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1948

A Manual on

GROUND RESISTANCE TESTING

"MEGGER."

JAMES G. BIDDLE CO.
ELECTRICAL AND SCIENTIFIC INSTRUMENTS
1316 ARCH ST., PHILADELPHIA 7, PA.

A Manual on
GROUND RESISTANCE TESTING
for users of

"MEGGER"
TRADE MARK REGISTERED U.S. PAT. OFF.

GROUND TESTERS

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CONTENTS

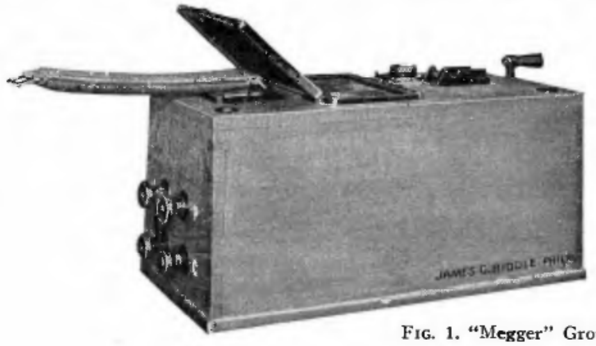

FIG. 1. "Megger" Ground Tester ready for use.

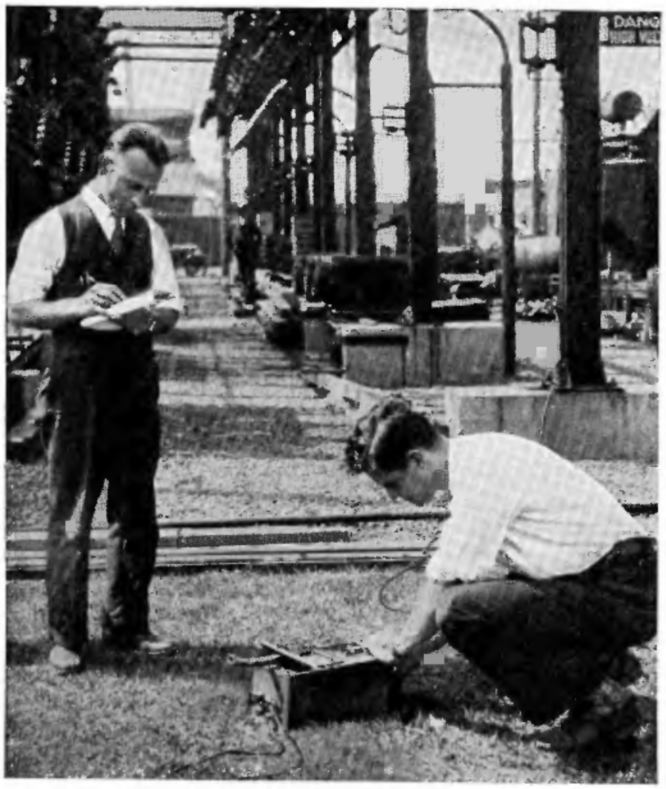

FIG. 2. Testing ground resistance is done with minimum of effort with the "Megger" Ground Tester.

INTRODUCTION

This Manual is intended to serve two purposes:

1. As instructions for the use of our "Megger" Ground Resistance Testers, and
2. As an introduction to the general subject of ground resistance measurements.

There is included also some information of a technical character that should be helpful to engineers dealing with grounding problems, and geophysical prospecting by earth resistance measurements.

The U. S. Bureau of Standards has defined the terms "ground," "permanent ground," "ground connection" as referring 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".* It is the resistance to the flow of current from these metallic electrodes into the surrounding earth, with which we are concerned.

This book was written in 1930 and was published as a "Technical Bulletin" at the time when "Megger" Ground Testers were being introduced. With but slight editing, it serves today as a "classical" work on ground resistance measurements for engineers and is well suited as a manual for the use of "Megger" Ground Testers.

On the subject of how to provide effective grounding facilities we have reprinted a series of articles on "Grounding Electrical Circuits Effectively" by Mr. J. R. Eaton. These articles were published under our sponsorship in the GENERAL ELECTRIC REVIEW in 1941. They include:

I—Characteristics of Grounds

II—Calculations & Installations

III—Ground System Requirements

If you would like copies, please ask for our Bulletin 25T2.

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*Page 7, Technological Paper 108, GROUND CONNECTIONS FOR ELECTRICAL SYSTEMS, by O. S. Peters, Assistant Physicist, June 20, 1918. The paper is referred to frequently throughout this Bulletin as B. of S. Paper.

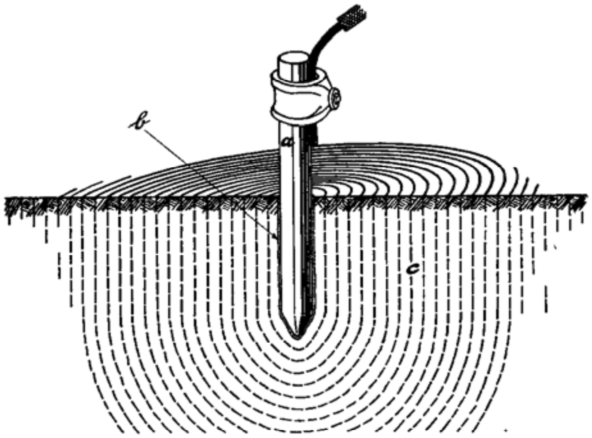

FIG. 3. Showing the components of resistance to earth of a ground connection.

a—Resistance of the electrode and connections to it.

b—Contact resistance between the electrode and the soil adjacent to it.

c—Resistance of the surrounding earth,—which may be pictured as successive shells of earth of equal thickness around the electrode. With increased distance from the electrode these earth-shells are of greater cross-section and therefore of lower resistance.

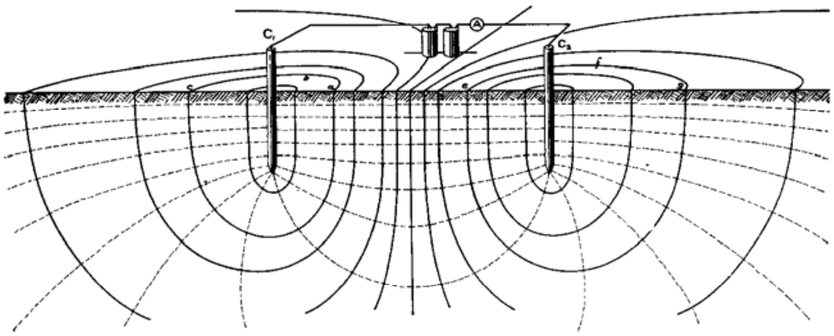

FIG. 4. Showing—in principle—the lines of current flow (dotted) in the earth between two rod or pipe electrodes placed relatively close together, and also the lines of equipotential (full lines) both in the earth and on the surface.

CHAPTER I.

NATURE OF A GROUND CONNECTION

RESISTANCE to the flow of current through a grounded electrode, or ground connection, into the surrounding earth is made up of three component parts: (1) Resistance offered by the electrode itself; (2) Contact resistance between the electrode and the earth or soil adjacent to it; (3) Resistance of the surrounding earth.

Rods, pipes, masses of metal, structures and other devices commonly used for ground connections ordinarily are of sufficient size or cross section so that their resistance is a negligible part of the total resistance of the ground connection.

Contact between electrodes and surrounding earth offers much less resistance than what at first might seem to be the case. In fact, if an electrode is free from paint or grease, and if the earth is packed firmly around it, the Bureau of Standards has shown that the contact resistance is negligible. Rust on the surface of an iron electrode has little or no effect in increasing contact resistance. Since rust is iron oxide, is readily soaked with water and is of lower specific resistivity than most soils, usually it will interpose less resistance than an equal amount of earth. Of course if an iron rod or pipe has rusted through altogether, the part below the break is not effective as a part of the ground connection.

Resistance of the Surrounding Earth:

An electrode driven into earth of uniform resistivity will radiate current in all directions. Consider the electrode to be surrounded by shells of earth, all having equal thickness. Naturally, the first earth-shell which surrounds the electrode has the smallest cross-section and offers the greatest resistance to the flow of current. The next earth-shell has a greater cross-section, and therefore offers less resistance to the flow of current. And so, as we go on adding earth-shells around an electrode, the cross-section becomes greater, but the resistance of each succeeding shell becomes less. Thus a point will be reached where the inclusion of additional earth-shells will not add appreciably to the total resistance of the earth surrounding the electrode.

Obviously, the greater part of the resistance to earth of any grounded electrode will be found close to the electrode. The B. of S. Paper* states (on page 12) that in the case of driven pipes, about 90% of the total resistance is generally encountered within the first 6 to 10 ft. from the electrode. This seems to apply to small pipes driven to a depth of not over 5 ft. and checks with results obtained with the direct-reading "Megger" Ground Tester; but with larger ground connections of any character whatever, the percentage increase of resistance with distance is less rapid. This matter is discussed in greater detail in Chapter VII. However, with the "Megger" Ground Tester, the resistance to earth of any kind of a grounded electrode can be tested to as high a degree of practical accuracy as may be desired, providing the simple instructions given in this bulletin are carried out.

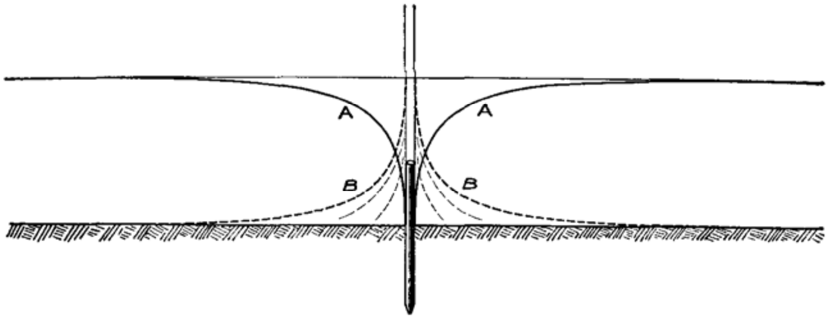

FIG. 5. A ground connection may be pictured as a volcano *BB* rising out of a level plain. The sides of the mountain are the inverse of the ground resistance (or potential difference) curve *AA* made to any point surrounding the ground connection.

Physical Analogy of a Ground Connection:

If we plot on paper the resistance to earth of a grounded electrode against distance away from it, as shown in *A* of Fig. 5, we find that the resistance rises rapidly at first and then less and less rapidly, until finally it becomes practically constant.** Now, invert curve *A*, and observe it as curve *B*. The ground immediately surrounding the electrode is *raised* in potential (and resistance). The ground connection may thus be compared to a volcanic mountain rising out of a level plain. The descent is steep near the crater of the volcano, but slopes off more and more gradually until finally at a considerable distance away it joins the plain.

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*See footnote, page 5.

**This curve, of course, is identically the same as a potential-difference curve measured on the surface of the earth surrounding a grounded electrode, because when current flows into the earth through the electrode the potential difference between the electrode and a given point is directly proportional to the resistance to that point.

In Fig. 5 *AA* is a typical resistance (or potential-difference) curve as observed on the surface of the earth surrounding a pipe ground connection, and *BB* is the exact inversion of it.

In this manner the resistance to earth of *any* ground connection may be pictured as a volcanic mountain, large or small, regular or irregular, depending on the size and shape of the ground connection, and the characteristics of the earth in the vicinity. The important thing to remember is that no two ground connections are exactly alike; but, as set forth in the next chapter, their resistance to earth can be tested with the "Megger" Ground Tester simply, easily and accurately.

A further consideration of this earth-shell conception and volcanic analogy of ground connections will be found in Chapters IV and VII of this bulletin; meanwhile the above will suffice for a simple and practical consideration of the subject.

FIG. 6. The heavy-duty type of "Megger" Ground Tester, top view. Approximate dimensions—14x7x7 inches. See facsimile scale, FIG. 21, page 39.

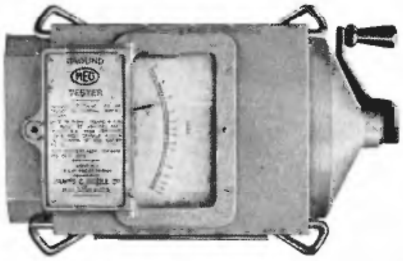

FIG. 6a. The "Meg" type of "Megger" Ground Tester, top view. Approximate dimensions—$9\frac{1}{4}$x5x$6\frac{1}{4}$ inches. Weight—$7\frac{1}{2}$ lbs.

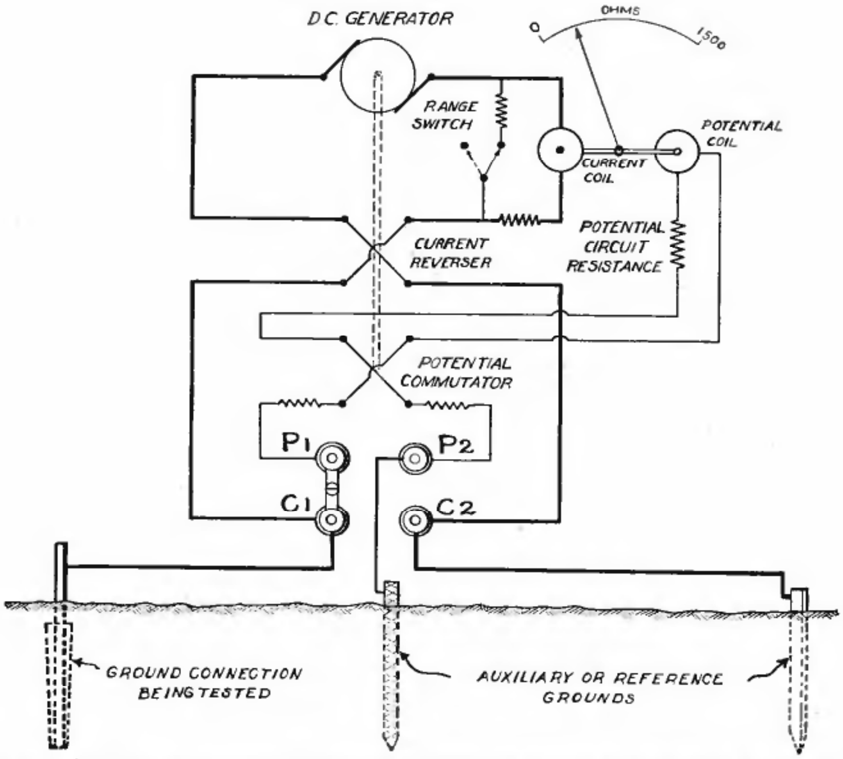

FIG. 7. Schematic diagram of connections of the "Megger" Ground Tester showing the principle of operation.

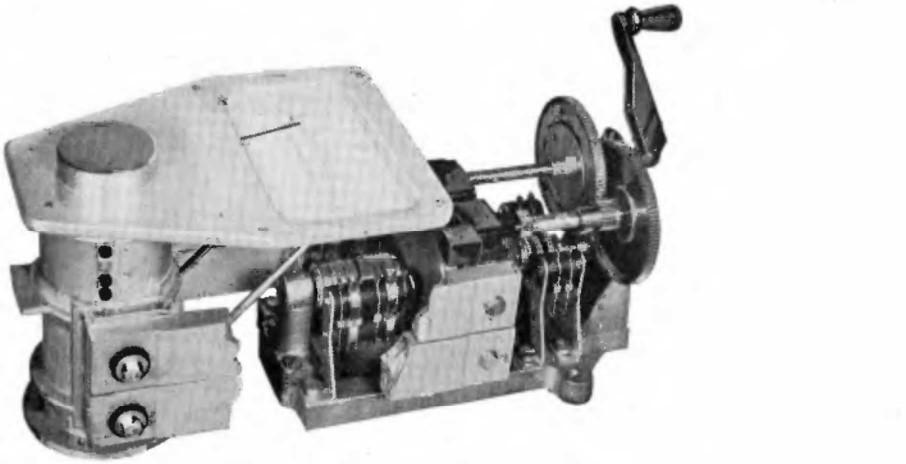

FIG. 8. Ohmmeter, generator and driving mechanism of the "Megger" Ground Tester, with magnets cut away showing the reversing commutators.

