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LIGHTNING PROTECTION AT TELEVISION TRANSMITTING STATIONS.

CONTENTS

1. INTRODUCTION.

1.1 Where television transmitting stations are required to serve as large an area as possible, as is generally the case in this country, it is usual to establish them on, or near a mountain peak to gain the necessary elevation over the surrounding country-side. Mountain peaks of over 4,000 ft. elevation have been used. A typical mast or tower has its height up to 500 ft. which usually puts it above the highest natural feature on the mountain peak. This circumstance makes the mast prone to lightning strikes, particularly in tropical areas and when coupled with the sparse soil conditions and poor ground conductivity often found on mountain peaks, the protection of the station and personnel becomes a difficult problem.

1.2 This E.I. aims to set out the physical principles involved and recommended installation procedures for the protection of such stations.

2. DESCRIPTION OF A TELEVISION TRANSMITTING STATION.

2.1 The main characteristics of a television transmitting station from the aspect of lightning protection are:-

(i) A typical station is generally established on a high mountain peak.

(ii) The antenna mast/tower usually of the order of 500 ft. in height projects above the mountain range and becomes the most likely object in the vicinity to receive a lightning strike.

(iii) Due to the often rocky nature of the ground and a probability of high rainfall, the soil is sparse and of low conductivity making the establishment of an adequate earth system difficult.

3. PRINCIPLE OF PROTECTION.

3.1 Protection against the effects of lightning discharges can be obtained by providing a good conducting path between the general mass of the earth and the atmosphere above the station so that the discharges can pass to ground via the safest and most direct path without producing high potentials between metallic components in, on, near or connected to the station.

3.2 A tall earthed structure, such as a typical television antenna mast, offers a zone of protection to neighbouring objects against direct strikes. This zone is in the form of a vertical cone with the mast as its axis, and the apex at the top most point. The degree of protection depends on the cone vertex angle considered, but a cone with a semi-vertex angle of 45° offers a high degree of protection to objects within it. (Ref. No. 1.)

3.3 Most Australian television station ground installations come well within this zone of protection so that direct strikes to station buildings are unlikely and it is unnecessary to instal special lightning air terminations on or around the building.

3.4 The mast can thus be relied on to protect the station building from the vast majority of direct strikes, but there are secondary problems involved. The essential connections between the station equipment and the mast in the form of coaxial, power and communication feeders permit the entry of heavy discharge currents into the station with the consequent risk of damage and danger to life. These risks can be minimised by providing a low resistance ground connection for the tower to divert current away from the building, and installing heavily bonded inter-connections between all station equipment to provide as near as possible an equi-potential area in and about the station.

3.5 It will be necessary to provide a buried earth system around the station to minimise potential differences between station equipment and the nearby ground and to provide a path to ground for discharge currents which could flow along power and communication lines from distant strikes.

4. DISCUSSION.

4.1 The basic elements of a lightning protection system for a television transmitting installation comprise an earthed mast/tower with the station building inside its cone of protection and various equipments connected to it. The components of this protection system are discussed in the following paragraphs.

4.2 Mast Earthing. The degree of protection offered by the tower depends not only on its height and the zone of protection around it but also on the degree to which the tower earth connection diverts discharge currents away from the connected equipment. The most vital requirement is the installation of a low resistance earth system. The British Standard Code of Practice recommends a D.C. or L.F. earth resistance of 10 ohms or less (Ref. No. 1).

Each site has its own features to be taken into account when designing an earth system. These factors, such as quantity and depth of soil, quantity and nature of rock, conductivity of soil and rock, access and site layout, can only be assessed by undertaking visual inspection and performing conductivity measurements at the site.

Consequently, detailed specification in this report of an economical earthing installation applicable to all sites is not realistic. Although current Schedules for television masts and towers specify that the contractor provides an earth system and the details of such a system are given, this is not to be considered the final solution but a minimum requirement only. Where the ground conductivity is very low this system may need to be reinforced to obtain the required low earth resistance.

The most economical earthing system in poor conductivity ground is a system of regularly spaced stakes driven as deeply into the ground as is practical under the prevailing site conditions, set out in radial lines and interconnected by heavy conductors buried well into the ground. The number and length of such radials will be dictated by the soil and rock conductivity as found by measurement at the site.

The theoretical principles underlying the earth resistivity measuring techniques are set out in Appendix 1. Methods of measuring earth resistivity and the earth resistance of buried conductors are described in earth testing equipment handbooks examples of which are given in Appendices 3 and 4 and formulae for the earth resistances of typical arrangements of buried conductors are set out in Appendix 2. For a system of interconnected driven stakes spaced at intervals equal to the stake depth, the earth resistance is approximately midway between that of the interconnecting conductor alone and that of a vertical conducting sheet of width equal to the stake depth. Curves showing the earth resistance v. conductor length are shown in Fig. 1. The effect of depth of burial of a single conductor on the earth resistance is shown in Fig. 2, while the effect on the earth resistance of increasing the number of radials is shown in Fig. 3. Similar curves for an earth system of buried rods connected by a conductor above the ground are shown in Figs. 4, 5 and 6.

In designing this earth system, it must be borne in mind that the effective impedance of the earth system is its surge impedance. To achieve low values of surge impedance, it is better to provide a greater number of short radials rather than a few long radials. The maximum recommended length of any buried conductor is about 200 ft. (Ref. 2).

4.3 Tower or Mast as "Down" Conductor. When lightning strikes the structure, discharge current will flow through the steel structure to ground relying on the bolted joints to offer adequate conductivity.

The tower will usually be galvanised and painted, and it is specified that normally no structural member should be painted over before assembly in order to provide this conductivity. An exception occurs with some prefabricated members such as the tapered section of a mast and the base structure. These may be permitted to be "DIMET" coated which is a sprayed coating of metallic powder suspended in an inorganic vehicle. The conductivity of such a finish is quite poor, and depending on the members involved, there could be a discontinuity in the downward current path. Particular attention should be paid to this point and if necessary special conductors should be attached to bridge the discontinuity.

4.4 Guys of Mast. There are two conflicting aspects to the question as to whether to earth the guy system. On the one hand, if the guys are earthed, it is difficult to provide a guaranteed high conductivity over the joints and there is the danger of damage to the guy attachments due to heavy currents and arcing, which could cause serious weakening of the structure. On the other hand, if the guys are not earthed, there is the hazard to life due to the high potential difference between the lower ends of the guys and the ground, and there is the possibility of damage through arcing at the guy anchors.

In the case of television masts, due to the heavy guy ropes and substantial attachments which are under considerable stress, conductivity across the joints should be high and it is proposed to provide earths for the guy anchors. This arrangement has been adopted for some electrical transmission line masts (see Ref. No. 3).

4.5 Antenna and Feeders. If the tower earth resistance is adequately low, and the antenna elements lie within the cone of protection of the tower, direct strikes to the antenna elements are unlikely. In cases where the top antenna elements lie outside the protection cone of the tower a spike lightning conductor of galvanised mild steel should be bolted to one corner of the tower to protect the antenna elements from direct strikes.

The main coaxial feeders, together with power and communication circuits, run between the transmitter building and the mast, which means that when the mast is struck they may conduct heavy currents to earthed equipment in the station. These currents are likely to cause considerable damage to the cables and equipment from overheating, arcing across bends and gaps or by magnetic forces. The high potential differences liable to be set up could be a danger to life. A good earth system to the mast will serve to limit this current, since most of the discharge will then flow direct to earth.

Usually the coaxial antenna feeders will have both inner and outer conductors well bonded to the mast at the upper end via the antenna distribution feeders, the matching stubs, the numerous antenna attaching points, and the main cable anchors. It is not possible to provide any special protection for the antenna and small distribution feeders beyond relying on the naturally occurring metallic contacts at the antenna supports and the matching stubs. Heavy currents will tend to flow down the coaxial feeders, and to minimize the potential differences set up between the mast and feeders due to the different surge impedances it is advisable to bond the feeders to the mast at several points throughout their downward run and particularly at the point of exit.

