," and, in a few cases, "earth connection," as herein used, refer to electrical connections intentionally made between electrical circuits, or conducting bodies in close proximity to electrical circuits, and metallic bodies embedded in the earth, such as water pipes, plates, or driven pipes.

Every connection between electrical circuits and ground or near-by conducting bodies made, not by design, but by accident, as by the breaking of wires or failure of insulation, is referred to as an "accidental ground."

2. PURPOSE OF GROUND CONNECTIONS

The purpose of a ground connection is to keep some point in an electrical circuit, or some conducting body, at, or as near as practicable to, the potential of the ground in order either that safety to life and property be secured, or that there be increased convenience and continuity of service in the operation of electrical systems. "Ground" here may mean either the soil itself, or conducting bodies in contact with it or extending into it. Examples of the latter are steel building frames, steel poles, and water and gas pipes, and fixtures in buildings. In many instances it is necessary that there be a considerable flow of current through the ground connection in order to prevent the potential of an electrical circuit or a conducting body from rising to a dangerously high value above that of the ground. The soil offers more or less resistance to this current flow, and this resistance determines in large measure the effectiveness of the ground in protecting against high voltage. The nature of the resistance of a ground connection will therefore first be considered.

II. RESISTANCE OF GROUND CONNECTIONS

If two electrodes, such as pieces of iron pipe several feet in length or plates or other bodies of metal, are embedded in earth at a distance from each other and have impressed upon them a steady alternating difference of potential, a current will flow between

them, the value of which depends upon the electrical resistance offered by the soil. This resistance is made evident by the liberation of heat when current is flowing, and because of its effects on the performance of ground connections in service, it is of interest to consider the factors which affect it and its distribution in the region surrounding the metallic bodies.

1. CONTACT RESISTANCE BETWEEN METAL AND EARTH

One factor which has in many instances been considered as contributing to the resistance of a ground connection is that of contact resistance between metal and earth. In order to obtain an idea of the magnitude of this contact resistance, some measurements were made at the Bureau of Standards. For the purpose of these measurements, several samples of earth were used, each of which was thoroughly mixed before testing in order to make the resistivity as uniform as possible throughout. Tests were then made by placing different quantities of each sample in a cylindrical vessel having an iron bottom and glass-lined sides, compressing it by forcing an iron piston down upon it, and measuring the electrical resistance between the piston and the metallic bottom, using alternating current at 60 cycles per second. Measurements made at the same unit pressure, and with the cylinder filled to depths ranging from 2 to 9 cm., showed the same specific resistance for each depth; that is, within the limits of accuracy of the measurements, or about 2 per cent. If contact resistance were present, an apparently greater specific resistance would have been shown with the smaller depths of earth in the cylinder than with the greater depths, but this was found not to be the case; consequently, it may be concluded that the effects of contact resistance between clean iron and earth when firmly pressed together are negligible, at least as far as practical purposes are concerned. The contact resistance between earth and metals other than iron has not been determined, but it seems reasonable to infer that for those metals commonly used for ground connections, viz, copper and galvanized iron, the latter of which presents a zinc-coated surface, the same results would be obtained.

In practice, however, clean metal is not always found. The electrodes used in making ground connections may be covered with substances such as rust, paint, or grease, and these in some instances are not unlikely to form a more or less insulating layer between metal and soil. Rust, of course, is the one most commonly

found, but in none of the experiments thus far conducted by this Bureau upon the corrosion of iron in soil has it developed that a layer of rust appreciably increases the resistance to flow of current away from the metal. From the results of these tests, and also from the fact that rust layers formed in soil are permeable to soil water and consist of particles of iron oxide of no greater insulating qualities than the particles forming the soil itself, it may be safely stated that rust is of no effect in increasing the resistance of a ground connection. Paint or grease, however, should be removed before the metal is buried.

A case in which an apparent contact resistance between metal and earth may arise is where a ground connection is required to carry direct current. This may be important, especially in making resistance measurements at low voltage, and the effects of direct current, as compared with these of alternating current, should be given careful consideration. For when direct current is used in making resistance measurements, electrolysis takes place at the surface of the electrode. By this means gas is liberated which soon forms a high-resistance layer between metal and earth, and in conjunction with other factors, makes a very marked difference (generally an increase) in the apparent resistance as compared with the resistance obtained with alternating current. The magnitude of this difference in resistance depends upon the polarity of the electrode, upon the rate of current flow, upon the rate at which gas is able to diffuse from the surface, and also upon the counter electromotive force of polarization. It may amount to as much as 20 or 25 per cent.

On the other hand, when alternating current is used, the resultant electrolysis is very small. The rate at which reversals of current would have to take place in order entirely to prevent electrolysis under all conditions has not been determined, but some experiments have been conducted recently at the Bureau of Standards which indicate the magnitude of the resultant electrolysis with current at 60 cycles, or 120 reversals per second. These experiments were made on iron and lead in moist clay. It was found from tests lasting through several weeks that the amount of iron or lead lost with a certain number of ampere-hours of alternating current was a fraction of 1 per cent of the loss with an equal number of ampere-hours of direct current.² There are, of course, other products of electrolysis than dissolved

² Technologic Paper No. 72 of the Bureau of Standards.

metal which would affect measurements of the resistance of ground connections, but it seems that it may safely be inferred from the results just mentioned that they are comparable in amount with the dissolved metal and are, therefore, of negligible effect as far as measurements in practice are concerned.

From the foregoing discussion, it appears, then, that if contact resistance is present in a ground connection, it is something which is not inherent in the contact between clean metal and packed earth, or even between rusty metal and packed earth. As indicated above, it is most likely to be due to an impervious nonconducting coating on the surface of the metal, such as paint, grease, or gas formed by chemical action or electrolysis. Furthermore, in the measurement of resistance of ground connections with direct current, the contact conditions between metal and soil are disturbed to an appreciable extent by the action of the current, whereas with alternating current at 60 cycles per second, this disturbance is inappreciable. Alternating current is, therefore, preferable for making measurements of the resistance of ground connections.

2. TOTAL RESISTANCE OF A GROUND CONNECTION

Having considered the matter of contact resistance between metal and earth, attention may now be turned toward what may be called the actual or total resistance of a ground connection. This must be considered in every case. It consists of three parts, viz, (1) a part contributed by the ground wire or other conductor, which serves to make an electrical connection between the buried electrode and the electric circuit or metallic body which the ground connection is designed to serve; (2) a part contributed by the buried electrode itself; (3) a part contributed by the soil. The part contributed by the ground conductor may properly be taken as a part of the total resistance because, as far as the effect on the electric circuit or metallic body mentioned above is concerned, it makes no difference whether the resistance is in the conductor or the soil. Its importance is not great, however, unless an exceedingly long ground wire is used, or connection is made to a long service pipe in making water-pipe grounds.

The resistance of the buried electrode enters because of the fact that the current flows into the electrode at a point, that is, where the ground conductor is attached, and to reach the surface must pass through the metal. Each element of current, there-

fore, traverses a path of greater or less length depending upon the distance between the point where the ground conductor is attached and the point where the particular element of current passes into the soil. The part of the total resistance contributed by the buried metal is the combined resistance of all these paths in parallel. The resistivity of metals, however, is exceedingly small in comparison with that of soils, which has been found by measurement to range from a few hundreds to many thousands of ohms³ for a centimeter cube.³ Hence, for electrodes of limited extent, the part of the total resistance contributed by the metal can be neglected and consideration confined to that due to the soil surrounding it. For electrodes of great length and comparatively small cross section, however, this may not be the case. Where water pipes are used, for instance, a large part of the elements of current must traverse the pipe over considerable distances before passing into the ground, and since these paths are of great length in comparison with their cross section, they may contribute very appreciably to the total resistance, especially if the pipe contains high-resistance joints. Lead joints, under ordinary circumstances, of course, are of such low resistance that their effects are of little consequence, but cement or "leadite" joints are of high resistance, and where these are used they may so contribute to the total resistance of a water-pipe ground connection as seriously to impair its effectiveness. The resistance of water-pipe grounds is considered again in Section IV, 5 (a).

The part of the total resistance contributed by the soil is the most important in nearly all cases. When current flows away from the electrode, each element of current traverses a path of variable cross section to its destination, which in practice is always another electrode at some distance away. The resistance offered by the soil, then, is the combined resistance of all the paths of the current elements in parallel, and since the resistivity of soil, as already pointed out, is high, this resistance will be high unless the electrode is very large and the comparative number of paths, therefore, very great. It should be mentioned that where current flows from one electrode to another, the resistance, as just set forth, is due to the soil surrounding two electrodes which may be said to be in series. To obtain the resistance to flow of current away from a single electrode, current may be made to flow from it to an electrode of such great extent that its resistance could be

³ Technologic Paper No. 26 of the Bureau of Standards.

considered negligible. If two electrodes are placed at a distance from each other equal to several times their greatest dimension, the resistance to flow of current from one to the other is practically the sum of the resistances of each of the two grounds, a fact which is very useful in making resistance measurements. It is of interest to point out briefly the manner in which the resistance of the soil is distributed, especially about buried electrodes of limited extent.

3. DISTRIBUTION OF RESISTANCE IN THE EARTH ABOUT A METALLIC BODY

As a concrete example it is convenient to take a hemispherical electrode which may be supposed to be embedded in earth of uniform resistivity with its convex surface down and its plane surface flush with the surface of the ground. If very thin shells of uniform thickness are marked off concentrically with such a hemisphere, their mean areas will vary directly as the squares of their radii, and hence their resistances will vary inversely as the squares of their radii. Any part of the total resistance to flow of current away from such an electrode can be exactly stated by taking the sum of the resistances of the shells from the surface of the hemisphere to the desired distance. This inverse-square law, which holds exactly for a hemispherically shaped electrode, may also be considered as a rough approximation to the conditions as to distribution of resistance about any small electrode, such as a driven pipe; that is, a large part of the total resistance is found near by. It should be added that if the soil, instead of being of uniform resistivity as assumed above were variable, the foregoing simple case would not hold; the distribution of resistance would be more complex. An example is given later in which a quantity of salt is placed around a driven pipe in order to reduce the resistivity of the adjacent soil.

The practical importance of the character of the distribution of resistance about an electrode buried in the earth appears in its effect on the potential gradient in the vicinity of the electrode when heavy current is passing from it. Actual measurements, the results of which will be given later in this paper, show that in the case of driven pipes about 90 per cent of the total resistance is generally encountered in the first 6 to 10 feet; hence, the potential gradients on the earth's surface near the pipe may be high enough in the event of heavy current flow to cause a drop of potential between the pipe and points within reaching distance of it great enough to be dangerous to human life. This matter is discussed in detail in Section IV, 10.

4. FORMULA FOR THE RESISTANCE OF A GROUND CONNECTION

The simple physical idea of the distribution and value of the resistance of a ground connection which has just been given, serves very well for the purpose of illustration. But for working up certain kinds of experimental data, and also for showing the most advantageous way in which to make ground connections, it is desirable to go a step further and express the value of the resistance in terms of the resistivity of the soil and the dimensions and position of the metallic body. A mathematical formula which fulfills these conditions is readily derived and is given in many textbooks on electricity and magnetism. Its common form is as follows: $R = \frac{\rho}{2\pi C}$, where R is the resistance to flow of current away from the electrode forming the ground connection; ρ , the resistivity of the soil; and C , the combined electrostatic capacity in free space of the electrode and its image above the surface of the ground.⁴ The value of C , it may be added, is a constant for any given shape and arrangement of an electrode.

From this formula, it appears that the resistance of a ground connection of any form can be calculated if the resistivity of the soil is known, but in practice difficulties are encountered which limit the use of the method very materially. The chief difficulty is that of obtaining convenient means for expressing the value of C , and this confines the use of the formula to a few simple cases. The resistivity of most soils is also far from uniform, and this presents another difficulty. The principal use of the formula in experimental work is that of drawing smooth curves from the results of observations on driven pipes, which, on account of the nature of the soil in most localities, are bound to be irregular. In this case the value of the electrostatic capacity of the pipe and its image in free space can be approximated by considering it an ellipsoid of revolution. Approximations which are very useful can also be made for other forms of electrodes such as long metal strips or wires.

In addition to serving to a certain extent as the basis of a method for working up observations, the formula given above also serves another purpose, which is, perhaps, still more important, and that is to show that the manner in which buried metal must be distributed in order to obtain the best results—that is, the

⁴ For a derivation of this formula and a short discussion of electrical images as applied to this case, see Appendix III.

least resistance for a given amount of material—is also the manner in which it must be distributed to give the greatest value of C . This is a fact which can not be too strongly emphasized, inasmuch as there are recommendations in existence concerning the installation of ground connections in which area of plate or other electrode seems to be considered the most important matter and no thought given to distribution of metal. If due regard is given to this, much better results can be obtained in many cases for a given amount of material and labor, than if it is neglected. As an illustration, there is the matter of laying a wire in a stream bed to form a ground connection. Instead of coiling the wire, it should be strung out to its greatest length, because in this position the value of C is greatest, and hence, the value of R is the least. The importance of having a low value for R appears from a consideration of the uses found for ground connections in practice and the conditions under which they must operate.

III. USES AND SERVICE CONDITIONS OF GROUND CONNECTIONS

There are great differences in the service conditions imposed upon ground connections in the different practical cases involving their uses, and for that reason it is desirable to consider each case separately. The most important kinds of electrical circuits and apparatus or machinery with which ground connections are used, are the following: (1) Low-voltage,⁵ alternating-current circuits; (2) direct-current distribution systems; (3) detectors of accidental grounds; (4) frames of electrical machines; (5) metallic bodies near or inclosing electrical circuits; (6) high-voltage transmission and distribution systems; (7) electrical systems under construction or repair; (8) lightning arresters and overhead ground wires; (9) lightning rods; (10) meter circuits. Ground connections are also used in signaling circuits, and in a number of ways for testing purposes. In the following discussion special emphasis is given to cases involving life hazard, for here the conditions to be met by the ground connection are more rigorous than where simply property hazard or convenience of operation and continuity of service are concerned.

⁵ The term "low voltage," as here used, refers to circuits of the voltages commonly used for distribution within buildings to electrical utilization installations, generally 750 volts or less, while "high voltage" refers to circuits of the voltages commonly used for transmission and distribution in overhead and underground lines, except those directly connected to electrical utilization installations, generally over 750 volts.

Earth connections for signal systems often form part of the operating circuit, and for that reason special attention needs to be given to their resistance, more particularly, to the variation of the resistance with seasons. A signal system installed in summer might work in a satisfactory manner, but with freezing weather an increase of resistance of the ground connections would take place, possibly enough to render the system inoperative. In making the installation, therefore, care should be taken to allow for seasonal changes.

Auxiliary ground connections are frequently needed for testing purposes. The resistance and other electrical characteristics are here determined by the requirements of each case. In testing insulation, for example, the resistance of the ground connection may be very high—several thousand ohms need not be considered too high for good results—but for other purposes it may need to be low. A case in point is testing for the energy-absorbing capacity of ground connections for electrical circuits, which is taken up later under Section VI, "Inspection and Testing."

IV. DIFFERENT FORMS OF GROUND CONNECTIONS AND THE ELECTRICAL CHARACTERISTICS OF EACH

The different types of ground connections in common use may be enumerated as follows: (1) Driven pipes, (2) plates, (3) strips, (4) patented devices, and (5) water pipes. The electrical characteristics of each type and the extent of its suitability for grounding electrical systems are discussed below, patented devices being included under one head because, although there are many of them on the market, they are not fundamentally different from one another. Some space is also devoted to multiple ground connections.

1. DRIVEN PIPES

For many purposes driven pipes are economical and reasonably satisfactory, especially if the soil is deep and not so stony as to prevent driving them. They serve very well for lightning rods, lightning arresters, low-voltage circuits fed by transformers of small power rating where there is little likelihood of contact between high-voltage and low-voltage wires, and for other electrical circuits and apparatus which do not require a resistance to flow of current into the earth of less than a few ohms. Where very low resistances are required, however, they are, in general, not satis-

factory. Nevertheless, as compared with other types of grounds, they possess a marked advantage in that connection between pipe and ground wire can be made above the surface of the soil, enabling easy inspection; and they are renewable at relatively low cost. Moreover, the ground area required for an earth connection of this type is small, making for convenience in some places where excavation is out of the question because of restricted space, or pavements.

(a) VARIATION OF RESISTANCE WITH DEPTH.—This characteristic of driven pipes has been investigated heretofore by Creighton.²¹ His results have been checked in this investigation, using 54 specimens of three-fourth inch galvanized iron pipe of lengths varying in steps of 1 foot up to 10 feet. These were driven in rather stony clay soil. Table 1 gives the number of specimens and the average of their measured resistances for each length. The measurements were made by means of the ammeter-voltmeter method, with alternating current at 60 cycles per second. A detailed description of this method is given further on in this paper under "Testing" in Section VI, 2 (a), (b), and (c). When the pipes were driven, the ground was very wet, and when the data given in Table 1 were obtained, they had been in place seven months, so there was ample opportunity for the soil to settle and eliminate disturbances due to driving. The values of resistance, however, are to be considered as having probable errors of 2 or 3 per cent because of fluctuations of voltage while readings were taken, which were due to varying loads on the line at other points.

TABLE 1.—Variation of Resistance of Driven Pipes with Depth^a

Specimens	Depth in feet	2 $l=L$ in centimeters	Capacity in electrostatic units	Average measured resistance	Calculated resistance, uniform soil
				Ohms	Ohms
8	1	61.0	7.92	167	149.3
8	2	122.0	13.45	76.3	87.8
8	3	183.0	18.52	47.2	63.8
8	4	244.0	23.35	37.5	50.6
8	5	304.0	28.00	49.5	42.3
1	6	366.0	32.40	42.5	36.5
3	7	427.0	36.85	31.0	32.1
1	8	488.0	41.20	22.5	28.7
1	9	549.0	45.40	23.5	26.0
8	10	610.0	49.60	36.5	23.8

^a External diameter of pipes used in this test, 1.02 inches. $\rho=7420$ ohms per cubic centimeter.

²¹ General Electric Review, 15, pp. 15 and 66.

Referring to Table 1 it will be seen that the results of the measurements are very irregular; for instance, the average resistance to flow of current away from a group of pipes driven 10 feet into the ground is practically the same as for a group driven 4 feet. The resistances to flow of current away from individual specimens were also found to be very irregular, and in all cases the irregularities were much greater than those which could be attributed to errors in measurement. The soil, however, was found to be very nonhomogeneous, and it is undoubtedly to this that the larger part of the irregularities must be attributed. In fact, in driving it was discovered that the greater lengths of pipe penetrated a stratum which consisted of nearly all small boulders of 2 to 5 inches in diameter. The resistivity of such boulders is extremely high in comparison with that of soil and their presence tends to produce differences in resistances between specimens of the same kind on account of their nonuniform distribution. Because of these irregularities it would be more or less misleading to attempt to show the relation between resistance and depth by drawing a curve through the points representing the observed values, so a curve was constructed the shape of which would at least approximate that obtained by making observations on pipes driven in soil of uniform resistivity.

In constructing this curve use was made of the formula

$$R = \frac{\rho}{2\pi C}, \text{ which was given under resistance of ground con-}$$

nections. In this formula R is the resistance to flow of current away from a ground connection, ρ the resistivity of the soil, and C the combined electrostatic capacity in free space of the electrode and its image above the surface of the ground, the surface of the ground being supposed in this case to lie in a plane at right angles to the axis of the pipe. There seems to be no available formula for the electrostatic capacity of a cylinder in free space, so in calculating C an approximation was made by using the formula for the capacity of an ellipsoid of revolution, assuming the axes of the ellipsoid to be equal to the length and external diameter, respectively, of the pipe. This formula, for an ellipsoid of revolution of which the length of the major axis

$$\text{is great in comparison with that of the minor axis, is } C = \frac{L}{2 \log \frac{2L}{d}},$$

where L is the length of the major axis and d of the minor axis.

The image of a driven pipe above the surface of the ground would be another pipe of the same length l and external diameter d extending above the surface. The value of L is therefore equal to $2l$, since C refers to the combination of electrode and image. The ratio of major to minor axis for the lengths of pipe under consideration ranges from 24 to 240. Just what error arises from the use of this formula can not, of course, be told. Because of the method of cutting and driving, however, a pipe can be considered as a cylinder with rounded corners. Hence, it does not seem that the difference in capacity between a pipe of given length and diameter and an ellipsoid of revolution of which the major and minor axes corresponded, respectively, to the length and diameter of the pipe would be more than a few per cent. At any rate the method can be considered as a rough approximation and is the most convenient means at hand for smoothing out irregularities in the observations.

From the foregoing formula C has been calculated for the various lengths of pipe, the results being given in Table 1. Substituting in $\rho = 2\pi C R$, the value of ρ corresponding to each set of measurements is found. The average value of ρ for the 10 sets of measurements is 7420 ohms per cm³, from which in turn has been calculated the resistance for each length of pipe as if the resistivity of the soil were uniform. These results are given in the last column of Table 1 and have been used to plot the curve in Fig. 11. The circles show where the points corresponding to the measured resistances fall and are about evenly distributed on either side of the curve. As stated above, this curve can be considered as only a rough approximation to the true curve, but nevertheless shows clearly how the resistance to flow of current away from a pipe driven in soil of uniform resistivity varies with the depth. Evidently not much is to be gained by driving pipes more than 10 feet after moist earth has been reached. As will be shown later, it is, in most cases, more economical to decrease the resistance by putting pipes in parallel than by driving deeper than 10 feet into conducting earth.

Since R depends directly upon ρ , the shape of the curve will be the same no matter what the resistivity may be; that is, if ρ_1 represents the resistivity corresponding to a given curve, and ρ_2 the resistivity corresponding to any other curve, the latter curve may be found by multiplying the ordinates of the given curve by $\frac{\rho_2}{\rho_1}$.

if the sizes and lengths of pipe concerned are the same in the two cases. Practically, however, the curve shows only what depth in conducting earth it is most desirable to attain with driven pipes.

(b) VARIATION OF RESISTANCE BETWEEN TWO DRIVEN PIPES WITH DEPTH AND DISTANCE APART.—For this experiment 40 specimens were used. As indicated in Table 2, where the results of the measurements are given, their lengths ranged from 2 to 10 feet and their distances apart from 6 inches to 25 feet. They were driven in the soil as described in the preceding section, the specimens in

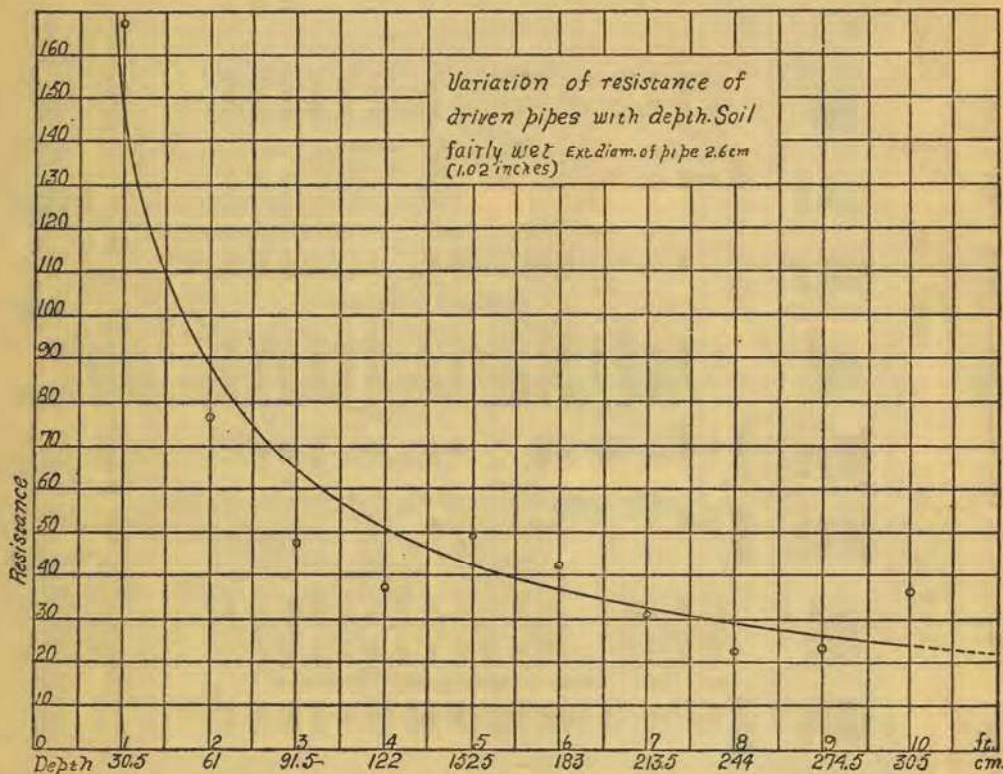


FIG. 11

the two cases, with certain exceptions, being, in fact, identical. The measurements were made by the ammeter voltmeter method. As stated heretofore, this method is described under "Testing" in Section VI, 2 (a), (b), and (c).