CHAPTER II.

THE SINGLE-TEST "MEGGER" METHOD

FOR DETERMINING THE RESISTANCE TO EARTH OF GROUND CONNECTIONS

TESTS by this method are made with "Megger" Ground Testers. These instruments are unique in that the value in ohms of the resistance under test is given by the deflection of a pointer over a scale —directly (like a voltmeter)—in one operation and without any computations. After making connections, all that is necessary is to turn the crank and read the scale.

In common with other methods for measuring the resistance to earth of ground connections, the "Megger" method requires two auxiliary or reference ground connections, and these must be spaced properly with respect to the ground under test and each other. (This is exceedingly important if accurate results are to be obtained, and is discussed later.)

NOTE:—The heavy-duty type of "Megger" Ground Tester was introduced in 1927; and in 1931 it was supplemented by the "Meg" type which is smaller in size and lighter in weight, see Figs. 6 and 6a, also Figs. 10 and 11. Both of these instruments operate on identically the same "Megger" principle.

Principle of Operation:

The fundamental principle of operation of the "Megger" Ground Tester is that of the A.C. fall-of-potential method, as set forth on page 38 of this bulletin. In the "Megger" Ground Tester, alternating current is used for the test (so as to avoid the effects of polarization, electrolysis and stray current in the earth), but the result is indicated by a sensitive and accurate direct-current ohmmeter, which is also direct-reading.

Fig. 7 shows the essential electrical connections. Current is supplied by a self-contained direct-current hand-driven generator, and after passing through the current coil of the ohmmeter, is changed into alternating current for the test by means of a commutator or current reverser. The potential drop across the ground under test is picked up at P_1 and P_2 and again converted into direct current for actuating the potential coil of the ohmmeter. Thus the result is shown at once by a direct-current ohmmeter, having all the advantages of sensitiveness and accuracy of this type of instrument.

The two coils of the ohmmeter are mounted on the same shaft and work in opposition in the field of a permanent magnet. Thus the instrument is a true ohmmeter and indicates R as a ratio of $\frac{E}{I}$, unaffected by the exact voltage generated in the armature, or strength of the magnetic field. Therefore, the reading will remain constant, even though the speed of the hand-crank is varied considerably above or below normal. The current reverser and potential commutator are on the same shaft as the armature of the generator and so run in synchronism, whatever the speed. At normal speed of the hand-crank—100 r.p.m.—the frequency of the testing current is 50 cycles per second, and the open circuit potential is on the order of 50 volts. Internal ballast resistance is included to limit the current delivered by the instrument, which depends on the range being used as well as on the resistance under test, but in no case does the current exceed about .5 ampere.

As the moving element is without mechanical control, the pointer will stand anywhere on the scale unless connections are made and the crank turned.

No Effect of Stray Current in the Earth:

Since the current sent through the ground circuit by the "Megger" Ground Tester is alternating, errors due to stray direct current in the earth, and to polarization and electrolysis at electrodes, are eliminated. If there is stray direct current in the earth, the pointer will move up or down the scale as soon as connections are made. However, when the crank is turned the effect of all stray current is removed.

Should there be stray alternating current in the earth of a frequency nearly the same as that of the test current, the pointer becomes unsteady. The remedy is very simple—turn the crank slower or faster so as to make the frequency of the test current different by several cycles per second from that of the stray current. Thus the effect of *all* stray current is eliminated automatically without the use of a manually operated compensating device.

NOTE: Satisfactory and consistent results have been obtained with the "Megger" Ground Tester at locations where the difference of potential in the earth, due to stray alternating current, between the ground under test and one of the reference points, was as much as 50 volts, with sufficient power back of it to cause a 100-watt lamp to glow perceptibly in bright sunlight. It had been impossible to test grounds at these locations satisfactorily by *any other device or method.*

FIG. 9. Testing a substation ground connection with the "Megger" Ground Tester.
A is a lead to a portion of the ground network which is disconnected from another portion of the ground network at *B*. There was so much stray current in the earth around the station that a 100-watt lamp glowed perceptibly in bright sunlight when connected between *A* and *B*. The instrument gave consistent results even when *A* was used as a reference ground.

Variable Resistance Grounds:

Occasionally grounds will be found which vary in their resistance to earth during the test. The "Megger" Ground Tester can be used to test such grounds, because it follows such variations accurately, in the same way that a voltmeter will follow any change in potential.

Effect of Reference Grounds—Their Resistance and Location:

The resistance to earth of the current reference ground C_2 does not at all affect the accuracy of the test; it can make no difference except in the sensitiveness of the ohmmeter. Tests show that even if the resistance at C_2 is several times the range of the instrument, the ohmmeter remains amply sensitive.

The potential circuit of the ohmmeter is of high resistance so as to minimize the effect of the resistance to earth of the potential reference ground P_2. In all ranges of the "Megger" Ground Tester, except for the 0 to 3 ohm range, the potential circuits have resistances varying from 10,000 ohms to 100,000 ohms or higher depending upon the instrument and range. In these values 1 percent (100 to 1000 ohms) is allowed for the resistance to earth of the potential reference stake P_2. Thus a wide variation in resistance of the P_2 reference ground connection is permissible without introducing any serious error in the indication of the instrument. In the lowest range of 0 to 3 ohms, the potential circuit has a resistance on the order of 2000 ohms including an allowance of approximately 40 ohms for the P_2 connection.

It will be noted that a permissible resistance of 40 to 50 ohms in the reference grounds for testing low resistance ground connections up to 3 ohms, is exceedingly liberal by comparison with the low resistances required in the three-point voltmeter-ammeter and other methods, if even reasonable accuracy is to be secured.* Furthermore, the *location* of the reference grounds C_2 and P_2 with respect to the ground under test and to each other is apt to be of much greater importance than the actual resistance of the reference grounds in the "Megger" method, as will be brought out later. (See page 19.) Meanwhile it is a fact that the resistance to earth of the reference ground connections has been ably taken care of in the design of the "Megger" Ground Tester.

The matter of obtaining suitable resistance to earth for the reference grounds cannot be expressed in terms of the kind of electrode used or the depth of a driven rod or pipe, for the simple reason that soil is different in different locations, and its moisture content varies continually with weather conditions. Sometimes highly accurate results can be obtained merely by sticking the points of the test rods into the ground, while in dry rocky country it may be very difficult to make good contact with the earth. In such cases, however, the resistance to earth of the ground under rest is apt to be high, calling for a high-range instrument, such as 0 to 1500 or 0 to 3000 ohms, where high resistance auxiliary grounds have negligible effects. Further reference to this subject is made under "*Resistance of Reference Grounds*" on page 18.

Exceptionally High Resistance Reference Grounds:

In locations where reference ground electrodes run exceptionally high in resistance—e.g. 5000 ohms and higher—the "Megger" Ground Tester *still* gives a very definite indication of the *order* of resistance of the ground under test. For example, in one location in sandy soil, the true resistance to earth of a transmission tower was approximately 100 ohms. Using reference electrodes each measuring 4800 ohms the instrument read 81 ohms for the tower resistance. Many engineers are well satisfied if the accuracy is within 20%—as in this case—but for those who wish the *highest* accuracy under extreme conditions, the "Megger" Ground Tester *can be used* and a correction applied for each test. The method is quite simple, and full details regarding it will be sent upon request. See also page 29.

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*Compare these values with those required for the ammeter-voltmeter method as illustrated on page 38.

CHAPTER III.

DIRECTIONS FOR USING THE "MEGGER" GROUND TESTERS

THE "Megger" Ground Tester is designed for testing the resistance to earth of ground connections—using auxiliary or reference ground electrodes—by the **Direct-Reading Single-Test "Megger" Method.** It may be used also for testing ground connections by direct reference to a water system or any large and well distributed mass of underground metal having low resistance to earth, if such is available.

There are required three connecting leads and two auxiliary ground rods or pipes, with a means of driving them.

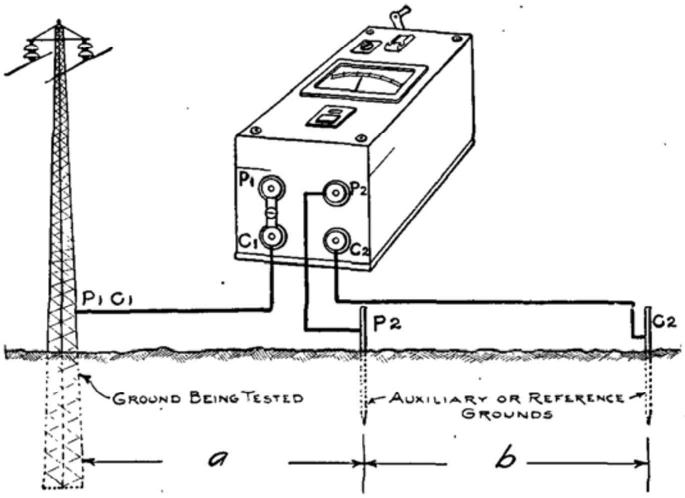


FIG. 10. Direct-Reading Single-Test "Megger" Method for testing the resistance to earth of ground connections. Make connections; turn crank; read scale—which shows the resistance to earth of the ground under test.
For accurate results under ordinary conditions:
Rod or pipe grounds down to 8 feet in the earth: $A = B = 50$ feet or more.
Large ground connections: $A = 5$ times (or more) the length of the longest diagonal line traversing the area covered by the ground under test; $B = 100$ feet or more.

To Make a Test with the *Heavy-Duty Type:*

Connect terminals C_1 and P_1 on the instrument together by means of the link provided for the purpose and to the ground under test; also connect C_2 and P_2 to auxiliary ground connections as shown in Fig. 10.

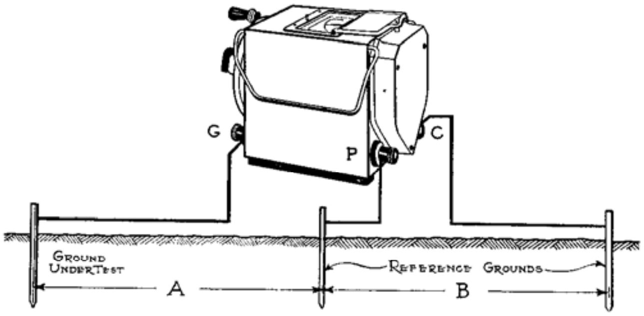


FIG. 11. To use the "Meg" Ground Tester, make connections as shown, turn the crank at about 160 r.p.m. and read the scale—the pointer indicates the resistance to earth of the ground under test.

For accurate results under ordinary conditions:

Rod or pipe grounds down to 8 feet in the earth: $A = B = 50$ feet or more.

Large ground connections: $A = 5$ times (or more) the length of the longest diagonal line traversing the area covered by the ground under test; $B = 100$ feet or more.

To Make a Test with the "Meg" Type:

Connect the terminal marked *G* on the instrument to the ground under test. Connect *C* and *P* to auxiliary ground connections as shown in Fig. 11. (The "Meg" type has only three terminals, the one marked *G* corresponding to C_1 P_1 on the heavy-duty type, and *C* and *P* corresponding to C_2 and P_2.)

Additional instructions for the "Meg" type are the same as for the heavy-duty type which follow, except that the crank should be turned at about 160 r.p.m.

To Use the Low-Resistance Type:

See page 64.

Operation:

With the instrument on a firm and fairly level base, turn the crank at approximately 100 r.p.m. The result—indicated at once by the position of pointer over the scale—is the resistance to earth in ohms of the ground under test. It is desirable, of course, that the range switch be in a position to bring the reading at as high a position on the scale as possible. No harm is done to the instrument if the pointer goes off scale, or if the testing terminals should accidentally become short-circuited.

The resistance measured includes the resistance of the lead wire and connections from terminals C_1P_1 on the instrument to the ground under test, but does not include the resistance of the P_2 and C_2 leads.

Usually the resistance of the C_1 P_1 lead and its contact resistance to the ground under test are negligible, but may be allowed for if known. However, if the ground under test has low resistance, or the lead C_1 P_1 and its connection are suspected of having high resistance, it is very simple to open the link on the instrument joining C_1 and P_1 and run separate leads from C_1 and P_1 to the ground under test so as not to include the resistance of the current lead and its connection to the ground rod; see Fig. 13. This test cannot be made with the "Meg" type.

If the pointer becomes unsteady at any particular crank-speed, it indicates the presence in the earth of stray alternating current having a frequency close to that supplied by the instrument at that speed. The effect will be eliminated by either increasing or decreasing the speed of the crank.

Connecting Leads:

For general purposes it is convenient to have three or four leads each at least 100 ft. long and one or two leads about 20 ft. in length. Longer lengths are required in some cases. As the current carried is small, the size of the wire will be determined largely by mechanical strength. Number 14 stranded wire is recommended, with extra high grade rubber insulation to avoid the effect of leakage, particularly when tests are made in damp locations or when grass and shrubbery are wet with dew or rain. It is convenient to have a lug soldered to one end of each lead for connection to the instrument, and a stout clip on the other end for attaching to the auxiliary ground. Should it be necessary to work in rainy or foggy weather, care should be taken to avoid leakage between the binding posts on the instrument. A thin coating of grease or paraffin oil applied with a rag around the base of the terminals will prove quite effective. However, work under such conditions should be avoided if possible on account of the temporarily abnormal surface soil conditions which are apt to exist.

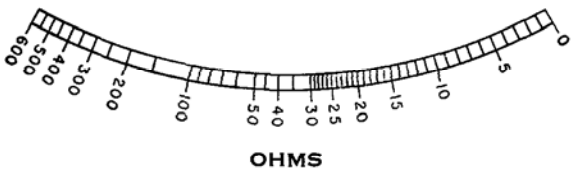


FIG. 11a. Facsimile scale of a "Meg" Ground Tester, range 0 to 600 ohms. Various ranges are available. It will be noted that this scale is logarithmic in character, being opened up at the lower end and graduated in units of 1 ohm up to 30 ohms.

Auxiliary or Reference Grounds:

Reference to Figures 22 and 23 on page 44 will show that it is usually satisfactory to use rods not more than 1 in. or 1¼ in. in diameter or pipes not larger than ¾-in. or 1-in. size, driven 3 ft. to 5 ft. into the earth. Of course, if a greater depth is necessary to secure a good ground or the soil is very hard, the diameter should be increased to secure stiffness. Both rods and pipes should be pointed conically so they may be driven easily by a hand hammer or light sledge hammer. Sometimes angle iron is used, as for a given weight it offers both stiffness and a large surface in contact with the earth. In any event, the auxiliary ground electrodes should be driven true without being allowed to sway back and forth, so as to be in complete contact with the soil. Where soil conditions permit and an unreasonably high resistance does not result, it is often convenient to use slender pointed steel rods which can be pushed into the earth by hand.

If extra grounds are already available, such as rods, pipes, plates, steel poles, metal fence posts, guy-anchors, water pipes, steel structures or other artificial conductors, they may be used as auxiliary grounds, *provided* they are not connected together, are properly located with respect to the ground under test and to each other and are not of unduly high resistance. (See under "*Effect of Reference Grounds*," *page* 13.)