Current will also flow down the inner conductor of the coaxial feeder and again the different surge impedances and the unequal currents will set up potential differences, possibly high enough to cause arcing damage to the cable. It is not possible to do anything to equalize the potentials other than to ensure good D.C. continuity through the end circuits (which is usually the case) and to reduce the total current flow by diverting it to the mast earth system.

The coaxial feeder will be laid in a duct and supported by some means within it. It is undesirable to bury the feeders directly into the ground since they would then form part of the mast earth system and could be damaged by heavy arcing. For the same reason, power and communication circuits to the tower should not be buried in the ground, particularly tower lighting circuits which require a high degree of security.

4.6 Station Equipment. The station and station equipment, although protected from a direct strike, can be endangered in several ways. First, there can be damage from heavy currents flowing between the tower and the station through the coaxial and other feeders. Secondly, there is the danger of currents being conducted into the building from remote strikes to power or communication lines. The usual protection provisions such as air gap or gas arrestors, longitudinal retard and drainage coils would normally be provided on aerial lines. Insulating transformers and neutralizing transformers could also be employed. (Ref. 16 and 17.)

Buried cables should be provided with low voltage gas arrestors between the inner conductors and the cable sheath, the latter being bonded to the station earth system.

Thirdly, if the station and tower earth system has too high a resistance, there is the danger to life as well as to power and communication equipment from a strike at the station site sending a heavy current flow along the lines or cables to a remote earth. For these reasons a good station earth system should be provided through which lightning surges can be diverted away from vulnerable equipment.

4.7 Station Earth System. To minimize excessive potential gradients in the immediate vicinity of the station which could be a danger to life and to provide the most direct route for earthing of the station equipment, the station should be provided with a good earth system in the nature of a buried ring conductor around the building with intermediate stakes, and, if necessary, a system of radials. This earth system can be extended to the mast earth system if close enough, to attain a lower surge impedance for the whole earthing arrangement. However, if this condition applies it is still advisable to make the resistance of the mast earth as low as possible and lower than that of the station ring earth, to minimize the current flow along the coaxial feeders.

All lightning protection equipment at the station should be connected to this station earth and the coaxial and other cable feeders should be bonded to it at the point of entry to the building. A system of earthed busbars should be extended throughout the building to which all heavy metallic station equipment and metallic members of the building structure should be bonded. In this manner the danger to personnel from high potential gradients is reduced to a minimum.

Despite this bonding to minimize potential differences there remains a danger to personnel handling communication equipment connected to external lines or cables - such as a telephone during lightning conditions, from the potential difference between the station and the remotely earthed equipment. For such equipment it is advisable to use heavily insulated isolating transformers.

4.8 Power Supply System. The power supply authority usually provides a buried earth for the installed power equipment and the neutral point may or may not be earthed. It is advisable whenever possible to have this earth firmly bonded to the station protection earth busbar. If the neutral point is grounded, complications may arise with unbalanced loads due to noise and hum currents, flowing through the earth system and setting up e.m.f's in the video and sound circuits through finite earth impedances and the presence of earth loops. This effect would be minimized by having only one point of contact between the neutral and earth and one point of contact between the mains earth busbar and the station earth. Heavy bonding between equipment cabinets, separate earth busbar systems for heavy power equipment and communication equipment cabinets, and careful layout of signal circuits and earth bonding to eliminate earth loops will also minimize the effect.

Any attempt to reduce induced hum by separating the two earth systems so that unbalanced neutral currents do not flow through the station protection earth would not necessarily be successful. At most sites the ground conductivity is so low and the site conditions are such that it is usually not physically possible to fit in two separate systems, but even if possible, the two otherwise separated systems would probably be coupled together via interpenetrating earth current paths.

4.9 Corrosion. It is desirable from the aspect of corrosion to carefully choose the materials for earthing and bonding conductors. The steel mast structure is usually hot dip zinc galvanised and in order to protect the coating it is recommended that galvanised mild steel conductors be used for the mast earth system. In the case of the bonds between aluminium coaxial feeder and the mast, zinc is more likely to corrode than the aluminium, and zinc galvanised mild steel straps are recommended. In this way corrosion will attack the bonding strip rather than the coaxial feeder. For the same reasons, zinc galvanised mild steel straps should be used to bond the coaxial feeder to the station earth busbar at the point of entry to the station building.

Similarly, station earth busbar material should be galvanised mild steel, but if copper busbar is used to take advantage of the higher conductivity, the copper should not contact the ground and the copper-station earth junction should be clear of the ground and protected from moisture.

At a station where a power supply authority earth system is provided, galvanised mild steel is the preferred conductor material, but if the authority normally recommends a copper earth system, the corrosion problems should be fully discussed between the two authorities in order to arrive at a mutually acceptable earthing system.

Appendix 5 lists various metals and alloys in order of their position in the Galvanic Series and Appendix 6 depicts the corrosion hazard with various combinations of metals in contact.

4.10 Co-Masting. Co-masting arrangements between commercial and national stations offer difficult problems. The two station earth systems are connected together via their respective coaxial feeders and the common mast. It is essential that in this case the two authorities use galvanised mild steel conductors for their station earths in order to avoid electrolytic action between the separate earth systems, since the mast earth will be of galvanised mild steel.

If the commercial licensee should use copper coaxial antenna feeders it is essential that they should not be in contact with the ground to avoid electrolytic cell action and consequent risk to the earth system. The bonding clamps between the copper feeders and the mast should preferably be of zinc galvanised mild steel. The copper-zinc joints should be treated by painting over to protect them from ingress of moisture and subsequent corrosion. Direct or rubbing contact between the copper feeders and the tower should be avoided. It is preferred that hangers be insulated or otherwise made from galvanised mild steel and painted over as for the bonding strap.

5. RECOMMENDATIONS.

5.1 Certain design considerations and installation procedures are set out in the following recommendations for the lightning protection system at a television transmitting installation.

5.2 Towers and Masts. Bolted joints of the mast shall not be painted before assembly and any "Dimet" coated assembly whose presence interrupts the downward current path shall be provided with an adequate system of galvanised mild steel down conductors to by-pass the lightning discharge currents to the mast earth.

Each coaxial feeder shall be bonded at approximately four points along its run down the mast structure. One of the bonds shall be at the point of exit from the mast. The bonding straps shall preferably be made of mild steel and zinc galvanised, and the junction at the coaxial cable shall be painted over. The condition and conductivity of these bonds should be checked at least annually.

Copper feeders shall be supported by insulated or galvanised mild steel hangers, and shall not be in direct contact with the mast at any point, except for the bonding clamps referred to above.

5.3 Tower or Mast Earth System. The tower shall be earthed by at least 3 radial conductors spaced about 120° apart in the direction of the guy anchors, each 200 ft. long of 2" X 1/8" galvanised mild steel conductor buried 12" deep where possible and reinforced by the provision 4' X 1" galvanised steel star cross-section stakes or equivalent driven into the ground at about 20 ft. intervals and bonded to the radials with 1/2" diameter galvanised bolts. All holes shall be punched and drilled before galvanising and bonds between the stakes and radials shall be painted after bolting. All bolts, nuts and washers used for these joints shall be hot dip galvanised. The radial conductors shall be bonded together by a buried conductor surrounding the mast foundation block and approximately 18" from it.

Each buried earth conductor shall be brought up above the ground and bonded to the tower with its separate bolted joint using at least two 1/2" diameter galvanised bolts which shall not be part of a structural joint. British Standard Code of Practice (Ref. 1) recommends that the resistance at a joint should be less than 0.05 milliohm. Sharp bends shall be avoided when taking the conductors over the foundation and at the point of bonding to the mast.

In the case of a mast, as distinct from a tower, the buried earth conductors shall be bonded to the main mast members above the ball joint.

The earth resistance of the mast earth system as measured at least 6 weeks after installation and during dry summer weather with an approved earth tester (Example in Appendix 3) shall be no greater than 10 ohms. Where the site conditions are such that the above design is inadequate the system shall be reinforced by the provision of more radials and/or longer stakes. Techniques for calculating the earth resistance are outlined in Para. 4.2, Appendix 1, and Figs. 1-6. The earth resistivity shall be measured in order to adequately design the required earth system, in accordance with the technique set out in Appendix 4.