In this case, of course, irregularities in the results due to the non-homogeneity of the soil are present the same as in the preceding experiment. In order to draw a curve which will give a clear idea of the way in which the resistance to flow of current from one pipe to another varies with the distance between them, it is therefore necessary to eliminate these irregularities. As previously shown, it is possible to calculate from $R = \frac{\rho}{2\pi C}$ the

TABLE 2.—Variation of Resistance Between Driven Pipes With Distance Apart^a

Resistance of each specimen			Dis- tance apart	Depth, 2 feet			Depth, 3 feet			Depth, 4 feet			Depth, 5 feet			Depth, 10 feet		
No.	Resist- ance	No.		Resist- ance	Speci- mens in series	Meas- ured resist- ance	Calcu- lated resist- ance	Speci- mens in series	Meas- ured resist- ance	Calcu- lated resist- ance	Speci- mens in series	Meas- ured resist- ance	Calcu- lated resist- ance	Speci- mens in series	Meas- ured resist- ance	Calcu- lated resist- ance		
	Ohms		Feet	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms		
66	127	99	0.5	75-76	164	161	112-113	96	84	105-106	59	82-83	74	76	98-99	52		
67	57	100	1	76-77	187	185	113-114	110	101	106-107	84	83-84	93	87	99-100	64		
68	44	101	2	77-78	216	214	114-115	120	117	107-108	99	84-85	131	118	100-101	74		
69	62	102	3	78-79	217	221	115-116	127	125	106-108	98	83-85	139	124	99-101	90		
74	42	103	3	76-78		113-115	108-109		85-86	101-102		101-102						
75	125	104	4	79-80	224	225	116-117	126	129	109-110	100	86-87	144	133	102-103	104		
76	125	105	5	77-79	215	229	114-116	134	134	107-109	118	84-86	157	135	100-102	96		
77	123	106	6	80-81	227	232	117-118	137	136	106-109	106	83-86	131	132	99-102	105		
78	125	107	6	76-79		113-116	110-111		87-88	103-104								
79	108	108	7	78-80	255	239	115-117	137	137	108-110	104	85-87	141	136	101-103	109		
80	137	109	9	77-80	256	242	114-117	145	140	107-110	117	84-87	144	140	100-103	104		
81	110	110	10	81-86	231	238	118-67	134	141	111-68	105	88-69	129	137	104-74	105		
82	69	111	10	79-81			116-118			109-111		86-88			102-104			
83	76	112	88	76-80	231	242	113-117	140	143	106-110	111	83-87	134	140	99-103	105		
84	82	113	84	78-81			108-111			101-104								
85	83	114	80	77-81	231	243	114-118	146	145	107-111	121	84-88	136	143	100-104	105		
86	90	115	75	79-86	231	243	116-67	123	144	109-68	103	86-69	148	144	102-74	108		
87	71	116	71	77-86	252	248	114-67	152	145	107-68	110	84-69	141	145	100-74	108		
88	59	117	76															
98	54	118	72															

^a Where more than one pair of electrodes were available at any given distance apart, average results were used in tabulation and in plotting curves.

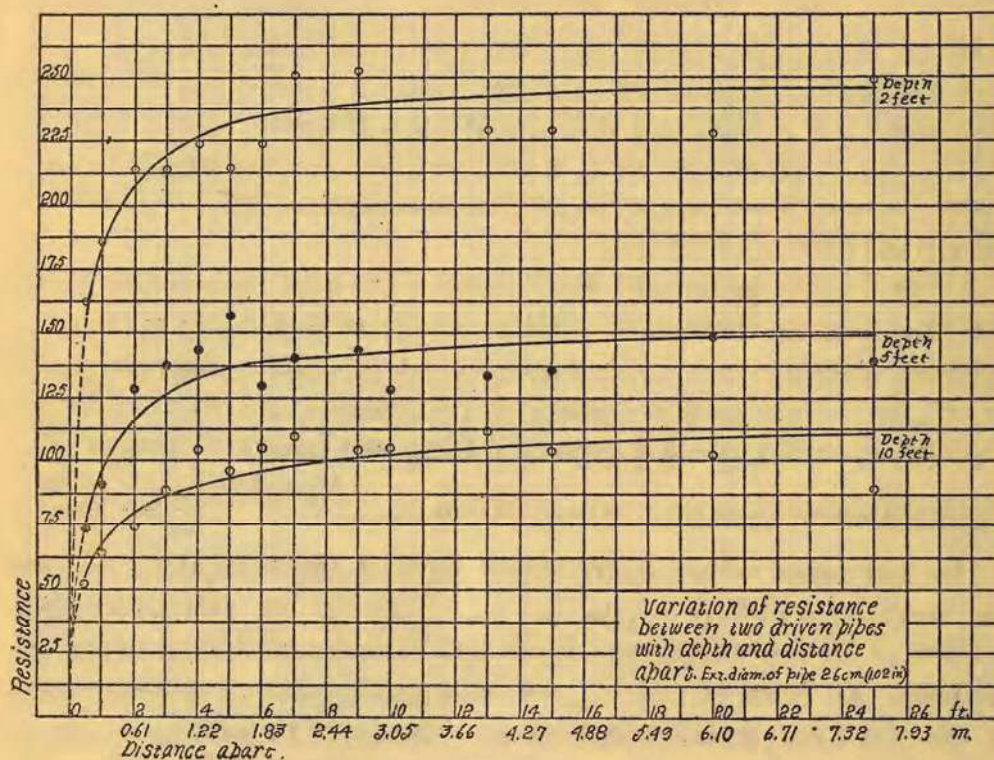
resistance to flow of current from one electrode to another if ρ and C are known, ρ being the resistivity of the soil and C the electrostatic capacity of the condenser formed by one of the electrodes and its image above the surface of the ground, on the one hand, and the other electrode and its image on the other hand. If C were known for the different lengths of pipe and their distances apart, an average value of ρ could be obtained, from which, in turn, could be calculated the different values of R as if the resistivity of the soil were uniform throughout. At present there seems, however, to be no available formula for calculating the value of C in the case of pipes, so it was necessary to resort to a less desirable means of eliminating irregularities, a method which, in fact, eliminates irregularities with a fair degree of approximation between measurements on pipes of the same length, but not between groups of different lengths.

As previously indicated, the resistance to flow of current from one electrode to another, as well as away from a single electrode, depends directly upon the resistivity of the soil. Suppose that $R_1, R_2, R_3 \dots R_n$ are the measured resistances to flow of current away from each pipe of a group of the same length driven at different distances from each other. Then $R_{av} = \frac{R_1 + R_2 + R_3 + \dots + R_n}{n}$

is the resistance which each would have if the resistivity of the soil were everywhere equal to ρ_{av} . Let R' be the measured resistance to flow of current from any one of the driven pipes to another, say from (1) to (2); R' will correspond to a resistivity of the soil everywhere equal to ρ' . In order to reduce R' to a value R which it would have if the resistivity of the soil were everywhere equal to ρ_{av} , it is only necessary to put $R = \frac{\rho_{av}}{\rho'} R'$.

The value of ρ' must be determined, however, before use can be made of the formula. If the pipes are at an infinite distance from each other, it is evident that $\rho' = \frac{\rho_1 + \rho_2}{2}$ where ρ_1 and ρ_2 are the values of resistivity corresponding to R_1 and R_2 . Then $R = \frac{2 \rho_{av}}{\rho_1 + \rho_2} R' = \frac{2 R_{av}}{R_1 + R_2} R'$, since $\frac{2 \rho_{av}}{\rho_1 + \rho_2} = \frac{2 R_{av}}{R_1 + R_2}$. This holds exactly for pipes driven at a great distance from each other, but when they are brought close together the formula is only an approximation. However, because of the fact that it is the soil in the immediate vicinity of the electrode which has the greatest effect in producing resistance, the error becomes appreciable only when the electrodes are very near each other.

The results of Table 2 have been reduced in accordance with this formula, and curves corresponding to groups of pipes 2 feet, 5 feet, and 10 feet lengths are shown in Fig. 12. The circles and dots represent the observed values of resistance and seem more or less evenly distributed on either side of their respective curves. As the distance between the pipes increases the ordinate of the curve approaches a constant value, $2 R_{av}$, rapidly at first and then more slowly, reaching its maximum at an infinite distance. At 10



group were connected and the resistance to flow of current away from them measured by the ammeter-voltmeter method. This was done for each pair of specimens in each group. The results are given in Table 3, the irregularities having been eliminated in much the same way as under (b); for if two pipes are in parallel and at

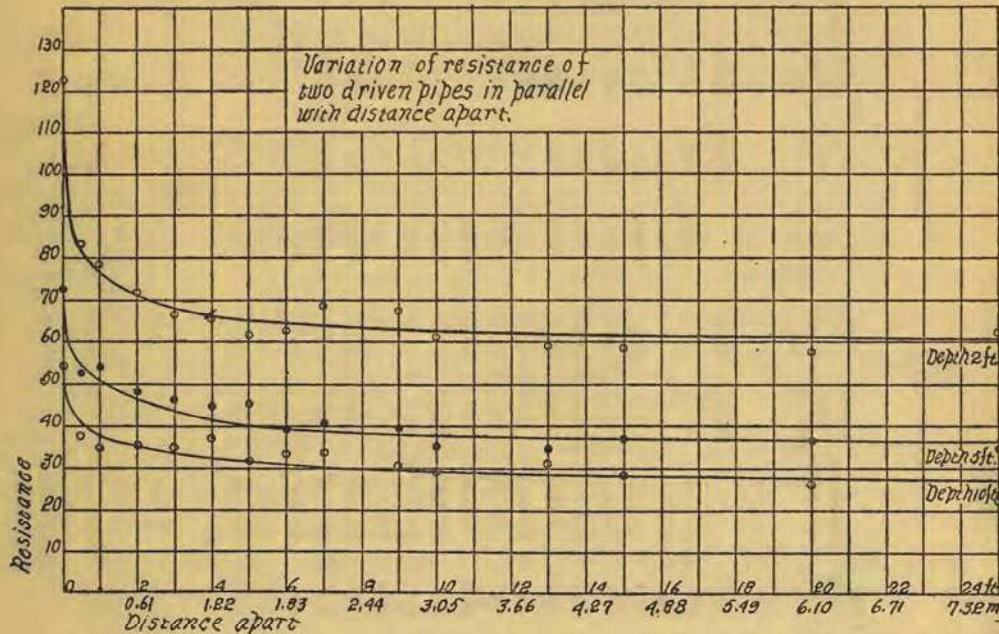


FIG. 13

a great distance from each other, the combined resistance to flow of current away from them may be expressed by $R'' = \frac{R_1 R_2}{R_1 + R_2}$, the well-known formula for the resistance of conductors in parallel, in which R_1 and R_2 are the measured resistances to flow of current away from each of the pipes. Moreover, if the soil were everywhere of resistivity ρ , R'' would be equal to $\frac{R_{av}}{2}$. Hence, as in the preceding section, $R = \frac{\rho_{av}}{\rho''} R'' = \frac{R_{av} (R_1 + R_2)}{2 R_1 R_2} R''$, since $\frac{R_{av}}{2}$ and $\frac{R_1 R_2}{R_1 + R_2}$ are proportional to ρ_{av} and ρ'' , respectively. This formula is exact when the pipes are at a great distance from each other and does not introduce an appreciable error unless they are quite close together. The results for the groups of 2 feet, 5 feet, and 10 feet lengths are plotted in Fig. 13, the curves representing the corrected values of resistance and the circles and dots the observed values. At zero distance the resistance is taken to be the average of all of the specimens in the group.

TABLE 3.—Variation of Resistance of Two Pipes in Parallel With Distance Apart and Depth ^a

Resistance of each specimen.				Depth, 2 feet			Depth, 3 feet			Depth, 4 feet			Depth, 5 feet			Depth, 10 feet		
No.	Resist- ance	No.	Resist- ance	Dis- tance apart	Specimens in parallel	Meas- ured re- sistance	Calcu- lated resist- ance	Specimens in parallel	Meas- ured re- sistance	Calcu- lated resist- ance	Specimens in parallel	Meas- ured re- sistance	Calcu- lated resist- ance	Specimens in parallel	Meas- ured re- sistance	Calcu- lated resist- ance		
	Ohms		Ohms	Feet		Ohms	Ohms		Ohms	Ohms		Ohms	Ohms		Ohms	Ohms		
66	127.3	99	51.9	0.5	75-76	83.8	82.2	112-113	60.8	53.2	105-106	44.0	43.3	82-83	52.9	54.5		
67	54.2	100	49.5	1	76-77	79.1	77.6	113-114	53.5	49.3	106-107	42.6	38.9	83-84	54.5	51.3		
68	42.6	101	58.4	2	77-78	72.4	71.1	114-115	45.7	44.4	107-108	39.1	35.9	84-85	48.7	43.6		
69	61.2	102	63.1	3	78-79	64.6	68.8	115-116	42.2	43.4	108-109	36.5	34.6	85-86	48.3	41.0		
74	40.4	103	63.6	3	76-78	69.4	67.7	113-115	44.8	42.4	106-108	35.3	34.6	83-85	45.3	42.3		
75	124.9	104	60.0	4	79-80	66.1	67.0	116-117	41.0	42.0	109-110	34.9	33.9	86-87	44.9	41.3		
76	126.6	105	58.8	5	77-79	61.9	66.7	114-116	40.7	40.5	107-109	36.7	32.4	84-86	46.1	39.4		
77	124.9	106	59.4	6	80-81	64.7	64.8	117-118	39.6	40.2	106-109	33.9	32.1	83-86	43.8	39.1		
78	126.4	107	68.3	6	76-79	61.2	65.1	113-116	41.0	40.0	110-111	31.7	32.4	87-88	34.7	40.4		
79	107.0	108	59.1	7	78-80	69.3	64.1	115-117	39.9	39.8	108-110	32.0	32.2	85-87	40.7	39.2		
80	141.5	109	63.3	9	77-80	68.2	63.4	114-117	40.4	39.1	107-110	33.0	31.0	84-87	39.8	38.5		
81	109.0	110	56.4	10	81-66	60.5	63.5	118-67	32.9	39.4	111-68	26.6	31.7	88-69	31.3	38.7		
82	67.7	111	57.2	10	79-81	56.2	64.2	116-118	36.9	38.7	109-111	32.2	31.0	86-88	36.7	38.4		
83	74.6	112	86.0	10	76-80	67.9	62.8	113-117	41.2	38.8	106-110	30.9	31.0	83-87	37.9	38.1		
84	81.1	113	82.0	13	78-81	59.6	62.8	115-118	37.3	38.1	108-111	30.7	30.7	85-88	34.9	38.0		
85	82.0	114	78.0	15	77-81	59.0	62.5	114-118	37.9	37.5	107-111	32.4	30.0	84-88	37.6	.....		
86	90.4	115	73.3	20	79-66	58.2	61.7	116-67	31.3	37.8	109-68	26.3	30.0	86-69	36.7	36.8		
87	70.6	116	69.5	25	77-66	62.7	61.3	114-67	34.2	38.0	107-68	26.8	29.7	84-69	35.1	36.8		
88	56.9	117	74.1	.....	b 123.4	.....	.....	b 73.5	.....	.....	b 58.1	.....	.....	b 73.1	.....	.....		
98	50.4	118	70.7	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	b 54.7	.....	.....		

^a In cases where more than one pair of electrodes were available at any given distance apart, the average results were used in plotting the curves.^b Average resistance of specimens in each group.

The curves show that as the distance between the pipes increases the resistance decreases, rapidly at first and then more slowly, tending toward a value $\frac{R_{av}}{2}$ at infinity. After 6 feet is reached, however, the rate of decrease becomes very slow and, in fact from 6 to 10 feet becomes practically negligible. At 6 feet apart the resistance of two pipes in parallel is approximately 55 per cent of one of them and at 2 feet apart is approximately 65 per cent.

It is desirable to know whether these approximate relations between number and resistance hold when the number of pipes is increased. Accordingly, eight specimens 10 feet in length were driven in a row 10 feet apart and the resistance to flow of current away from them measured singly and in parallel. The results of these measurements are given in Table 4, also the results of measurements on four pipes 10 feet in length driven in a row 5 feet apart. In the table the second column gives the measured resistance of each specimen, the fourth the resistance to flow of current away from specimens (1) and (2); (1), (2), and (3); and so on, in parallel. The fifth column gives the resistance which each combination of specimens would have if they were so far away from each other that their respective electric fields would not interfere; that is, at an infinite distance. These values were calculated from $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots + \frac{1}{R_n}$, the familiar formula for the conductance of conductors in parallel. In Fig. 14 the results are shown in the form of a curve, the dotted-line curves representing calculated values and the full-line curves measured values. At 10 feet apart it is evident that the number of pipes could be extended almost indefinitely and the ratio of calculated to measured resistance would not be less than 80 or 90 per cent. At 5 feet apart the ratio of calculated to measured resistance is only 60 or 70 per cent, the curve indicating that this percentage decreases as the number of pipes increases. At 10 feet apart the ratio is practically constant as far as the curve goes. It is not likely that it would be practicable in many cases to drive a row of pipes of greater length than 70 feet, so the curve was not carried further. The steepness of the curve depends upon the distance apart of the pipes. For a row of given length, however, the greater the number the less the resistance.

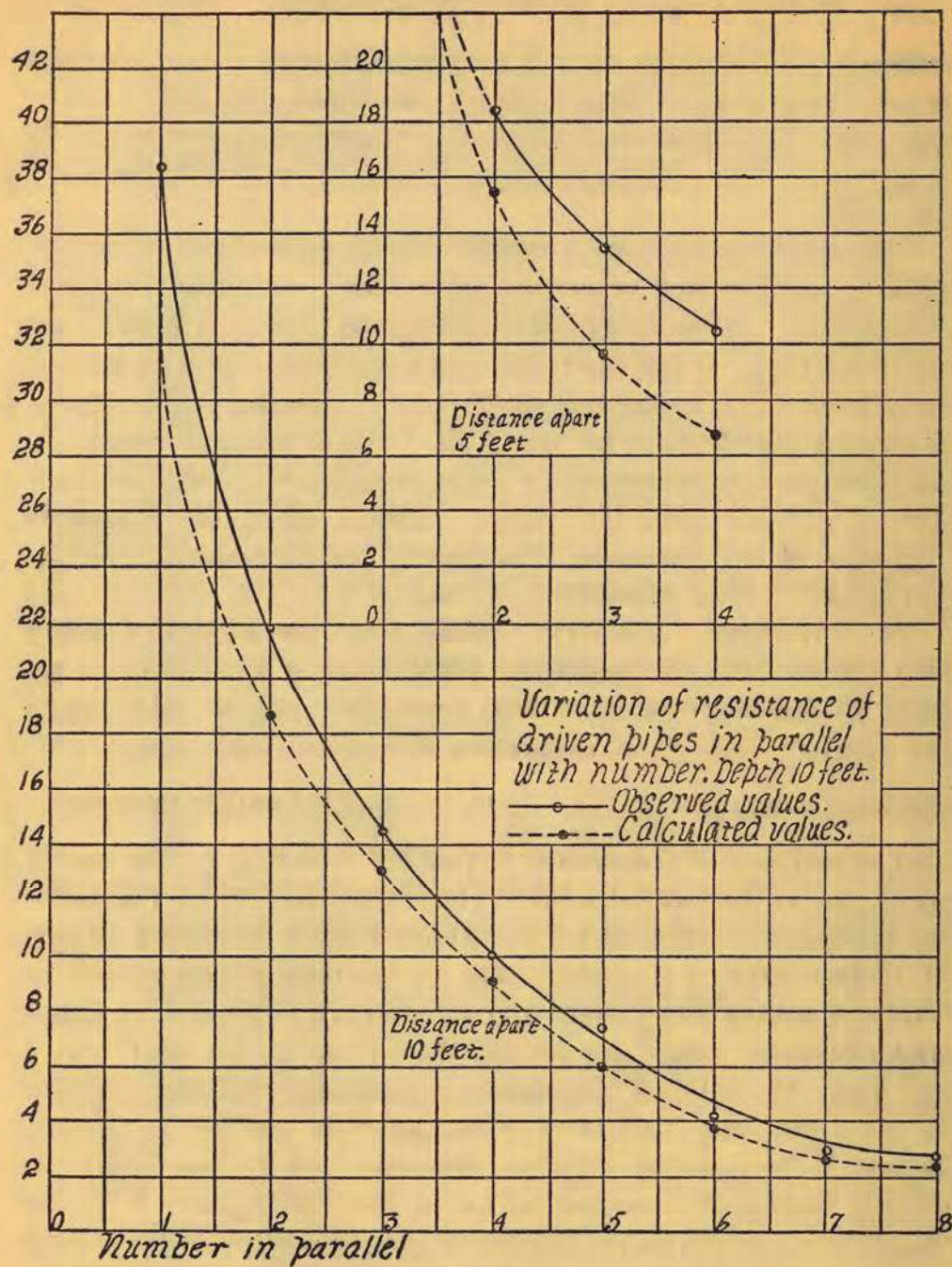


FIG. 14

TABLE 4.—Variation of Resistance of Driven Pipes in Parallel With Number
PIPES 10 FEET APART

Specimens	Resistance ^a	Specimens in parallel	Measured resistance	Calculated resistance
	Ohms		Ohms	Ohms
1	30.3	1, 2	19.8	18.4
2	47.1	1, 2, 3	14.4	13.2
3	45.9	1, 2, 3, 4	10.0	9.1
4	29.1	1, 2, 3, 4, 5	7.4	5.9
5	17.0	1, 6	4.1	3.7
6	9.9	1, 7	2.9	2.7
7	9.7	1, 8	2.7	2.5
8	39.7			

PIPES 5 FEET APART

9	34.5	9, 10	18.2	15.0
10	26.0	9, 11	13.5	9.6
11	27.6	9, 12	10.8	7.2
12	28.5			

^aAverage of numbers 1 and 2=38.7.

In some instances it is necessary to make the resistance of an earth connection as small as practicable, but space is lacking in which to drive pipes at some distance from each other. This may be the case near telephone and power poles. Referring to Fig. 13, it is seen that the first foot or so of separation between a pair of pipes has the greatest influence in reducing the resistance to flow of current. Hence, much can be accomplished by driving two or more pipes even as close as 1 foot or so from each other. This is especially to be recommended as a course to follow when pipes are driven alongside of poles. Where a single pipe is driven beside a pole and close to it, the pole, which in most cases is of much greater resistivity than the soil, shuts off a large part of the current flow, unless the pipe extends some distance below the bottom of the pole. By driving another pipe on the opposite side, the resistance to flow of current can be considerably reduced. A particular instance may be cited in which three pipes 8 feet in length were driven equidistant from one another around a pole set about 4.5 feet in the ground. Measurements of resistance gave results as shown in Table 5. These results indicate that two pipes driven on opposite sides of a pole will give a resistance of approximately 65 per cent, and three pipes at 120 degrees apart approximately 53 per cent, of that of a single pipe. It is not likely, however, that a further increase in the number of pipes would produce an additional decrease in resistance sufficient to justify the expense of driving.

TABLE 5.—Resistance of Pipes Driven Around a Pole

Specimens	Resistance of each ground	Specimens in parallel	Resistance in parallel
	Ohms		Ohms
1	53.3	1-2	34.0
2	54.1	1-2-3	28.0
3	48.0	.....	.....

(d) VARIATION OF RESISTANCE WITH CONTACT AREA.—The specimens used for this experiment consisted of four 0.75-inch pipes, and three each of 1.25-inch, 2-inch, and 2.5-inch pipes, respectively, driven to a depth of 10 feet. The measurements, the results of which are given in Table 6, were made in the same manner as those previously recorded. On account of the nonuniformity of the soil, however, the results are so irregular as to give very little indication of the way in which the resistance would vary with contact area if the soil were uniform.

From this table it appears that the resistance to flow of current away from a 2.5-inch pipe is nearly as great as from a 1.25-inch pipe. This, of course, is not the case, at least not to the extent indicated by the observed values. A clearer idea of the variation of resistance with size of pipe may be obtained by making use of the observation equation $R = \frac{\rho}{2\pi C}$ as in some of the previous work, than by comparing the observed values themselves. As stated heretofore, R is the resistance to flow of current away from the electrode, ρ the resistivity of the soil, and C the electrostatic capacity in free space of the pipe and its image above the surface of the ground.