Resistance of Reference Grounds:

As stated under "*Effect of Reference Grounds*" on page 13 the accuracy of the "Megger" Ground Tester is not affected by high resistance in the C_2 reference ground, but is affected by an abnormally high resistance in the P_2 reference ground. Usually, however, if the potential reference ground has a resistance of 500 ohms or less the reading will be very close to correct. For the 0 to 3 ohm range the figure should be 150 ohms or less, and for the 0 to 3000 ohm range it may be 3000 ohms or less. A rod or pipe driven 3 or 4 ft. into the earth ordinarily will have a resistance to earth of 500 ohms or less, and therefore, for practical work, this whole detail can be forgotten except perhaps when the most accurate results are desired on the 0 to 3 ohm range. The *location* of the reference grounds with respect to the ground under test and to each other usually has a greater effect on the accuracy of the results than the exact resistance to earth of the reference grounds, when using the "Megger" Ground Tester.

Should any doubt exist as to the resistance to earth of either of the reference ground connections, it is very simple to test them by interchanging connections on the instrument and referring the reference grounds in turn to the ground under test and the other reference ground. Where it is desirable or necessary to reduce the resistance to earth of the reference grounds, the following suggestions are offered:

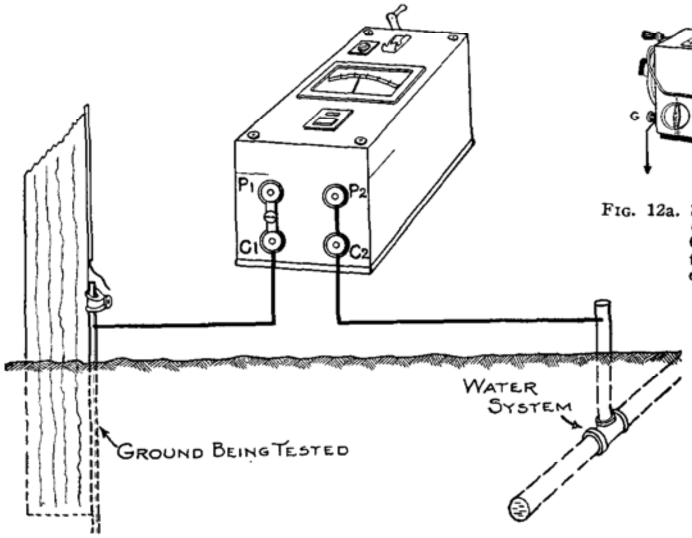
a. Drive rods or pipes to a greater depth in an effort to reach permanent moisture or a more highly conducting stratum.
b. Wet the earth immediately surrounding the electrodes. Remove a few inches of surface earth from around the electrodes, so the water will not run away. Use salt solution if necessary.
c. Drive a number of rods or pipes not less than 5 to 10 feet apart, and connect them together. Unless there is considerable separation between the test electrodes and the ground under test, such multiple electrodes should be placed at right-angles to the line of test, i.e.—to the line joining the ground under test and C_2.

In locations where there is no top soil and only bare rock, electrodes may be made by inserting wire mesh between pads or cloths, soaking them thoroughly with a strong salt solution and placing them on the surface of the rock, pressed down firmly. In difficult situations nails driven into trees may prove to be a convenient solution, although their resistance to earth is apt to be fairly high. See under "*Exceptionally High Resistance Reference Grounds*," page 14.

Location of Reference Grounds:

The proper spacing or location of the auxiliary or reference grounds introduces a natural phenomenon which affects the results in *all methods* for testing ground connections, and must be considered if comparative as well as accurate results are to be obtained. The subject is so important that the following chapter is devoted to it. Meanwhile, a "boiled-down" rough formula for the spacing of the reference grounds is given in the caption under Fig. 10.

If it is impossible or inconvenient to drive auxiliary grounds, as in a solidly built-up city district, or to obtain proper spacing between them, note should be made of exactly what were used for the reference ground connections, depth to which they were driven, and where they were located so that subsequent tests can be made for comparison under similar conditions.



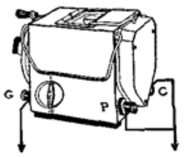


FIG. 12a. Showing how to connect the "Meg" Ground Tester for the Direct Reference method.

FIG. 12. Direct Reference "Megger" Method for testing ground connections with respect to a water system. The instrument indicates the resistance to earth of the ground under test *plus* that of the water system.

Direct Reference Method:

By connecting as shown in Figs. 12 and 12a the "Megger" Ground Tester may be used as direct reading ohmmeter to test any resistance within its range, and therefore to test the resistance of two grounds in series.

Water Pipe as Reference Earth:

In this mannner grounds may be tested by direct reference to a water system, if conveniently accessible, and *providing* it has low resistance to earth,–see Fig. 12. The reading on the scale will be the sum of the resistance to earth of the ground under test, the connecting leads and contact resistances (where single leads are used) and the resistance to earth of the water pipe to which attachment is made.

In most cases the resistance of a water pipe to earth will be found to be small, and where considerable resistance exists it is usually due to joints made with some poor-conducting material. If the resistance to earth is suspected of being more than a few tenths of an ohm, it can be measured by the Single Test "Megger" Method as described on page 15, with the auxiliary grounds in a line approximately at a right angle to the main line of pipe in the ground.

To Avoid Lead and Contact Resistance:

If the current leads used in the Direct Reference Method are of appreciable resistance, they can be measured by joining them in series between P_1C_1 and P_2C_2. Then subtract this value from the test result. A better plan, however, is to run separate leads from P_1 and C_1 on the instrument to the ground under test and from P_2 and C_2 on the instrument to the water system, as shown in Fig. 13. This avoids both lead resistance and contact resistance. This method can be used to advantage with low-range "Megger" Ground Testers for testing resistance between clamps and pipes, as well as for testing other electrical resistances which come within the range.

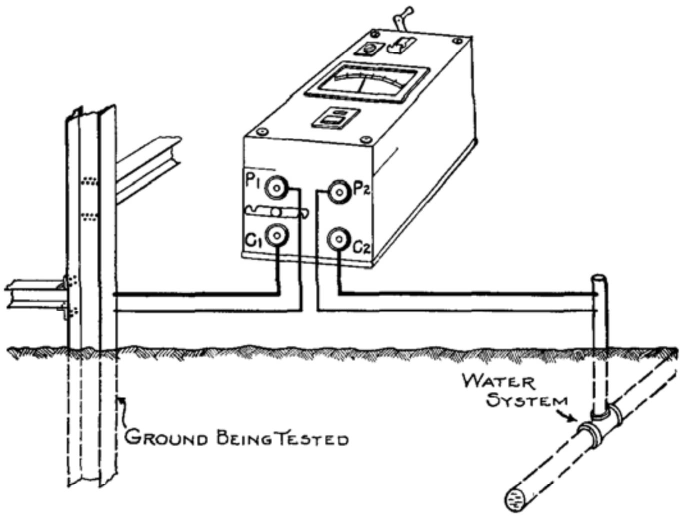


FIG. 13. Direct Reference "Megger" Method with connections arranged to avoid lead and contact resistance. This connection is not possible with the "Meg" Ground Tester.

CAUTIONS

All methods for testing ground connections involve a hazard to the operator, against which every precaution should be taken.

1. When testing generating station, substation and transformer neutral ground connections, an accidental ground anywhere on the system is likely to involve a return of current to the ground connection under test. This causes a difference of potential between that ground connection and the surrounding earth which is brought directly to the instrument and the hands of the operator if he is making ground tests at that time.

2. A dangerous difference of potential between a ground under test and the surrounding earth, may be experienced in testing lightning arrester, transmission tower and any other ground connection where a leaking arrester, bushing or insulator is allowing high voltage current to pass into the earth at that point.
3. If the test lines are very long and are near and parallel to transmission lines, switching and other surges in the line may produce a dangerous "kick" in the test lines.
4. Stray current in the earth is apt to produce a difference of potential between any two points in that vicinity, the amount of which is difficult to predetermine.
5. Do not test grounds while there is a thunder-storm in the vicinity! Anything may happen!

PROTECTION

For protection—rubber gloves, an insulated platform, etc. are recommended, capable of protecting the operator against full line voltage. (See also paragraph on "*Reduction of Hazard*," page 53.)

◆

For the Low-Resistance Type of "Megger" Ground Tester

See page 64.

IT takes much less time to make a test with the "Megger" Ground Tester than it has taken to tell about it. **Simply make connections, turn the crank and read the scale. It reads like a voltmeter.** The "brains" are inside the instrument and *any person* of ordinary intelligence can do the work.

There are, however, certain characteristics of earth and earth connections with which those seriously interested in ground testing may wish to be familiar. These characteristics determine the potential distribution surrounding grounded electrodes when current is flowing, and have a direct bearing on the effectiveness of a ground connection as a protection to life and property, and also upon the proper location of auxiliary electrodes which must be used for test purposes. In Chapter VII of this Manual considerable space is devoted to the characteristics of earth and data on testing ground connections.

CHAPTER IV.

LOCATION OF REFERENCE GROUNDS

FOR MEASURING ACCURATELY THE RESISTANCE TO EARTH OF GROUND CONNECTIONS

THE location of the auxiliary or reference grounds with respect to the ground under test and to each other is an important factor in obtaining accurate results with any method of ground testing. Other factors such as the resistance of reference grounds, stray current, electrolytic effects, necessity for calculations, etc. which usually are of primary significance in other methods, are taken care of automatically by the "Megger" Ground Tester, and therefore are relatively of minor importance in the "Megger" method. For this reason, it has been possible, with the "Megger" Ground Tester, to make a careful study of the matter of the location of reference grounds for test purposes without interference from other variables. The facts here cited are in accordance with the observed characteristics of earth and earth connections, and will be found to apply to any method of testing ground connections.

When a ground connection is called upon to carry current, the flow is to a return connection which usually is at a great distance. Therefore, in measuring the resistance to earth of a ground connection, the current reference ground by which the test current returns, should be placed at a considerable distance, so that the resistance of the ground as determined by the test may be the same as that of the ground connection when it is called upon to carry lightning or fault current. As is shown later, this is not the case if the current return electrode used for the test is too close to the ground being tested.

With whatever are used for auxiliary ground connections, close proximity to other conductors in the earth, such as metallic structures, pipes, etc. should be avoided if accurate results are desired, on account of parallel current paths thus introduced. Of course, if a water system or other *well grounded* metals exist in the vicinity of a ground to be tested, the test may be made by the direct reference method described already.

For convenience, grounds or ground connections may be classified in two groups, one being rod or pipe grounds of small area such as lightning arrester grounds; and the other, distributed grounds such as generating station or substation ground connections involving steel structures, pipe systems, etc., as well as multiple ground connections, covering a large area. Transmission tower grounds are considered as a special class of the second group.

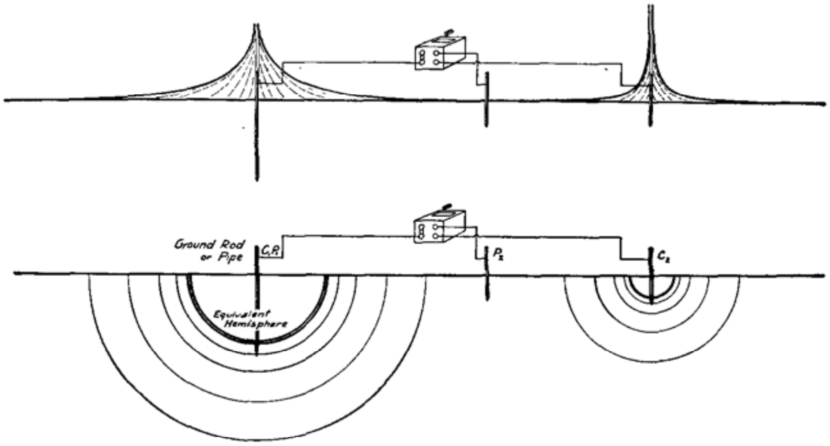


FIG. 14. Illustrating by the volcano analogy how far away the reference grounds should be placed for testing the resistance to earth of a rod or pipe ground connection. See also FIG. 15.

Volcano Analogy:

Referring to the physical nature of a ground connection in the volcano analogy, as set forth in Chapter I, we have there a graphic illustration of how far away from a ground connection the potential test-electrode must be placed in order to span all—or nearly all—the resistance between the ground connection and the surrounding earth. It should be located at or nearly down to the base of the volcano. This distance for most rod or pipe grounds is at least 50 to 100 ft., and for large ground connections is much greater.

Obviously the current-return electrode—which likewise is surrounded by a field of resistance, or a number of earth-shells,— should be sufficiently far away from the ground under test so that the resistance fields of the two electrodes do not crowd each other. The ground under test is one volcano, the current-return electrode is another volcano, and for accurate measurements they must be placed far enough apart so that the potential electrode may be placed on the level plain between them, as shown in Figs. 14 and 15.

SPACING OF REFERENCE GROUNDS FOR TESTING ROD AND PIPE GROUND CONNECTIONS

For testing ground connections of small size, place the current auxiliary ground C_2 (see Fig. 10) at a distance of about 100 ft. from the ground under test, and the potential auxiliary ground P_2 about half-way between. A distance of 50 ft. for the C_2 connection will give results of commercial accuracy, but it becomes more important that the P_2 connection be placed very close to the half-way point.

An alternative is to place C_2 and P_2 at points equidistant from the ground under test and from each other—that is, at the points of an equilateral triangle. A good distance is 100 ft. However, a distance of 50 ft. will give results of commercial accuracy.

It is assumed that the auxiliary ground connections are of small diameter and driven not over 5 ft. into the earth.

SPACING OF REFERENCE GROUNDS FOR TESTING LARGE AND DISTRIBUTED GROUND CONNECTIONS

Usually when testing such grounds, if the potential auxiliary ground P_2 is placed at a distance from the ground under test equal to five times the greatest diagonal of the ground under test, and the current auxiliary ground C_2 at least 100 ft. farther away, the resistance as indicated by the "Megger" Ground Tester will be correct within 10 percent. Similarly if P_2 is made ten times the greatest diagonal, the result may be considered correct within 5 percent.

From this will be seen the necessity of placing the auxiliary or reference ground connections at a very considerable distance from a large ground under test, because with such a ground we must include a great number of the earth-shells mentioned in Chapter I in order to reach the point where succeeding shells add but little resistance.

Again we assume that the auxiliary or reference ground connections are of small diameter and driven not over 5 ft. into the earth.

NOTE: The above schemes for the location of the reference grounds have been deduced from the work of the U. S. Bureau of Standards, and are very well borne out in practice with the "Megger" Ground Tester. However, the difficulties in the way of a practical application of these schemes (which of course apply to all methods for testing grounds) are various and cannot be ignored. We cannot be sure the earth is a homogeneous conducting material; the dimensions of the area covered by the ground connection are not always known or readily ascertainable; similarly, the depth may be an unknown factor; also, where these facts are known, the spacing of the test electrodes demanded for an accurate ground resistance measurement may be beyond the range of practicability.

In these events it is frequently satisfactory to resort to a *relative* indication of the resistance to earth of the ground in question. By making note of what were used as reference or auxiliary grounds and where they were located, subsequent tests made under the same test conditions will have value.

A practical method for making comparative tests of large ground connections having low resistance is to install and use permanent reference grounds. These should be placed as far away as practicable from the ground under test and from each other. Also they should be as low in resistance as possible and preferably of small size, for the reason given on page 34.