In the case where a guy system is used, the guys shall be earthed by bonding to an earth system comprising at least four 1" star section or equivalent galvanised m.s. stakes driven 4 feet into the ground, one at each corner of the concrete anchor and no nearer than 18" from it and inter-connected by a buried ring conductor around the anchor block. At least one buried radial conductor of the same material shall be extended to meet with the main mast earth and the colinear guy anchor. The conductor shall be buried at least 1 ft. into the ground where possible and shall otherwise be as specified for the main mast earthing system.

5.4 Station Ring Earth Conductor. The station earth system shall be provided in the form of a buried ring conductor of 2" X 1/8" galvanised mild steel surrounding the building, approximately 6 ft. from the foundations and bolted to 4' X 1" star cross-section galvanised mild steel stakes driven into the ground. The exact number of stakes required will depend on the resistivity of the ground and can be calculated from the data given in Appendix 2 but shall be at most 20 ft. apart. Use of stakes separated by less than their length will not be effective in reducing the resistance to ground. In the case of high resistivity soil, buried radial conductors may be required to achieve a low earth resistance. The resistance of such a station earth system, measured at least six weeks after installation and in dry weather shall be no greater than 10 ohms.

This earth system shall be connected by one or more buried conductors to the mast earth system via removable links at the mast base, and if the mast is 100 ft. or less from the station building, the two systems may be integrated with these conductors into one composite earth system. As far as is practicable the arrangement of the composite earth system shall be designed to minimise the flow of lightning current along the coaxial feeders. This may be achieved by designing as good an earth system as possible connected to the mast alone, and providing only as much material in the station ring earth as is necessary to achieve the required total conductance, yet meeting its minimum specification as set out above. Interconnection should be routed in such a way as to have the minimum surge impedance, i.e. heavy conductors and a minimum of bends.

5.5 Station Bonding System. There shall be provided a system of earth bonding within the station comprising an arrangement of busbars to which the station metallic equipment is firmly connected. To minimise problems due to earth loops and to isolate various groups of equipment for earth testing purposes the following design is recommended.

A bonding conductor shall be installed within the building external walls roughly concentric with the buried station earth system and connected to it at frequent intervals by radial conductors. All heavy metallic building equipment, plumbing, metallic building structural members and metallic equipment mounted to the external building wall, shall be bonded to this conductor, to be called the Station Earth Busbar.

A second and separate conductor, Power Earth Busbar, shall be provided to which all heavy power equipment frames and cubicles, the auxiliary power supply equipment and the power authority earth shall be connected. In addition, a third separated conductor, Transmitter Earth Busbar, shall be run through the building to which all electronic equipment and communication equipment cabinets, including the transmitter and control desk, shall be bonded. The latter two conductors shall each be connected to the station earth busbar at a single point via removable links. External programme cables shall be bonded to the electronic equipment busbar to eliminate earth loops. The position of these tie points will depend on the station and site layout but shall be chosen so as to provide as short a path from equipment to ground as is possible with a minimum number of bends. The tie point for the electronic equipment busbar should be made as close as possible to the point of entry of programme cables.

The communication line protective equipment ground conductor and the connection to the tower earth system shall be made at a convenient location on the station earth busbar, via removable links. A single connection between the station earth and the power authority earth system shall be made via the power authority earth busbar. The earth connection to the coaxial feeders shall be made to the station earth busbar at the point of entry to the building. A typical layout for such a bonding system is shown in Fig. 7.

The busbars shall comprise of 2" X 1/8" galvanised mild steel conductor or alternatively copper. In the latter event, connection to the main station ground shall be made with heavily galvanised mild steel links at points above ground and in places where the copper-zinc junction is protected from the weather and condensation.

It shall be possible by the use of links to disconnect any of the bonds from the equipment groups to the earth busbar, and the earth busbar from the ring earth system at any time for test purposes.

Wherever possible, the supply authority earth system and the station earth system shall be integrated into a single earth system, bearing in mind the precautions to be observed with respect to corrosion, discussed in para. 4.9.

5.6 Mast-Station Interconnecting Feeders. The coaxial cables and other feeders between the mast and the station shall be bonded to the tower as outlined in Section B, para. 5.2, and to the station earth busbar directly at the point of exit from the building. It shall be possible to remove these bonds for test purposes. These bonds shall consist of at least two straps each bonding the two cables together via suitable galvanised clamps and to the station earth. The straps shall comprise galvanised mild steel strips 2" X 1/16" cross-section.

Copper feeders shall also be bonded via zinc galvanised mild steel straps and the copper-zinc joints painted over to prevent corrosion.

Feeders shall not be buried directly into the ground, and as far as is possible shall not contact it along the surface run from the station to the mast.

Buried communication cables, including video cables, shall have low voltage gas arrestors fitted between the inner conductors and the earthed cable sheath as long as a suitable method of application can be devised which will not interfere with the required electrical performance of the cable or the attached equipment. The sheaths of such cables shall be bonded to the electronic equipment earth busbar at the building entry via suitable connecting conductors chosen and installed in such a way as to minimise the possibility of corrosion. More specific instructions on the protection of buried and open wire feeders will be prepared after further investigation.

5.7 Inspection of Bonds. All bonding straps and links should be frequently inspected and replaced if showing damage through corrosion. In such cases steps shall be taken by suitably protecting the joints from moisture ingress to minimise the onset of further corrosion.

5.8 Additives. No salts or other chemical additives shall be deposited in the soil to improve the earth system conductivity.

5.9 Testing. Provision shall be made in the form of removable links to isolate the tower structure from its earth system for testing purposes and similarly the station internal earth busbars from the station ring earth system. In the case where separate tower and station earths are provided there shall be provision for isolating the inter-connecting conductors for separate measurements of the tower and station earths.

The resistance to earth of the tower and station earth systems shall be separately measured at annual intervals in dry summer weather, and a final measurement made of the earth resistance of the complete earthing system. If the resistance to earth of a composite system or the separate resistances of a system with individual mast and station earths are found to be above 10 ohms, further reinforcement to the earth system will be required. Appendix 3 shows the technique of earth resistance measurements.

6. CONCLUSION.

6.1 The protective system discussed and formulated in this report should, if adopted, minimise the effects of lightning strikes to the station equipment and personnel but it is never possible to guarantee complete protection. For this reason, the station staff should bear in mind the frequency of lightning strikes in the area and the prevailing atmospheric conditions when working on the tower or undertaking routine measurements on the earth system, which may involve disconnection of earth bonding links.

It is not expected that the above recommendations can be put into effect in toto at every site since every station has its individual features. However, by studying the physical principles discussed in Section 4 in relation to the site conditions, it should be possible to engineer an adequate protection system for most stations.