TABLE 6.—Variation of Resistance of Driven Pipes With Contact Area ^a

Specimens of each size	Size of pipe, internal diameter	External diameter of pipe	Electrostatic capacity	Average resistance	Calculated resistance
	Inches	Centimeters		Ohms	Ohms
.....	.....	0.5	39.1	(b)	40.2
.....	.....	1.0	43.6	(b)	36.1
.....	.....	1.5	45.5	(b)	34.5
.....	.....	2.0	47.7	(b)	32.9
4	0.75	2.6	49.6	38	31.7
3	1.25	4.2	53.8	26	29.2
3	2.0	6.0	57.3	27	27.4
3	2.5	7.3	59.6	24.5	26.4

^a Depth—10 feet.^b No observations.

In Table 6 are given the values of C for the different sizes of pipe on which measurements were taken and also for smaller sizes to enable extending the curve back toward the axis of ordinates. In calculating C the formula for an ellipsoid of revolution,

$$C = \frac{L}{2 \log_e \frac{2L}{d}},$$

was taken as the nearest obtainable approximation to the real value in the same way as under (a) where variation of resistance with depth was discussed. Substituting the measured

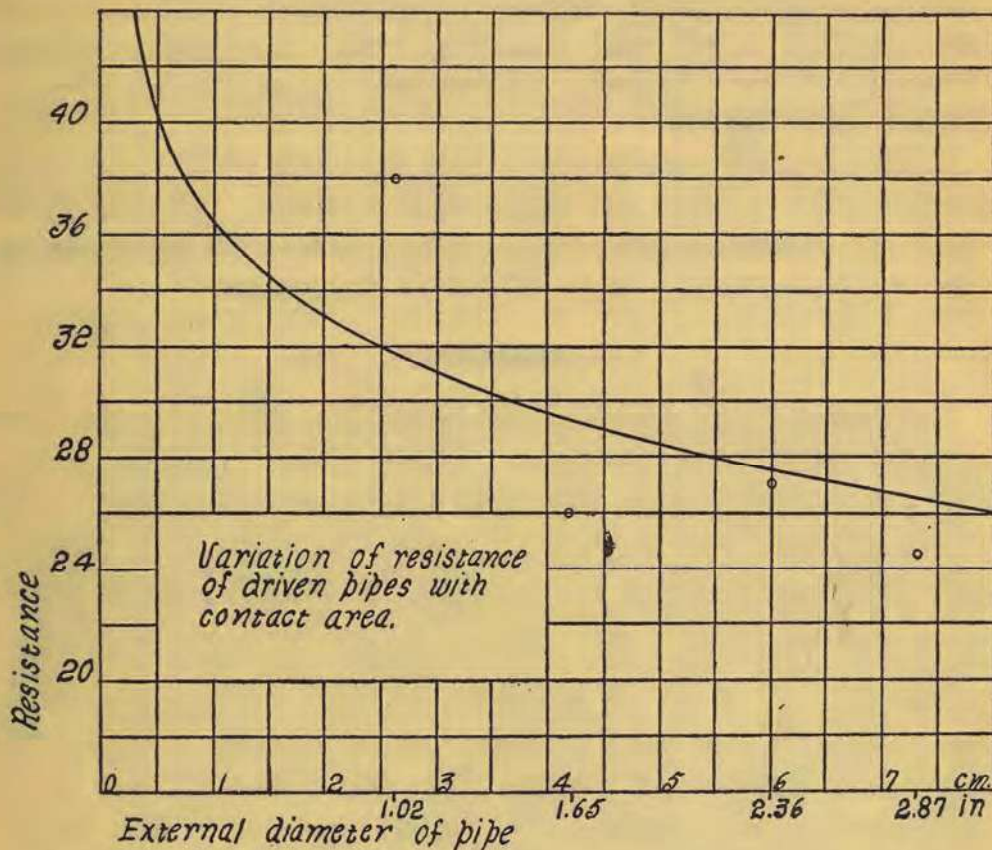


FIG. 15

values of resistance and corresponding values of C in $\rho = 2\pi CR$, the average value of ρ is found to be 9870 ohms per cm³. From this, in turn, the resistance for each size of pipe is calculated as if the resistivity of the soil were uniform. These calculated values of resistance are given in the last column of Table 6 and have been used to plot the curve of Fig. 15. The circles represent the observed values of resistance, the distance of the point above the curve being practically equal to the sum of the distances of the three points below the curve. The curve may, therefore, be taken

as a fair indication of the results which would be obtained in uniform soil, and shows that as the diameter of the pipe, and consequently the area of contact, increases the resistance decreases at a steadily decreasing rate. For instance, increasing the external diameter of the pipe from 1 to 2 cm (0.394 to 0.787 inch) decreases the resistance 9.34 per cent, from 2 to 3 cm (0.787 to 1.18 inches), 5.88 per cent, from 3 to 4 cm (1.18 to 1.57 inches), 4.84 per cent, and so on. Doubling the diameter or increasing it from 1 to 2 cm, 2 to 4 cm, and 4 to 8 cm (0.394 to 0.787 inch, 0.787 to 1.57 inches, and 1.57 to 3.15 inches) cause decreases of resistance of 9.34 per cent, 10.6 per cent, and 11.85 per cent, respectively. These values have been checked experimentally by other investigators, notably by Creighton.²²

In driving pipes, therefore, it does not seem wise to use sizes smaller than 0.75 inch nor larger than 2 inches. Between these limits mechanical considerations determine whether the larger or smaller sizes should be used, as will be shown later.

2. PLATES

The use of buried plates for the purpose of grounding electrical systems seems to be decreasing. This is due, no doubt, to the fact that in most places the same results can be obtained with driven pipes as with plates, and at much less expense. Nevertheless, it may in some cases be necessary or advisable to use them, and it is, therefore, of interest to discuss their electrical characteristics. The discussion which follows, however, is largely theoretical. It would be desirable to obtain experimental data upon which to base the discussion, but in the case of plates the expense of obtaining consistent data seems greater than their importance would justify. To obtain consistent data would require observations on a great many specimens, since there is no practicable way of eliminating irregularities due to nonhomogeneity of the soil except by taking the average of a large number of measurements. In this investigation, therefore, the number of plates buried was limited to 12, of different sizes, which were put down mainly for the purpose of determining the variation of resistance with seasons and the effects of coke and salt.

(a) VARIATION OF RESISTANCE WITH DEPTH.—If a circular thin metal plate is embedded in the surface of the ground to a depth

²² General Electric Review, 15, pp. 15 and 66.

equal to one-half its thickness, the resistance to flow of current away from it can be expressed by $R = \frac{\rho}{2\pi C}$, where ρ is the resistivity of the soil and C is the electrostatic capacity in free space of the plate. In this case $C = \frac{d}{\pi}$, where d is the diameter. If, now, the plate is sunk below the surface of the ground, the value of C which must be used in the formula for R is that of the combination of the plate and its image.²³ When the plate is so far beneath the surface that its image may be considered as at an infinite distance away from it, C becomes equal to $\frac{2d}{\pi}$. In passing from the surface of the ground to a great depth, therefore, the resistance to flow of current away from the plate changes from $R = \frac{\rho}{2d}$ to $R = \frac{\rho}{4d}$. This holds for a plate of any shape—that is, the resistance at the surface of the ground is twice that at a great depth, if the resistivity of the soil is uniform—and the shape of the curve showing variation of resistance with depth would be something like that of the curves in Fig. 13, showing variation of resistance of two driven pipes in parallel with distance apart, because the rate of change of C with increasing distance would be much the same. At least, R would decrease rapidly with the first few feet increase in depth and then more slowly, approaching a constant value at an infinite depth. Hence, for plates of ordinary size—that is, of areas from 10 to 20 square feet—the depth in conducting soil should be from 5 to 8 feet, since the curves of Fig. 13 indicate that greater depths would not show a further marked decrease of resistance. In fact, for a plate or other electrode of any size or shape, when the depth is such as to make the distance between the electrode and its image several times the dimensions of the electrode, increasing the depth will not result in a further marked decrease of resistance, because at those distances the rate of increase of C with increase of distance becomes very slow.

(b) VARIATION OF RESISTANCE WITH AREA OF PLATE.—Referring again to the example of the circular plate embedded in the surface of the ground, it will be seen that the resistance to flow of current away from it varies inversely as the diameter; that is, doubling

²³ See Appendix III.

the diameter, and thus quadrupling the area of such a plate, halves the resistance. On the other hand, for a plate of rectangular shape which is very long in comparison with its width, quadrupling the area by increasing the length much more than halves the resistance. A particular instance may be given in which increasing the length of a buried strip of metal 1.5 inches wide from 40 feet to 160 feet reduced the resistance from 9.6 to 3.3 ohms. For rectangular plates of which the width is one-third to one-half the length, however, the case of the circular plate more nearly represents the conditions; i. e., quadrupling the area by a proportional increase of dimensions practically halves the resistance. This relationship between area and resistance is indicated by the fact that measurements on plates buried near other other showed resistances as follows: (1) Average resistance of two plates 2 feet by 4 feet buried 5 feet deep, 32.5 ohms; (2) resistance of one plate 2 feet by 8 feet buried 4 feet deep, 24.5 ohms; (3) resistance of one plate 4 feet by 8 feet buried 4 feet deep, 17.5 ohms. Because of the nonhomogeneity of the soil, however, these data must be taken only as indicating the relationship mentioned above and not as a check upon it.

To gain an idea of the rate at which resistance to flow of current away from a plate decreases with increasing size, the curve shown in Fig. 16 is given. This curve represents values calculated from

the formula $R = \frac{\rho}{2d} = \frac{\rho}{4} \sqrt{\frac{\pi}{A}}$, where A is the area of the circular

plate. The value of ρ in this case is assumed to be 7000 ohms per cubic centimeter, or very nearly the value found in one or two cases of driven pipes previously given. This curve shows that when a circular plate embedded in the surface of the ground reaches an area of 20 or 30 square feet the rate of decrease of resistance with increasing area becomes very slow. This represents, roughly, the conditions for a plate of rectangular shape beneath the surface, so it appears that the area of a single plate can not economically be increased beyond these dimensions. As indicated below, it requires much less labor and material to bury two small plates at a distance from each other and connect them by a heavy wire than to bury a single large plate which will have the same resistance to flow of current away from it into the earth as the two small plates in parallel.

(c) RESISTANCE OF TWO PLATES IN PARALLEL.—In this case measurements were made on five plates 2 feet by 4 feet in size,

which were buried at different distances from one another in rather stony clay soil. They were laid in a row with distances between ends as indicated in Table 7, where the results of the measurements are given. Nos. 32, 33, and 36 were buried on edge in trenches 6 feet deep; Nos. 34 and 35 were buried flat in holes 5 feet deep. The center lines of those on edge were therefore at the same depth as the plane of those which were laid flat.

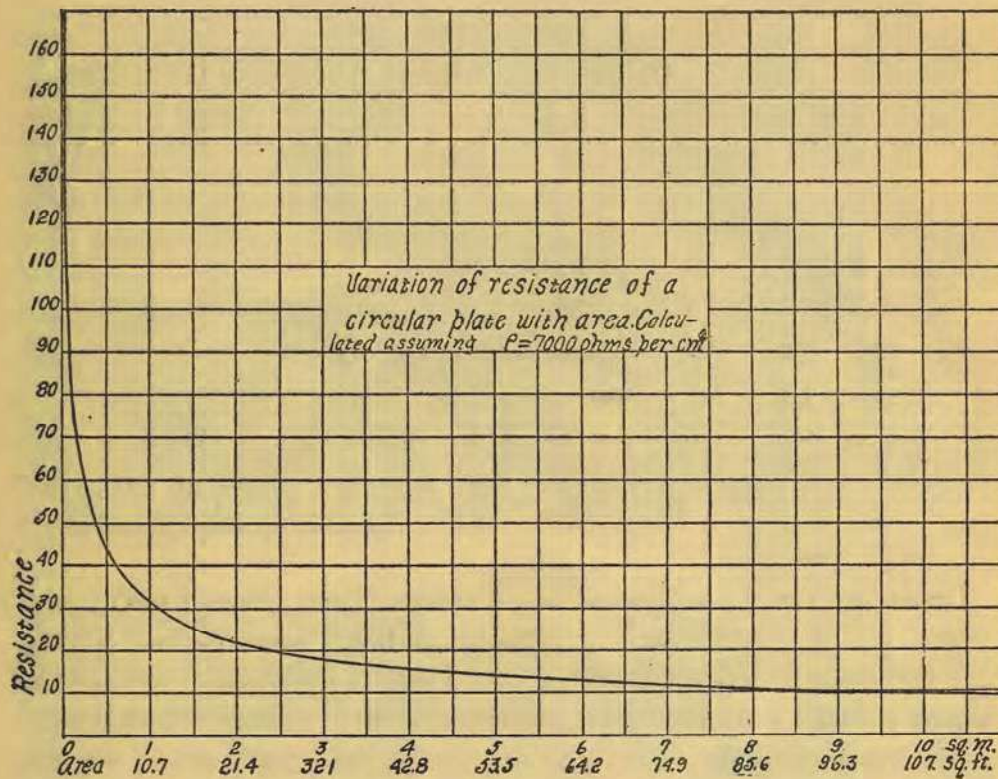


FIG. 16

The measurements of resistance were made by means of the ammeter-voltmeter method.

TABLE 7.—Resistance of Two Plates in Parallel

Plates	Resistance	Plates in parallel	Distance between ends	Measured resistance	Calculated resistance	Ratio of calculated to measured resistance
	Ohms		Feet	Ohms	Ohms	Per cent
32	31.2	32-33	1	18.8	14.5	77.2
33	27.2	33-34	5	16.1	13.6	84.4
34	27.4	32-34	10	16.2	14.5	90.0
35	44.3	32-35	29	18.7	18.3	97.8
36	31.6	35-36	30	18.6	18.4	99.0

The resistance of each specimen was first measured and then the resistances of the different pairs in parallel. From the results of the measurements on each specimen have been calculated the resistances which the different pairs in parallel would have if they were at an infinite distance apart. These values were obtained by applying the formula for the resistance of conductors in parallel, or $R = \frac{R_1 R_2}{R_1 + R_2}$, R_1 and R_2 being the resistances of the individual specimens. The results of these calculations are given in the sixth column of Table 7. In the last column are given the ratios of calculated to measured resistances. From these ratios it appears that to obtain practically the minimum resistance for two plates in parallel they must be placed 25 or 30 feet apart. At 10 feet apart the ratio of calculated to measured resistance is about 90 per cent and at 1 foot apart about 77 per cent.

It has been stated heretofore that quadrupling the area of a rectangular plate, say, by increasing the dimensions from 2 feet by 4 feet to 4 feet by 8 feet, practically halves the resistance. In the case of Nos. 32 and 33 it will be noted that if the area were doubled by doubling the length and the two halves of the plate were then moved 1 foot apart, the resistance would be reduced by about one-third.

From the foregoing discussion it seems, then, that if two plates 2 feet by 4 feet are buried in uniform soil at a distance of 25 to 30 feet from each other, practically the same resistance will be obtained as with a single plate 4 feet by 8 feet. Moreover, the excavation and material required for the smaller plates will be but little more than half that for the larger plate. To bury a number of small plates would, of course, require considerable ground space, and where this is not available it would be impracticable; but where space is available, the required conductance can be more economically obtained with the small plates in parallel than with a single large one. It should be stated that the sizes of the small plates here referred to approximate 20 to 30 square feet. Up to that size it is economical to increase the area of the plate in order to decrease the resistance. When less resistance is required than these sizes will give, however, economy lies in an increased number of plates.

(d) PLATES ON EDGE V. PLATES LAID FLAT.—In some cases it may be more advantageous to bury plates on edge than flat. In the first place, if the width of the plate is more than 2 feet less excavation may be required, because the trench need only be

wide enough to work in. It should be deep enough, however, to give an average depth equal to the depth which would be given if the plates were laid flat. In the second place, when a plate is placed on edge better contact can be made, usually, with the ground. In filling the trench the earth can be rammed on both sides of the plate, making good contact over the entire surface. On the other hand when a plate is laid flat it may rest on humps in the bottom of the trench and prevent good contact with the ground at all points. This is a condition which is very difficult to avoid. It is likely, however, that after a plate has been in place for some time, settlement will take place to a sufficient extent to eliminate the humps, unless the ground is very hard or stony. Nevertheless, to have good contact from the start is very desirable.

In the course of this investigation measurements were made on several plates, part of which were laid flat and part on edge. In the case of those laid flat there appeared to be a tendency for the resistance to be higher at the start than in the case of those on edge, with considerable decreases in the first few months, indicating settling as pointed out above. On the other hand, after settlement had taken place, there was no indication of a marked difference of resistance that could not be attributed to the non-homogeneity of the soil.

3. STRIPS

Where bedrock is near the surface of the ground, it is in many cases out of the question to drive pipes or to dig deep enough to make an effective ground connection with plates. Moreover, the ground in such places is likely to be very dry, particularly during periods when there is little rain, for there is but slight opportunity for storage of moisture deep in the ground during wet seasons to be absorbed by the surface strata through capillary action when periods of drought occur. The best procedure under such circumstances is to connect to earth by burying narrow strips of metal in trenches dug as deep as the rock layer will allow. Because of the high resistivity of the soil which is encountered in dry seasons, it is necessary to have a ground connection of considerable extent, and metal in the form of narrow strips offers the most efficient means of obtaining it. This is shown by the fact that for a given amount of metal the strip form can be made to give a greater value of the electrostatic capacity, and hence a lower value of resistance, than any other, as mentioned under "Resistance of ground connections," Section II.

The use of buried strips is most likely to be necessary in the case of lightning-rod systems, but may be made to serve any purpose for which a ground connection may be required. For lightning rods, however, this type of ground connection is very desirable where the soil is shallow, and it may be said further that its use in soils of high resistivity will be found advantageous whether the conditions are such as to prevent the use of driven pipes or not. Its desirability in this case, especially if a considerable network of strips is used around a building, arises from the facility with

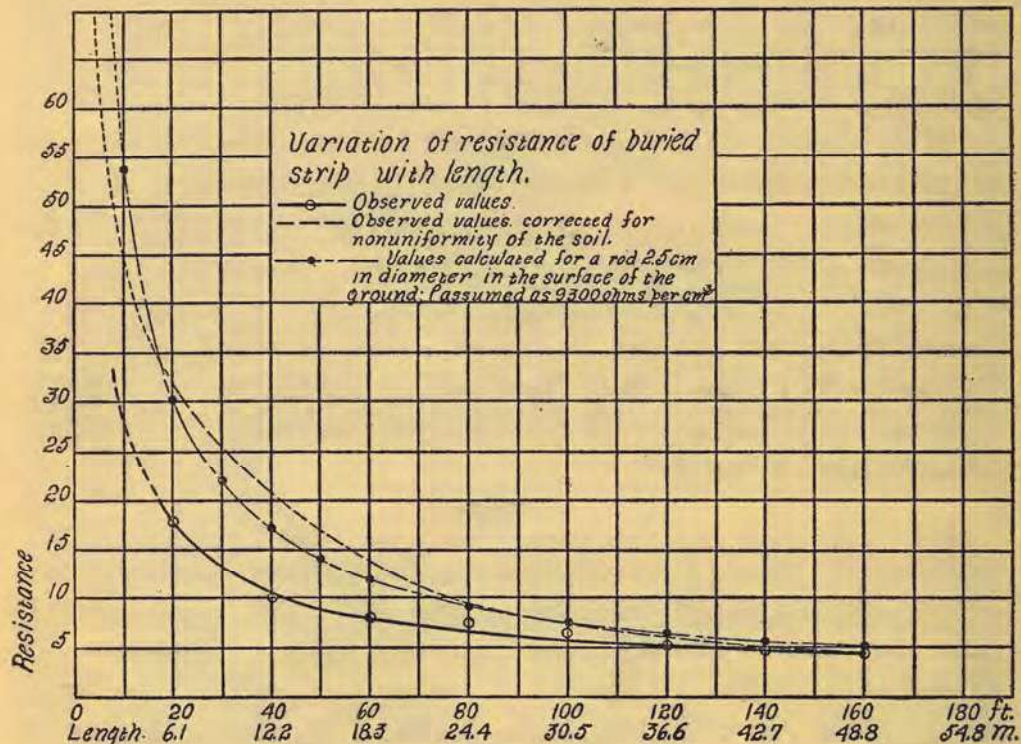


FIG. 17

which it can pick up the earth charge when a lightning stroke occurs. As pointed out heretofore, if conditions exist favorable to a lightning stroke, the charge on the earth covers a considerable area, of which the building may be the center, or at least the point toward which the stroke is likely to be directed. When the stroke occurs, there is a tendency for the charge to rush toward the building, and it is obvious that a network of metal in the ground will collect this moving electricity with greater ease than ground connections at a few points, which in this case would necessarily be of high resistance.

On the other hand, to make a ground connection by means of strips requires a large amount of ground space, and where this

is lacking their use is, of course, impracticable. In addition considerable excavation is required. Nevertheless, there are many places where their use is practicable and it is possible to get an effective connection to earth with them that could not otherwise be obtained.

(a) VARIATION OF RESISTANCE WITH LENGTH.—In order to determine the effect of length on the resistance of a ground connection made of strips of metal, 8 specimens of galvanized strap iron 1.5 inches wide and 20 feet in length were buried in a trench 12 inches deep and 160 feet long. Each specimen had leads soldered to its ends, which were brought out of the ground so the resistance of the separate specimens, or any number of them connected, could be measured. To make certain that the ends of the specimens were fully separated from each other, a wooden stake 4 inches wide was driven between them. The resistances to flow of current away from these specimens were measured each month, and a set made on July 27, 1915, when the resistances were somewhat above their minimum value for the year, are given in Table 8. This set of measurements contains values for each specimen and for combinations of the different specimens connected to give lengths from 20 to 160 feet. The results obtained on the different lengths are shown plotted in Fig. 17.

TABLE 8.—Resistance of Buried Strips

Strips	Resistance	Strips in parallel	Length	Resistance	Resistance corrected for nonhomogeneity of soil	Length of rod (Diam 2.5 cm)	C for rod	Calculate resistance, assuming $\rho = 9300$ ohms per cm ²
	Ohms		Feet	Ohms		Cm		
3	17.7	3	20	17.7	31.6	305	27.7	53.4
						609	49.2	30.1
						914	69.3	21.4
4	13.6	3-4	40	10.1	20.5	1220	88.6	16.7
						1524	107.4	13.8
5	25.5	3-5	60	8.2	13.6	1829	125.7	11.8
6	48.2	3-6	80	7.5	9.0	2438	161.0	9.2
7	39.8	3-7	100	6.5	7.1	3050	195.3	7.6
8	21.2	3-8	120	5.2	5.9	3660	229.5	6.5
9	39.5	3-9	140	4.8	5.1	4270	262.5	5.6
10	47.6	3-10	160	4.4	4.4	4880	295.0	5.1
Av.	31.6							

It will be noted in Table 8 that the resistances of Nos. 3 and 4 are much lower than the average for all of the specimens, which is 31.6 ohms. The effect of these low values for the resistances of Nos. 3 and 4 is to depress the left-hand end of the curve of observed values in Fig. 17 and make the right-hand portion flatter than it should be. This arises from the nonuniformity of the soil, whereas if the soil were uniform, the resistance of No. 3 would be 31.6 ohms instead of 17.7, and that of Nos. 3 and 4 connected would be more than 10.1 ohms, the value shown by the table. To give an idea of the slope the curve would have if the soil were uniform, it is necessary to correct the observed values of resistance by means of the formula $R = \frac{R_{av}}{R_1} R'$, where R' is the observed value, R_{av} the average of all the individual specimens, in this case 31.6 ohms, and R_1 the average of the resistances of the individual specimens used in obtaining R' . This is the same as multiplying the observed values by $\frac{\rho_{av}}{\rho_1}$, where ρ_{av} is the resistivity of the soil corresponding to the measured resistance to flow of current away from all of the specimens connected and ρ_1 the resistivity corresponding to R' or the measured resistance to flow of current away from any number of them connected. The values obtained in this manner are also plotted in Fig. 17.

Furthermore, for the purpose of comparison, there is also plotted in Fig. 17, a curve obtained by calculating values of resistance for a rod 1 inch (2.5 cm) in diameter embedded in the surface of the ground to a depth equal to its radius. These values of resistance were calculated from $R = \frac{\rho}{2\pi C}$, C being obtained for the dif-

ferent lengths of rod from the formula $C = \frac{L}{2 \log_e \frac{2L}{d}}$, where L is

the length of the rod and d its diameter. The quantity ρ was arbitrarily assumed to be 9300 ohms per cubic centimeter to make the curves for calculated and corrected values nearly coincide.