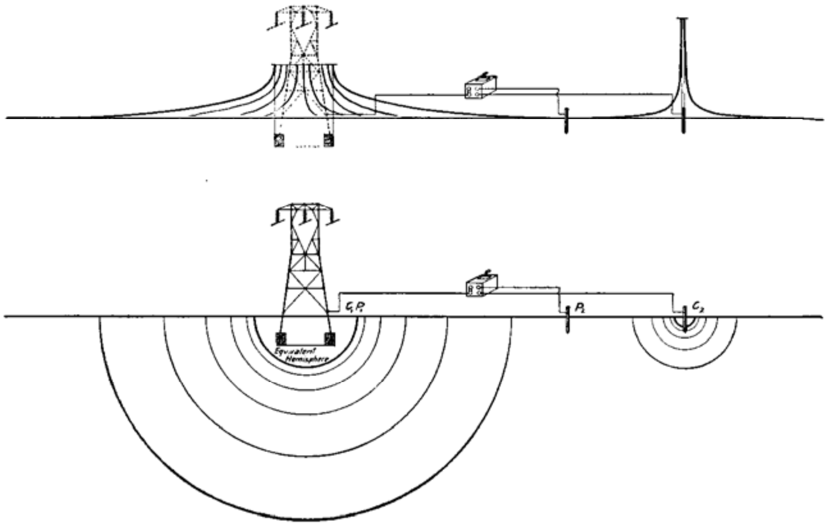


FIG. 15. Illustrating by the volcano analogy how far away the reference grounds should be placed for testing the resistance to earth of transmission towers or other large and distributed ground connections. See also FIG. 14.

Arrangement of Test Electrodes:

It is not necessary that the potential electrode be placed on a straight line between the two volcanoes; it may be placed anywhere in the earth outside the influence of both (see page 54).

There is some advantage, however, in using a straight-line arrangement, for it facilitates the making of ground resistance curves by which the true resistance to earth of a ground connection may be determined, as described on page 33.

One cannot reason properly that the old Three-Point Method of testing ground connections, as described on page 36, will overcome the difficulties referred to, because you then introduce three volcanoes which crowd each other if they are too close, and introduce the same or even greater complication. Repeated checks using the "Megger" Method, in comparison with the Three-Point Method, show practically the same results when using the same reference electrodes, but the "Megger" tests are made much more easily and usually with greater accuracy. See Fig. 16, page 30.

Where the ground under test covers a considerable area and is of very low resistance, making it necessary to place the reference grounds at considerable distance, errors may arise due to coupling between the P_2 and C_2 leads. To avoid the effect of coupling, place the instrument at the ground under test, place the C_2 electrode at a suitable distance in one direction and the P_2 electrode at least half as far away *in the opposite* direction. As a check, extend the P_2 lead farther and take a second reading. If the selected distances are sufficiently great, there should be little or no difference in the two readings and they may be considered correct.

NOTE: A convenient and reportedly effective method for measuring large, low resistance structures, such as hydroelectric and steam generating stations, is to use telephone lines or power circuits for leads, going out several thousand feet or more in opposite directions. Also use the low-resistance type of "Megger" Ground Tester, referred to on page 64.

TESTING THE RESISTANCE TO EARTH OF TRANSMISSION TOWERS

(1) Under Normal Conditions *without* Overhead Ground Line:

Using rods, pipes, etc. as reference ground connections, the spacing for P_2 and C_2 just set forth under "*Large Area Grounds*" will apply. A few Ground Resistance Curves, as explained later in Chapter V, plotted for two or three towers will readily indicate about what spacing can or should be used for tests on all the towers of the same size and footing.

(2) Under Normal Conditions *with* Overhead Ground Line:

This is a problem which presents some difficulties. Technically the right thing to do is to raise the ground line from each tower while it is being tested, making the tests in either or both of two ways:

(a) With respect to reference grounds, as just described;

(b) By direct reference to the overhead ground line, arbitrarily considering it as zero.

The latter is accomplished in a manner similar to the Direct-Reference Method described on page 20. Connect C_1 and P_1 of the instrument to the tower and C_2 and P_2 to the overhead ground line. The result will be the resistance to earth of the tower *plus* the resistance to earth of the ground line as a whole. In most cases the latter can be considered as zero. If results by these two methods do not check reasonably well, the solution is to be sought in (1) the character of the earth in which the tower is located, and (2) the location of the reference grounds.

Ground Tests with Ground Line in Place: Since the removal of the overhead ground line or lines for a test on each tower involves difficulty and expense, certain companies have resorted to making tests on towers with ground lines in place. One would think that with all the towers in parallel to earth and with relatively low contact resistance between the ground line and the towers, as well as low resistance in the ground line itself, very nearly the same result would be obtained at each tower, providing of course, similar spacing for the reference grounds was used. However, such has not always proved to be the case.

The method of test is relatively simple. Make several ground resistance curves (see Chapter V) on towers at two or three locations, and from them select a spacing for the reference grounds – such as $a = b = 75$ ft. (Fig. 10)—according to the character of the curves—and use this figure for all tests. As it is usually best to run the reference ground lines parallel to the transmission line rather than at right angles to it, so as to avoid trespassing on other property, the total distance $a+b$ should not be more than half the distance to the next tower—in order to avoid interference from that tower. When making tests, watch out for induced voltage in the test leads—particularly if there are any line disturbances.

While it is generally agreed that such tests (without removing the ground line) do not give the actual resistance to earth of each tower, there is some evidence that they show whether towers are high or low in their resistance to earth, and relatively how much. For example, in a series of tests made by one company, conducted according to the method just described, on a transmission line about 55 miles in length—a wide variation in the resistance at different towers was found—ranging from 2 to 40 ohms,—and the results as plotted on a profile map of the line, present a very interesting picture. High resistances were found in general on rocky hill tops and well-drained slopes—as would be expected if there were no overhead ground line. Uniformly lower resistances were observed where for several miles the line parallels two railroad lines, also in low lands, and particularly in one region where a low grade of iron ore is known to exist. The picture is that of *rela-*

tive variations—which have been obtained quickly and easily, on a production basis, and at *relatively slight expense.*

The following explanation is offered for the above-mentioned variations. A ground resistance test made on a transmission tower carrying an overhead ground line is presumably the resistance to earth of that tower in parallel with all the other towers. However, if the test is made with the reference electrodes placed relatively close to the tower, the result will be influenced by—(a) close proximity of the reference electrodes to the line as a whole, and perhaps to each other; and (b) local soil conditions surrounding the tower under test. The result indicated by the "Megger" Ground Tester has every appearance of bearing some direct relation to the resistance to earth of the tower alone. In other words, instead of the result being the resistance to earth of the transmission line as a whole, it appears to be relatively proportional to the specific resistance *of the soil at that particular tower.* It would seem reasonable to conclude that if the soil surrounding a given tower is of high specific resistance, a tower placed in that location would also have relatively high resistance to earth. In order to obtain the true resistance to earth of the line as a whole, the reference electrodes would have to be placed at a great distance from the line.

(3) Where the Soil is of Extremely High Resistance:

Towers placed in locations where the soil is of extremely high specific resistance are quite apt to have high resistance to earth, requiring the use of a high-range "Megger" Ground Tester to measure their resistance. There is also likely to be introduced the factor of exceptionally high resistance reference grounds, and on this matter please refer to the discussion given on page 14.

One company has met the situation on a transmission line which does not carry an overhead ground line, by using adjacent towers as reference grounds. Although this involved the use of a considerable length of test lead wire, three towers were tested with each setup by interchanging connections at the instrument, and satisfactory and consistent results were obtained. Many of the towers had a resistance to earth of 1500 ohms and higher.

If, under the conditions just referred to, the towers carrry an overhead ground line, it may prove less expensive to raise the ground line from each tower while it is being tested and test by direct reference to the overhead ground line as in (b) under (2) on page 27.

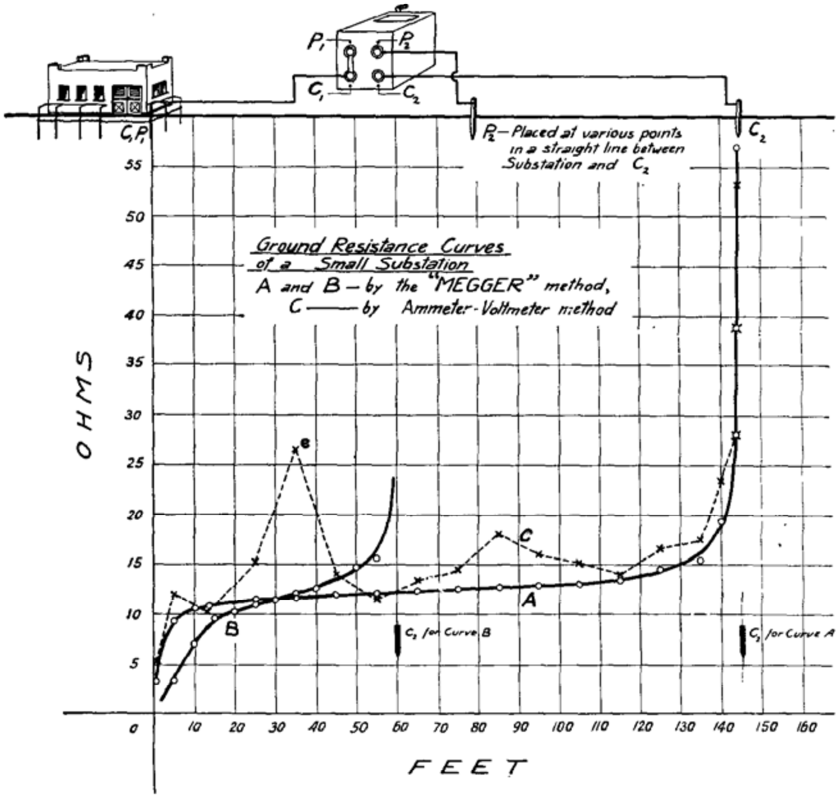


FIG. 16. Showing how ground resistance curves are made—by the "Megger" Method, and also two typical ground resistance curves—*A* and *B*.

Curve *C* was made with respect to the same reference electrodes as curve *A*, but by using the a.c. ammeter-voltmeter method. Its similarity to curve *A* is apparent, except for point *e* which undoubtedly is an error. Curve *C* required between four and five hours time, it being necessary to salt the reference grounds for the a.c. ammeter-voltmeter method, while curve *A* was made—by the "Megger" Method—in about forty minutes, no treatment of the soil surrounding the reference grounds being necessary.

Curve *B*, with the C_2 reference ground at 60 ft., was made hurriedly in about fifteen minutes by the "Megger" Method.

The substation is located in Michigan.

CHAPTER V.

GROUND RESISTANCE CURVES

IN order to gain a clear conception of the effect of the location of auxiliary ground electrodes in testing ground connections, it is necessary to use a straight line arrangement for the auxiliary grounds, as per instructions given on page 15 for using the "Megger" Ground Tester.* The straight line arrangement not only lends itself readily to mathematical treatment, but—with the "Megger" method of testing—allows a "picture" to be made very simply and quickly. Such a "picture" is a ground resistance curve. Two such curves are shown in Fig. 16, and several additional curves are reproduced in connection with a further discussion of this subject, pages 47 to 51.

How a Ground Resistance Curve is Made:

A ground resistance curve is made—by the "Megger" method—by making a series of tests on a given ground connection. In curve *A*, Fig. 16, the test is made each time on the substation structure. The C_2 reference ground electrode is placed at a fixed point—145 feet—and the P_2 reference electrode is used as a "probe" along a straight line between the substation and C_2. The readings of the resistance of the substation structure for P_2 at different points are plotted vertically in the curve, against distance horizontally. Curve *B*, Fig. 16, was made at the same time, using a closer point—at a distance of 60 ft. for the C_2 electrode.

It is obvious from curves *A* and *B*, Fig. 16, that if the ground resistance curve is steep, as in curve *B*, it is difficult to approximate the true value of the resistance to earth of the ground under test. With the C_2 reference ground at a greater distance, as in *A*, the curve becomes much more flat through the center portion. From curve *A* it is probably safe to conclude that the substation under test had a resistance to earth of 12.5 ohms, within plus or minus 5%.

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* This is a departure from the conventional triangular arrangement as formerly used in the three-point method of test as described on page 36. However for a simple ground test the "Megger" Ground Tester may be used with a triangular arrangement of electrodes providing it is either known or assumed that the spacing is sufficiently great. The spacing is more easily checked by the straight line arrangement as here described.

While the above ground resistance curves are typical, a considerable variation in them is found, depending largely on the size or area of the ground under test, the resistivity of the surrounding soil, and the size and resistance of the C_2 electrode as well as its location with respect to the ground under test. Conclusions regarding the spacing of the auxiliary ground connections, as given on page 25, are made as the result of a practical and theoretical study of the subject as set forth in Chapter VII of this bulletin.

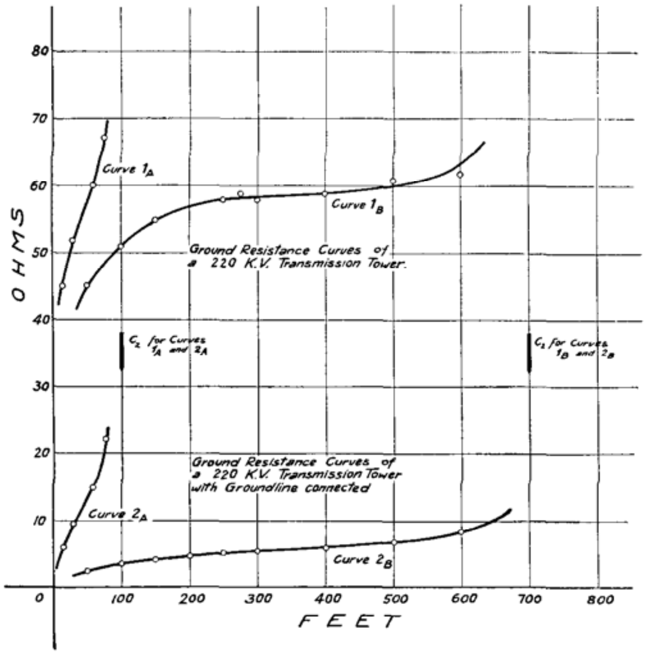

FIG. 17. A series of ground resistance curves made on a 220-KV transmission tower with and without buried ground line connected. (The ground line was buried 6″ in the earth and connected three towers only, this being the centre tower.)

Curves 1_A and 1_B are without the ground line connected and are with respect to C_2 located at 100 ft. and 700 ft. respectively from the tower. Curves 2_A and 2_B are the same, but with the ground line connected.

Obviously curves 1_A and 2_A, made with respect to C_2 at 100 ft., are too steep to give an accurate indication of the resistance to earth. Curve 2_B compared to curve 1_B indicates lower resistance and has relatively less slope at the beginning. These effects are to be expected, because with the ground line connected, the effective area of the ground is increased. Also curve 2_B does not show a flat portion which is evidence that for the ground under test the distance to the reference ground C_2 is too small.

Practical Uses for Ground Resistance Curves:

A—For determining the *true* resistance to earth of ground connections.

By taking readings of a ground under test with the reference electrode C_2 at a given location and P_2 at several points along the ground resistance curve, the flatness of any portion of the curve can be determined readily without making an entire curve. If the curve is reasonably flat, the C_2 reference ground may be considered as being located at a sufficient distance and the value as indicated by the "Megger" Ground Tester near the center of the flat portion of the curve may be taken as the correct value for the resistance to earth of the ground under test. Tests of this sort are particularly helpful when attempting to measure generating station, substation, telephone central office, and other relatively large-area ground connections. (See also page 27.) In the event that the curve or curves do not become flat with extended spacing of the C_2 electrode, check the *mid-points* of the curves, for example—*A* and *B* Fig. 16. If the mid-points of two or more curves give practically the same value for the resistance to earth of the ground under test, experience seems to indicate that such a figure may be taken as approximately the true value.