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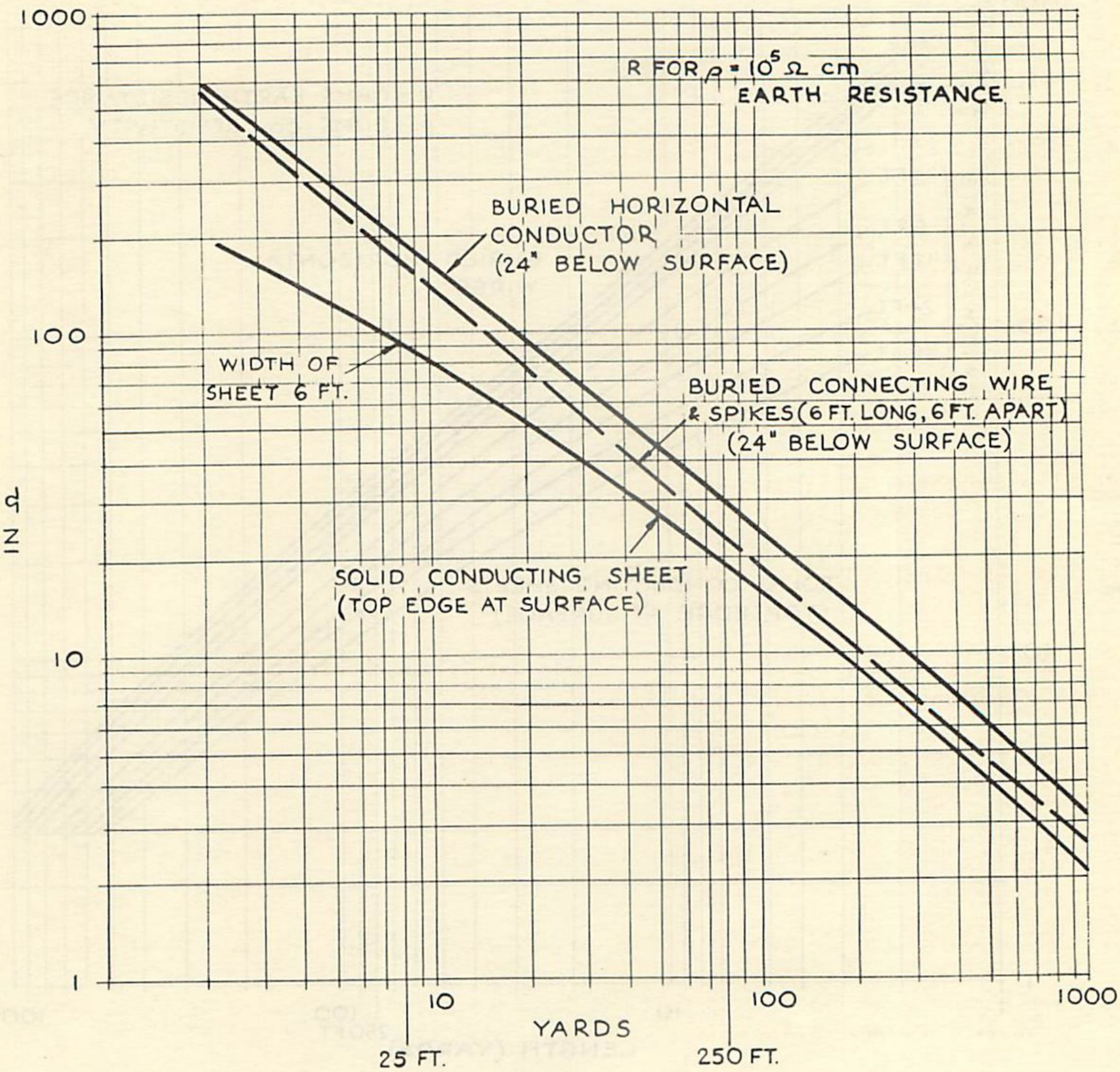
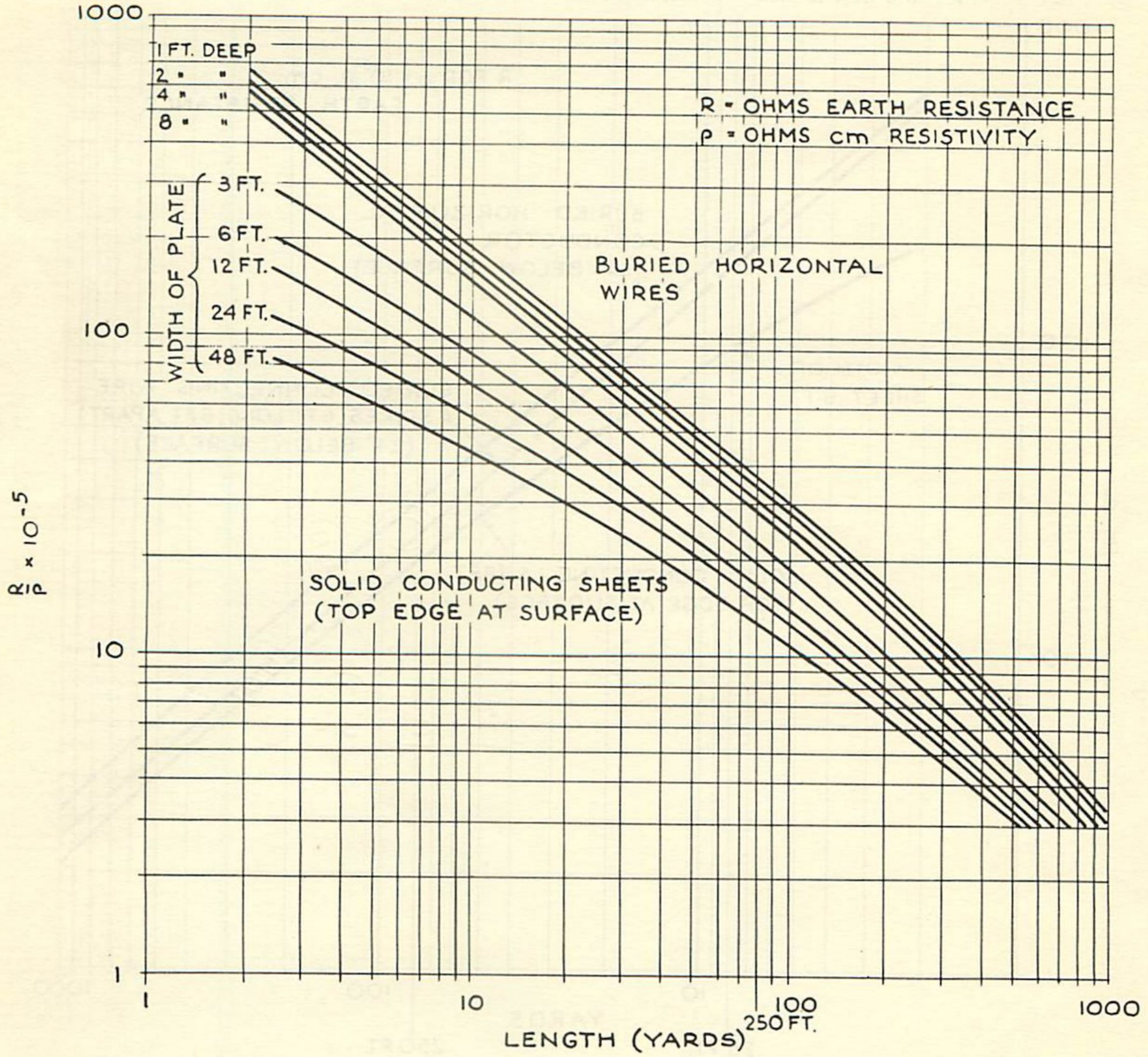