It appears from these curves that if the length of a buried strip is doubled, the resistance to flow of current away from it is practically halved. In particular, in the case of the rod, when the length is doubled, the calculated resistance is decreased about 45 per cent. In the case of the buried strip, when the length is

increased from 20 to 40 feet the corrected values show that the resistance is decreased about 35 per cent; from 40 to 80 feet, 56 per cent; and from 80 to 160 feet, 51 per cent. When the length of the rod is increased from 20 to 160 feet the calculated resistance is decreased 83 per cent, while in the case of the strip the decrease is 86 per cent. The observed values do not check with these so far as decrease of resistance with increasing length is concerned, for the reason that the trench in which the specimens were buried extended from a region where the resistivity of the soil was of one value to another where it was nearly twice as great, as shown by the resistances of Nos. 3 and 10 in Table 8.

All of the values of resistance mentioned above were obtained on strips lying in a straight line. It is obvious that in this position, if the resistivity of the soil is uniform, the resistance to flow of current into the earth is less than in any other because the value of C is greatest. If the strip were curved or coiled, the resistance would be greater because C would be less. In burying strips, therefore, it is well to remember that for a given length of strip the wider the distribution the more effective the ground connection that will be obtained, unless the resistivity of the soil is nonuniform, and then it is best, in some cases, to put the metal where the resistivity is least. In most places local conditions as to resistivity of the soil will be a large factor in determining the way in which a ground connection is to be made.

(b) VARIATION OF RESISTANCE WITH DEPTH.—Where buried strips are used, it is not likely that the depth at which they are placed can be arbitrarily chosen, because, in general, the depth that can be attained will be determined by the obstruction which prevents the use of driven pipes. Nevertheless, in some instances it may be well to know something of the effect of depth. This case is similar to the one previously considered of resistance to flow of current away from two driven pipes in parallel. In fact, if a pipe of the same size as the driven pipes were substituted for the strip, the two cases would be exactly the same, for in the case of the driven pipes the electrostatic capacity C applies to the combination of the pipes and their images above the surface of the ground, while in the case of the buried pipe the value of C is the same if the depth is one-half the distance between the driven pipes and the length is the sum of that of one of the driven pipes and its image. The fact that in the case of the driven pipes the surface of the ground cuts the axes of the pipes perpendicularly

and midway between their ends, whereas in the case of the buried pipe the surface of the earth passes parallel to the axis of the pipe and midway between the pipe and its image, does not make a difference in resistance if the resistivity of the soil is the same in the two cases. It follows, therefore, that the resistance to flow of current away from a pipe 20 feet in length buried 3 feet in the ground will be the same as from two driven pipes 10 feet in length and 6 feet apart. Moreover, the curve showing decrease of resistance with increase of depth in the case of the buried pipe will be of exactly the same value and shape as the curve showing decrease of resistance with increase of distance in the case of the driven pipes. For the strip the shape of the curve would not be much different, except, perhaps, when very near the surface of the ground. At a depth of a few centimeters the curves would be practically of the same shape. In burying strips, therefore, it would not be expected that after a depth of 3 feet had been reached there would be a further marked decrease of resistance with increasing depth, because for driven pipes 10 feet in length the rate of decrease of resistance with increasing distance apart becomes very slow after 6 feet is reached. For strips of great length this depth would probably be somewhat increased, but not appreciably under lengths of 40 or 50 feet.

The foregoing deduction is borne out, to a certain degree at least, by data obtained on strips buried at different depths. These specimens were 20 feet long and 1.5 inches wide. One of them buried 6 inches deep showed a resistance of 43 ohms; eight of them 12 inches deep showed an average resistance of 31.6 ohms, as indicated in Table 8; one at 18 inches, 26 ohms; one at 2 feet, 13 ohms; and one at 3 feet, 17 ohms. It appears from these values that after a depth of 2 or 3 feet has been reached, there is no further marked decrease of resistance with increasing depth, but because of the nonhomogeneity of the soil these values must be taken only as an indication of the relationship mentioned above and not as a check upon it. The depth of 3 feet referred to above, means of course, in conducting soil. If there is a stratum of dry earth on top it may, in some instances, be necessary to place strips at a greater depth than 3 feet. To go more than 3 feet in conducting soil, however, will not result in material benefit.

4. PATENTED GROUNDING DEVICES

Many patented devices for making ground connections have been put on the market by manufacturers. Some of these devices have come to the attention of the Bureau of Standards, and in all that have been tested the feature which is supposed especially to recommend them to the prospective purchaser is that they are intended to absorb water in wet seasons and give it out in dry seasons in sufficient quantities to keep the adjacent soil moist at all times and thus prevent marked fluctuations of resistance. A grounding device with this feature incorporated would be very desirable, but practically it is not accomplished by any of the designs that have been tested up to this time. For their absorptive power some of the devices depend upon charcoal and others upon substances the compositions of which are not disclosed by their makers. One consists of a perforated sheet copper cone about 2 feet in height and 6 inches in diameter at the base, which is filled with finely divided charcoal. As regards gases the absorptive power of charcoal is enormous, a given volume of charcoal being able to absorb many times its volume of gas, but as regards water its absorptive power is only of the same magnitude as that of an equal volume of earth. The quantity of water which could be stored in such a small volume of charcoal is therefore not sufficient to be of any moment, and moreover, the charcoal would tend to dry out as fast as the surrounding earth and not lag appreciably behind it. Hence the cone might as well be unperforated and as well be empty as filled with charcoal. The same thing is true of the other devices. As shown later, however, the addition to the soil surrounding an electrode of a soluble salt which is highly conducting in solution materially decreases the resistance in comparison with what it would be with normal earth, and insofar as the substances used in these earthing devices contribute to this effect they are of benefit; but as far as absorbing water in wet seasons and giving it out in dry seasons is concerned their effects are negligible.

As stated above, a number of these devices have been tested. Table 9 contains a summary of the results obtained and also some data which enable comparisons to be made between these special devices and driven pipes and plates. In column 5 are given the resistances of the different kinds of specimens measured August 31, 1915, when they showed the minimum recorded resistance for the year, and in column 6 are given the resistances

of the same specimens measured on December 1, 1915. Where there was more than one specimen of the same kind or size the average value is given. Because of lack of rain and decrease of temperature, the values obtained in December 1 show considerable increases over those for August 31. Column 7 gives the percentage increase of resistance.

It will be noted that none of the special devices showed a resistance markedly lower than the pipes and, in fact, in all but one case the resistance was higher. None of them showed lower resistance than the plates. The figures showing percentage increase of resistance are the most important because the special virtue of these devices is supposed to lie in the comparatively uniform resistance which they maintain. It is shown that the resistance of all the devices increased much more than that of the pipes, and in most cases more than that of the plates. It does not appear, therefore, that the use of these devices will give a result that can not be obtained with pipes, and, moreover, with pipes the cost is less.

TABLE 9.—Comparison of Patented Devices With Pipes and Plates

Specimens	Description	Length or size	Depth	Average resistance, Aug. 31, 1915	Average resistance, Dec. 1, 1915	Percentage increase
				Ohms	Ohms	
25-26.....	Paragon ground cones in coke ...	2 feet	5	39.5	62.2	54.9
27-28.....	do.....	1 foot.....	5	46.4	72.1	55.4
29-30-31.....	Maxum ground boxes in clay .....	.....	5	33.2	57.4	72.9
43.....	L. S. Brach hydroground in clay	Large	5	39.8	61.2	53.8
44-45-46.....	do.....	Standard.....	5	42.2	57.1	35.3
47.....	do.....	Medium.....	5	37.5	52.7	40.5
48-49.....	Lord Manufacturing Co. disk type hydroground in clay .....	.....	5	76.1	124.0	63.0
54-55.....	Federal Sign System cartridge ground plate in clay	22 inch.....	5	42.6	71.9	68.8
56-57.....	do.....	10 inch.....	5	47.3	80.6	70.4
32-33 and 36.....	Plates on edge in clay	2 by 4 feet...	6	20.3	29.9	47.3
34-35.....	Plates flat in clay.....	do.....	5	25.4	35.6	40.2
74 and 98 to 104..	Three-fourths inch galvanized-iron pipes.	10 feet.....	10	35.6	47.1	32.3

5. WATER PIPES

As a means of grounding electrical systems water pipes easily come first in point of desirability. In the first place, on account of their great extent they offer but little resistance to flow of current away from them into the earth, the total resistance of

water-pipe ground connections being found in most cases to be but a fraction of an ohm. A resistance of 2 ohms would be extraordinarily high. In the second place, they are easily accessible at service pipes or at other places; and in the third place, ground connections to them are economical in first cost, are easy to inspect, and are permanent. Moreover, the areas covered by electric lighting systems are approximately the same as those covered by water systems, within city limits at least, so it is practicable to ground to them in nearly all cases where ground connections are required. To use the water pipes is, therefore, highly advantageous in many cases, and is especially so where low-voltage alternating-current circuits must be grounded through a low resistance for the sake of personal safety. In this connection it should be emphasized that because of the high degree of security obtained from electrical dangers, the chief advantage is to the public, and in view of this fact, no obstacle should be placed in the way of grounding to water pipes. At the same time, however, it must be shown that the use of water pipes for making ground connections is not in any appreciable degree a disadvantage to the pipe-owning utility. In the past it has been stated that trouble for the utility would arise from three sources, viz, (1) electrolysis by stray currents from grounded circuits; (2) danger to employees while working on service or other pipes to which circuits were grounded; (3) complications from allowing a second public-service utility the use of the pipes. The factors which affect the resistance and effectiveness of water-pipe ground connections and the extent of the possibilities that the use of water pipes for grounding may inconvenience the water utility are discussed under the following heads: (a) Resistance of water-pipe ground connections; (b) electrolysis by alternating current; (c) electrolysis by direct current; (d) heating of pipes by current flow; and (e) extent of danger to employees of the water utility.

(a) RESISTANCE OF WATER-PIPE GROUND CONNECTIONS.—As stated above, the resistances of water-pipe ground connections are found in most cases to be a fraction of an ohm. Where these low resistances exist, however, it will be found that the pipe joints for a considerable distance from the point of connection give as good metallic contact as will be the case with lead or screw joints, which under favorable circumstances have resistances of only a few thousandths of an ohm. On the other hand, where high resistances exist they will almost always be accompanied by

high-resistance joints such as those made with cement or "leadite," which may have resistances of several ohms or even several hundred ohms. The extent to which the effect of the resistance of the pipe may exceed the effect of the resistance of the soil in hindering flow of current through a water-pipe ground connection is indicated by reference to the case of the buried strip previously considered. It was there shown that if the length of a rod or strip buried in the ground is doubled, the resistance is practically halved. The measured resistance to flow of current away from a buried strip 160 feet in length was found to be about 5 ohms. Assuming the law of variation of resistance with length, as stated above, to hold and neglecting the resistivity of the metal, it is readily seen that if the length were increased from 160 feet to 20 miles the resistance to flow of current away from the strip would be decreased from 5 ohms to a value of the order of 0.007 ohm. Furthermore, if a water pipe 6 or 12 inches in diameter were substituted for the strip, the resistance would be less than 0.007 ohm. Hence, it appears that for water systems of considerable extent, the portion of the total resistance contributed by the surrounding earth is very small. On the other hand, measurements in many cases have shown that an average value for the total resistance is about 0.25 ohm, indicating that the resistance of the pipe contributes an important part and must be considered. In fact, cases may arise where many joints of high resistance in a pipe may make it undesirable as a means of grounding electrical circuits. An example of such a pipe would be one laid with cement joints, or with other insulating joints at short intervals, such as those mentioned above.

In grounding to pipes, however, a distinction must be made between cases where a low resistance to flow of current from an electrical circuit into the earth is desired and those where the object is to keep an electrical circuit, or a conducting body near an electrical circuit, at the same potential as a near by section of pipe. For, even though a length of pipe may have so many joints of high resistance as to make it useless as a ground connection designed to carry considerable current, it may still have sufficient conductance to carry currents large enough to produce severe shocks at moderate voltages in the event of persons making contact with circuit and pipe simultaneously. To prevent accidents of this kind it may be advisable to ground to pipes in some instances even though the resistance to the earth itself is very high.

Cases where such grounding would be necessary are most likely to arise in buildings.

A point which should be mentioned here is the effect which changes in the resistivity of the soil have on the total resistance of a water-pipe ground connection. In the types of ground connections previously considered, the resistivity of the soil is one of the most important factors. To double the resistivity of the soil where one of these ground connections is made would double the resistance. With water pipes, however, the part of the total resistance contributed by the soil is small, unless the resistivity is extremely high, so considerable changes due to drying or other causes will not seriously change the total resistance. In fact, for water-pipe systems of great extent, the resistivity of the soil might change from a value of say 5000 ohms per cubic centimeter to many times that value without markedly affecting the total resistance. In making ground connections of this type, therefore, little attention need be given to the kind of soil in which the pipe is laid. On the contrary, the most important matter in this case is that of high conductance of the pipe joints, such as would be found with lead or screw joints.

It is of interest to compare the average resistance of water-pipe ground connections with that of other forms. For instance, it has been shown previously in this paper that if pipes 10 feet in length are driven in a row 8 or 10 feet apart, their resistance in parallel is about 15 per cent more than it would be if they were at an infinite distance apart, or is not far from inversely as the number. Assuming a single driven pipe in a certain locality to have a resistance of 15 ohms, which is a rather low value, to obtain a resistance of 0.25 ohm would require 50 or 60 pipes 10 feet in length driven in a row 10 feet apart and electrically connected. To obtain the same resistance with plates would require about the same number, unless they were very large, and in addition, it would be necessary to place them more than 10 feet apart. This is plainly impracticable.

At the same time it must be granted, of course, that it is practicable by the use of driven pipes or buried plates to obtain a ground connection which is amply effective for some purposes. For example, a ground connection can be made which will serve satisfactorily for low-voltage alternating-current circuits where transformers are small and fed by lines of limited current-carrying capacity, and an appreciable degree of protection may be obtained

in this way for lines of almost any capacity. As the power rating of the lines and transformers increases, the resistance presented by the ground connection must decrease if ample protection is to be afforded. The practicable limit of decrease of resistance with driven pipes or buried plates is soon reached, and for circuits of large capacity it is imperative that some other means be found. The most obvious solution of the problem is to connect to water pipes which, in most cities as mentioned heretofore, cover approximately the same areas as the electrical systems. Other means should be resorted to only when the water pipes are out of reach.²⁴ In the case of lightning rods on the other hand, and also of lightning arresters, machine frames, and any other cases where low resistance is not so essential, driven pipes or plates may serve very well, but there is no case in which water pipes having low-resistance joints can not be used to advantage.

(b) **ELECTROLYSIS BY ALTERNATING CURRENT.**—Such electrolytic damage from alternating currents as may accrue because of earthing electrical circuits to water pipes will, as a rule, be due to currents set up in the pipes by the circuits themselves. It is possible, of course, that there may, in some cases, be stray currents on the pipes from alternating current railways, and grounding electrical circuits to the pipes at several points may divert part of the flow of these currents, as indicated in the next section in regard to direct currents. But these cases are few, and as shown below the extent of the electrolytic damage negligible, so the consideration here given is confined to stray currents set up in the pipes by the grounded circuits, either under normal operating conditions or under conditions of faulty insulation. Referring to Fig. 18, *A* represents an extensive low-voltage alternating-current circuit which is grounded at a number of points to service pipes, these service pipes being all connected to the same water main. It is readily apparent that under normal conditions of operation, or with insulation everywhere in good condition, some current would flow in the pipes, for with an even slightly unbalanced load on the system, current would flow in the middle wire, and because of the accompanying differences of potential between the points *e*, *f*, and *g*, the pipes would carry part of the current, the total current being shared in inverse proportion to the resistances. The current in the middle wire, however, is usually only a small part of the full-load current, and for that reason the current flow in the pipes is not likely to reach serious proportions.

²⁴ See rule 94, Appendix II.

On the other hand, normally there can be no interchange of current between circuits *A* and *B*. In order for this to occur, the flow would have to take place from *A* through earth wires *a*, *b*, and *c* in parallel, over the water pipe to wire *a* and circuit *B*, and back to *A* on the high-voltage line. Two layers of transformer insulation prevent this, so such an interchange of currents is practically impossible, unless faults develop in the insulation of both transformers. If this should be the case, fuses 1, 2, 3, or 4 would be likely to blow and isolate the low-voltage circuit, or, if they did not blow, the current would be limited to their rated capacity.

With a low-voltage circuit connected to the pipes at a single point as in *B*, Fig. 18, there is obviously no opportunity for any

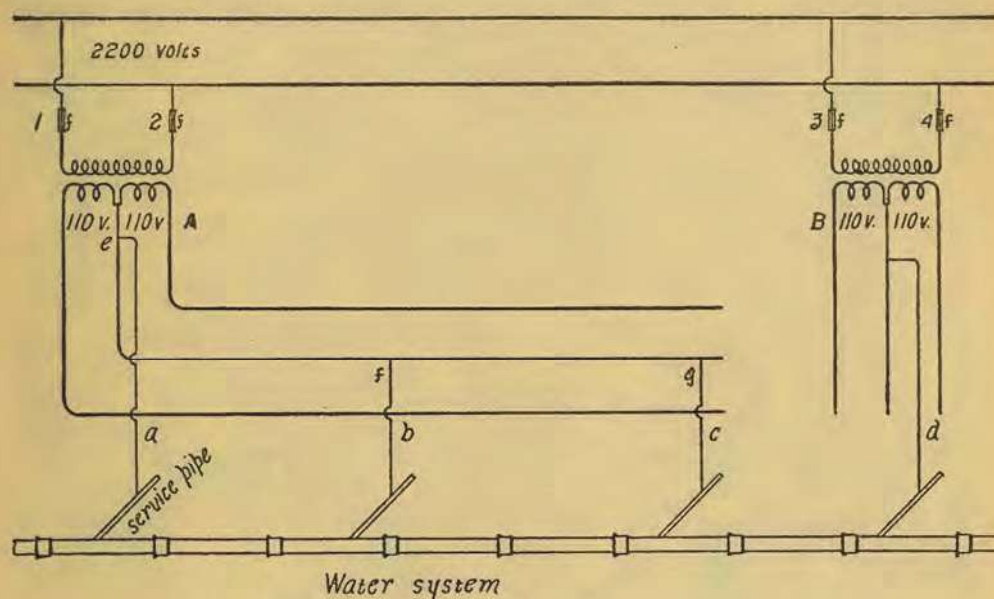


FIG. 18.—Parallel ground connections to water system.

but the very slightest flow of current into the pipes over wire *d* as long as the insulation remains intact. The slight current that would flow would be due to electrostatic capacity and leakage effects and would hardly be measurable by any ordinary means.

With a condition existing such as that shown in Fig. 4, however—i. e., a contact between wires—considerable current might flow. If the leak should occur to circuit *A*, Fig. 18, for example, the current would pass from one side of the high-voltage line through the fault to circuit *A* and to the pipes over ground wires *a*, *b*, and *c*, whence it would flow through the earth back to whatever accidental grounds there happened to be on the opposite side. This current flow would obviously continue until the circuit was opened either by automatic cut-outs or by switches.

Nevertheless, granting that under normal conditions of operation slight alternating currents may flow continually and that in the event of failure of insulation large currents may flow temporarily, it has repeatedly been shown by experiments both by the Bureau of Standards and by others that the damage which may result by electrolysis from such currents is practically negligible.²⁵ These experiments, made on both iron and lead, show that with alternating current at commercial frequencies the amount of metal dissolved is but a fraction of 1 per cent of that dissolved by direct current, the quantities of electricity passed being the same. To express the same thing in different words, it may be said that with currents in pipes which are equal in point of quantity of electricity passed, it will take the alternating current hundreds of years to accomplish the damage that would be accomplished by the direct current in a single year. Therefore, from the stray alternating currents which may be found in pipes from grounding low-voltage alternating-current circuits to them no perceptible damage through electrolysis need be feared.

(c) ELECTROLYSIS BY DIRECT CURRENT.—Electrolysis by direct current may arise where the middle wire of a low-voltage direct-current system is grounded to a pipe at a number of points. The pipe forms a conductor in parallel with the middle wire, and when current flows in the wire current may also flow in the pipe. If the resistance of the pipe is comparable in magnitude with that of the middle wire these currents will also be comparable, being shared in inverse proportion to the resistances. Practically the same effect will be produced where a direct-current system is grounded to a water system at the central station and at other places to driven pipes or plates. The combined resistance of all these pipe and plate grounds in parallel may be low enough to result in a very considerable current flow in pipes near the station. This current flow may, in some cases, be sufficient to result in time in serious electrolytic damage. Damage may also arise from direct currents where an electrical circuit of any kind is grounded to two metallically separate pipe systems, for if there are stray currents from street railways on the pipes, there may be a considerable difference of potential between the two systems, with the result that current flow may be diverted by the grounded circuit and carried into buildings or other places. Another case in which damage may arise from

²⁵ Technologic Paper No. 72 of the Bureau of Standards.

stray currents from street railways is where an electrical circuit is grounded on each side of an insulating joint installed in a pipe for the purpose of mitigating electrolysis. The grounded circuit here acts as a shunt to the joint and may carry a heavy current if there is a considerable potential difference between the two sections of pipe, thus nullifying in a measure the effect of the joint.

Where direct-current systems alone are concerned, electrolysis from currents originating in the systems themselves, or in street-railway systems and being diverted by grounded circuits from their normal paths, may be obviated by making ground connections only at stations and insulating the rest of the system. No especial advantage is gained by making multiple grounds on direct-current circuits, and by using a single ground any possibility of appreciable damage by electrolysis is prevented. It should be mentioned, however, that while grounds on direct-current systems other than those at the stations are objectionable, an exception may be made in the case of connections to service boxes. These connections are desirable to prevent burning out of lamps and appliances in the event of breakage of the middle wire, and since the resistance to ground of these boxes is generally high, connections to them will not result in appreciable flow of current to earth. In the case of alternating-current systems, however, the use of multiple grounds is, as mentioned later, a decided advantage, and with slight precautions such grounds may be used in nearly all places where their use is required or desirable. The main precaution to be observed is to ground only at points between which there are no appreciable potential differences.

(d) *HEATING OF PIPES BY FLOW OF CURRENT.*—As shown heretofore, in the event of a failure of insulation in a transformer, or an accidental contact between wires, there may be considerable current flow through the ground connection, and where water-pipe grounds are used, this current may have to traverse a greater or less length of service pipe before it passes into the earth. This, of course, causes a certain amount of heat to be liberated in the pipe, and it has been stated by some that it may be sufficient to raise the temperature of the water high enough to injure the hard rubber parts of water meters. Cases of injury to the hard rubber parts of water meters have been reported, but upon investigation most of them have been found to be due to backing up of hot water from water boilers into service pipes on account of overheating.

Only one case has come to the notice of the Bureau in which there was sufficient current flow in a service pipe to heat the water to a dangerous temperature. In this a street-railway track was bonded to a service pipe which was required to carry a large part of the return current from the cars. A case of this kind, however, is exceptional, and no case has come to the notice of the Bureau in which sufficient current flow to cause heating has occurred from secondary circuits. Moreover, the likelihood of such heating occurring is small, because where there is a possibility of large currents flowing, it will, in most instances, be found that grounding is done either to a large service pipe or to several service pipes in

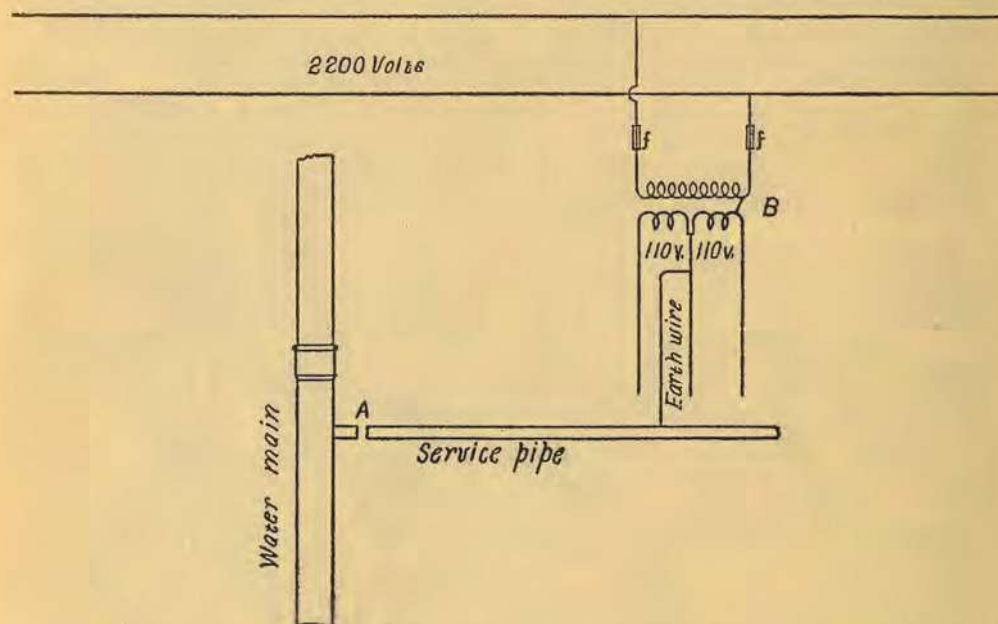


FIG. 19.—Effect of disconnected service pipe

parallel, in which case each service pipe carries only a part of the total current.