B—As an accurate indication of Surrounding Resistance, and therefore of Potential Difference and Potential Gradient.

One would reasonably expect to find some diversity in the distribution of potential surrounding different kinds of grounded electrodes, so that a potential-difference chart for one ground connection would be different from that of another.

Since, by Ohm's Law, potential difference is directly proportional to resistance, a potential-difference curve along a given line from a ground connection is directly proportional to a ground resistance curve along the same line. The ground resistance curve includes also an inverted portion which is proportional to the potential-difference curve for the C_2 electrode. The dividing line between the two is the flex or flat portion of the curve.

In this manner—with the C_2 electrode at a sufficient distance from the ground connection under observation—a potential-difference or potential-distribution chart may be made with the "Megger" Ground Tester. Simply drive the P_2 electrode at as many points as desired, turn the crank, read the scale and plot the readings.

The slope of a ground resistance curve at any point is proportional to the potential gradient at that point. Therefore, in testing the resistance to earth of a ground connection, the P_2 electrode should be located where the potential gradient is as near zero as possible,—in other words on the flat portion of the ground resistance curve. Of necessity the C_2 electrode should be far enough away for the ground resistance curve to have a relatively extended and practically flat portion if results of highest accuracy are to be obtained. Also, when measuring large and very low resistance ground connections—where it may be impracticable to place the reference grounds at a theoretically sufficient distance—the C_2 reference ground should be as small in size and as low in resistance as possible, so as to avoid errors due to distortion of the ground resistance field. This is illustrated by the general upward swing of curves *A* and *B* in Fig. 28, page 50.

FIG. 18. Testing the resistance to earth of a combined substation ground, which is made up of a large number of separate ground connections,—rods, pipes, steel structure, etc.—tied together.

CHAPTER VI.

VARIOUS METHODS FOR TESTING GROUND RESISTANCE

THERE are a number of methods for testing the resistance to earth of installed ground connections, but all of them are alike in that two reference ground connections are necessary, a suitable source of current is required for the test, and the accuracy of the result is a function of the location of the auxiliary or reference grounds with respect to the ground under test and to each other.

Various methods for testing ground connections may be classified as follows:

(1) **THREE-POINT METHOD:**
  (a) *Using* a Wheatstone Bridge with alternating current or oscillating current.
  (b) Using Ammeter and Voltmeter with alternating current (the usual Ammeter-Voltmeter Method).
  (c) Using Ammeter and Voltmeter with direct current.

(2) **FALL-OF-POTENTIAL METHOD:**
  (a) Using Ammeter and Voltmeter with alternating current.
  (b) Using Ammeter and Voltmeter with direct current.
  (c) Using various bridge and balance arrangements with either alternating current or oscillating current.

(3) **SINGLE-TEST "MEGGER" METHOD:**
  A modified fall-of-potential method—using a direct-reading ohmmeter and alternating current for the test.

The accuracy of the first two methods is apt to be very seriously affected by one or more of the following conditions: (1) Resistance to earth of the auxiliary ground connections; polarization at electrodes; electrolysis; stray current in the earth (which frequently is variable in amount). (2) Need for an external source of power, which if taken from a power line is likely to be of the same frequency as that of stray current in the earth; multiplicity of equipment such as transformer or battery, instruments, rheostats, etc. (3) Necessity for calculations requiring men of extra intelligence for the job.

Comparing the Single-Test "Megger" Method with other methods it will be seen to possess every advantage and none of their attendant disadvantages. With such an easy, rapid and accurate method now in use, there has already been a considerable advance in the testing of grounds.

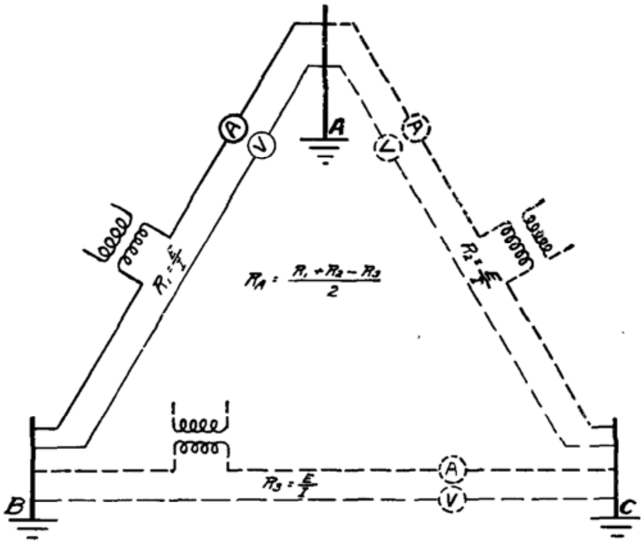

FIG. 19. Three-Point, A. C. Ammeter-Voltmeter Method of Measuring Ground Resistance. Note how many connections, current adjustments, readings and calculations are required to test one ground.

Three-Point Method:

This involves the use of the ground under test whose resistance we will call *A*, and two auxiliary or reference grounds of resistance *B* and *C*, spaced a reasonable distance from the ground under test and from each other. (Spacing is discussed in Chapter IV.) The three grounds are measured two at a time in series, giving—

$$\begin{array}{ll} & A + B = R_1 \\ & A + C = R_2 \\ & B + C = R_3 \\ \hline \text{By addition} & 2A + 2B + 2C = R_1 + R_2 + R_3 \\ & \qquad 2B + 2C = \qquad\qquad 2R_3 \\ \hline \text{By subtraction} & 2A \qquad\qquad = R_1 + R_2 - R_3 \\ \text{(1)} & \qquad A = \dfrac{R_1 + R_2 - R_3}{2} \end{array}$$

Usually the actual measurements are made by one of the following schemes:

Wheatstone Bridge—operating on alternating current at say 1000 cycles per second and with a head-phone as a detector to determine the point of balance. Theoretically this method eliminates the effects of stray earth currents, either direct or of ordinary alternating frequency. The point of balance is indicated by the absence of tone in the telephone receiver, but in actual practice this is seldom obtained due to stray currents and electrolytic effects in the earth, and capacity and inductance effects between lead wires and the earth; so that getting a good balance is apt to be very difficult or even impossible. Furthermore the use of a head-phone involves a considerable element of personal risk when testing on live systems, particularly those of high voltage.

A. C. Ammeter-Voltmeter—used with current of commercial frequency to determine resistance of each pair of grounds in series from $R = \frac{E}{I}$. Connections are shown in Fig. 19. Tests are limited to locations where current is available. A transformer is necessary to isolate the test circuit from the line, some regulating apparatus must be used to control the flow of current, and often the services of a line-man are required to tap the line. Stray direct currents in the earth have no effect; but if alternating current of the same frequency as the test current is present, an error will be introduced, because the stray alternating current will affect the reading of the testing instruments.

D. C. Ammeter-Voltmeter—to determine the resistance of each pair of grounds in series from $R = \frac{E}{I}$. Again tests are limited to locations where current is available or else a storage battery must be used in addition to such regulating apparatus as is always required. It is not possible to apply this method if additional grounds are present on the line supplying the current, because of cross-currents which result. The effect of stray alternating currents in the earth is eliminated but the effect of stray direct currents can be eliminated only be reversing the test current, and then only provided the stray current remains constant in amount. This increases the number of readings and computations, which is objectionable. Furthermore there is always present a back E.M.F. of polarization which is unaccounted for and the collection of gas at the electrodes may give too high a value of resistance.

Sources of Error in the Three-Point Method:

No matter which scheme of measurement is used for testing by the Three-Point Method, there are several connections to be made and changed, several readings to be taken, and one or more calculations. Furthermore, if the resistances are not of the same order, and readings are not taken to a good degree of accuracy, small errors in the individual measurements may result in a large error in the computed resistance A. If A is numerically small it is quite possible for the errors to result even in a negative value. Suppose, for illustration $A = 2.0$ ohms, $B = 100$ ohms, $C = 90$ ohms, and also that with the grounds taken two at a time we can measure the resistances to within 2 or 3 ohms, which in this sort of work is good accuracy for the values in question. Then by actual measurement we may obtain—from equation (1) page 36—$R_1 = 101$ ohms, $R_2 = 91$ ohms, $R_3 = 193$ ohms. By computation $A = —.5$ ohm, which is impossible.

On the other hand, if reference grounds can be secured which are on the same order of resistance as the ground under test, results of somewhat better accuracy are possible with this method.* For example: If $A = 2.0$ ohms, $B = 5$ ohms, $C = 4$ ohms, and instruments are used which will give results accurate to within .1 ohm (which would be exceptionally good), we may obtain: $R_1 = 7.1$, $R_2 = 6.1$ and $R_3 = 8.9$. By computation $A = 2.15$ ohms, which is accurate to within 7.5%—the true value of A being 2.0 ohms.

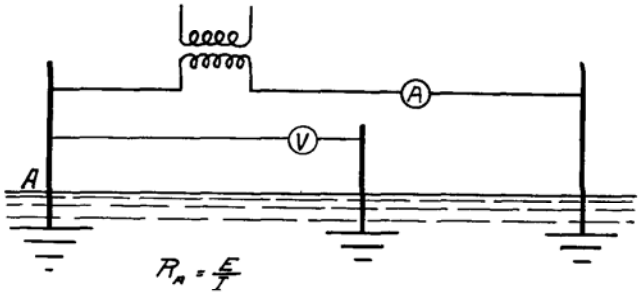

FIG. 20. A. C. Fall-of-Potential Method of Measuring Ground Resistance.

Fall-of-Potential Method, Using A. C. or D. C.:

In this method the ground under test is connected as shown in Fig. 20 in series with an auxiliary return ground at a reasonable distance away (discussed in Chapter IV) through an ammeter, across a source

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*Compare the resistance of the reference grounds in this case with the values permissible with the "Megger" method, page 13.

of current. The fall of potential is observed from the ground under test to a second auxiliary ground approximately midway between the grounds carrying the current. The resistance of the ground *A*, Fig. 20, is computed directly from $R = \frac{E}{I}$.

While the method is superior to the Three-Point Method in that it requires only one set of readings and one calculation, in general it is open to the same objections as the A.C. and D.C. Ammeter-Voltmeter Methods. If a low-resistance voltmeter is used, as mostly is the case with alternating current, the resistance of the auxiliary ground at which the potential is picked up, may result in a serious error.

Single-Test "Megger" Method:

The "Megger" Method fits into the picture at this point. It is—in principle—a modified fall-of-potential method whereby alternating current is used for the test and the result is indicated directly by the deflection of the pointer of a direct-current true ohmmeter. Full particulars regarding this method are given in Chapter II and directions for using the "Megger" Ground Tester in Chapter III of this bulletin.

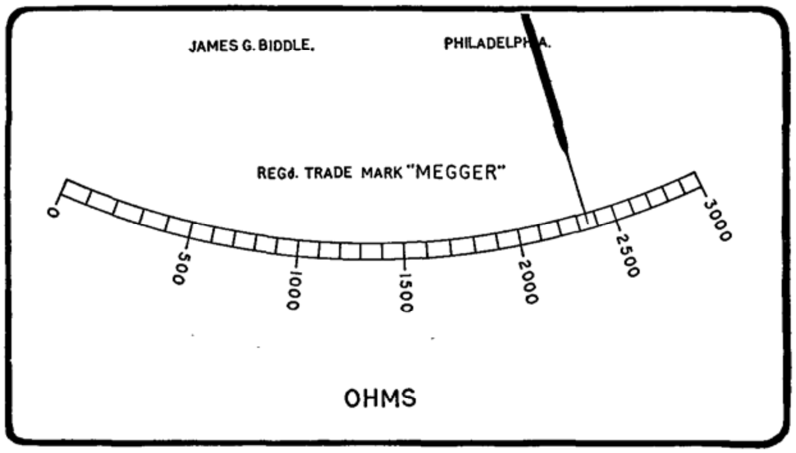

FIG. 21. Facsimile scale-plate of a 4-range "Megger" Ground Tester, ranges 0 to 3000, 0 to 300, 0 to 30 and 0 to 3 ohms. The pointer is indicating 2350, 235.0, 23.5 or 2.35 ohms, depending on the range in use. The range switch is shown on top of the instrument in FIG. 6, page 9. The instrument is *direct-reading*, like a voltmeter.

TESTS WITH HIGH VOLTAGE vs. TESTS WITH LOW VOLTAGE

There has been some discussion whether the same results will be obtained when measuring the resistance of a ground with high voltage and low voltage. The question naturally resolves itself into a comparison of tests in which the ground carries a large amount of current and small amount of current. The B. of S. Paper, page 163, shows a series of measurements of relatively low resistance grounds in which practically the same values of resistance were obtained with currents from about 60 amperes, down to those as small as used with a Wheatstone Bridge.

It is stated—"Where the higher voltages (higher currents) were used the current was allowed to flow only while readings were being made in order to avoid heating the soil surrounding the pipes and thus changing the resistance. Nevertheless slight changes did occur, especially at the higher voltages (higher currents) where readings were repeated to check for errors. . . . . It appears fair to conclude, therefore, that in measuring the resistance of ground connections using alternating current the voltage (current) makes little, if any, difference in the results."

The higher the resistance of the ground under test, the greater the heating effect for a given current, and the greater the liability to error due to heating and drying out of the soil. Also a high current requires a considerable amount of heavy test apparatus. Therefore, there seems to be every reason for testing by the much more convenient and quicker Single-Test "Megger" Method with its small test current.

Capacity of a Ground Connection to Carry Current:

While this matter is not directly involved in the measurement of ground resistance, it is worth brief consideration. The B. of S. Paper, pages 161 and 162, shows that for such tests, the transformer to supply the current should be of sufficient capacity to supply up to about 100 K. W. at 1100 volts. Furthermore the auxiliary current return ground should have greater capacity to carry current than the ground under test so as not to fail first. This condition is often difficult to obtain.

In any event the current should be adjusted until a maximum value is reached which gives a constant resistance of the ground over a period of several hours. This value of current may be considered as that which the ground can safely carry.

In actual practice the flow of high current to ground ordinarily is of short duration, so for short periods the permissible value of current will be some undetermined value.

From what has been said, we see that the use of high test current is not necessary except to determine capacity of a ground to carry current and that the results of such tests are apt to be of uncertain value.

CHAPTER VII.

THEORETICAL VALUE OF RESISTANCE TO EARTH OF A GROUND CONNECTION

NATURE did not make the surface of the earth of homogeneous material. Rock, soil and water differ in mechanical structure and also in electrical conductivity. However, in order to gain some understanding of electrical connections to earth, and in what manner they can be tested or measured, we must of necessity start with the assumption of homogeneous earth. This chapter is a discussion of what happens—in theory—in homogeneous earth when current flows from a ground connection into the surrounding earth. Experience gained so far indicates that the theories given here are sound; and such practical conclusions as are made or suggested depart from the theoretical *only* as experience and good judgment dictate.

Textbooks on electricity and magnetism give the formula (also developed in B. of S. Paper, pages 219 and 220):

$$R = \rho \frac{1}{2\pi C} \tag{2}$$

where R = resistance to flow of current away from an electrode with the return electrode located at a great distance.

ρ = uniform resistivity of the surrounding soil (ohms per centimeter-cube).

C = combined electrostatic capacity in free space of the electrode and its image above the surface of the earth.

For any given form and size of electrode buried similarly in the earth C will always be the same.