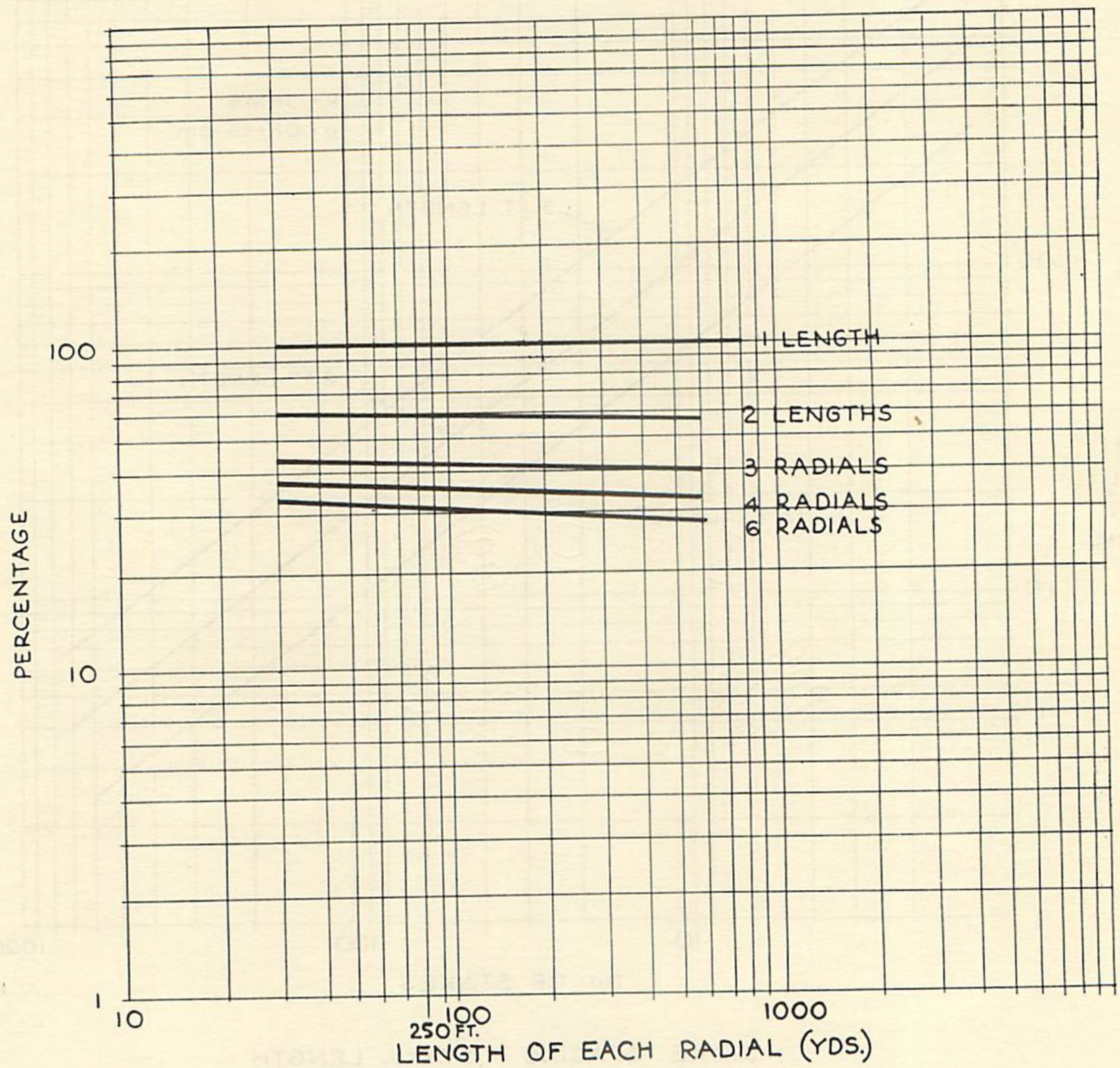
EARTH RESISTANCE OF EACH RADIAL.

FIG. 1.



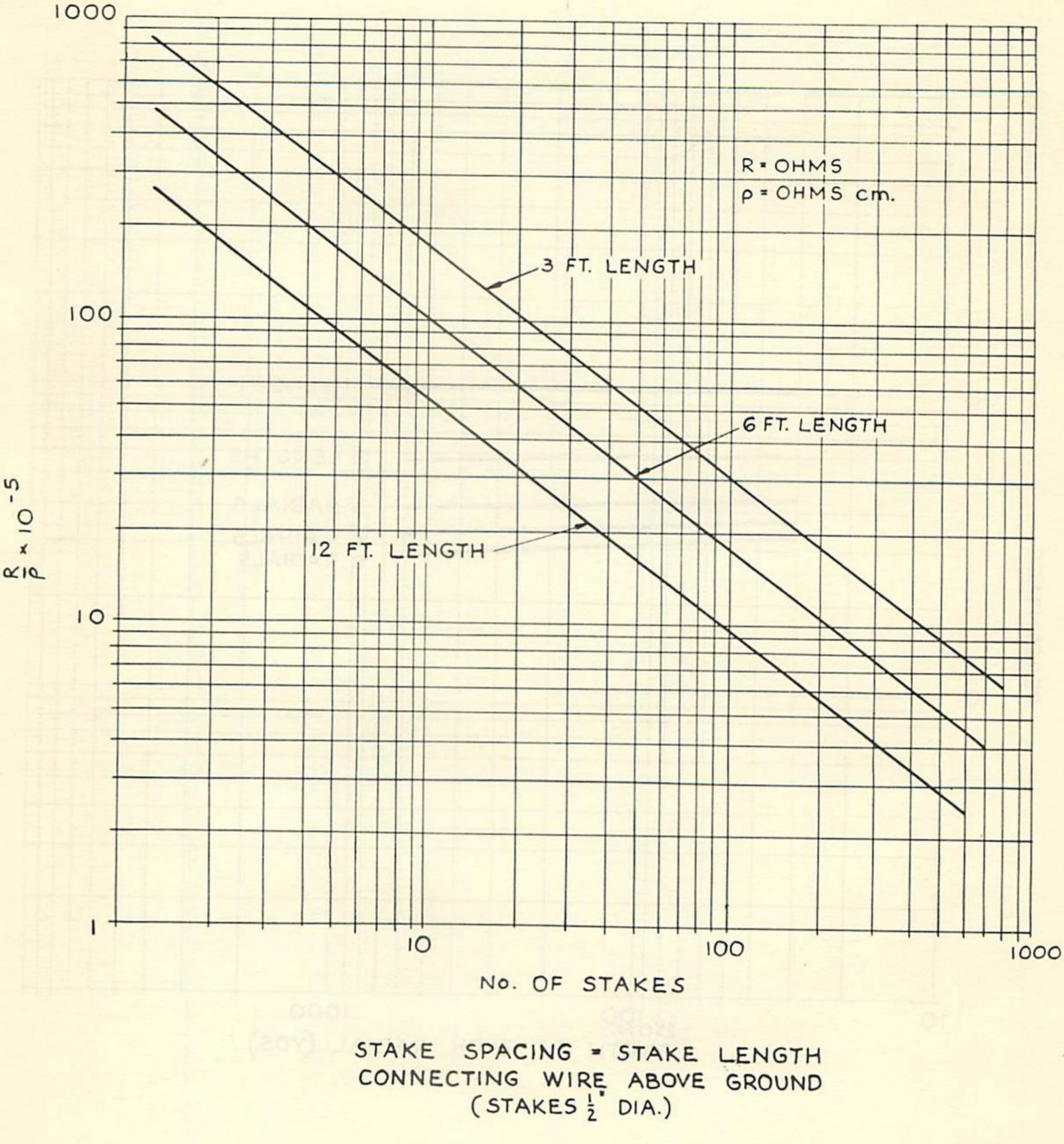
EARTH RESISTANCE OF HORIZONTAL BURIED WIRE AND BURIED VERTICAL PLATE.

FIG. 2.