(e) EXTENT OF DANGER TO EMPLOYEES OF THE WATER UTILITY.—In general it may be stated that danger to employees of the water utility is likely to arise only under the conditions illustrated in Fig. 19. This shows a low-voltage circuit grounded at one point to a service pipe, a failure of transformer insulation having occurred at *B*. If the service pipe is disconnected at *A*, the person making the disconnection is liable to an electric shock. The severity of the shock depends upon a number of factors which have previously been discussed, and it has been shown that conditions may easily arise under which the severity would be great enough to cause death. Therefore, with low-voltage circuits

grounded at a single point to service pipes, precautions are advisable to prevent such accidents to employees of the water utility when working on them. This can readily be provided for by requiring the electric company to disconnect ground wires from service pipes when work is to be done on them and reconnect when the work is finished. This is a reasonable and sufficient requirement and has been in force in several places for years with satisfaction to both parties.

In this connection, however, it should be mentioned that the probability of employees of the water utility being injured in the manner described above is exceedingly remote. The foregoing paragraph is intended to indicate only what might occur, for, where water-pipe grounds are used, it will be found that but few low-voltage circuits are grounded at a single point; and where this occurs, the low percentage of failures of insulation, and the infrequency with which service pipes are disturbed, makes the chance of work on a service pipe and a failure of insulation occurring at the same time, almost negligible. Nevertheless, where low-voltage circuits are grounded to service pipes at a single point, the precaution of disconnecting the ground wire before beginning work on the pipe should not be neglected. On the other hand, with multiple ground connections to water pipes, as shown in Fig. 18, precautions of this kind are not necessary. Unless all of the service pipes to which ground wires have been attached are disconnected there is no danger. A person may work on one of the service pipes in perfect safety as far as electric shock is concerned if the connection to the others are undisturbed.

6. MULTIPLE GROUND CONNECTIONS

As previously indicated, it is, in many cases, desirable to ground electrical circuits at more than one point. Moreover, the general practice at the present time is to use multiple grounds, especially where connections are made to water pipes. Where driven pipes, plates, and other small electrodes are used this practice is not so general, but systems in which the custom is followed of making but a single connection to ground on each circuit are not frequently found, unless it be in the case of direct-current systems. The advantages and disadvantages of using multiple ground connections in direct-current and alternating-current systems, the precautions to be observed in their use, and the desirability in some cases of using a common ground wire are set forth below.

(a) DIRECT-CURRENT SYSTEMS.—From considerations given in the foregoing discussion on electrolysis by direct current, it is evident that the use of multiple ground connections on direct-current systems is to be avoided to as great an extent as possible, principally on account of electrolysis effects which may arise from the diversion into metallic structures of currents from the circuits themselves. And because the currents carried by many direct-current systems are heavy, these effects may be marked, not only where water pipes are used exclusively, but also where driven pipes and plates are used, particularly if the ground connection at the power house is made to a water system and the rest to pipes and plates. A further reason why multiple grounds on direct-current systems should be avoided, especially multiple grounds to water pipes, is that return currents from electric railways may be diverted from their normal paths of flow by the grounded circuit. In direct-current systems the opportunities for this are greater than in any other because direct-current systems are used mostly in the business districts of cities where traffic is more or less congested and the density of the return current from street cars correspondingly high.

On the other hand, the advantages in the use of multiple grounds on direct-current systems are not great. In fact, in most systems very little is to be gained by making more than a single ground of low resistance at the power house or substation. In the first place, these systems being mostly underground and seldom so situated as to be liable to contact with high-voltage lines, the chance of an abnormal rise of potential against earth, even though the circuit were insulated throughout, is so small as to be of no moment whatever. Consequently, breakage of the ground wire and complete insulation from ground of the entire system, which multiple grounds are designed particularly to overcome, is not likely to prove as serious as in the case of circuits in which dangerously high voltages to ground may appear. In the second place, on account of the large size of the conductors, especially in main lines, and also because of the fact that where they are underground they are unlikely to be subject to mechanical injury, there is very little chance of a break occurring in the middle wire. Hence, there is no need for multiple grounds to prevent the isolation of a section of line having an unbalanced load with no ground connection. As mentioned heretofore, however, connections to service boxes for this purpose need not

be abandoned, because the resistance of these boxes to ground will, in general, be high. In the third place, to have a single ground connection of low resistance facilitates the detection of accidental grounds. In direct-current systems, therefore, a single ground connection at the central station or substation not only eliminates the possibility of damage by electrolysis but serves every purpose for which grounds on direct-current systems are needed; that is, if the circuits are not exposed to contact with high-voltage lines. Where the latter is the case multiple grounds are preferable. In low-voltage alternating-current circuits, for instance, the desirability of multiple grounds for the purpose of reducing the life hazard is great enough far to outweigh any considerations which may arise in regard to electrolysis.

(b) ALTERNATING-CURRENT SYSTEMS.—In grounding low-voltage alternating-current circuits the use of multiple ground connections presents the following advantages: In the first place, if a circuit is connected to earth at more than one point, the protection against high voltage is not so likely to be destroyed by breakage of the ground wires as where there is but a single ground connection. In the second place, where multiple grounds are made to water pipes a high degree of safety is afforded employees of the water utility when working on the pipes. In the third place, the greater the number of connections to earth, the less the possibility of a dangerous rise of potential between circuit and ground in the event of a failure of insulation or an accidental contact between wires. This is particularly the case where driven pipes, plates, or grounds other than water pipes are used, since the total combined resistance of such grounds in parallel varies approximately inversely as the number. Moreover, in the event of heavy current flow to earth, overheating of the ground wires is not likely to occur because the total current is divided among a number of them. Finally, as shown already, damage from currents in water pipes set up by the circuits themselves is extremely unlikely to occur, and as will be shown, damage by diversion of stray currents from their normal paths of flow is easily avoided. Multiple grounding of low-voltage alternating-current circuits, whether to water pipes or other forms of grounds, is therefore strongly to be recommended.²⁶

As just mentioned, however, cases sometimes arise in which it is necessary to guard against trouble from stray currents from street

²⁶ See rule 92b, Appendix II.

railways. Such cases are rare, of course, but they present a possibility which must be taken into consideration. For instance, if a low-voltage circuit is grounded at different points to two metal-lically separate pipe systems which are at a difference of potential with respect to each other due to stray currents, current will flow from one pipe system to the other over the grounded circuit. The magnitude of this current flow may be sufficient to overheat the wires, or it may be carried by the circuit into the frames of buildings, conduit, or cable sheaths and cause damage by electrolysis. A similar effect may be produced if a circuit is grounded at one point to a water pipe or street car rail which is at a potential difference of several volts from ground and at another to the steelwork of a building or some other metallic structure. The metallic structure takes the potential against ground of the pipe or rail, and danger of electrolysis ensues.²⁷

Another way in which stray currents may be diverted from their normal paths of flow is by grounding a low-voltage circuit on each side of an insulating joint which has been installed in a water pipe for the purpose of mitigating electrolysis. The circuit then acts as a shunt to the joint, and the resulting current-flow over the wires may not only cause overheating or electrolysis but also in a measure nullify the effect of the joint. To avoid trouble, both on account of electrolysis and interference with the operation of the circuit, this general rule should be followed. In every case where a low voltage circuit is to be grounded at more than one point, the ground connection should be made at places between which no appreciable differences of potential exist.²⁸

A statement should also be made here in regard to grounding the armor or sheathing of extended power or telephone cables to water pipes, for the same precautions must be observed in the case of these sheaths as in the case of low-voltage circuits. In fact, where it is desirable to ground any conducting body of considerable length to water pipes at more than one point, careful consideration should be given to the possibility of picking up enough stray current to cause trouble, either from electrolysis or from overheating. On the other hand, where multiple grounding is done solely by means of driven pipes or plates, the possibility of picking up enough stray current to cause trouble is practically negligible; for in the first place, the potential differences usually found between points in the soil itself do not exceed a very few volts, unless it be between points remote from each other but very

²⁷ See rule 94d, Appendix II.

²⁸ See rule 94a, Appendix II.

near to pipes or rails carrying heavy current flow; and in the second place, the resistances of pipe and plate grounds are so high that at the low voltages encountered but very little current flow over the grounded conductor results. Hence, in making multiple grounds with driven pipes or other electrodes of small extent, little care need be exercised in regard to stray currents, but in the case of water-pipe grounds, as mentioned above, care, in some cases at least, is necessary.

Wherever such care seems to be called for, the resistance of the pipe line between the two farthest removed points of connection can be measured to make certain that no insulating joints are present. If there are no insulating joints, the resistance will, in general, be found to be but a fraction of an ohm. If there are insulating joints, it may be as much as an ohm or even several ohms. In the case of separate pipe systems, voltage measurements between them will generally give the desired information. A better method, perhaps, of finding whether a circuit can be grounded at more than one point is to ground its extreme ends with a recording ammeter in circuit and ascertain whether current flow results. If there is none, or if it does not amount to more than a very few amperes at any time during the day, grounding at more than one point may be considered practicable. If, however, the current flow is sufficient to cause unbalancing of the voltage or overheating of the wires, it will, of course, be necessary to confine the number of ground connections to one or else to several very near each other.

(c) COMMON GROUND WIRE.—In sections where water pipes are not available and the soil is not particularly favorable toward making grounds with driven pipes or other devices, the problem of securing adequate protection against high voltages is best solved by making use of a common ground wire. The usual form of common ground wire is illustrated in Fig. 20. Here a wire of the same size as the line wires connects a number of low-voltage circuits, with ground connections installed at each transformer and at advantageous points along the line. Thus the protection of each circuit is derived, not only from the grounds on the circuit itself but also from those on the ground wire and all of the other circuits in parallel. If the extent of the ground wire is considerable and it is grounded at many points, the degree of protection afforded, while not equal to that offered by water pipes, may be rated as next to it.

In providing grounds for such an installation as that described above, advantage should be taken of local conditions—that is, rather elaborate ground connections should be made in locations which are the most favorable as regards soil and moisture—and use should also be made of local water systems, driven wells, and other underground metal. If care in this respect is exercised, good results may be obtained even where the soil consists principally of gravel, sand, or stones.

The cost of a common ground wire where a special wire has to be run to bridge gaps between low-voltage circuits is, of course, the same as for a line wire. Aside from this the expense necessarily incurred in excess of that which would otherwise be required is inconsiderable. It is advisable, however, to make as many ground connections as practicable, because the greater the

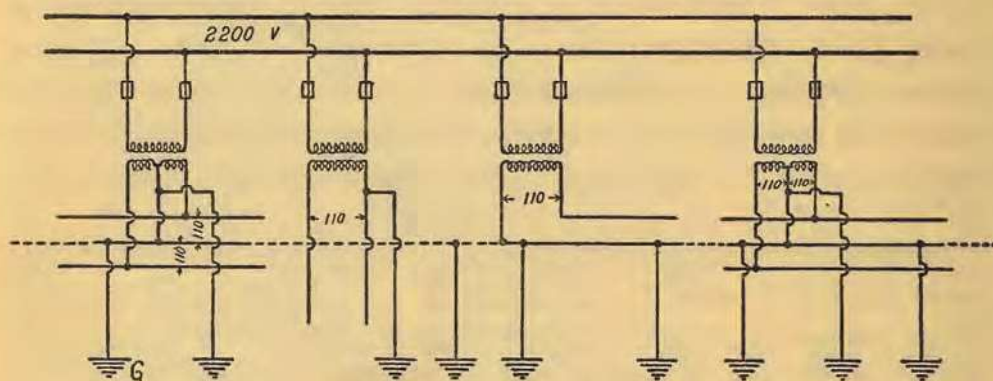


FIG. 20.—Common ground wire system.

number the better the protection that is afforded. This is also true whether a common ground wire is used or not. In fact, a single ground connection on a low-voltage secondary circuit should be avoided wherever possible, and multiple grounds used instead whether connection is made to water pipes or to grounds of other forms. The increase in the degree of protection is well worth the expense.

7. VARIATION OF RESISTANCE OF GROUND CONNECTIONS WITH SEASONS

The seasonal variation of resistance of ground connections is great enough in some localities to be of considerable importance. The principal factors which cause this variation are the temperature and moisture content of the soil. For changes in the temperature and moisture content of soil cause its resistivity to change between wide limits, and since the resistance to flow of current away from an electrode buried in the earth depends directly upon

the resistivity of the soil, changes in the latter will also cause changes in the resistance to flow of current. The degree to which such changes will affect the total resistance of an earth connection depends upon the extent of the electrode. With electrodes of limited extent, such as driven pipes, the part of the total resistance contributed by the metal is negligible in comparison with that contributed by the soil. Hence, changes caused by temperature and moisture content cause practically proportional changes in the total resistance. With electrodes of great extent, however, such as water pipes, the case is different. The total resistance of an earth connection made in this way may depend in larger part upon the resistance of the pipe per unit length than upon the resistivity of the soil, so changes in the latter are not likely to produce serious changes in the total resistance. The effects of the temperature and moisture content of soils on their resistivity are discussed briefly below, and some experimental data are also given which show the magnitude of the variation in resistance of ground connections with seasons that may be expected under climatic and soil conditions similar to those prevailing in the vicinity of Washington.

(a) TEMPERATURE EFFECTS.—The effect of temperature upon the resistivity of soils has been studied at the Bureau of Standards,²⁹ and it has been found that at a temperature of 18° C the rate change of resistivity with change of temperature is about 5 per cent per degree. This value holds approximately until 0° is reached. At this point a sudden change in the rate occurs and it becomes more rapid. From -4 to -8° it is about 30 per cent, from -8 to -12° about 13 per cent, and from -16 to -20° about 9 per cent. Reducing the temperature from +20 to -19° increases the resistivity more than 200 times, with a sharp change in the rate of increase at 0°, of course, where the water contained in the soil begins to freeze. With decreasing temperature below 0° the resistivity tends toward values commonly associated with dielectrics. These data were obtained on a sample of clay containing 18.6 per cent of moisture and having a resistivity of 6260 ohms per cubic centimeter at 20°. With different soils, deviations from these figures may be expected but the order of magnitude will remain the same.

It is apparent, therefore, that a ground connection which is intended to be operative at all times of the year must be well

²⁹ Technologic Paper No. 25, Bureau of Standards, Electrolytic Corrosion of Iron in Soils.

below the frost line. In some localities in the United States where the winter seasons are severe, this may be at a depth of 6 or 8 feet; in others, it may not exceed a few inches, and there are places where the ground does not freeze at all. If at any place freezing temperatures prevail for some time, however, considerable increases in the resistance of ground connections may be anticipated, unless it be in the case of water pipes. These, in general, are laid well below the frost line, and as pointed out above, great changes in the resistivity of the soil are required to produce material changes in the resistance of ground connections made to them. Above freezing, the effect of change in temperature upon the resistivity of soil is not great, and for that reason, the resistance of water-pipe ground connections will be found fairly uniform the year round, at least as far as the effect of temperature is concerned.

(b) **MOISTURE EFFECTS.**—The moisture content of soil is much more important than temperature in its effects on the resistivity at temperatures above freezing. For a particular sample of red clay, it has been found³⁰ that decreasing the moisture content from 22 per cent to 16 per cent increases the resistivity about 2 times, from 16 per cent to 11 per cent about 20 times, and from 11 per cent to 5 per cent about 10 times. Decreasing the moisture content from 30 per cent to 5 per cent increases the resistivity about 400 times. A decrease from 22 per cent to 5 per cent causes a change in the resistivity from 6800 ohms per cubic centimeter to 3 340 000 ohms per cubic centimeter. When air dried this soil contains about 5 per cent moisture. For different soils the resistivity for a given moisture content may differ widely, but the foregoing figures may be taken as indicating the magnitude of the changes to be expected in the case of any soil as the moisture content varies.

The importance of the effect of moisture is thus made apparent. A difference of a few per cent makes a very marked difference in the effectiveness of ground connections made with electrodes of limited extent, especially at low values; that is, 15 per cent or less. Hence, every effort should be made to select locations for ground connections where the greatest amount of moisture is to be obtained; that is, if there is any choice in the matter. Many cases will arise where waste water of some kind can be utilized to good advantage.

³⁰ Technologic Paper No. 25, Bureau of Standards, *Electrolytic Corrosion of Iron in Soils*.

(c) EXPERIMENTAL RESULTS.—In order to determine the seasonal variation of resistance of earth connections which might be expected under the climatic and soil conditions prevailing in the vicinity of Washington, measurements were made at intervals of one month for about a year and a half on the specimens already described in this paper. These specimens, it may be repeated, consisted of driven pipes, plates, strips, and a number of patented devices. The ground in which the tests were made is a rather stony clay, which has been found by measurement to be of somewhat higher resistivity than most of the soils met with in other localities, although the soil in some places will be of even higher resistivity and, hence, worse for the purpose of making ground connections. The measurements were made by the ammeter-voltmeter method.

The results of measurements on a number of specimens representative of each type are shown plotted in Figs. 21, 22, and 23. Where more than one specimen of each kind was available, the average resistance is given. As would be expected, the maximum resistance for nearly all of the specimens occurs in midwinter and the minimum in midsummer. The average total change is seen to be about 70 per cent. In particular, for 0.75-inch pipe 3 feet long the maximum is 1.7 times the minimum; for 0.75-inch pipe 10 feet long, 1.4 times; for strips 20 feet long, 1.8 times; for a plate 2 by 8 feet, 1.7 times; for Paragon ground cones, 1.7 times; Maxum ground boxes, 1.6 times; Brach hydrogrounds, 1.6 times; Lord Manufacturing Co. hydrogrounds, 1.9 times; and Federal Sign System cartridge ground plates, 2 times.

With the exception of Nos. 8 and 9, Fig. 23, there seems to be no material increase of resistance with time. In fact, it may be considered that there has been an improvement in the condition of the ground connections, because the resistances of January, 1915, are practically the same as of January, 1916, although on the latter date the soil was drier than on the earlier date, and the temperature about the same. With Nos. 8 and 9, however, the case is different. These specimens show a marked increase of resistance during the course of the year. On the other hand, it is seen that in several cases there was a marked decrease of resistance during the first month after the measurements were begun. This is largely due to the fact that holes were dug and allowed to stand open for several days before the electrodes were buried. When the holes were filled the metal was surrounded

by soil which had been more or less dried by exposure to air so the resistance to flow of current was at first rather high in comparison with values obtained later.

In making the measurements mentioned above, it was necessary to determine each time the resistance of a ground connection made to the city water system. The conductor leading to the water main consisted of 250 feet of enameled steel conduit in series with a long service pipe. The conduit was laid underground with joints which had been screwed together after being daubed with a mixture of red lead and oil. The total resistance of this ground connection was found to be about 1.7 ohms, of which ap-

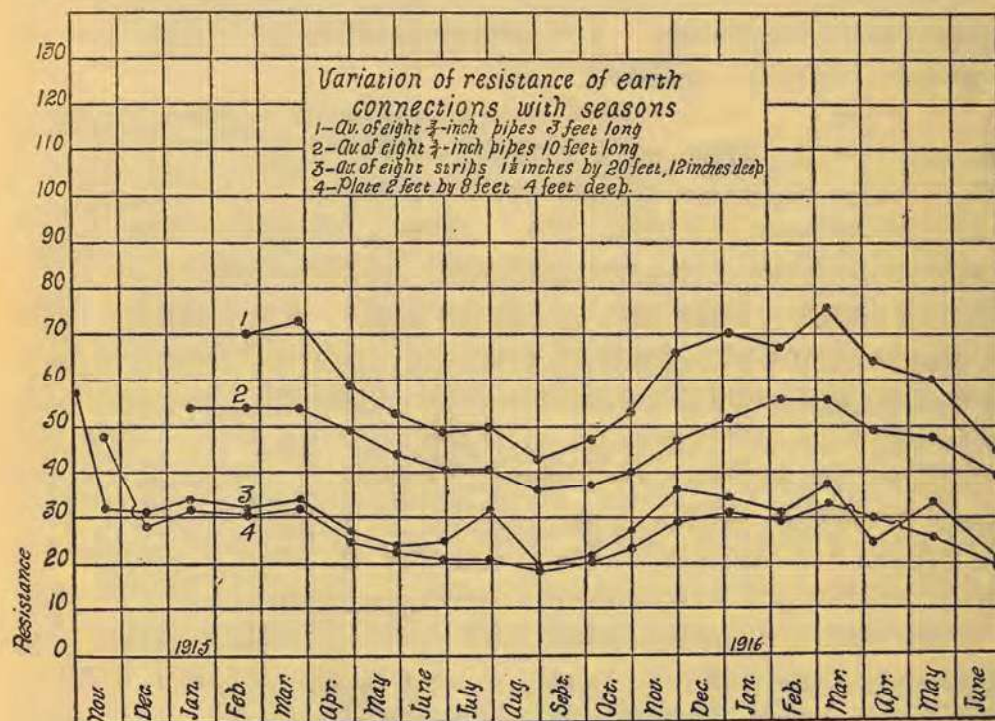


FIG. 21

proximately 1 ohm was found to be in the conduit. The remaining 0.7 ohm was the resistance offered by the service pipe and water main. Measurements each month showed no variation of resistance with time that could not be attributed to errors in measurement.

It should be noted in connection with these tests that there was but little freezing weather and most of the time the soil was fairly moist, and at times, especially in January, 1915, very wet. There were no extremely cold or dry periods. The only dry periods of any consequence occurred just before the measurements made at the end of March and at the end of July in 1915. Preced-

ing the measurements at the end of August there was much hot weather with several heavy rains, 3.32 cm (1.31 inches) of rain falling on August 30. On August 31 the lowest recorded resistance for the year was obtained. Following August the precipitation was light, with the exception of one or two hard rains in October, and the temperature decreasing, so the resistances increased steadily.

Other data showing the seasonal variation of resistance of earth connections have been published by Hayden ³¹ from tests made on some driven pipes. These pipes were 3.75, 2.75, and 3.1 feet in length, respectively. Measurements were made on them at

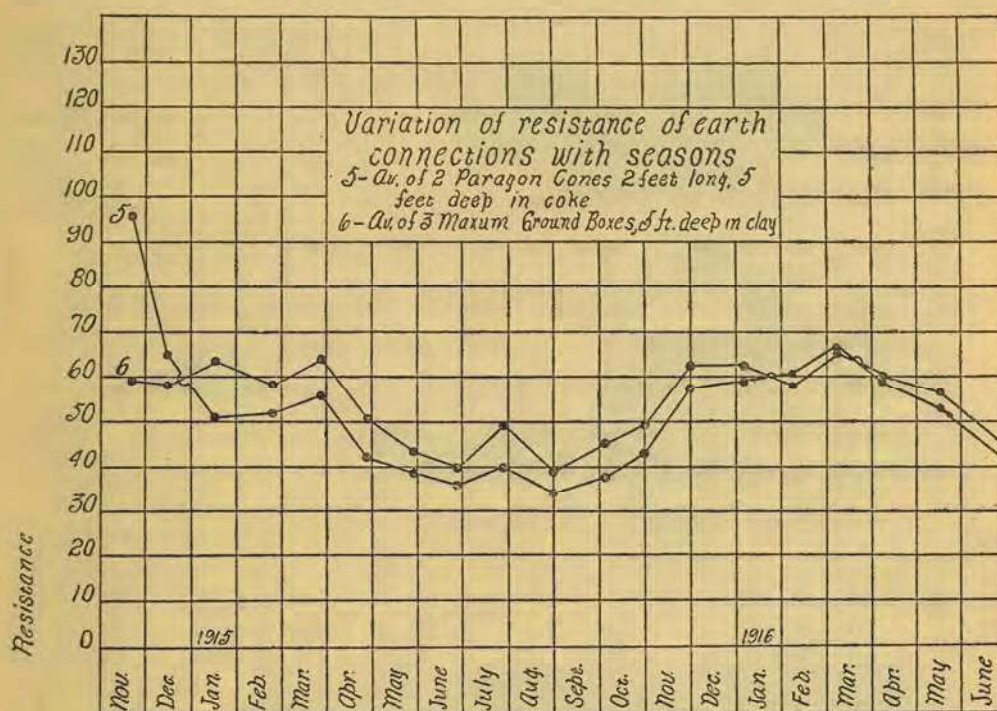


FIG. 22

regular intervals over a period of three years. The curves correspond to those described in the preceding paragraph in so far as the time of maximum and minimum values of resistance are concerned, the maximum value occurring in February and March and the minimum in July and August; but the differences between maximum and minimum values were found to be much greater than in the present investigation. In the case of one specimen, the maximum was three times the minimum, and in another seven times the minimum. This was probably due to deeper frost in the wintertime. Some of the curves given by Hayden are much more in detail than those in Figs. 21, 22, and 23 and

³¹ Trans. A. I. E. E., 26, Pt. II, p. 1209.

show the variation from day to day. Curves showing the variation from day to day are of a saw-toothed form, because a heavy rain or a few dry days produce considerable abrupt changes. As shown by Hayden's curves, these in some cases may be as much as 20 per cent in two or three days, but they are not important. It is the large changes from season to season that are of real significance.