The electrostatic capacity of a sphere is numerically equal to its radius in centimeters, so we can substitute for any electrode, a hemisphere buried in the earth with its flat surface flush with the surface of the earth, and having a radius in centimeters numerically equal to C. As a matter of fact the electrostatic capacity, C, can be computed exactly or approximately for only a few simple forms of electrodes (see B. of S. Paper, pages 219 to 221; nevertheless any ground rod or plate may be represented by some equivalent hemisphere. (See page 43 of this bulletin, for sizes of hemispheres equivalent to certain sizes of rods and circular plates.)

DISTRIBUTION OF RESISTANCE IN EARTH ABOUT A METALLIC BODY

As explained in Chapter I of this bulletin (page 7) and as substantiated by the U. S. Bureau of Standards (see B. of S. Paper, pages 8 and 9) the resistance of a ground connection is confined very largely to the body of earth immediately surrounding it.

Concentric Earth Shells:

On page 12 of the B. of S. Paper we find the following statement:

> "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."

This earth-shell conception of the resistance of earth surrounding a grounded electrode lends itself as indicated, to mathematical treatment, so that for any value of resistivity of the soil it is possible to compute the resistance from the *equivalent hemisphere* for a ground rod or plate, etc. to any point in the earth. Even if the resistivity of the soil is not known we can compute the distance at which any percentage of the total resistance is attained.

The formula relating resistance and distance is developed in the appendix to this bulletin; it is--

$$(3) \quad R_r = \frac{\rho}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r}\right)$$

where R_r = resistance from the centre to a radius r.

ρ = uniform resistivity of the soil (ohms per centimeter-cube).

r_1 = radius in centimeters of equivalent hemisphere.

r = distance in centimeters up to which resistance is included.

If only percentage of the total resistance is desired, r_1 and r may be in feet.

Tabulation of Resistance Distribution:

The distribution of resistance in terms of the total resistance, for a number of rods and plates is as follows:

Type of Ground Electrode	Radius in feet of Equivalent hemisphere (approximate)	Percent. of total resistance	Distance in feet from centre (approximate)
¾-inch pipe driven 3′ deep...	.61	90	6
		95	12
		98	31
		99	61
¾-inch pipe driven 5′ deep...	.92	90	9
		95	18
		98	46
		99	92
1¼-inch pipe driven 10′ deep.	1.76	90	18
		95	35
		98	88
		99	176
2½-inch pipe driven 20′ deep.	3.45	90	35
		95	69
		98	173
		99	345
Plate 3 feet diameter at considerable depth........	1.91	90	19
		95	38
		98	96
		99	191
Plate 5-feet diameter at considerable depth........	3.18	90	32
		95	64
		98	159
		99	318

It seems reasonable to assume that for square or rectangular plates buried at considerable depths the following values will hold with a fair degree of approximation:

At a distance of 5 x diagonal, resistance = 90% of total
10 x " " = 95% " "
25 x " " = 98% " "
50 x " " = 99% " "

For large grounds: Experience indicates that the same relation as for square or rectangular plates—using the greatest diagonal—is sufficiently accurate for grounded structures covering large areas, such as generating stations, substations, transmission towers, etc.

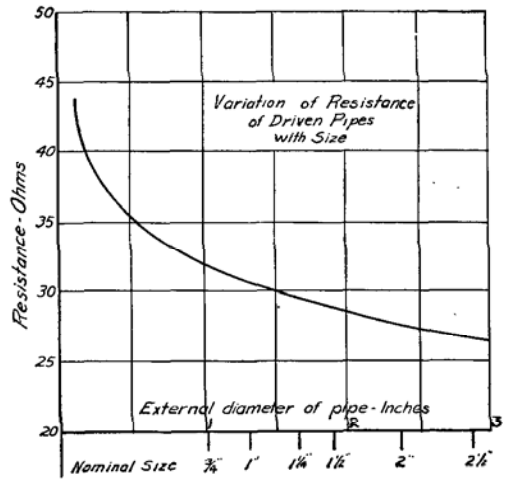

FIG. 22. Showing the variation of resistance to earth of driven pipes with the size of pipe.

The exact values of resistance vary with the resistivity of the soil, but the relative values for different sizes of pipe remain constant.

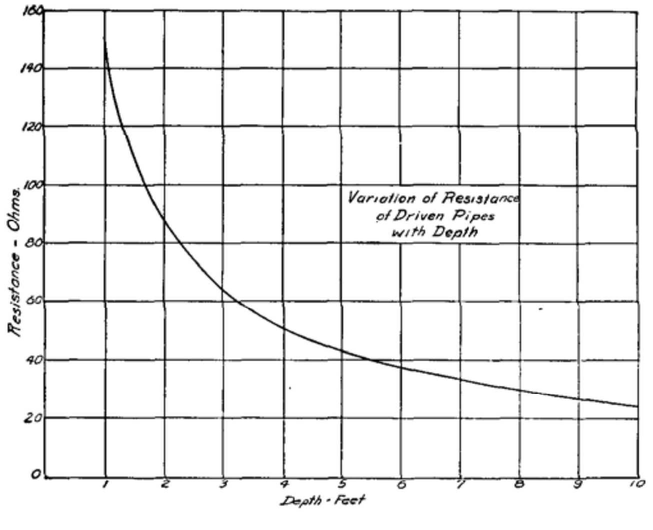

FIG. 23. Showing the variation of resistance to earth of driven pipes with the depth to which the pipes are driven.

The exact values of resistance depend on the resistivity of the soil, but the relative values for different depths of pipe remain constant.

Diameter of Pipe Electrodes and Resistance to Earth:

Fig. 22 is taken from the B. of S. Paper, page 79, and shows the relation between the diameter of pipes and their resistance to earth. The pipes are all driven to a depth of ten feet into soil of uniform quality and having rather low resistivity.

From equation (2), page 41, we see that the form of the curve is independent of ρ, the resistivity of the soil, and for any other soil of uniform quality the resistances for each size of pipe will be in the ratio of $\frac{\rho_1}{\rho_2}$.

The curve shows that it is seldom worth while to use large diameter pipes or rods except for driving into hard soil or to a considerable depth, where stiffness is needed.

Depth of Pipe Electrodes and Resistance to Earth:

The deeper a pipe is driven, the lower the resistance to earth, as can be seen from Fig. 23 taken from the B. of S. Paper, page 69. The curve shows the relation between the depth to which pipes are driven and their resistance to earth. The pipes are all of ¾-inch size and are driven into soil of uniform quality having rather low resistivity.

Once more we see from equation (2) that the form of the curve is independent of ρ, the resistivity of the soil. With a different value for ρ the resistance for each length of pipe will be in the ratio $\frac{\rho_1}{\rho_2}$.

It will be noted that ordinarily a depth of 5 feet is sufficient, although in soil which is not homogeneous, a much lower resistance may be obtained if, at a greater depth, the pipe reaches a better conducting stratum. In the case of a permanent ground a greater depth is advisable as a permanently moist stratum is more likely to be reached. The National Electric Code recommends a minimum depth of 8 feet.

LOCATION OF REFERENCE GROUNDS FOR TEST PURPOSES

We are now in a position to discuss this important matter in detail.*

It will be evident that to measure the resistance of a ground connection accurately, the distance between the ground under test and the current return auxiliary or reference ground should be such as to include all those earth-shells surrounding both the ground under test

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*See practical consideration of this subject in Chapter IV.

and the current auxiliary ground which add appreciably to the resistance of each, so that they do not crowd each other. Reverting to the volcano analogy on page 24 this means the volcanoes must be far enough apart so that the sides of each come down practically to the level of the plain. Also the potential reference ground connection should be at such a distance as to include practically all the earth-shells adding to the resistance of the ground under test, and yet not to include any of the earth-shells which add more than a small amount of resistance to the current return reference ground. The data given on page 43 serves as a guide for distances for any desired degree of accuracy. For example–suppose we are testing the resistance to earth of a plate 3 ft. in diameter and the current auxiliary ground is a ¾-in. pipe driven 3 ft. into the earth. If we desire an accuracy of 95 percent, the spacing should be about $38 + 61 = 99$ ft. and the potential reference should be at about 38 ft.

In measuring a low resistance ground and using a current return auxiliary ground of fairly high resistance, particular care must be taken to see that even the small percentage of the resistance of the current return reference ground which may be included in the measurement, is not a fairly large percentage of the low resistance ground under test. This may be illustrated as follows:

Suppose we are testing a substation grounded network 30 ft. x 40 ft.—diagonal 50 ft.—the resistance of which is likely to be low. Let the current auxiliary ground be a ¾-in. pipe driven to a depth of 3 ft. If we desire an accuracy of 90 percent the potential auxiliary connection should be $5 \times 50 = 250$ ft. from the substation and the current auxiliary ground at least 61 ft. farther on, so as to include not more than 1 percent of the resistance of the current reference connection. If distances must be reduced in such cases where the ground under test has low resistance and the current stake is likely to have much higher resistance, the least effect on the measured resistance can be secured by shortening the distance from the ground under test to the potential stake by a greater percentage than the distance between the potential and current stakes. In such instances a part of the ground resistance curve as outlined on page 31 may be plotted with profit.

Spacing not Affected by Resistivity of the Soil:

The equation (3), page 42, shows that if for any ground, a curve is plotted between various distances r and percentage of total resistance, the *shape of the curve* depends only on r_1 which is a function of the form, dimensions and arrangement of the ground under test. On the other hand, the resistivity of the soil ρ affects only the actual value of resistance and so *is not a factor* in determining the spacing of the auxiliary grounds.

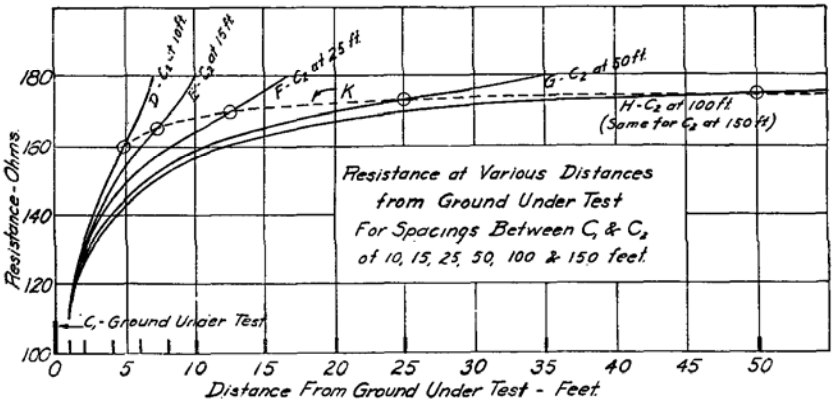

FIG. 24. A series of ground resistance curves of a ¾-in. pipe ground with respect to C_2 located at 10, 15, 25, 50, 100 and 150 ft. respectively. These are plotted from the figures given in the tabulation, FIG. 25.

DISCUSSION OF GROUND RESISTANCE CURVES†

(1) As Applying to Rod and Pipe Grounds:

A series of ground resistance curves was made on a single ¾-inch pipe ground driven three feet into the earth. The readings are tabulated in Fig. 25 and the curves–drawn to a distance slightly past their mid-points–are shown in Fig. 24. It will be noted that the curves are for various spacings between the pipe under test and C_2 namely 10, 15, 25, 50, 100 and 150 feet respectively. The curve for C_2 at 150 feet is coincident with curve *H* (for C_2 at 100 ft.) within probable limits of observation.

Values indicated by an asterisk (*) in the tabulation (Fig. 25) and in the small circles on the curves (Fig. 24) represent readings with P_2 at points midway between C_1 and C_2 (for 5, 7.5 and 12.5 feet the values were obtained by interpolation). Curve *K*, shown dotted in Fig. 24, is drawn through the mid-point values of the other curves.

As all pipes were of the same diameter and driven the same depth into soil which was found to be of very nearly uniform quality, the distribution of resistance in each case will be symmetrical about the mid-point between C_1 and C_2. Therefore, to save space, the curves have been plotted from the ground under test C_1 to a point only slightly more than half way to C_2.

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†See Chapter V, page 31.

It will be noticed that for spacings of 10, 15 and 25 ft. between the pipe under test and C_2, the mid-point readings are correct within an error not exceeding 10 percent. However, the slope of these curves at their mid-points is quite steep, so that a slight misplacement of the potential stake may result in a considerable change in the reading. Also for close spacing we must bear in mind that if the resistances to earth at C_1 and C_2, are not nearly equal in value the curves will be distorted and the reading at the mid-point may not give a true idea of the actual resistance of the ground under test.

From curve *G* for a spacing C_1-C_2 of 50 feet, the difficulties mentioned can be seen to be much reduced; and for spacings of 100 and 150 feet for C_1-C_2, curve *H* shows the difficulty appears practically not at all.

Conclusions: From the foregoing—which is typical of a large amount of data obtained—it would seem safe to conclude that for testing ordinary rod and pipe grounds the C_2 reference ground should be at least 100 feet from the ground under test, C_1, and the potential reference ground approximately 50 feet from the ground under test. For commercial accuracy the distance may be reduced to 50 feet and 25 feet respectively.

Distance in Feet from P_1 to P_2	SPACING C_1-C_2					
	10 Feet	15 Feet	25 Feet	50 Feet	100 Feet	150 Feet
	RESISTANCE-OHMS					
1	112	112	110	110	110	109
2	132	130	128			
4	152	148	144	141	139	140
5	160*					
6	170	160	153			
7.5		166*				
8		168	159	155	153	
10		180	164	158	156	157
12.5			170*			
15			176	165	163	163
20				170	167	167
25				173*	168	170
35				180	173	172
50					175*	173
65					176	173
75						175*
100						175

FIG. 25. Test data for ground resistance curves shown in FIG. 24.

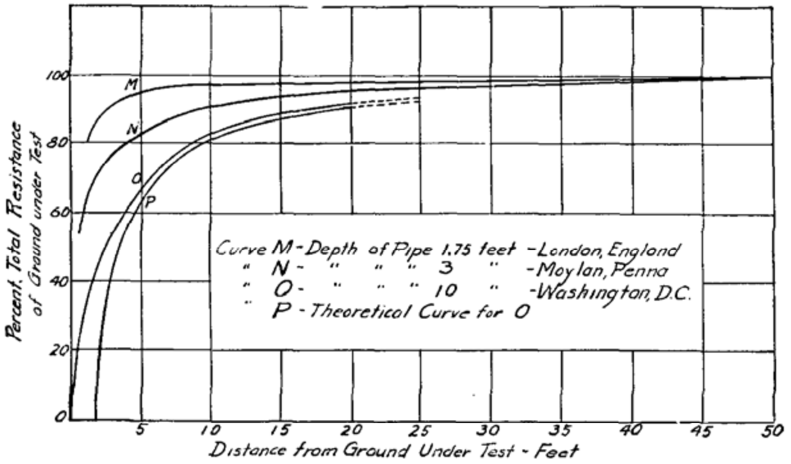

FIG. 26. Showing the distribution of resistance in the earth surrounding pipes driven to various depths in the earth.

Pipe Grounds of Various Depths:

Fig. 26 shows resistance distribution curves for three pipe grounds driven to different depths. They happen to be located in different parts of the world, but as the curves are plotted in percentage of total resistance, they can be compared. The fourth curve *P* is the theoretical curve for *O*, plotted from equation (3), page 42.

The general similarity in the form of the curves is evident, but their differences obviously bear some relation to the depth to which they are driven. They show rather clearly that with greater depth of pipe a greater distance is required to bridge an equal percentage of the total resistance. For example 90% of the total resistance of the 1.75-ft. pipe is included at a distance of 2.5 ft., while for the 3-ft. pipe a distance of 10 ft. is required, and for the 10-ft. pipe—about 18 ft. This characteristic obviously has a very definite bearing on the distance at which reference grounds should be placed for test purposes; its meaning in terms of life hazard is brought out on page 53.