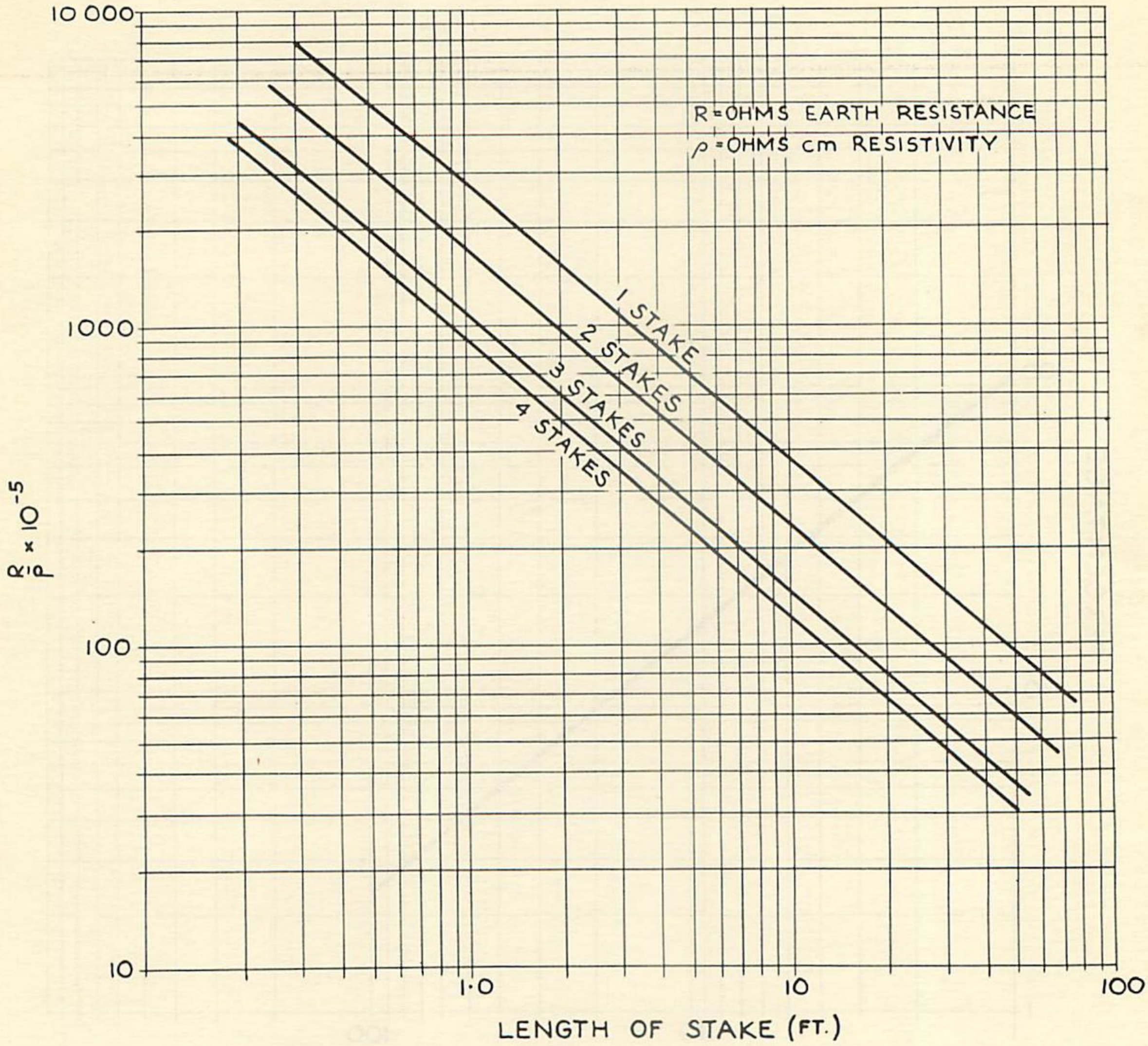
COMBINED EARTH RESISTANCE OF GROUP OF RADIALS AS PERCENTAGE OF SINGLE LENGTH.

FIG. 3.



COMBINED EARTH RESISTANCE OF GROUP OF STAKES.

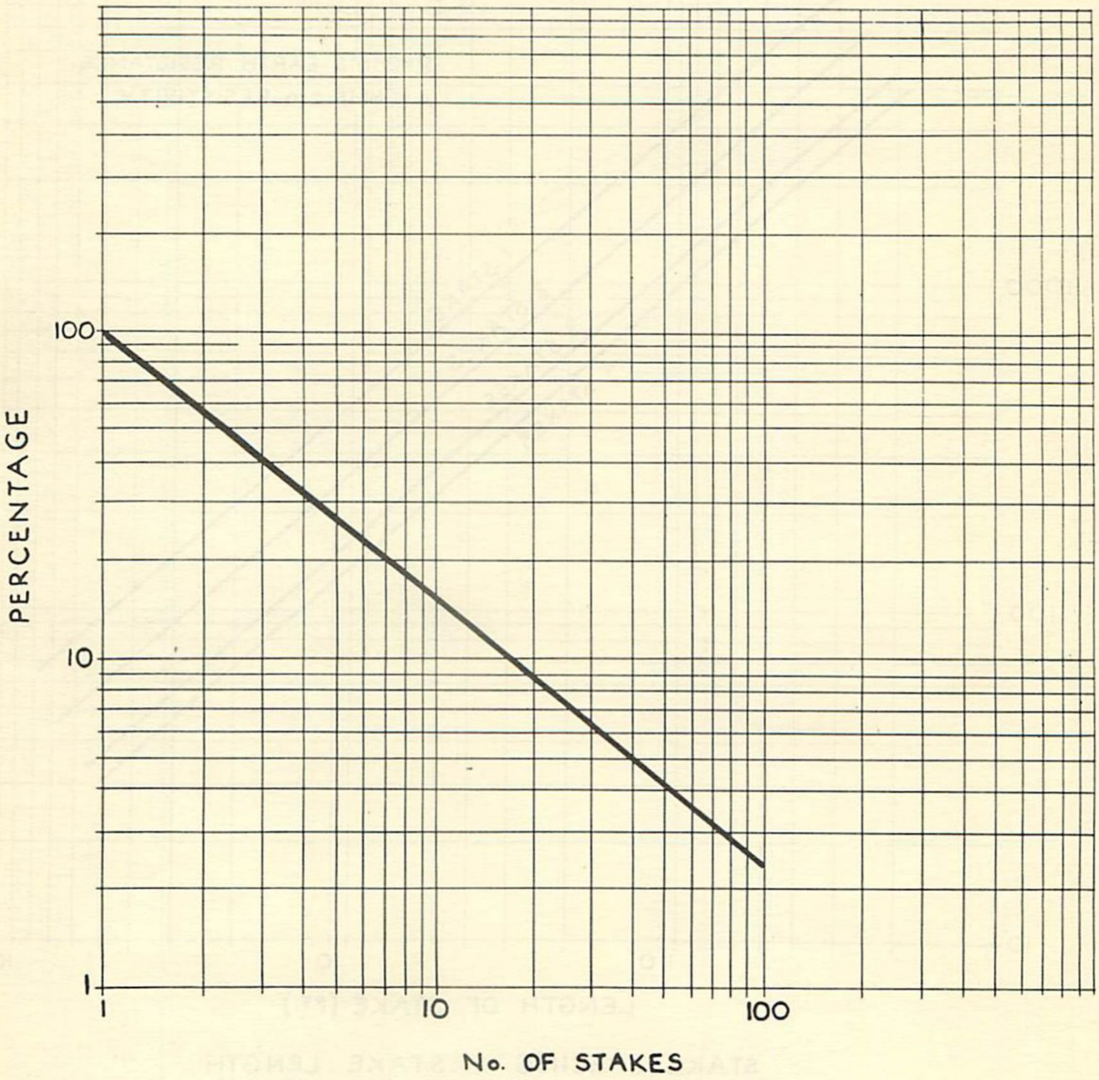
FIG. 4.



STAKE SPACING = STAKE LENGTH
CONNECTING WIRE ABOVE GROUND.
(STAKES $\frac{1}{2}$" DIA.)

COMBINED RESISTANCE TO EARTH OF GROUP OF STAKES.

FIG. 5.



COMBINED RESISTANCE TO EARTH OF GROUP OF STAKES AS PERCENTAGE OF SINGLE STAKE.
(SPACING OF STAKE = STAKE LENGTH)

FIG. 6.

APPENDIX 1.

THE CALCULATION OF EARTH RESISTIVITY.

(Extracted from Ref. 9.)

Let two point electrodes touch the surface of the earth (assumed homogenous) and let a current I enter the ground at one electrode, the second electrode being sufficiently remote so that its presence may be neglected. The current is then radial about the electrode. The area of a hemispherical surface with centre at the electrode and radius a is $2\pi a^2$ and the radial current density in the ground at the distance a is

$$C = \frac{I}{2\pi a^2} \tag{1}$$

If ρ is the earth resistivity, the radial electric intensity in the ground at a distance a from the electrode is

$$E_a = \frac{I\rho}{2\pi a^2} \tag{2}$$

The potential at the distance a is the integral of electric force between a and an infinitely remote point

$$P_a = \int_a^\infty E_a \, da = \frac{I\rho}{2\pi a} \tag{3}$$

The ratio of potential to current at radius a is

$$R = \frac{\rho}{2\pi a} \tag{4}$$

THREE ELECTRODES METHOD.