It is obvious, of course, that measurements such as those described above can be taken only as indicating the magnitude of the changes that may be expected in the particular locality in which they are made. These changes will be different for different soils

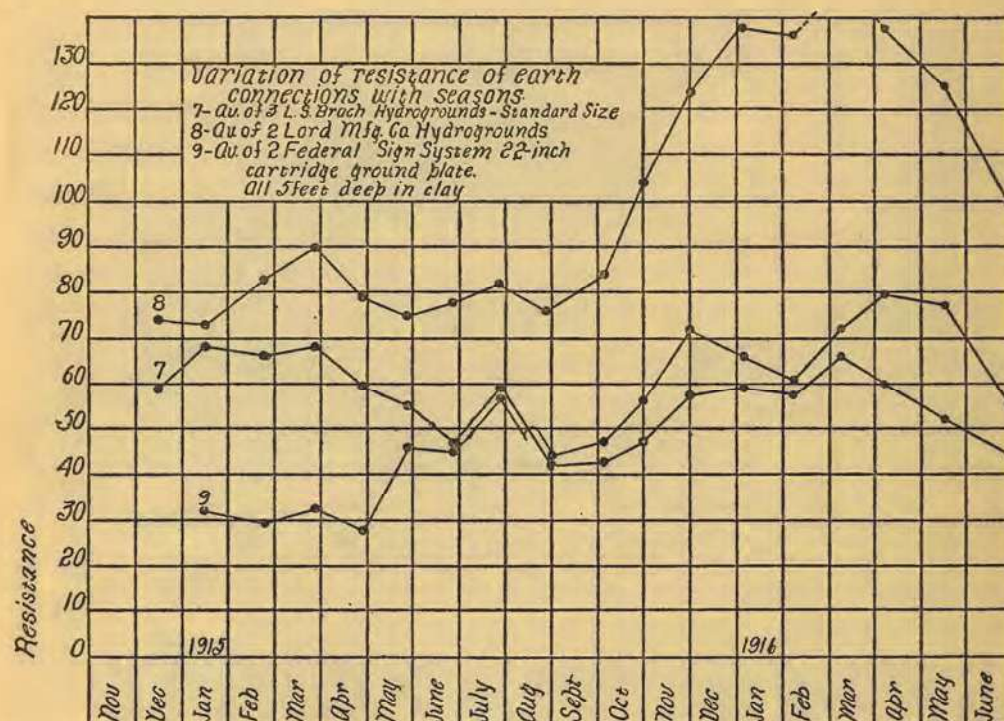


FIG. 23

and for different climatic conditions. They may even vary widely from year to year for the same locality. Thus, a very cold winter followed by a hot summer with heavy rainfall would produce an exceedingly great change in the resistance, whereas a mild winter followed by a dry summer might show nearly uniform resistance throughout the year. Moreover, with a given variation in temperature and rainfall, the soil conditions have great influence; for if the soil is of fine texture with bedrock at a great depth, moisture is accumulated in wet seasons and retained to a greater or less extent in dry seasons, which tends to produce a uniform value of resistance from season to season. On the other hand,

with soil of a loose sandy or gravelly nature, moisture is not retained so readily, and large fluctuations of resistance may be expected. With bedrock near the surface of the ground, large variations of resistance may also be expected whatever the nature of the soil, because evaporation rapidly exhausts the supply of moisture which can be stored in wet seasons in the thin layer covering the rock. Ordinarily the depth at which ground connections are placed—that is, within practical limits—also has some influence on changes in resistance. This, in some cases, may be considerable, and in others it may be negligible. In the measurements described above it will be noted that in the case of driven pipes 3 feet long the maximum was 1.7 times the minimum, while in the case of pipes 10 feet long the maximum was 1.4 times the minimum. Generally the deeper a ground connection is the more uniform its resistance is likely to be. In passing, it should be emphasized again that the foregoing remarks apply more particularly to ground connections made with electrodes of limited extent.

8. INCREASING THE CONDUCTANCE OF GROUND CONNECTIONS

As indicated heretofore in this paper, the normal resistivity of the soil in most localities is such as to make the resistance of a ground connection made with an electrode of limited extent rather high. In such places ground connections of low resistance can be made by placing a sufficient number of electrodes in parallel, but this requires considerable space and is expensive, especially if the resistance required is comparable with that of ground connection made to a water pipe. In order to lessen this difficulty an expedient has been many times resorted to, which is that of reducing the resistivity of the soil immediately surrounding the electrode, thus enabling the attainment of a low resistance with a much smaller number of electrodes than would otherwise be the case. To reduce the resistivity of soil it is only necessary to dissolve in the moisture normally contained in it some substance which is highly conducting in its water solution. There are many substances which could be used for this purpose, but most of them are expensive or are otherwise unsuitable. The substance most often used is salt (NaCl). Another which could be used to greater or less advantage is calcium chloride (CaCl_2). Both are highly soluble in water, are highly conducting in solution, and are comparatively cheap. The ratio of the conductivities of solutions of these substances to that of ground water may be stated to be of the order

of 1:100. They possess disadvantages, however, in that they are more or less corrosive, at least toward iron, and their effects are not permanent. The supply of salt must also be renewed at intervals to replace that washed away by water percolating through the soil.

Another method of increasing the conductance of ground connections, especially buried plates, is that of surrounding the electrode with charcoal or coke. It is thought by many that this method presents distinct advantages, but others discredit it. Experiments by Sloss and Fish,³² for instance, do not show that the addition of charcoal reduces the resistance of a ground connection, and experiments by Ford³³ point to the same conclusion. In both of these investigations it was also found that ground connections made in this way vary in resistance with seasons and increase in resistance with age to a greater extent than ground connections made without these substances. In fact, all of the results obtained seem to indicate that either charcoal or coke is more of a disadvantage than a help. This experience is not reported from other quarters, however, and it may be that the instances cited above are exceptional. At any rate the idea is prevalent in many places that a good ground connection can not be made without using one or the other. Their effects in reducing the resistance of a ground connection have been attributed by some to their power of attracting and absorbing moisture, which is stated to tend to lower the resistance to flow of current away from the electrode into the earth. Whether this is the case is open to question. It seems more likely that a view held by others more nearly represents the facts. This view is that the highly conducting coke or charcoal has an effect equivalent to that produced by increasing the surface area of the electrode in contact with the soil.

In order to determine some of the effects of salt and coke, and more particularly the time required for rain water seeping through soil to wash the salt away, several specimens were buried and measurements of resistance made on them at intervals of one month for about a year and a half. A discussion of the results of these experiments, and also the results of some measurements of the resistivity of samples of soil containing different quantities of salt, is given below.

(a) EFFECTS OF SALT.—To obtain an idea of the time required to eliminate the effects of salt by percolation of moisture through

³² *Electrical World*, 55, p. 1134.

³³ *Electrical World*, 58, p. 622.

soil two specimens were buried, one consisting of a strip of No. 20 gage galvanized sheet iron 1.5 inches wide and 60 feet long, and the other of a plate of No. 16 gage galvanized sheet iron 2 by 8 feet. The strip was buried in a trench 12 inches deep with 1 pound of salt per foot of strip. The plate was buried in a hole 4 feet deep, with 74 pounds of salt. The soil, as before stated, was a rather stony clay of fine texture.

The results of the monthly measurements of resistance have been plotted in Figs. 24 and 25, curves (3) and (6). In both cases results obtained on similar specimens buried in clay without salt are also shown to aid comparison. In the case of the

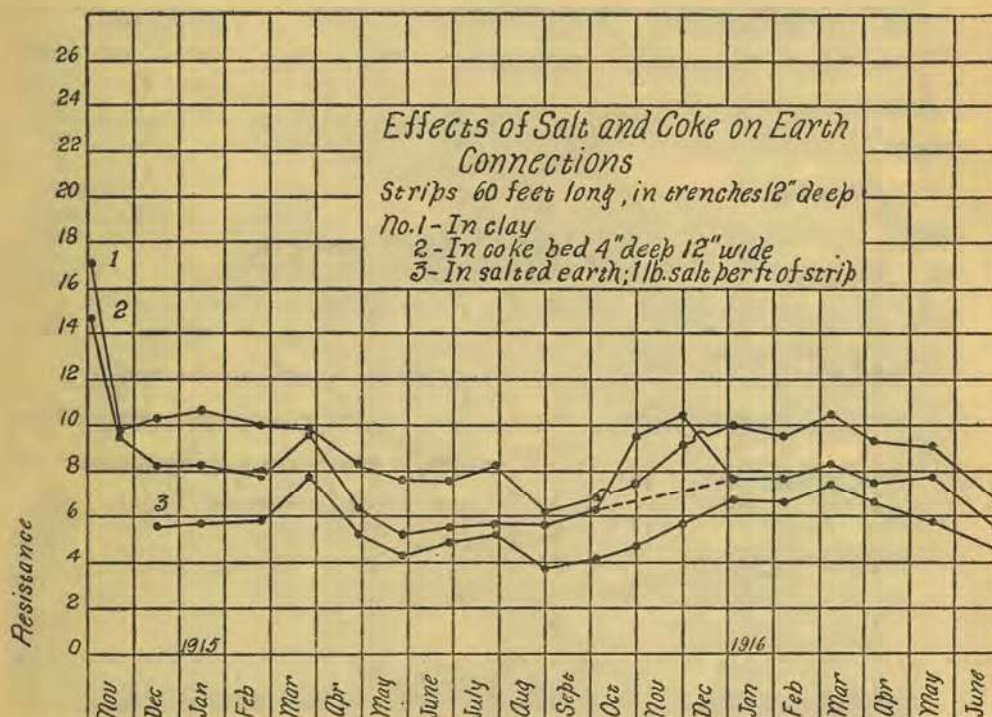


FIG. 24

strip, the addition of the salt appears to have reduced the resistance by about 30 per cent. This is somewhat less than would be expected. There is, however, no way of telling what the resistance would have been if the strip had been buried in the same trench without salt, and it may be that curve (3) under those conditions would be considerably above curve (1). This supposition is strengthened by the fact that measurements made on other specimens indicate the resistivity of the soil in the vicinity of the specimen from which curve (1) was obtained to be lower than elsewhere. The apparent reduction of 30 per cent is therefore undoubtedly to be considered as rather small. On

the other hand, in the case of the plate, the reduction of resistance is about 75 per cent. In addition, the specimens from which curves (4) and (6) were obtained were only about 20 feet apart, and nothing developed in the course of the measurements which would suggest that there was much difference in the resistivity of the soil in the two places. The reduction shown may therefore be taken as indicating the actual change caused by the salt.

The most important fact brought out by these tests is that of the lasting effect of an application of salt, for there appears to be no permanent increase of resistance of either the strip or the plate during the period covered by the measurements. More-

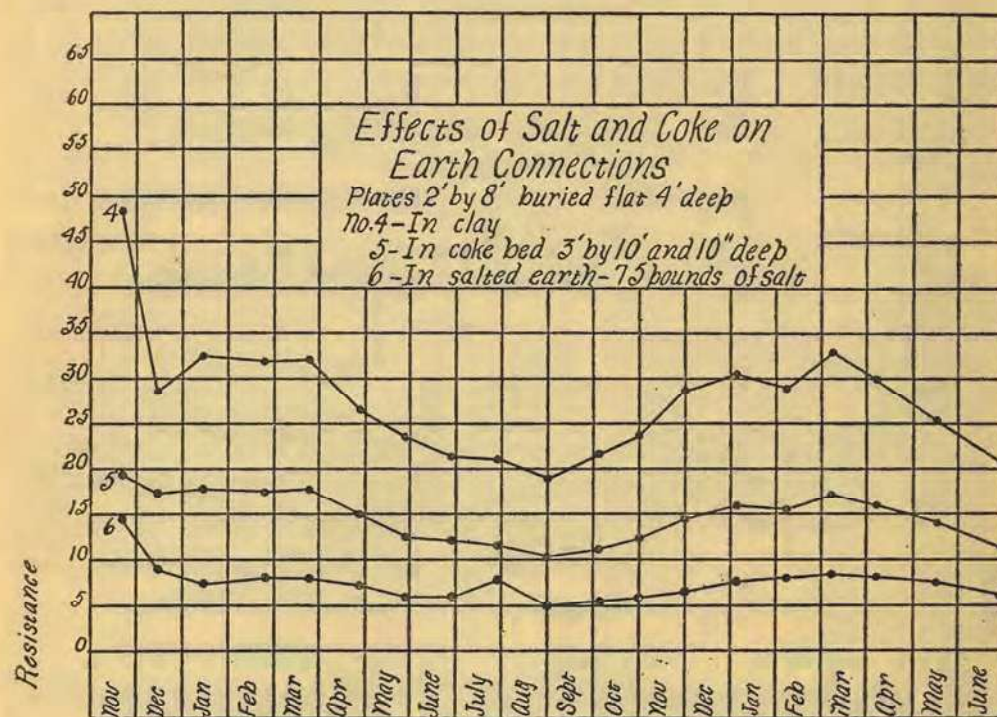


FIG. 25

over, the precipitation during this period was close to normal, the records of the Weather Bureau showing the actual precipitation from November 1, 1914, to January 31, 1916, to be 47.78 inches, and the normal precipitation to be 52.74 inches. The rate of washing away of the salt may therefore be considered as being practically as rapid as during a similar period of normal precipitation. Hence, it is not likely that with soil of the kind in which these ground connections were made, the salt would have to be renewed oftener than once in two years. This soil, however, is of close texture. In soils of loose texture, percolation of moisture from the surface downward would be more rapid during

rainfall, and salt would be carried away at a greater rate; and when once carried to a considerable depth in loose soil the tendency for the solution to return by capillary action during dry seasons would be much less than in soil of close texture. Consequently, the salt would have to be renewed oftener than in soils through which water does not pass so readily, but to state definitely the length of time between renewals in any case would require further experiments.

A question which arises is that of the amount of salt to be used to produce the best results from a ground connection. To obtain some information on this subject, 12 samples of dry red clay were prepared by adding water until the contained moisture amounted to 30 per cent by weight of the dry earth, and salt (NaCl) in different proportions to each sample until the moisture in the different samples formed solutions ranging in strengths from 0 to 16.6 per cent by weight of the water. The salt was dissolved in the water and the resulting solution and earth thoroughly mixed, after which the samples were placed in air-tight glass jars and allowed to stand two days for diffusion of the solution to take place. The resistivity of each sample was then measured by tamping it into a glass-lined cylinder with an iron bottom, forcing an iron piston down upon it, and using alternating current at 60 cycles per second with an ammeter and voltmeter. The results of these measurements are shown plotted in Fig. 26. It is there seen that the addition of 0.33 per cent of salt to the contained moisture causes the resistivity to drop from 4100 ohms per cubic centimeter to about 700 ohms per cubic centimeter. At this point the rate of decrease of resistivity with increase in the percentage of salt in the moisture becomes much slower but is still considerable, and with the moisture containing 16 per cent salt the resistivity is about 55 ohms per cubic centimeter. After 10 per cent is reached, however, further additions of salt produce but slight changes in resistivity, at least as compared with the changes produced by the first small additions.

In making this test a record was kept of the volume and weight of the earth used, the volume being taken as that of the tamped earth when ready for the resistivity measurements. The weight of the dry earth was found to be about 90 pounds per cubic foot. The moisture content of soils ranges from about 15 per cent in dry seasons to 35 or 40 per cent in wet seasons, so the weight of the contained moisture ranges from 13.5 to 36 pounds per cubic

foot. From the curve of Fig. 26 it is seen that if enough salt is dissolved in the moisture to make of it a 0.5 per cent solution, the resistivity of the soil will be reduced to about 14 per cent of its normal value. To produce this result with 40 per cent moisture in the soil would therefore require the addition of about 0.18

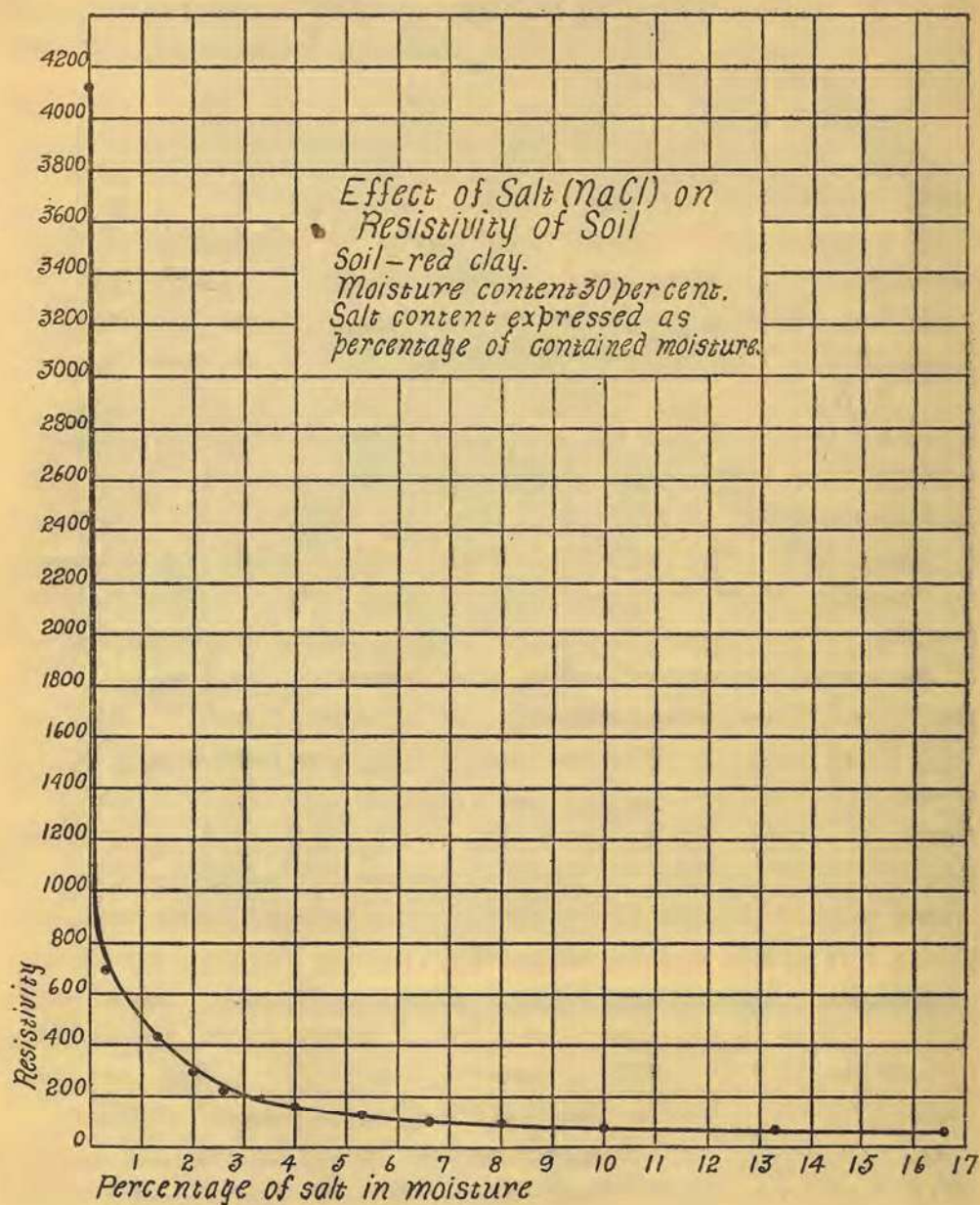


FIG. 26

pound per cubic foot of earth; to reduce the resistivity to 10 per cent of its normal value would require the addition of 3 times as much, to 5 per cent of its normal value 6 times as much, and so on.

From these data may be obtained an idea of the quantity of salt required to produce large reductions in the resistance of

a ground connection. With an electrode of any shape, the production of large changes would necessitate the addition of salt to all of that portion of the surrounding earth which contributes in any considerable measure to the resistance to flow of current. For example, let a pipe driven in soil of fairly uniform resistivity be considered. As will be shown later, if current is flowing away from such a pipe into the earth, approximately 90 per cent of the total difference of potential between the pipe and a point in the earth a great distance away occurs in a region within 6 feet of the pipe. Hence, if to the water contained in a cylinder of earth 12 feet in diameter and extending some distance below the bottom of the pipe enough salt were added to make of it a 0.5 per cent solution, the portion of the total resistance contributed by this cylinder would be reduced to 14 per cent of its normal value. If the total resistance were originally 25 ohms, the resistance after being salted as described above would be about 5.6 ohms, for that part of the soil contributing 10 per cent of the original resistance would be unaffected, while the remainder, or the portion contributing 22.5 ohms, would be so affected that its resistance would be reduced to 3.15 ohms, the sum of the components then being 5.6 ohms. If the pipe were 10 feet in length, the cylinder of earth 12 feet in length and containing 40 per cent of moisture, the weight of salt required would be 245 pounds, since the volume of the cylinder is 1360 cubic feet.

By increasing the quantity of salt a still further reduction of resistance could be effected. If salt were added until the contained moisture become a 10 per cent solution the resistivity of the soil would be about 1.87 per cent of its normal value. The total resistance of the earth connection would then be about 2.9 ohms. This, however, would require 20 times as much salt as in the case described in the preceding paragraph, or about 5900 pounds, and the added reduction would not be worth the added expense. The same result could be accomplished for less than half the cost by driving two pipes 10 feet apart and using but a fraction of this amount of salt. In fact, in any case where a ground connection of a given resistance must be made, especially if the resistance required is very low, maximum economy will probably lie in the use of several electrodes combined with an amount of salt which will not be a source of excessive expense for renewals.

Nevertheless, the foregoing data indicate that a more liberal use of salt than has heretofore been the general practice is desir-

able. In the past it has been considered by many that when a few pounds of salt had been added all had been done that could reasonably be expected. But it is obvious from what has been said above that several hundred pounds could be used to advantage with earth connections that are of importance, and where low resistance is necessary, and for earth connections of almost any kind a hundred pounds would not be too large an amount.

Moreover, with a liberal use of salt an advantage aside from that of reduction of resistance is obtained, although it is much less than has sometimes been stated to be the case. This is in an increased uniformity of resistance; that is, alternate dry and wet or hot and cold seasons make smaller proportional changes in salted ground connections than in those that are unsalted, or are made with charcoal or coke. Referring to Fig. 26, it is apparent that if the moisture around an earth connection contained enough salt to form a 0.5 per cent solution at a moisture content of 40 per cent, a reduction of the moisture to 20 per cent would increase the concentration of salt and hence decrease the resistivity of the solution to an extent sufficient under some conditions largely to counteract the effect of the drying. For instance, measurements of the resistivity of soil containing different percentages of moisture show that changing the moisture from 40 to 20 per cent changes the resistivity by about 30 per cent.³⁴ Doubling the concentration of salt produces practically the same change in the opposite direction, so the two tendencies would almost exactly counteract each other. With further drying, however, the rate of increase of resistivity with decrease of moisture becomes much more rapid, and, on the other hand, with increasing concentration of salt the decrease of resistivity becomes slower, so the effect of the salt in producing uniformity of resistance become less with increasing dryness of the soil.