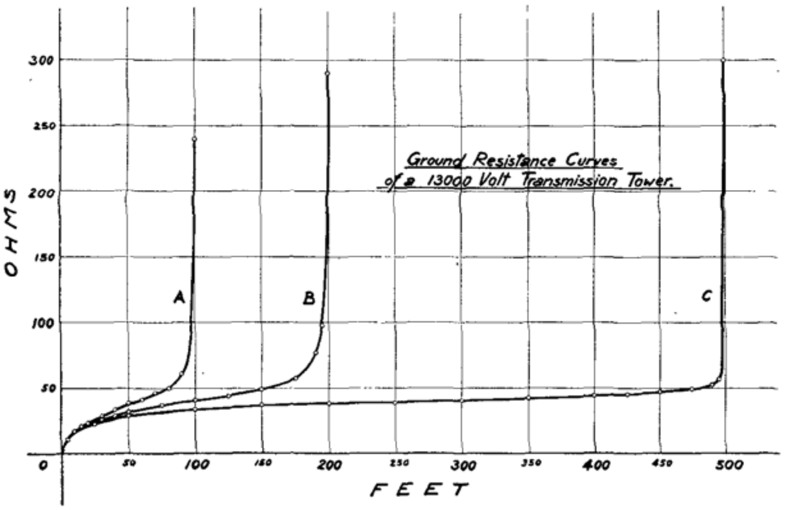

FIG. 27. Three ground resistance curves of a 13,200-volt steel transmission tower, made with the C_2 reference at *A*—100 ft., *B*—200 ft., and *C*—500 ft.

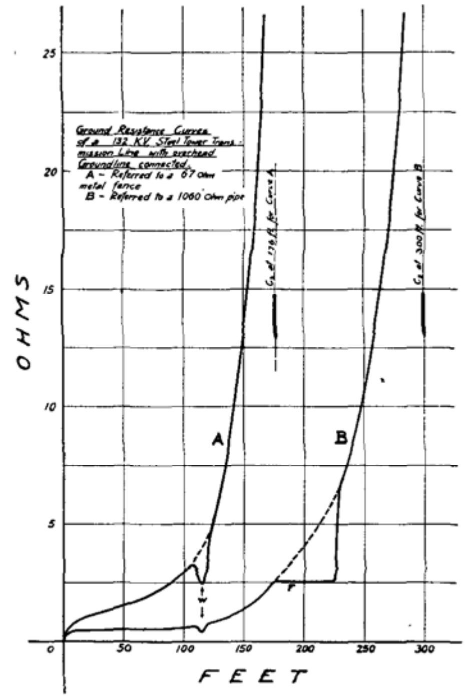

FIG. 28. Ground resistance curves of a 132-KV steel tower transmission line with overhead ground line connected.

A—Referred to a metal fence at a distance of 176 ft. having a resistance to earth of 67 ohms.

B—Referred to a driven pipe ground at a distance of 300 ft. having a resistance to earth of 1060 ohms.

By comparison with the curves in FIG. 27, these curves are distorted. This is due to the relatively close proximity of the C_2 reference grounds to the very large ground under test, and also the relatively high resistance of the C_2 reference grounds.

It is clear that if the latter were only 2 ohms, for example, the curves would be of very different character. This is the most obvious reason for the recommendation given on page 34, namely—when measuring very low resistance ground connections, the C_2 reference grounds should be small in size and low in resistance in order to obtain the most consistent and accurate results.

(2) Ground Resistance Curves for Transmission Towers without Overhead Ground Line:

Fig. 27 is a series of ground resistance curves made on a transmission tower located in a valley on the shore of an artificial lake. The tower covers an area about 15 ft. square at the surface of the ground and extends to a depth of about 7 ft. It does not carry an overhead ground line. A 13,200-volt power line was in operation at the time of test.

Comparing these curves with those for a pipe ground in Fig. 24 shows the desirability of going to a considerably greater distance with the reference grounds for a transmission tower than for a rod or pipe ground in order to obtain results of comparable accuracy. This is as it should be from equation (3), page 42, because the transmission tower ground has a greater area than a pipe ground, and its practical meaning in terms of life hazard is explained on page 53.

(3) Ground Resistance Curves for Large Area and Distributed Grounds:

Fig. 28 shows two ground resistance curves made on a 132-K.V. steel tower transmission line carrying an overhead ground line. Curve *A* is made with respect to a metal fence enclosing a garden about 60 ft. square and having a resistance to earth of 67 ohms. This fence was used as the C_2 connection, the nearest point being 176 ft. from the tower line under test.

Curve *B* was made with respect to a rod driven into the earth beyond the garden fence, 300 ft. from the tower and having a resistance of 1060 ohms.

Because of the relative flatness of curve *B* along its first hundred feet, this curve indicates that the resistance to earth of the transmission tower under test in parallel with the other towers on the line is about .5 ohm. A further check could be made by making another curve with the C_2 reference ground at a greater distance, and also—if possible—having less than 5 ohms resistance to earth.

An interesting feature shown by these curves is that of dips or deflections owing to the P_2 "probe" coming into proximity with a water main at *W*, and with the garden fence at *F*. The location of the water main is shown quite accurately by each curve.

FIG. 29. Testing the resistance to earth of a 220-KV transmission tower, using the "Megger" Ground Tester.

All that has been said regarding the spacing of reference grounds and all that has been shown in such curves as Figs. 24, 27 and 28 applies to any method of testing due to characteristics of the earth rather than to a particular method of test.

Reduction of Hazard with Low Resistance and Large Area Grounds:

Equation (2) page 41 shows that the larger the area of a ground connection in soil of a given resistivity, the lower its resistance to earth. Consideration of Equation (3) page 42 indicates also that the larger the area of a ground connection, the more gradual the rate at which resistance increases with distance from the ground connection. Comparison of curves in Fig. 26 and also curves 1_B and 2_B in Fig. 17 illustrates this. Then with leakage current flowing from the ground connection to the earth, we see from $E = IR$ that the greater the dimensions of the ground, the lower the difference of potential at points 1 foot apart on the surface of the earth within close proximity to the ground connection, and also the lower the difference of potential between the ground connection and any point within reaching distance of a man or animal. This is important as affecting safety to life. Protection is secured not only by making the resistance of the ground connection low in value, but also by making the ground connection of such size or so distributed as to reduce the potential gradient on the surface of the earth surrounding it.

Fig. 30. Testing the resistance to earth of a substation ground connection, using the "Megger" Ground Tester.

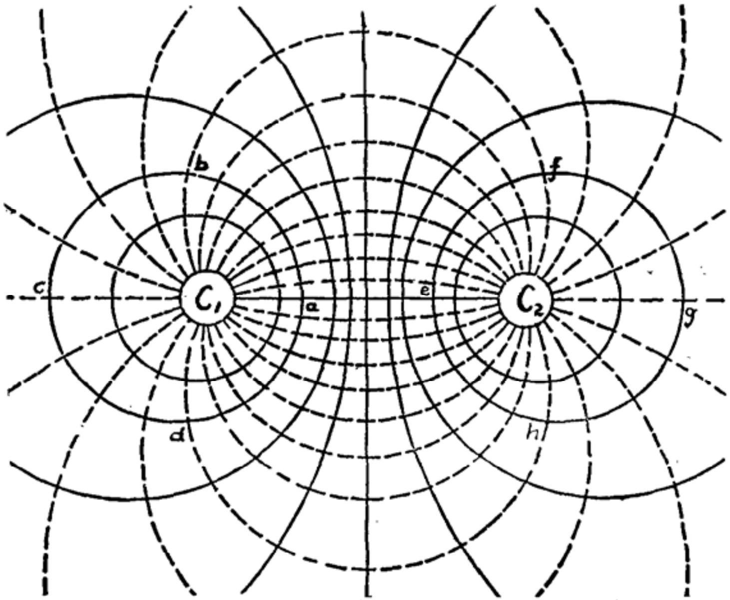

FIG. 31. Current distribution and equipotential lines at the surface of the earth between two equal hemispherical electrodes buried with their flat sides flush with the surface of the earth. The dotted lines represent current paths, and the full lines are equipotential lines.

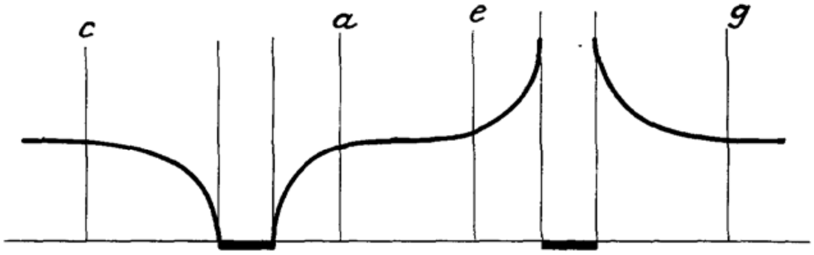

FIG. 32. Showing—in principle—the variation of resistance along a straight line between C_1 and C_2 of FIG. 31 when C_1 and C_2 are of equal size and resistance to earth.

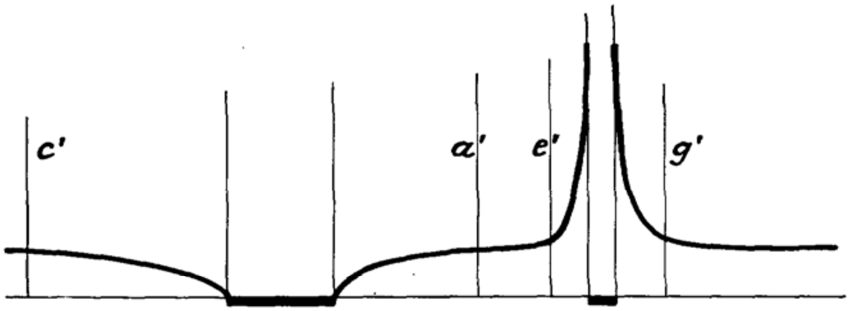

FIG. 33. Showing—in principle—the variation of resistance along a straight line between C_1 and C_2 of FIG. 31 when C_1 and C_2 are of unequal size and resistance to earth.

CHAPTER VIII.

CURRENT DISTRIBUTION AND EQUIPOTENTIAL LINES IN EARTH

TURN now to Fig. 31 which shows the general form of current distribution and equipotential lines at the surface of the earth for two equal hemispherical electrodes C_1 and C_2 buried flush with the surface of the earth and between which current flows. The dotted lines represent current flow and the solid lines represent equal potentials, although no attempt has been made to draw them to scale. If we take half of the diagram to one side of the line C_1-C_2 and rotate it through 180 degrees below the horizontal we develop surfaces which give a good idea of current flow and equal potentials in the body of the earth. See also Fig. 4 which is an approximation of the same thing for two rod or pipe electrodes placed relatively close together.

For proper spacing of C_1-C_2 to measure ground resistance, the electrodes will usually be relatively small and relatively near the surface of the earth; therefore we need consider only the distribution as in Fig. 31 at the surface of the earth. If we measure the flow of current into the earth, and the potential from C_1 to point *a* we can obtain a value of resistance. A measurement to any point on the line *a-b-c-d* will give the same value. Therefore the equipotential lines become lines of equal resistance.

Suppose that C_1 and C_2 are far enough apart so that a measurement of resistance on the line joining them, and taken anywhere between *a* and *e* gives a resulting value of a satisfactory degree of accuracy. (For example see curve *A* between 50 and 100 ft., in Fig. 16.) Then a measurement on any equipotential line passing between *a* and *e* will give an equally good result. In other words, for making ground resistance tests the potential reference P_2 can be placed anywhere except within two relatively small restricted areas, *a-b-c-d* and *e-f-g-h*; and therefore P_2 may be placed far to one side of the line joining C_1 and C_2 or back of C_1 or C_2. (Note paragraph on arrangement of test electrodes, page 26.)

The statement has been made by the U.S. Bureau of Standards that in the case of driven pipes, about 90 percent of the total resistance to earth is generally encountered within the first 6 to 10 feet.* Curves *M* and *N* of Fig. 26 agree with this. However, curve *O* fails to agree and, from the tabulation given on page 43, the Bureau of Standards' statement appears not to hold for rods or pipes driven to a depth of more than about five feet into the earth.

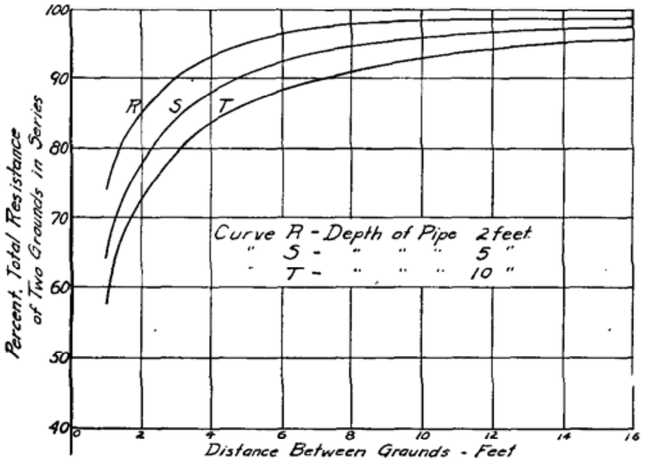

FIG. 34. Showing the effect of close spacing of the ground under test and the current return ground. This is for various depths of the ground connection. These tests were made by testing in series two grounds separated by the respective distances.

Effect of Close Spacing of Electrodes:

Let us now turn to Fig. 34. These curves give resistances for two similar pipe grounds measured in series and are the same as in the B. of S. Paper, Fig. 12, page 72, except that the ordinates are percent of total resistance. We see that for curves *R*, *S* and *T* we obtain values of resistance within 10 percent of the total resistance, at distances between the electrodes of approximately 3, 5 and 7 feet respectively. Therefore, we would expect to obtain within 10 percent of the resistance of *one* ground in each case at *one-half* of the respective distances, or at 1.5, 2.5 and 3.5 feet. But we have seen from theoretical and test data already given, that these distances are too small. Let us inquire into the reason for this apparent discrepancy.

At distances of 1.5, 2.5 and 3.5 feet, we have not included nearly all of the earth-shells which give 90 percent of the total resistance for pipes driven 2, 5 and 10 feet respectively into the earth. Therefore,

---

*B of S. Paper, page 12.

with the two grounds close together, some effect would seem to be present which tends to increase the resistance of each earth shell.

Turn again to Fig. 31 and consider C_1 and C_2 to be spaced a considerable distance apart—say 150 feet. At a distance of 5 feet in every direction from C_1 or C_2, we find the current density fairly equal. Now suppose C_1 and C_2 are spaced 15 feet apart. The distance of 5 feet from C_1 or C_2 becomes *relatively* ten times as great as before, because the electrodes are ten times closer together, and the current density toward the rear of C_1 and C_2 becomes much smaller than when the spacing of C_1 and C_2 is large. (The lines of Fig. 31 are general and independent of the distance C_1-C_2.)

Thus it will be noted that for small spacing of the electrodes C_1 and C_2, certain portions of those earth-shells lying close to the electrodes, and so having great effect in determining the total resistance of the electrodes to earth, are not carrying their full share of the current. This tends to increase the apparent resistance of each earth shell. (The effect is somewhat similar to the skin-effect in a large conductor carrying alternating current in which a part of the conductor fails to carry its full share of the current, with apparent increase of resistance.)

The result is that while for close spacing of a ground connection and its current return, a measurement of resistance of one or both electrodes by any method fails to include all of the earth shells which should be included, the effective resistance of each earth shell is increased. The errors involved are compensating to some extent.