If current enters Electrode 1 and leaves at Electrode 2, the mutual resistance with a third point Electrode 3, is the difference between R_{13} and R_{23}.

$$R_{13} - R_{23} = \frac{\rho}{2\pi} \left[\frac{1}{a_{13}} - \frac{1}{a_{23}} \right] \tag{5}$$

Where a_{13} is the distance between Points 1 and 3 and a_{23} the distance between Points 2 and 3.

FOUR ELECTRODES METHOD.

If there are four electrodes (see Fig. 8) (which is the usual arrangement for measuring earth resistivity), since current is passed between 1 and 2 and the voltage is measured between 3 and 4 the mutual resistance between 1 and 2 and on the other hand 3 and 4 is

$$R_{13} - R_{23} - R_{14} + R_{24} = \frac{\rho}{2\pi} \left(\frac{1}{a_{13}} - \frac{1}{a_{23}} - \frac{1}{a_{14}} + \frac{1}{a_{24}} \right) \tag{6}$$

If the four electrodes are equally spaced at distance a apart in a straight line, the mutual resistance is

$$R = \frac{\rho}{2\pi}\left(\frac{2}{a} - \frac{1}{a}\right) = \frac{\rho}{2\pi a} \qquad (7)$$

or

$$\rho = 2\pi aR \text{ ohm-cm. if a is in centimetres, the soil being assumed homogenous.} \qquad (8)$$

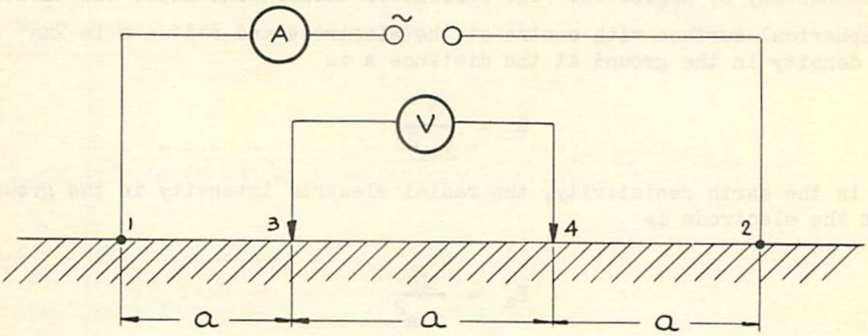


FIG. 8. FOUR-ELECTRODE METHOD OF EARTH-RESISTIVITY MEASUREMENT.

Measured mutual resistance $\frac{V}{A} = R.$

Apparent earth resistivity $= 2\pi a^{R}$

APPENDIX 2.

THE CALCULATION OF THE EARTH RESISTANCE OF A BURIED ELECTRODE.

(Extracted from Ref. 9.)

A current flowing from a buried electrode to earth produces a series of equipotential lines or shells. They are, in fact, equipotential hemispheres whose axes pass vertically through the electrode. At a great distance away there would be a zero potential surface and the resistance to earth of the electrode may be defined as the ratio -

$$R = \frac{\text{Voltage between electrode and zero potential area}}{\text{Current between electrode and zero potential area}} \qquad (1)$$

Most of the formulae for earth-electrode resistance have been calculated from a consideration of the electrostatic capacity of similar electrodes and their images situated in free space. The method of changing a formula for capacitance into one for resistance to earth may be found by considering the case of two parallel plates whose distance apart is small and the effect of whose edges may be neglected.

If each of the plates has an area of A square centimetres and if the charge densities are + q and - q on each of the plates respectively, the number of flux lines is 4π qA. The voltage gradient is $4\pi q$ volts/centimetre between the plates. If the distance between the plates is d, the potential difference V between the plates is $4\pi qd$. Thus,

$$\frac{1}{c} = \frac{V}{qA} = \frac{4\pi d}{A} \quad \text{or} \quad \frac{d}{A} = \frac{1}{4\pi C} \qquad (2)$$

For the current between the same plates when they are embedded in earth of resistivity ρ abohms per cubic centimetre, the resistance between the plates in abohms is

$$R = \frac{\rho d}{A} \qquad (3)$$

Thus in this case, from Eq (2) and (3)

$$R = \frac{\rho}{4\pi C} \text{ ohms} \qquad (4)$$

where C is in statfarads and ρ is in ohm-cm.

The equation (3) merely shows the relation between the units and has no connection with the geometry of the flow of dielectric flux and current. Equation (3) applies to any conductor or combination of conductors. If C includes the capacitance of the images of a conductor or conductors, the resistance to earth is

$$R = \frac{\rho}{2\pi C} \qquad (5)$$

The following Table of approximate formulae is given by H.B. Dwight (Ref. 13.)

In each case

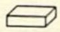
Radius of electrode = a cm

Length of electrode = L cm

Depth of buried electrode = $\frac{S}{2}$ cm

Width of rectangular plate = W cm

The formulae give ρ in ohm-cm.

Type of Electrode		Resistance (Ohms)	Equation
Vertical rod		$\frac{\rho}{2\ L}(\log_e \frac{4L}{a} - 1)$	6
Buried Horizontal wire		$\frac{\rho}{2\pi L}(\log_e \frac{2L}{a} + \mathrm{Log}_e \frac{2L}{S} - 2$ $+ \frac{S}{2L} - \frac{S^2}{4L^2} + \frac{S^4}{32L^4})$	7
Right-angle turn of wire Length of arm L.		$\frac{\rho}{4\pi L}(\log_e \frac{2L}{a} + \log_e \frac{2L}{S} - 0.2373$ $+ 0.2146 \frac{S}{L} + 0.0135 \frac{S^2}{L^2} - 0.0424 \frac{S^4}{L^4}$	8
Three-point star Length of arm L.		$\frac{\rho}{6\pi L}(\log_e \frac{2L}{a} + \log_e \frac{2L}{S} + 1.071$ $- 0.209 \frac{S}{L} + 0.238 \frac{S^2}{L^2} - 0.054 \frac{S^4}{L^4})$	9
Four-point star length of arm L.		$\frac{\rho}{8\pi L}(\log_e \frac{2L}{a} + \log_e \frac{2L}{S} + 2.912$ $- 1.071 \frac{S}{L} + 0.645 \frac{S^2}{L^2} - 0.145 \frac{S^4}{L^4})$	10
Vertical round plate		$\frac{\rho}{8a} + \frac{\rho}{4\pi S}(1 + \frac{7}{24} \frac{a^2}{S^2} + \frac{99}{320} \frac{a^4}{S^4})$	11
Buried Horizontal Strip Length 2L Section a × b Depth $\frac{S}{2}$ $b < \frac{a}{8}$		$\frac{\rho}{4\ L}(\log_e \frac{4L}{a} + \frac{a2 - \pi ab}{2(a+b)^2} + \log_e \frac{4L}{S} - 1$ $+ \frac{S}{2L} - \frac{S^2}{16L^2} + \frac{S^2}{16L^2} + \frac{S^4}{51aL^4} + - - -)$	13

APPENDIX 3.

MEASUREMENT OF EARTH RESISTIVITY.

(Extracted from Ref. 11.)

There are several methods of measuring earth resistivity, most of them being variants of the method originally due to Werner. In this, four electrical contacts are made with the ground by driving into the surface metal spikes as in Fig. 9. These electrodes are placed on a straight line at equal spacing "a" ft. and a depth of less than $\frac{\text{"a"}}{20}$ ft. The resistivity can be calculated using the measured value of mutual resistance and known separation of the four electrodes according to the formulae in Appendix 1.

STAKE SEPARATION.

Generally the resistivity of the ground is not uniform and a series of measurements (with constant electrode separation) can be taken at different points to find the most advantageous position for the earth electrode. Further, to decide the advantages of deeper stakes, more specific resistance to greater depths can be explored by using stakes with greater separation.

Fig. 10 is a nomogram for estimating the range of electrode separation with each type of instrument for homogenous earth. A straight line joining the minimum readable value of the instrument (i.e., $\frac{1}{10}$ of the F.S. of instrument) and the estimated value of earth resistivity will intersect the centre scale at the point giving the maximum value of electrode separation for the particular instrument.