With regard to minimizing the effects of changes in temperature salt is probably of most service in lowering the freezing point of the solution, thus putting the point of sudden large increase in the resistivity of soil several degrees below the freezing point of water. The relative importance of the effect of salt in producing uniformity of resistance is apparent on examination of Fig. 25, where it is shown that the ratio of maximum to minimum resistance is about 1.4 for the plate put down with salt and 1.7 for the plate put down without salt.

³⁴ Technologic Paper No. 25 of the Bureau of Standards, p. 57.

(b) EFFECTS OF COKE.—In order to obtain some information as to the extent to which coke may be depended upon to reduce the resistance of ground connections two specimens were put down, one of which consisted of a strip of No. 20 gauge galvanized sheet iron 1.5 inches wide and 60 feet long. This strip was buried in a trench 12 inches deep, with a bed of coke filling the trench to a depth of 4 inches and of the same width as the trench which was about 12 inches. The other specimen was a plate of No. 16 gauge galvanized sheet iron 2 feet wide by 8 feet long, which was buried flat in a hole 4 feet deep, with a bed of coke filling the hole to a depth of 10 inches. The area of the coke bed was about 3 by 10 feet. An attempt was made to place the coke as nearly uniformly about the electrodes as practicable.

The results of the periodical measurements of resistance have been plotted in Figs. 24 and 25, curves (2) and (5). Curves from specimens buried in clay are also given to aid comparison. In the case of the strip, as shown by curve (2), there is some reduction of resistance, but apparently not nearly as much as for the strip put down with salt. Moreover, the variation of resistance from time to time is obviously as great as in curve (1), although the high values noted on November 1 and December 1, 1915, are undoubtedly to be attributed to a loose lead. At any rate, on January 4, 1916, the lead was found detached from the strip and another substituted for it, so the dotted line connecting the points representing the values of resistance obtained on October 4 and January 4 probably nearly represents the actual resistance. In the case of the plate, on the other hand, the reduction of resistance is much greater than in that of the strip, being about 53 per cent, but with regard to uniformity of resistance the effect of the coke does not appear to be more marked here than above, since the ratio of maximum to minimum is 1.7, or the same as for the plate put down in clay.

Measurements made on the coke used in the experiments just described show its resistivity to be of the order of 130 ohms per cubic centimeter, or but a fraction of that of the average soil. This value was obtained on a sample that had been in the ground for more than a year. It was dug up, pounded fine in a mortar, tamped in a glass-lined iron cylinder in the same way as described for tests of the effect of salt on the resistivity of soils, and its resistivity measured with alternating current. It was then dried and its resistivity measured again, the result being practically the same. The resistivity was found to vary between wide limits with pressure and temperature, so the coke in the two conditions

was measured at as near the same temperature and pressure as practicable. The pressure was applied by means of a metallic piston, and was about 14 pounds per square inch. The temperature was a little higher than that of the room, which was 21°C , on account of the heating effect of the current which was allowed to flow for a short time before the readings were taken. The values obtained are to be considered only as showing that the resistivity of coke is very low in comparison with that of the soil, and that the difference in conductivity between wet and dry coke amounts practically to nothing.

When the resistivity was measured, the moisture content was also obtained, and found to be about 19 per cent, by weight, of the dry coke. The soil in which the sample was buried seemed to be quite saturated and must have contained more than 30 per cent moisture. The coke, therefore, had ample opportunity to become saturated. The weight of the packed dry coke was 70 pounds per cubic foot. The weight of the water per cubic foot of wet coke was 12.2 pounds. It was noted that the volume of the coke when dry was less than when wet. The shrinkage on drying was from 31 to 28.5 cubic inches, the volume in both instances being measured when packed and under pressure for the resistivity measurements. The total amount of water driven off was 0.22 pound.

From these data the function of the coke in reducing the resistance of ground connections is readily apparent. It is that of replacing a volume of earth of high resistivity surrounding the electrode with an equal volume of coke of low resistivity. The greater the volume of coke the greater the reduction of resistance, although not in the same proportion. Whether the coke is wet or dry makes but little difference. Moisture changes, in affecting the resistance of ground connections made with coke, act only on that part of the resistance contributed by the soil, but because the portion of the total resistance contributed by the soil is large in comparison with that contributed by the coke the effects appear to be practically as great, in percentage at least, as in ground connections made in clay. For example, take an electrode in earth having a resistivity of 5000 ohms per cubic centimeter which shows a resistance of 25 ohms to flow of current away from it. If enough coke is placed around it to reduce the resistance 40 per cent, the resulting resistance will be 15 ohms. Since the ratio of resistivities of coke to soil is about as 1:40, the portion of the resulting resistance contributed by the coke is about one-fortieth of that contributed by the earth which it replaces, or

0.25 ohm. The portion of the 15 ohms contributed by the soil is therefore $15 - 0.25 = 14.75$ ohms. Hence, moisture changes produce practically as large percentage changes as if the coke were not present. On account of its low resistivity, the coke bed constitutes virtually an extension of the electrode, and its distribution is for that reason of considerable importance. For the best results it should have a large area of contact with the soil in proportion to its volume.

The foregoing results do not agree in every respect with those of Sloss and Fish, and Ford, previously mentioned, but they do indicate that the benefits derived from the use of coke are not as great as has sometimes been stated to be the case. For instance, particular stress has been laid by some upon the uniformity of resistance obtained, but this statement is not supported by the tests because ground connections made with coke are seen to be almost as sensitive to changes in moisture conditions as those made in clay. There is, of course a considerable reduction of resistance, although this advantage is offset in large measure, at least, by the fact that it is in all cases necessary to excavate to get the coke in place. And in this respect it is at a disadvantage as compared with salt, which can be carried into the ground by burying it near the surface and flooding the hole with water, or allowing time enough for seepage of rain water to accomplish the same purpose. Coke and charcoal, however, do not have to be renewed, and in this respect present an advantage over salt.

The greatest disadvantage attending the use of either coke or salt is that touched upon in a previous paragraph, viz, an increased rate of corrosion of the electrode and consequent shortening of the life of the earth connection as compared with its life in normal soil, especially where galvanized iron is used. Just what this reduction in life may be can not at present be stated because of lack of data. In fact, experiments extending over several years would be necessary to obtain the desired information, but there seems to be no doubt in the minds of many that the reduction in life is considerable, coke in general being considered more detrimental than salt. Others state that the effects of salt on galvanized iron underground are negligible. In this connection it should be mentioned that the specimens described above showed no appreciable corrosion on superficial examination after being in the ground 14 months. Nevertheless, it is likely that the increase of corrosion due to the presence of salt will be considerable in its effects over a period of years, resulting in a material shortening

of the total life of the earth connection; and, moreover, the effects of coke may well be anticipated to be greater than those of salt. Copper, on the other hand, is much more resistant to corrosion than galvanized iron, and where long life of an earth connection with little attention is much to be desired copper should undoubtedly be used.

9. DISSIPATION OF ENERGY BY GROUND CONNECTIONS

For successful operation ground connections must in some cases be able to dissipate considerable amounts of energy without material changes in their resistances. An instance is afforded by an accidental contact between a high-voltage and a low-voltage circuit. Here the conditions may be such that the current flow through the ground connection is insufficient to operate the protective devices, and if it is it may continue almost any length of time before it is detected and the fault removed. In the meantime the rate of liberation of energy in the soil in the form of heat is proportional to I^2R , I being the current and R the resistance to its flow away from the electrode. A large part of this heat is absorbed by the soil water, and it is obvious that if the rate of its liberation at any point is high enough steam will be formed there and moisture thus driven into the neighboring soil or the atmosphere. An excessive current, therefore, is likely to cause drying of the earth immediately surrounding the electrode and a consequent great increase of resistance.

In the course of this investigation some experiments were conducted in collaboration with the Potomac Electric Power Co., of Washington, D. C., which show the behavior of ground connections when subjected to a greater rate of liberation of energy than they can continuously care for. These experiments were made on five specimens of 0.75-inch galvanized-iron pipe driven to a depth of about 10 feet in soil consisting of a fill containing cinders, ashes, and other refuse. They were put down by first driving a pointed 2-inch pipe to a depth of about 5 feet, pulling it out, and driving the smaller pipe in the bottom of the hole. Before driving the smaller pipe, however, about 2.6 gallons of 15 per cent salt (NaCl) solution was poured in. The resistances were measured and found to be as follows:

TABLE 10

No. of specimen.....	1	2	3	4	5
Ohms.....	12.4	11.2	15.4	7.6	16.7

In the first set of experiments 1100 volts were impressed upon Nos. 1 and 4 in series. The current at the beginning was 61 amperes. At the end of five minutes No. 1 began to steam. It soon stopped, however, and No. 4 commenced. At the end of 16 minutes the current had decreased to 24 amperes, with the greater part of the energy being consumed by No. 4. The soil nearest the pipe glowed and gave off clouds of smoke, due most likely to burning humus. A measurement of voltage between the pipe and a spot on the ground about 1 foot away showed a difference of potential of 885 volts. A similar measurement on No. 1 showed a difference of potential of only 30 volts. The current fluctuated with great rapidity after the earth connection began to smoke, making accurate measurements very difficult. Two or three buckets of water were poured on the ground around No. 4, but produced no permanent effect. At the end of the experiment the ground was flooded with water from a hose.

The following day the test on Nos. 1 and 4 was repeated. This time no disturbance occurred around No. 4, but within 10 minutes No. 1 began to steam, and in 52 minutes the current had decreased from 80 to 30 amperes. The soil immediately surrounding the pipe finally glowed and gave off clouds of smoke in the same way as described for No. 4 in the preceding paragraph. The current in No. 1 was then discontinued, and Nos. 4 and 5 connected in series. In 36 minutes No. 5 began to smoke, and the current had decreased from 35 to 4 amperes. At the conclusion of this series of experiments about 6.6 pounds of salt was buried in the soil around each specimen.

Three months later a similar test was made on Nos. 1 and 5, immediately following a heavy rain. A current of 60 amperes at 1100 volts was maintained for 40 minutes, but no increase of resistance became apparent, although No. 5 gave signs of failure by steaming. The circuit was broken at the end of 40 minutes to avoid overheating of the transformers. The effect of the salt and the increase of moisture due to rainfall is made evident by the resistances, measured before beginning the test, which show a marked decrease from the values obtained at the time of the first experiment, and were as follows:

TABLE 11

No. of specimen.....	1	2	3	4	5
Ohms.....	6.42	6.50	8.80	3.83	11.4

The most obvious fact brought out by these experiments is that mentioned above, viz, that if a ground connection is required to dissipate energy at an excessively high rate drying of the soil will occur, with a great increase of resistance. But this increase of resistance is not permanent; the original conductance is recovered in a short time. In addition it is apparent that the relative capacities of ground connections to dissipate energy are not reliably indicated by their resistances, at least not for electrodes of the same size and shape. For as indicated in the first experiment, No. 4 was first to fail, although its resistance was only a little more than half that of No. 1. Finally, the magnitude of the rate at which a ground connection of the dimensions of those described above can dissipate energy continuously without an increase of resistance may be estimated from the results of the last test. The current was 60 amperes, the resistance of No. 1 at the start 6.42 ohms, and of No. 5, 11.4 ohms. Hence, the value of I^2R for No. 1 is about 23 kw and for No. 5 about 41 kw. The latter gave signs of failure, but as far as could be told No. 1 would have carried 60 amperes indefinitely. It is possible, however, that after a number of hours an increase of resistance would have taken place. On the other hand, several tests showed that dissipation of energy at a rate of 3 to 5 kw produced no effect on any of the specimens beyond a slight decrease of resistance due to increase of temperature. It appears, therefore, that it may safely be assumed that the maximum rate at which a ground connection made by driving a pipe to a depth of 10 feet in moderately salted moist soil can dissipate energy continuously without an increase of resistance lies somewhere between 5 and 20 kw. Nevertheless, if there is a possibility that a ground connection of this kind will ever have to dissipate energy at a rate of more than 8 or 10 kw it is perhaps best that an investigation be made to determine whether it will meet the requirements.

The probable reason why the capacity of a ground connection to dissipate energy is limited appears from the following considerations: When current is flowing the rate of liberation of heat is, in general, greatest in the layer of earth nearest the electrode, for it is there that the current density is greatest, and the rate of liberation of heat varies as the square of the current density. As a consequence water evaporates more rapidly from this layer than elsewhere, and, if it is not replaced at a rate equal to that

at which it is driven away, drying of the soil will follow, causing an increase of resistance. On the other hand, if it is replaced at the same rate as it is driven away current can flow indefinitely without an increase of resistance. Now, the only way in which the evaporated moisture can be replaced is by water flowing in from the surrounding region by capillary action. This, of course, takes place, but there is a definite limit to the rate at which water can move through soil by this means. Hence, if the current flow through a ground connection is gradually increased, a point will ultimately be reached at which heating drives off moisture faster than it is supplied, with results as described in the preceding paragraphs.

No tests have been conducted on ground connections consisting of electrodes of different forms under different conditions, but it is readily apparent that the maximum capacity of a ground connection made with an electrode of any form to dissipate energy may differ widely with the kind of soil in which it is situated, and also vary from time to time for the same soil. Among the factors which affect it may be named the moisture content, the rate at which moisture moves by capillary action and the distance which it will cover, the surrounding temperature, and the size of the electrode. It is practically impossible to separate some of these various factors, or control them experimentally, and for that reason laws or performance records under a variety of conditions from which the maximum capacity of a ground connection to dissipate energy may be predicted with any degree of exactness are not readily obtainable. If this characteristic of a ground connection must be known it is nearly always necessary to make a test in each case. It may be stated, however, that the greater the moisture content of the soil the greater the rate at which energy can be dissipated. Moreover, with a given moisture content, this rate will be greater in soils of fine texture than in those of coarse texture, because the former carry moisture at a greater velocity and over greater distances by capillary action than the latter. The surrounding temperature may also produce a marked effect, for the lower it is the greater the rate at which heat will be carried away by radiation and conduction.

With regard to the size of the electrode, it is easily demonstrated, for certain special cases at least, that the larger it is the greater the rate at which energy can be dissipated without too

rapid evaporation of moisture. In order to do this suppose an electrode of any shape to be buried in the ground. Let

A_1 be the surface area of this electrode in contact with the soil,

R_1 the resistance to flow of current away from it,

I_1 the total current, and

i_1 the average current density.

The rate of dissipation of energy will be $I_1^2 R_1$.

Suppose the dimensions of the electrode to be increased. Let

A_2 then be the surface area in contact with the soil,

R_2 the resistance to flow of current,

I_2 the total current, and

i_2 the average current density.

If the rate of dissipation of energy in the two cases is the same, $I_1^2 R_1 = I_2^2 R_2$ (a). Evidently $i_1 A_1 = I_1$, and

$i_2 A_2 = I_2$. Substituting in (a), $i_2 = i_1 \frac{A_1}{A_2} \sqrt{\frac{R_1}{R_2}}$.

Now, as mentioned heretofore, in the case of a circular plate embedded to a depth equal to one-half its thickness in the ground the resistance is $R_1 = \rho/2d$, where d is the diameter of the plate and ρ the resistivity of the soil. If the diameter is increased by a factor n , $R_2 = \rho/2nd$. Also $A_1 = \pi r^2$ and $A_2 = \pi n^2 r^2$. From (a), therefore, $i_2 = i_1 \frac{\sqrt{n}}{n^2}$, in which, since $n > 1$, the factor $\sqrt{n}/n^2$ is always less than unity, and $i_2 < i_1$.

In the case of a driven pipe, $R_1 = \frac{\rho \log_e \frac{2L}{d}}{\pi L}$, where L is twice the length of the driven pipe, and d its external diameter. If the length of the pipe is increased by a factor n , $R_2 =$

$$\frac{\rho \log_e \frac{2nL}{d}}{\pi nL} \quad \text{Also } A_2 = nA_1.$$

$$\therefore i_2 = i_1 \frac{\log_e \frac{2L}{d}}{n \log_e \frac{2nL}{d}}$$

Here, since $n > 1$, the denominator of the fraction under the radical, is greater than the numerator, so the value of the fraction is always less than unity. Hence $i_2 < i_1$.

In the case of a buried strip, as shown by measurements previously discussed, increasing the length causes practically a propor-

tional inverse change in the resistance. That is, if the length is increased by a factor n , it follows that $A_2 = nA_1$ and $R_1 = nR_2$. Whence $i_2 = i_1 \sqrt{n/n}$ and $i_2 < i_1$.

It appears, therefore, that an increase in the size of an electrode, at least of those shapes commonly used in practice, results in a decrease of the average current density for the same rate of expenditure of energy. And, since the rate of liberation of energy in the form of heat at any point is proportional to the square of the current density, the tendency toward drying of the soil at the surface of the metal is diminished. Or, to put it in other words, an increase in the size of an electrode permits an increase in the rate at which energy can be dissipated without drying the soil and increasing the resistance.

In previous paragraphs the fact was mentioned that the rate of liberation of heat is greatest in the soil nearest the electrode, the rate being proportional to the square of the current density, and also to the resistivity. This being the case, if the resistivity is reduced by salting or otherwise, the capacity of the ground connection to dissipate energy will be increased, because the tendency toward drying of the soil at the surface of the electrode will be diminished. For example, take a driven pipe. A cylinder of earth 2 feet in radius and coaxial with the pipe may be estimated as contributing about 50 per cent to the total resistance. If a current is flowing, half of the total amount of heat will be liberated in this cylinder. Now, if the cylinder is impregnated with salt to a sufficient degree to make the resistivity one-fifth normal the portion of the total resistance contributed by it will be only 16.6 per cent instead of 50 per cent. Furthermore, if the same amount of heat is liberated as in the first case, the portion of the total liberated in the cylinder will also be 16.6 per cent instead of 50 per cent. Salting thus causes the distribution of heat liberation to be shifted in such a way that more of the heat is developed at a distance from the electrode than where salt is not used, with a consequent improvement in the facility with which it can be taken care of. Tests by Creighton³⁵ indicate that by thorough salting the capacity of an earth connection to dissipate energy may be increased by several times. The foregoing statement applies in greater or less degree to any treatment of the soil surrounding an electrode which decreases its resistivity.

³⁵ General Electric Review, 15, p. 12 and 66.

10. POTENTIAL GRADIENTS

When current flow takes place through a ground connection, a potential gradient exists in the surrounding surface of the ground. This potential gradient decreases on receding from the electrode and practically disappears at a distance of a few meters. It is of importance in that it may be a source of danger to persons and animals. In order to obtain data on its character in the vicinity of driven pipes when subjected to heavy current flow a test was made on some of the specimens previously described. This test consisted in passing a 60-cycle alternating current at constant

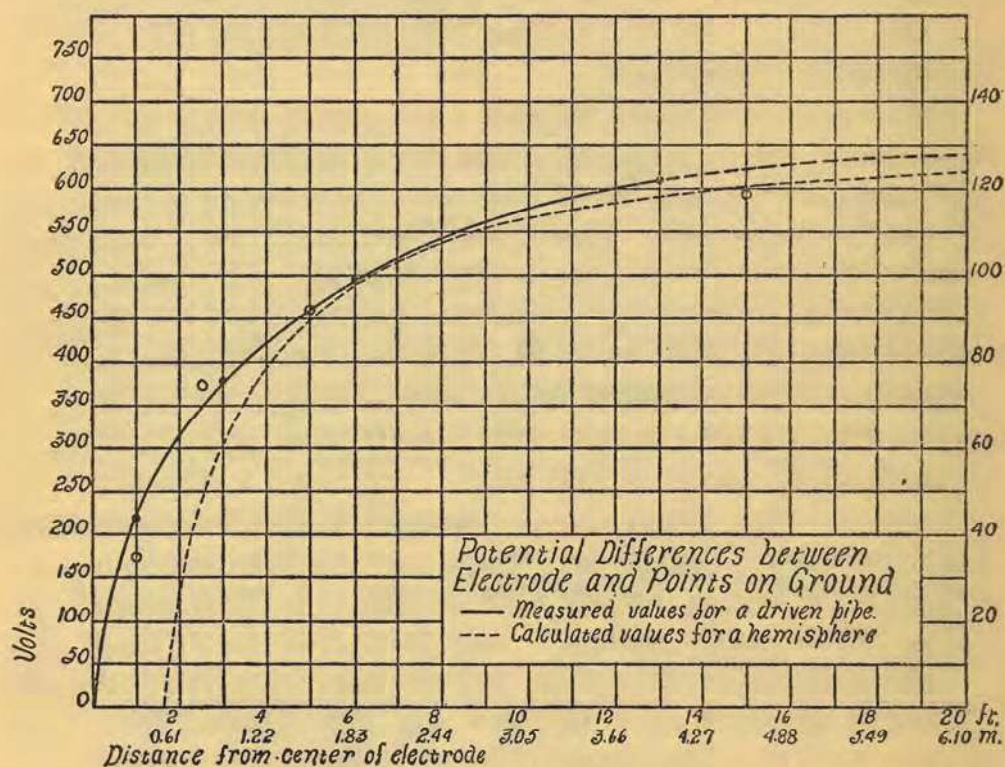


FIG. 27

voltage through the ground connection and measuring the potential differences between the pipe and points on the surface of the ground at various distances away. Plotting these potential differences as ordinates and distances as abscissæ gives a curve the slope of which at any point is proportional to the potential gradient. The results from a specimen which is more or less typical are shown in Fig. 27. This specimen is No. 1 of Table 10, Nos. 1 and 4 being in series in this particular case, with 232 volts impressed for one set of readings and 1100 volts for another. The total voltage was, of course, shared by the specimens very nearly in direct proportion to their resistances, since they were 104.5 feet

apart. Hence, the part taken by No. 1 can be calculated from the current and the resistance. The resistance was found to be 11.6 ohms, and the current at 12.5 amperes at 232 volts and 59 amperes at 1100 volts. The voltage impressed upon No. 1, therefore, was 143 in the first instance and 684 in the last. With the lower voltage the current was left on continuously, but with the higher voltage the current was allowed to flow only while readings were being taken to avoid change of temperature and a consequent change of resistance. Nevertheless, a slight change occurred, and there was a considerable change from the preceding day, for then, as shown in Table 10, No. 1 had a resistance of 12.4 ohms. In Fig. 27 the potential differences at the lower voltage are indicated by circles and refer to the scale at the right-hand margin, whereas the potential differences at the higher voltage are indicated by dots and refer to the scale at the left-hand margin.

For measuring the potential differences a double-scale voltmeter (0-150, 0-300) was used, and also a voltmeter (0-30) with a potential transformer. The resistance of the 150-volt coil of the voltmeter was 2044 ohms, and of the 300-volt coil 4083 ohms. The impedance of the high-voltage coil of the transformer, with the 0-30 voltmeter connected across the low-voltage terminals, was about 87 000 ohms. At each point of measurement some earth was loosened, water poured over it, and contact made with the ground by means of a brass disk, 7 inches in diameter, which was pressed into the wet soil.

The resistance to flow of current from the disk into the earth was not great enough seriously to interfere with the readings, that is, the reading recorded in each instance is not much less than the actual voltage. For, as shown below, the average resistivity of the soil appeared to be about 3600 ohms per cubic centimeter, and at the surface, on account of the admixture of coal dust, ashes, and other refuse, was probably less; 3000 ohms may be assumed as a fair value. Moreover, as indicated under resistance of ground connections, the resistance to flow of current away from such a disk is expressed by $R = \rho/2d$, where ρ is the resistivity of the soil and d is the diameter of the disk in centimeters. Hence, $R = 3000/2 \times 17.8 = 84$ ohms, a value which in this case can be neglected in comparison with the resistance of the voltmeter or the impedance of the transformer, since its effect on but few readings is sufficient to cause an error of as much as 4 per cent. In no

instance was difficulty experienced in repeating results with a fair degree of accuracy, especially at the higher voltage.

In Fig. 27 there is also plotted a curve showing potential differences calculated for a hemispherical electrode of a radius numerically equal to the combined electrostatic capacity in free space of the pipe described above (No. 1, Table 10) and its image, and embedded with its plane surface flush with the surface of the ground in uniform soil of the same resistivity as the average of that surrounding the pipe. The electrostatic capacity, and consequently the radius of the hemisphere, are seen from Table 1 to be 49.6 cm. The resistivity of the soil from $\rho = 2\pi CR = 2 \times 3.1416 \times 49.6 \times 11.6 = 3600$ ohms per cubic centimeter. The resistance to flow of current away from the hemisphere is therefore the same as for the pipe, or 11.6 ohms. Also, with 684 volts impressed the current will be 59 amperes. The potential differences may now be calculated as follows: Let r_1 be the radius of the hemisphere, in this case 49.6 cm, r the distance from its center to any point on the ground, dr the thickness of an elementary shell of earth concentric with it, I the total current flowing, E the potential applied, R the resistance, and ρ as above. The resistance to flow of current through the shell will be dR . Now $dR = \frac{\rho dr}{2\pi r^2}$ and $dE = IdR = \rho I dr / 2\pi r^2$. Whence $E_r = \frac{\rho I}{2\pi} \int_{r_1}^r \frac{dr}{r^2} = \frac{\rho I}{2\pi} \left[\frac{1}{r_1} - \frac{1}{r} \right]$. Substituting for ρ and I , $E_r = \frac{3600 \times 59}{2 \times 3.1416} \left(\frac{1}{r_1} - \frac{1}{r} \right) = 33\,800 \left(\frac{1}{r_1} - \frac{1}{r} \right)$. From this formula E_r has been calculated for different values of r and plotted in Fig. 27. The resistivity of the metal composing the electrode is neglected.