Refer to curve E of Fig. 24 plotted to show distribution of resistance to earth of a ¾-inch pipe driven 3 feet into the earth, with the current return C_2 15 feet away. Approximately 95% of the total resistance (175 ohms) is found within 7.5 feet of the pipe.

If the spacing is increased considerably, as it should be—say to 150 feet—we find from curve H and from the table on page 43 that to obtain 95% of the total resistance, we must go to a distance of approximately 18 feet. This is in entire agreement with the statement made in regard to the effect of close spacing of a ground under test and its current return electrode.

Usually it is not good practice to depend on errors or inaccuracies of any sort as being quite nearly compensating. For this reason as well as those mentioned on page 23, and in connection with curves D, E and F of Fig. 24, small spacing between the ground under test and the current return ground is to be avoided.

As already stated on page 52, it is important to note that all that has been said regarding the spacing of auxiliary ground connections applies to any of the various methods in common use for measuring ground resistance. The facts brought out are characteristics of the earth and not of the instrument used, but much data has become available because of the simplicity of the Single-Test "Megger" Method which makes possible the securing of a great amount of data in a very short time, without the necessity for any calculations.

Plotting Equipotential Lines:

The "Megger" Ground Tester can be used to plot equipotential lines for any location of C_1 and C_2. There are two ways of doing this. *First:*—Join the instrument terminals C_1 and P_1 and place P_2 at any point as *a* of Fig. 31. Note the reading on the scale. Now seek a number of locations for P_2, such as *b*, *c*, *d*, etc. which give the same reading. The line drawn through these points is an equipotential line. This method assumes that the resistance of the ground C_1 remains constant throughout the test. Consequently it should be checked frequently. *Second:*—Disconnect C_1 and P_1. Join P_1 to a rod driven at any point as *a* in Fig. 31, and seek a number of locations for P_2 which give zero reading on the scale; such points would be at *b*, *c*, *d*, etc. A line drawn through these points is an equipotential line. This method is independent of variation in resistance in the ground C_1. However, if a zero reading is persistently obtained by this method, it is well to look for an open connection.

CHAPTER IX.

GEOPHYSICAL PROSPECTING

IT is not within the scope of this manual to discuss electrical methods of Geophysical Prospecting, but the "Megger" Ground Tester has been found to be of definite value in connection with two very practical aspects of the subject. These are: (a) Measurement of Resistivity of Soil, and (b) Prospecting for Suitable Locations for Good Ground Connections.

The "Megger" Ground Tester is being used in work of this sort because it is self-contained, readily portable, direct-reading (in ohms) and simple to use. The instrument also can be used in schemes of Geophysical Prospecting other than those here described.

The "Meg" type instrument is not intended for this work.

Measurement of Resistivity of Soil:

In U. S. Bureau of Standards Bulletin No. 258, entitled "A Method of Measuring Earth Resistivity," Dr. F. Wenner shows that if two current electrodes and two intermediate potential electrodes, of small size, are buried in earth, all at equal distances A apart in a straight line, and at a depth B, and the resistance R between the two potential electrodes is measured, then—

$$\rho = \frac{4\pi AR}{1 + \dfrac{2A}{\sqrt{A^2+4B^2}} - \dfrac{2A}{\sqrt{4A^2+4B^2}}} \tag{4}$$

where ρ = average resistivity of the soil. (If A and B are in centimeters, ρ is resistance per centimeter-cube.)

If B is small compared to A, as is the case when the electrodes are at the surface of the earth, then

$$\rho = 2\pi AR \tag{5}$$

To use the "Megger" Ground Tester for this test, connect the instrument as shown in Fig. 35. C_1 and C_2 are the current electrodes; P_1 and P_2 are the potential electrodes; R is the reading on the scale when the crank is turned.

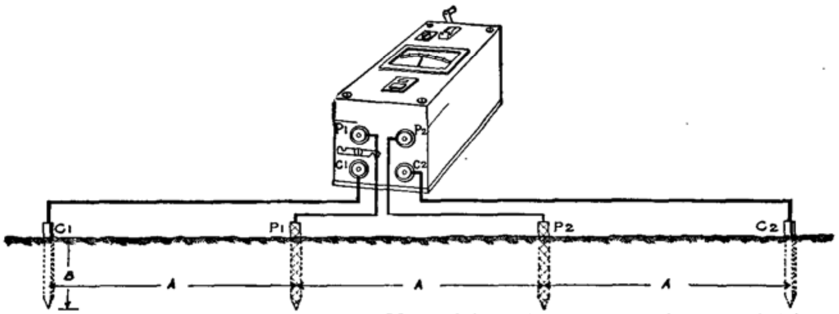

FIG. 35. Showing the method of using the "Megger" Ground Tester for testing the resistivity of soil. Distance *A* should be at least 20 x *B*.

The resistance *R* is actually the resistance of the earth between the two equipotential surfaces with which P_1 and P_2 are in contact. If *B* is great compared to *A*, the resistance *R* is numerically the same as for a cylinder of earth of length *A* and radius 2*A*, measured between the parallel ends. If *B* is small compared to *A*, the resistance *R* is numerically the same as for a half-cylinder of length *A* and radius 2*A*, measured between the parallel ends. By this method the average value of ρ is determined to a depth equal to *A*.

Prospecting for Good Ground Locations:

Frequently the necessity arises for securing a good, low resistance ground in what appears to be a most unfavorable location.

In such a case, lay out straight lines 10 feet apart, covering the earth in the vicinity. Drive four stakes 10 feet apart, but not more than one or two feet deep, along a line *a-b-c-d* as shown in Fig. 36, and measure the resistance *R* between the stakes *b* and *c*. This will be obtained when the instrument is connected as shown in Fig. 35. The value will be indicated on the scale of the "Megger" Ground Tester and is affected by the average resistivity of the soil to a depth about equal to the spacing, that is 10 feet.

Shift stakes along the line in question to points *b-c-d-e*, *c-d-e-f*, etc. (Fig. 36) and test until the entire line has been covered, then shift to the next line, and so on until the entire chosen area has been covered. The location giving the lowest value for *R* will have the lowest specific resistivity for the soil to the chosen depth of 10 feet, and is likely to be the best for locating the ground.

If desired, the survey can be repeated on lines 20 feet apart and with stakes spaced 20 feet apart. This will give results affected by the average resistivity of the soil to a depth of 20 feet.

To compare results for 10-foot and 20-foot spacings, it will be necessary to compute values for ρ, the average resistivity of the soil in any location. This need not be in ohms per centimeter cube, but can be obtained in ohms per foot cube by substituting values for spacing in feet and resistance measured, in equation (5) page 59. This procedure will indicate whether it is worth while to go to a considerable depth for the installed ground, as well as point out what appears to be the most favorable location.

The survey can be made in but little time and may result in considerable saving in the cost of the installed ground having the required low resistance.

Of course an alternative is to drive rods or pipes in various locations to such depth as may prove practicable and test their resistance to earth with the "Megger" Ground Tester while they are being driven. In this way one usually can tell at once when moisture or other good conducting medium is reached. However, the labor involved is apt to be much greater than by the first method.

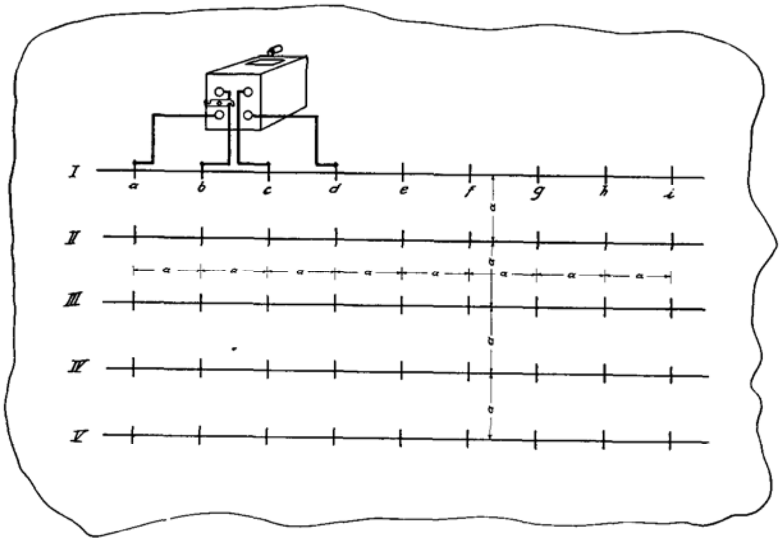

FIG. 36. Showing a method of prospecting for the best location for a ground connection to a depth equal to *a*. The location giving the lowest reading on the "Megger" Ground Tester will be the most desirable for the ground connection.

APPENDIX

IN this manual we have avoided mathematics to a great extent; nevertheless there are several equations relating to the resistance to earth of ground connections which deserve some consideration.

Text books on electricity and magnetism give the equation, also developed in B. of S. Paper, pages 219 and 220,—

(a) $$R = \frac{\rho}{2\pi C}$$

where R = resistance to flow of current away from an electrode with the return electrode located at a great distance.

ρ = uniform resistivity of the surrounding soil (ohms per centimeter-cube).

C = combined electrostatic capacity in free space of the electrode and its image above the surface of the earth.

Equation (a) enables us to compute the resistance to earth of any electrode if ρ and C are known.

For a hemisphere buried in the earth with its flat side flush with the surface of the earth, the image is the other half of the sphere, and as the electrostatic capacity of a sphere is numerically equal to the radius in centimeters, we have

(b) $$C = r_1$$

where r_1 = radius in centimeters of the hemisphere.

Substituting in (a)

(c) $$R = \frac{\rho}{2\pi r_1}$$

For a circular plate buried in the earth to a considerable depth, the image is a similar plate an equal distance above the surface of the earth, and for the electrostatic capacity we have

(d) $$C = \frac{2d}{\pi}$$

where d = diameter in centimeters of the plate.

Substituting in (a)

(e) $$R = \frac{\rho}{4d}$$

For a rod or pipe driven a distance l into the earth, the image is a similar pipe extending an equal distance above the surface of the earth. There is no means known for computing the exact value of the electrostatic capacity, but the B. of S. Paper, page 221, gives the following approximation:

(f) $$C = \frac{L}{2 \log_e \frac{2L}{d}}$$

where L = twice the distance l in centimeters to which the rod or pipe is driven into the earth

d = diameter in centimeters of the rod or pipe.

Substituting in (a) and writing $2l$ for L

(g) $$R = \frac{\rho}{2\pi l} \times \log_e \frac{4l}{d}$$

Whenever we can compute for an electrode buried in the earth, the value for C (combined electrostatic capacity in free space of the electrode and its image above the surface of the earth) we can substitute for the electrode a hemisphere having a radius r_1 (in centimeters) $= C$ and buried in the earth with its flat side flush with the surface of the earth.

If we have such a hemisphere, and know ρ, the uniform resistivity of the surrounding soil, we can compute the resistance of the earth to any distance from the hemisphere.

Let $R\mathrm{r}$ = resistance of the earth to a distance r from the center of the hemisphere.
ρ = uniform resistivity of the surrounding soil. (Ohms per Centimeter-cube.)
r_1 = radius in centimeters of the hemisphere.
r = distance from center of the hemisphere, to which the resistance of the earth is computed.

Consider the hemisphere to be surrounded by concentric earth-shells. These will be hemispherical in form and the thickness of an elementary shell will be dr. The resistance to flow of current through the shell will be dR.

(h) We have $dR = \frac{\rho dr}{2\pi r^2}$

$$\text{Whence } R_r = \frac{\rho}{2\pi}\int_{r_1}^{r}\frac{dr}{r^2}$$

$$= \frac{\rho}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r}\right) \tag{i}$$

From this it is evident that as r is increased, the value of R approaches $\frac{\rho}{2\pi r_1}$ as given in equation (c). Thus it is possible to calculate the distance at which the resistance equals any percentage of the total; and to do this r_1 and r need not be in centimeters, but may be in any convenient unit, as the foot. We see that if

$r = 2r_1$ we have 50% of the total resistance.
$r = 5r_1$ " " 80% " " " "
$r = 10r_1$ " " 90% " " " "
$r = 20r_1$ " " 95% " " " "
$r = 50r_1$ " " 98% " " " "
$r = 100r_1$ " " 99% " " " "
r = infinity " 100% " " " "

For a square plate buried at considerable depth, the diagonal = 1.41 x side.
Then the diameter of enclosing circular plate = 1.41 x side of square
From equation (d) the equivalent hemisphere has a radius

$$= \frac{2}{\pi} \text{ x Diameter of enclosing plate}$$

$$= \frac{2}{3.14} \text{ x } 1.41 \text{ x side of square} = .9 \text{ x side of square}$$

One-half the diagonal of square = .7 x side. This is probably as great as the radius of the actual equivalent hemisphere of a square plate, and for convenence is so taken. On this basis—

Taking $r = 10r_1$, we have 90 percent of the total resistance.
Also, $10r_1$ = 10 x .7 x side of square = 10 x .5 x diagonal = 5 x diagonal. Therefore we may consider that at 5 x diagonal we have 90 percent of the total resistance to earth.
And similarly for other distances.

For distributed grounds such as transmission towers, substations, etc. the same relation may be taken, that is, at least 90 percent of the total resistance to earth will be found at a distance equal to 5 times the diagonal.

The table on page 43, is computed on the basis set forth on this page.

DIRECTIONS FOR USING THE HEAVY-DUTY, LOW RESISTANCE TYPE OF "MEGGER" GROUND TESTER

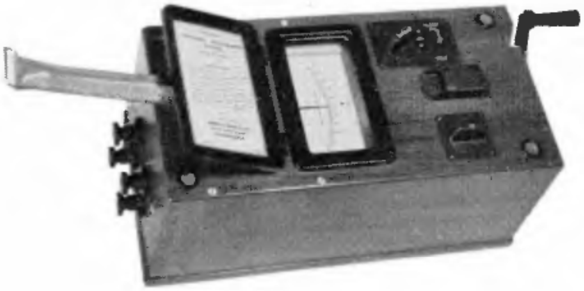

FIG. 37. The low resistance type of "Megger" Ground Tester.

The low resistance type of "Megger" Ground Tester operates on the same principle as the heavy-duty type as per Chapter III, page 15, but has manual compensation for potential electrode resistances. The instrument has been designed especially for measuring resistance to earth of large-area and low resistance ground connections such as hydro-electric and steam generating stations, telephone and telegraph central offices, oil and gas pipe lines and for earth resistivity measurements.

It has four ranges: 0 to 1, 0 to 10, 0 to 100 and 0 to 1000 ohms, available by means of a rotary selector switch.

Operation:

Connections are the same as for the heavy-duty type, Chapters III and IX.

Set the two-position switch to ADJUST PR. The ratio or "divide-by" switch may be in any position.

While turning the crank, manipulate the rheostat knob PR until the pointer stands over the red datum mark at 750 on the scale. This operation brings the total resistance of the potential circuit, including the resistance to earth of the potential electrode (or electrodes), to a predetermined value, on the basis of which the instrument is calibrated.

Turn the two-position switch to TEST. Operate the instrument and set the ratio or "divide-by" switch to the point that gives the highest pointer position on the scale. Read while cranking.

The above adjustment compensates for potential electrode resistances up to 2000 ohms. Further information on the characteristics of this instrument will be furnished upon request.

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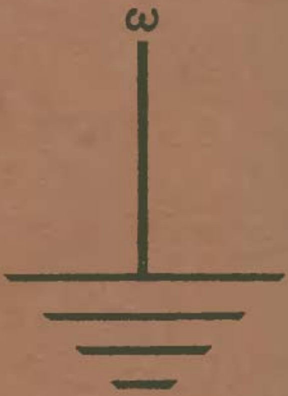
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