The two curves exhibit a marked degree of similarity. In addition, such measurements as have been made indicate that in the majority of cases measured values and calculated values will fall in close relation to each other, and for these reasons the curve for the pipe can doubtless be regarded as fairly typical of pipes driven in normal soil, at least for pipes up to 10 feet in length. At the same time, however, it should be stated that in many cases there will be wide deviations from the calculated curve, the extent of the deviations depending upon the condition of the soil in the immediate vicinity of the pipe, and also upon the firmness with which it is packed against the metal. Moreover, as the length of the pipe increases there is a tendency for the

curve of potential differences to become flatter and approach a curve represented by the expression. $E_r = \frac{\rho i}{2\pi} \log_e \frac{b}{a}$. This expression applies to a pipe or rod extending into the earth to such a depth that current flow away from it at the top is radial.

The quantity i is current per unit length of the electrode, a the radius, and b the distance from the axis to any point on the ground.

On the other hand, from the closeness with which the circles representing potential differences at 143 volts fall with respect to the curve through the dots, it is evident that the shape of the curve will be the same whatever the voltage. With the aid of this curve, therefore, and the resistance and current flow, a rough idea may be obtained in any given example of the potential differences between the pipe or earth wire leading to it and near-by points on the ground. For instance, if the resistance is 25 ohms and the current 6 amperes, the total voltage will be 150. This is nearly 0.22 of 684 volts. Therefore, upon multiplying this factor, or 0.22, into the ordinates of the curve in Fig. 27, it is seen that at a distance of 2 feet the potential difference between earth wire and ground will be about 66 volts; at 4 feet about 92 volts, and so on. As the current flow increases the potential differences will also increase in the same proportion, unless there is marked heating near the electrode. In this event the increase of temperature will cause the resistivity of the soil near the electrode at first to decrease, which in turn will cause the potential differences between the pipe and points near by also to decrease, but as heating proceeds to such a degree that drying of the soil occurs an opposite effect is produced. The resistivity increases enormously, which causes the potential differences in turn also to increase. For example, when No. 4 failed under too great a rate of dissipation of energy the difference of potential between the pipe and a point on the ground 1 foot away reached a value of 885 volts, instead of 100 or so as it would have if drying of the soil had not occurred. Consequently, in making earth connections in practice, careful consideration should be given to the possibility of failure through excessive flow of current.

At this point it may be mentioned that salting has an important effect, not only upon the capacity of a ground connection to dissipate energy, but also upon the potential gradient, especially in the vicinity of driven pipes. To demonstrate this effect an

experiment was made upon a 0.75 inch pipe driven to a depth of 5 feet in rather stony clay soil, with similar pipes driven at various distances away from it to serve as contacts in measuring potential differences. The first step taken was to impress 145 volts upon the driven pipe in series with a water pipe ground. The current was found to be 2.05 amperes, and the resistance, therefore, was 70.6 ohms, which corresponds to a soil resistivity $\rho = 2 \times 3.1416 \times 28 \times 70.6 = 12\,450$ ohms per cubic centimeter; that is, if the resistance of the water pipe ground, which was about 1 ohm, is neglected. The potential differences were measured with a voltmeter having a range of 150 volts and a resistance of 1996 ohms. The resistance to flow of current away from each driven pipe serving to make contact with the earth was known so corrections were made to the voltage readings, this correction being about 4 per cent. The results are shown plotted in Fig. 28, each potential difference being represented by a dot.

The next step was thoroughly to salt the specimen. A hole about 2 feet in radius and 1 foot deep was dug around it, 65 pounds of salt poured in, and covered with earth. At intervals of two or three days the soil was flooded with water to dissolve the salt and carry it deeper into the ground. The potential measurements were then repeated. With 145 volts impressed the current was found to be 6.6 amperes. The resistance, therefore, was 22 ohms, or about 31 per cent of its original value. This reduction is mostly due, of course, to the effect of the salt in lowering the resistivity of the soil near the pipe, but is also in small part due to the water used to dissolve the salt and to a rainstorm which increased the moisture content in the entire region. Nevertheless, any changes in the shape of the curve showing potential differences may be nearly all attributed to the salt, because a uniform change of resistivity due to rainfall would have no effect beyond decreasing the total resistance, and as the soil was quite moist to begin with, the water poured around the pipe would not produce an effect on the resistivity of the soil in any way comparable with that produced by the salt. The results are plotted in Fig. 28, the potential differences being represented by circles.

In Fig. 28 there are also plotted calculated potential differences for a hemispherical electrode in the same way as in Fig. 27. The radius of this hemisphere is taken as 28 cm (0.918 feet), or numerically equal to the combined electrostatic capacity in free space of the pipe and its image in the surface of the ground, as shown by Table 1. When buried in soil of resistivity equal to 12 450 ohms

per cubic centimeter, the resistance will therefore be the same as for the pipe, or 70.6 ohms, and with 145 volts impressed the current will be 2.05 amperes. Substituting these quantities in the formula

$$E_r = \frac{\rho l}{2\pi} \left[\frac{1}{r_1} - \frac{1}{r} \right],$$

results are obtained for different values of r , which correspond to the upper broken-line curve. On the other hand, the lower broken-line curve represents potential differences calculated on the assumption that the soil surrounding the hemisphere to a distance of 2.9 feet from its center is salted in the same way as described for the pipe. The quantity of salt placed around the pipe was sufficient to make nearly a 2 per cent solution of the soil water in a cylinder the length of the pipe, concentric with it, and about 2 feet in radius, if the moisture content is taken as 30 per cent. The soil was quite moist, so it is likely that this value is about right. From Fig. 26 it is seen that adding 2 per cent salt to the soil moisture decreases the resistivity by about 13 times. Assuming this to be the case for the pipe, the resistivity of the soil for 2 feet from it is roughly 1000 ohms per cubic centimeter. Beyond that it is greater, but because of the rain must be taken as less than 12 450, as indicated above. The calculation will come out about right if it is considered to be 10 170 ohms per cubic centimeter. That is, with $\rho=1000$ ohms per cubic centimeter to a distance of 2.9 feet from the center of the hemisphere, and 10 170 ohms per cubic centimeter beyond that, the total resistance to flow of current will be 22 ohms, and with 145 volts impressed the current will be 6.6 amperes. Substituting in the formula for E_r results are obtained which correspond to the lower broken-line curve of Fig. 28. The similarity between the curves representing calculated and measured values is even more marked than in Fig. 27.

The effect of the salt in changing the potential gradient near the pipe is practically that which might be expected from previous study of its effect on the resistivity of soil. In the main the change may be regarded as beneficial, although as far as danger to animals is concerned there is scarcely any improvement. For if a large animal, such as a horse, were standing near the pipe with front feet 1.5 feet from it the rear feet would be approximately 5 feet farther away. From Fig. 28 the potential difference between these two points is seen to be about 35 volts before salting, whereas afterwards it is about 70 volts. Hence, the application of salt appears to cause an increase in the danger to animals, but with regard to persons the danger is lessened, be-

cause injury is most likely to occur through touching the pipe or earth wire, and salting causes a marked reduction in the potential differences between the pipe and points within reaching distance of it. The greatest advantage, however, is that mentioned heretofore, viz, reduction of resistance, which facilitates the operation of protective devices.

With regard to plates, or other electrodes buried beneath the surface of the ground, the potential gradient is not nearly so important a matter as in the case of pipes or electrodes which are accessible. For with the former the region of greatest potential

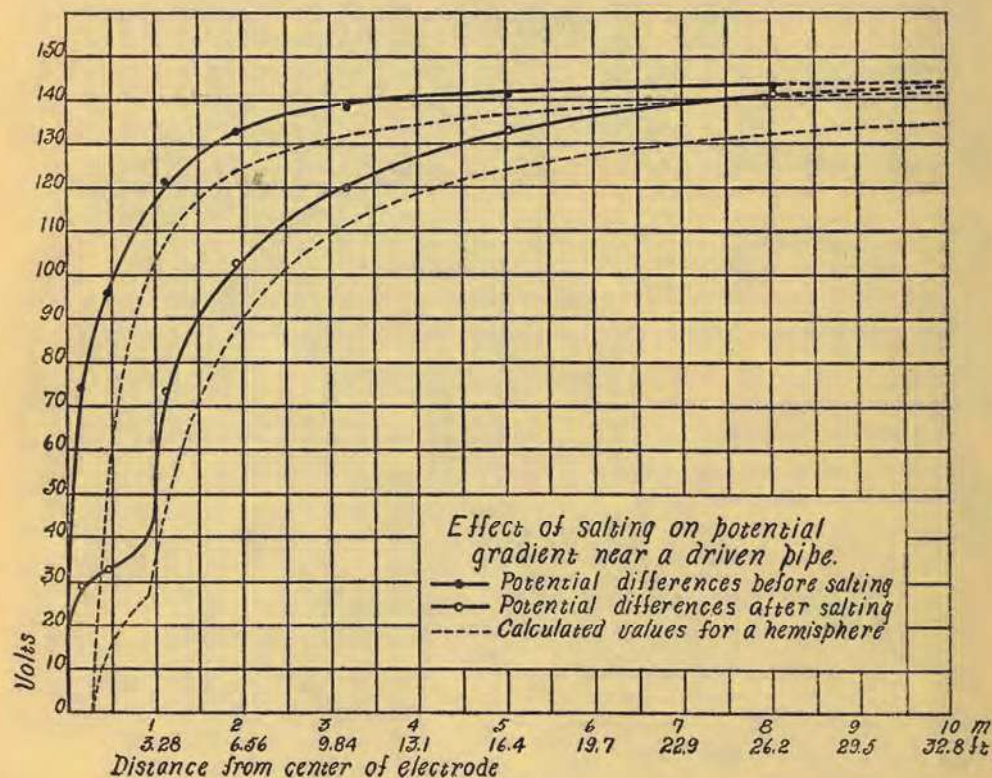


FIG. 28

gradient is underground and out of reach of persons, whereas that found at the surface is not likely to be of much moment. For instance, with a plate buried at a depth of about 6 feet, having a resistance of 2.2 ohms, and carrying a current of 100 amperes, the potential gradient immediately over the plate proved to be about 4.5 volts per foot.³⁶ A potential gradient of this magnitude would present very little danger to either persons or animals. Electrodes at lesser depths, of course, might show greater values, but only in extraordinary cases would they be sufficient to be of importance.

³⁶ Sparks, Journal I. E. E., 53, p. 401.

The greatest danger from ground connections made with electrodes buried beneath the surface arises from the high potential differences which may exist between the earth wire and points within reaching distance of it when current is flowing. In the case just mentioned this was 150 volts, the total voltage, being 220. With the earth wire well guarded, however, and every part of the ground connection mechanically strong, as described below, the likelihood of injury from it is very small.

V. MECHANICAL CONSTRUCTION OF GROUND CONNECTIONS

Substantial construction is one of the first considerations in making ground connections of any type and should never be sacrificed to expediency. For if grounding is poorly done it might in most cases as well not have been done at all; ground wires break, clamps come loose, electrodes corrode away, and even though repairs are constantly attended to, the protection afforded may be inadequate and unreliable. Moreover, the presence of a ground connection of any kind engenders a feeling of security which is false unless the materials and workmanship are of the best. Too much emphasis can hardly be laid upon the necessity for carefulness in this particular feature of electrical practice.

1. DRIVEN PIPES

In driving pipes difficulties are sometimes encountered, and as a consequence the work is not uncommonly slighted. The chief difficulties are presented by stones and crumpling of the pipe under the hammer. In some localities stones are so numerous as to prevent driving altogether, but very stony ground can be penetrated by first driving a steel bar with a tempered point. The bar can stand almost any amount of hammering, and when it is removed the pipe can be driven in the same place with comparative ease. By this means a good ground connection may in many cases be obtained where otherwise the operation might result in a waste of material. The size of the bar should be somewhat less than that of the pipe, because if the hole is made too large some time may be required for the soil to settle, and in the meantime the resistance is not unlikely to be so high as to be unsafe.

With a bar driven 10 to 12 feet in the ground considerable force is necessary to remove it, and where many ground connections

are to be made a great deal of time can be saved by making adequate preparations in advance. The force required may be estimated at from 3 to 4 tons. For applying it a 3-ton differential pulley will probably be found satisfactory, although other means may be used with good results; for instance, a lever of the proper dimensions, a lifting jack, or a chain and fulcrum with a team of horses or a motor truck. The bar may well have a heavy hook welded on near the top for attaching the chain in pulling. The pull should be as nearly vertical as practicable to avoid bending the bar or widening the hole.

In soft ground, however, or even rather hard ground where there are few stones, pipes may readily be driven to the required depth without the use of a bar. The greatest trouble which will be met with in this case, and also in stony ground, is crumpling and bending at the upper end. With ordinary galvanized iron pipe this is not easy to avoid. Nevertheless, if the hammering is not severe a coupling screwed on a threaded end as far as it will go will in some cases serve very well to prevent it, but these couplings split easily, or the pipe may break off in the thread. On the other hand, if heavy hammering is required, a more satisfactory method is to drive 4 to 6 inch lengths of lap-welded steel conduit over the end of the pipe. If the end is threaded or otherwise a little reduced in size, a 1-inch conduit can be driven over a 0.75-inch pipe or a 1.5-inch conduit over a 1.25-inch pipe. This conduit is tough and will be of great assistance in preventing battering. But where a great deal of pipe is to be driven which is all of the same size the most satisfactory method is to make a cap of mild steel similar to that shown in Fig. 29. The shank *A* is made to fit rather snugly on the inside of the pipe, and the circular slot *B* is of a width but little greater than the wall thickness. The farther *A* extends into the pipe the more effective it will be in preventing bending. Such a cap will serve for a great many pipes before wearing out.

In general it will be found that the medium sizes of pipe drive better than either the smaller or the larger sizes, as they can withstand far more hammering than the smaller sizes and at the same time do not require as much of it as the larger ones. In fact, in stony ground it is extremely difficult to drive a 2 or 2.5 inch pipe to the requisite depth even though a bar is driven in advance. For general purposes, therefore, the 1 or 1.25 inch sizes may be considered preferable. They can be driven with either square or

flattened ends, but neither seems to present a marked advantage over the other. The use of extra heavy pipe is to be recommended on account of its greater strength to resist the effects of driving and also the greater amount of metal to resist corrosion.

After a pipe is driven the crumpled part should be cut off near the surface of the ground with a hacksaw, the exposed end threaded, and a brass casting screwed on which is made with a lug to which the earth wire can be soldered, or an ordinary coupling can be used at the surface of the ground and the pipe extended upward 8 or 10 feet if beside a pole or building. The joint between wire and pipe is thus removed from the possibility of mechanical injury. Where a

number of pipes are to be connected together, pipe and ordinary fittings may be used, or brass castings and copper wire. With either the connections can best be placed underground, where they will be better protected from breakage than if exposed. Wires should be laid slack for the reason that if they are disturbed they are less likely to be broken.³⁷ Joints, or places where the galvanizing has been impaired, should be well daubed with hot pitch or tar and wrapped with cloth, or otherwise protected from soil corrosion. The brass castings just mentioned can be purchased in the market. In place

of them, however, a good joint between wire and pipe can be made by driving a wooden plug into the pipe until it is 3 to 4 inches below the top, inserting the wire and pouring the hole full of melted lead. Where salt is used it is advisable to dig a hole around the pipe to a depth of 1 foot or so, dump in the salt, and cover it with earth. With the salt buried in this way there is no chance of its being carried away by surface water, and its proper distribution through the soil is assured. To hasten distribution at first, water may be used, but this should not be overdone, as a large part of the salt may be washed away. As much dependence as practicable should be placed upon natural diffusion.

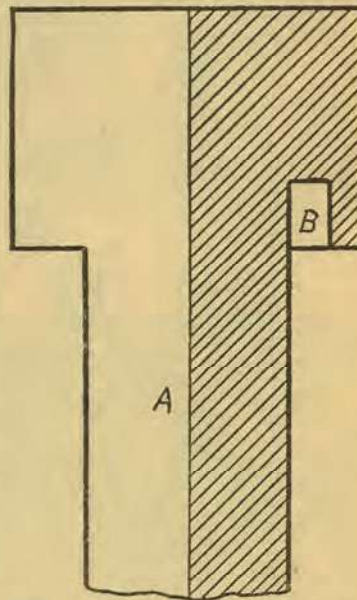


FIG. 29.—Cap for driving pipe

³⁷ See Rule 93d, Appendix II.

2. PLATES

In selecting materials for ground plates much depends upon the length of life required of them. If they are intended to be practically permanent, copper, of course, is about the only metal commercially available which will serve the purpose, although galvanized iron, will last for a number of years, even where salt is used, and is much less expensive. The thickness of a plate has very little to do with the resistance to flow of current away from it, and is therefore determined solely by mechanical considerations and the extent of the corrosion that is likely to take place. In general Nos. 14 to 18 gauge sheet metal will be found satisfactory in either copper or iron. With iron, however, because of its greater susceptibility to corrosion, heavier sizes may be used to slight advantage on account of the greater amount of metal, but it should be remarked that it is upon the galvanizing that the most of the life of such a plate depends. Hence, none but the best quality of galvanized sheet should be considered. Cast-iron plates do very well in some cases, being especially resistant to corrosion in ordinary soils. But, on the other hand, any of these materials may corrode very rapidly if exposed to some soils or to seepage from dumping places.

With plates the connection between electrode and earth wire must be made underground. This puts the joint out of reach of inspection and precautions are therefore necessary to make it last as long as the plate does. A procedure which has in many instances been recommended, and which is, perhaps, as good as any, is to use a heavy earth wire, or preferably a strap of metal, which can be riveted and then soldered, the strap extending a foot or so over the surface of the plate. After the soldering is done it is advisable thoroughly to clean the metal around the joint and coat it with tar or pitch to prevent corrosion. If the plate and earth wire are of different metals, this corrosion, due to galvanic action, may be considerable. If both are of copper, however, there is little danger of damage from this cause.

When plates are buried, care should be taken to make as good contact with the soil as practicable, for the effectiveness of the ground connection depends to a considerable extent upon the thoroughness with which the earth is packed against the metal. If the plate is placed on edge, no particular care in this respect is necessary; tamping on each side of it is sufficient. But if it is laid flat and the ground is stony, all of the stones should be removed

from the bottom of the hole, and, whether the ground is stony or not, the soil upon which the plate is to rest should be loosened to a depth of several inches. With this bed of loose earth, and the hole filled and rammed, good contact is likely to be obtained. Otherwise, the plate may rest on lumps and in that way make contact with the ground only in spots. It is also to be recommended that all stones be removed from the immediate vicinity of the plate whether it is placed on edge or flat, because, as previously mentioned, they are of high resistivity, and many of them nearby will affect the resistance to a marked degree. If salt is considered necessary, it can be worked into the loose soil around the plate. It can be renewed by burying it in much the same way as described above for pipes, and allowing natural diffusion to distribute it through the region below. Where coke is used, no particular care need be exercised beyond ramming it into the bottom and sides of the hole to insure good contact between coke and soil. It may be well to loosen the soil before putting in the coke, for better contact can thus be made.

3. STRIPS

The making of earth connections with strips involves nothing radically different from the process of making them with plates. The same kinds of metal may be used and for the same reasons. Joints may also be made in the same way, but since they are likely to be near the surface of the ground it may be well to protect them, not only against corrosion, but also against mechanical injury, by embedding them in concrete. Where the joints to be protected are those between strips and down conductors, or earth wires, the concrete should be flush with the surface of the ground and of sufficient volume to prevent its being easily moved, say a cylinder 8 to 10 inches in diameter and 1 foot long. It is true, of course, that the strip can be brought out of the ground at the point where it is attached to earth wires, which limits the possibility of corrosion, but at the same time this exposes the joint to mechanical injury. On the whole it seems better to keep such joints beneath the surface and protect them with concrete. In fact, this is a desirable means of protecting joints of any kind made underground which may be subject to galvanic action in the presence of moisture or be in need of mechanical reinforcement.

4. WATER PIPES

Where connection is to be made to a cast-iron pipe line with bell and spigot joints the most satisfactory method is probably that

prescribed by the National Fire Protection Association. This method consists in drilling a hole in the bell, tapping it, and screwing in a brass plug to which the earth wire is soldered. The joint thus made requires only a reasonable amount of labor and is permanent, especially if the surface of the plug and pipe in the immediate vicinity is heavily coated with pitch or something else to prevent corrosion. On the other hand, if connection is to be made to a service pipe which can be drained of water the wire can be wrapped several times around it and soldered, or a fitting can be utilized by screwing a plug into it and soldering the earth wire to the plug in the same way as described for bell and spigot joints. But if the pipe can not be drained conveniently the next best thing is a clamp to go around it, with a lug to receive the earth wire. To insure high conductance all scale and rust should be thoroughly removed before the clamp is put on. The pipe and clamp may also be treated with one of several amalgams now obtainable which are designed for the purpose of making good electrical connection between metallic surfaces which can not be soldered.

The selection of a clamp for attaching wires to service pipes requires some care in order to obtain a device that will maintain permanent contact. There are many clamps on the market, but such of them as have been examined at the Bureau of Standards appear to be of flimsy construction. The most of them consist of a copper strip not thicker than No. 20 gauge and about 0.75 inch wide, which encircles the pipe and is held by a set screw or small bolt passing through holes punched in the copper. Drawing the screw to a sufficiently firm grip puts too great a stress on the metal, and, in fact, strains it to such a degree that good contact is difficult to maintain. Moreover, in some cases lugs for the earth wire are not provided; one end of the copper strap is simply bent to the required shape. In view of these facts more substantial construction of clamps seems necessary. The metal used should be much thicker, say about No. 8 gauge, and a lug for the bolt should be riveted to each end of the strap. There should also in every case be a lug for the earth wire put in such a position that tightening the bolt results in a firm and permanent electrical contact.

The place at which it is desirable to make connection to service pipes must also be considered. In general, it may be stated that it should be so chosen that there is the least likelihood of the pipe being disconnected between the point at which the earth

wire is attached and the water main.³⁸ Moreover, where the water meter is placed in the basement of a building the point of attachment should be on the street side of the meter. Or, if the meter is located in a well or manhole under the sidewalk or street, a jumper, consisting of a wire as large or larger than the earth wire, should be placed around it. The necessity for these precautions arises from the fact that plumbers in making repairs may disconnect the pipe and destroy the effectiveness of the earth connection. Also, it is the practice of some water companies to remove water meters when buildings are vacated. It is desirable, however, to maintain the ground connection at all times, particularly if the circuit to which it is attached serves other customers in the vicinity, and the contingency presented by the removal of the meter can best be guarded against by shunting it with a heavy wire.

5. GROUND WIRES

The minimum allowable size of ground wires is determined principally by mechanical considerations, for they are more or less liable to mechanical injury, and must therefore be strong enough to resist any strain that is likely to be put upon them. The general practice in electrical construction is to place the minimum size at No. 6 copper, particularly for grounding circuits carrying current. This size is also specified in most codes of rules for the same purpose. The extent to which No. 6 is adhered to as a minimum size under all conditions is indicated by correspondence with electric companies.³⁹ In all, 418 companies were heard from. Four reported as using wires smaller than No. 6, 152 made no answer, while 262 reported as using No. 6 or larger. Hence, in view of the general use of No. 6 as a minimum size, it seems that it can be taken for granted that it is quite satisfactory, especially as there are no reports to the contrary. On the other hand, for earthing frames of machines and other noncurrent-carrying parts of electrical equipment it may in some cases be permissible to use smaller wires if they can be put where they are out of the way of possible damage. These smaller sizes, however, should be used only under certain conditions. For instance, if a small motor is connected to a low-voltage line which is already grounded for protection against high voltage, it is desirable also to ground the frame of the motor, but it is not so important a matter as it would be if the circuit from which energy is taken

³⁸ See rule 95^a, Appendix II.

³⁹ This correspondence is summarized in Appendix I.