Fig. 11 shows the effect on the maximum value of electrode separation by 2 layers of earth having different specific resistivities. Group A applies to instruments with a minimum readable scale of 0.1 ohms, and Group B 0.03 ohms.

PRINCIPLE OF OPERATION.

Direct current from the hand generator passes through the control coil of the ohmmeter (Fig. 12) and through the current reverse T_2 so that an alternating current I is delivered to the current electrodes C_1 and C_2.

An alternating potential therefore exists between the potential electrodes P_1 and P_2 equal to I X R, where R is the resistance of the earth between P_1 and P_2. The ensuing alternating current is rectified by the current reverser T_1 and passes through the deflecting coil of the ohmmeter.

The deflection of the two coil ohmmeter movement depends on the ratio of the currents in the deflecting and control coils so that the instrument measures $\frac{IR}{I}$ or R directly.

The reversing contactors are mounted on the generator shaft and their function is to render the instrument independent of back e.m.f. and stray soil currents.

The contact resistance of the electrode and the soil immediate to it has been found to be practically zero. Changes in ohmic resistances in the current electrodes circuit will merely alter the testing current, thereby the potential drop will also be affected in the same proportion and it would not therefore have any effect on the instrument readings.

The potential electrode circuit is of high resistance so that the effect of an appreciable resistance in the temporary potential electrodes and connecting wires is reduced to a minimum. In instruments for measuring high resistance a permanent fixed resistance is included in the potential circuit to allow for considerable variation of resistance in the potential circuit. In some low resistance measuring earth testers a fixed amount of resistance in the potential circuit has been taken into account during the calibration of the scale, so that for every measurement the total resistance in the circuit is increased by an adjustable potentiometer to the value allowed for in calibration.

In another type of specialised earth tester, a reversed potential from an auxiliary coil in the hand generator is applied across the potential deflection circuit and the voltage is adjusted so that no current will flow through the potential electrodes. In this way the resistance in the potential deflection circuit will have no effect on the deflection and the combined reading of resistance.

METHOD OF USE.

The instrument must be placed on a steady or approximately level base. The generator should be turned at about 135 r.p.m. when the resistance will be indicated on the scale. Stray direct current through the soil will produce a movement of the pointer when the generator handle is stationary, but will have no effect on the final reading when the generator handle is turned at full-speed. Stray alternating currents in the soil may produce a flickering of the pointer due to beating effects at certain handle speeds; this will be eliminated if the speed is increased or decreased slightly.

ELECTRODES.

These are of metal and may consist of 15" lengths of 1/2" diameter rod of L or T section fencing posts. They should be pointed at one end and are usually driven into the soil to a depth of about 9", except for small separations when their penetrations should not exceed 1/20 of the electrode separation.

The resistance to earth of the current electrodes is not of vital importance and as a rule there is little difficulty in ensuring adequate current through the earth. The contact resistance of the potential electrodes and circuit should be kept as low as possible as this will increase the accuracy of the instrument. Occasionally, in dry surface soils, the contact resistances may be inconveniently large, giving errors in the potential measurement and limiting the test current. They may be reduced either by watering the electrodes or by using two or more spikes with separation greater than their depth and connected together. In the latter case the line joining the spikes should be at right angles to the line joining the current electrodes and, for small electrode separations, their distance between the spikes forming a single electrode must be less than 1/20 of the electrode separation.

WIRES.

Heavy multi-strand cables with adequate insulation are essential especially for the potential electrodes. Rubber covered cable (3/0.036) taped and braided or similar would be satisfactory. A 100 yds. of the cable would have a resistance of the order of one ohm, and weigh about 10 lbs. Longer leads can be made up of units of 100 yds. and the joints should be of very low resistance and well insulated from the ground.

Details on field procedure and care of equipment can be found in handbooks usually provided with the earth testers.

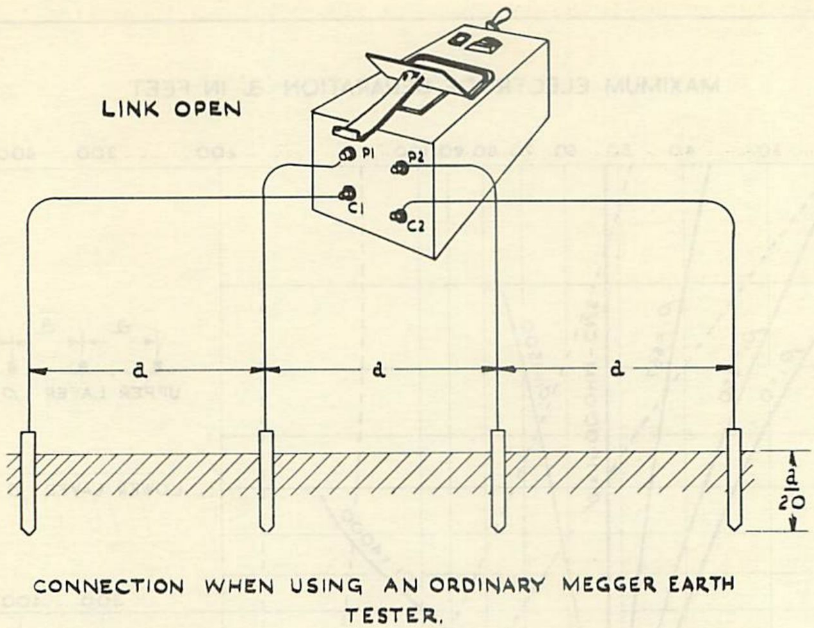

LINK OPEN
P1
P2
C1
C2
d
d
d
a/20
CONNECTION WHEN USING AN ORDINARY MEGGER EARTH TESTER.

FIG. 9.

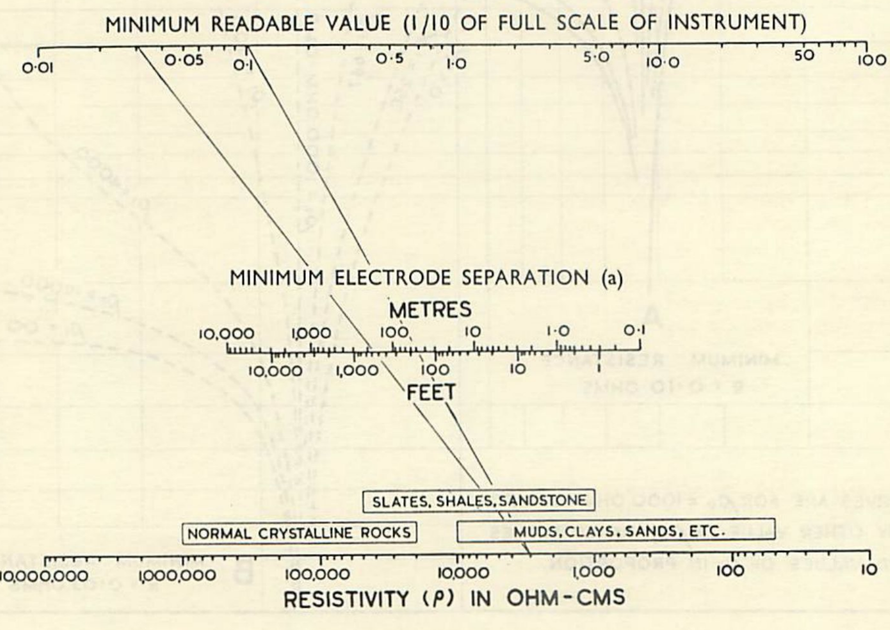

MINIMUM READABLE VALUE (1/10 OF FULL SCALE OF INSTRUMENT)
0·01
0·05
0·1
0·5
1·0
5·0
10·0
50
100
MINIMUM ELECTRODE SEPARATION (a)
METRES
10,000
1,000
100
10
1·0
0·1
10,000
1,000
100
10
1
FEET
SLATES, SHALES, SANDSTONE
NORMAL CRYSTALLINE ROCKS
MUDS, CLAYS, SANDS, ETC.
10,000,000
1,000,000
100,000
10,000
1,000
100
10
RESISTIVITY (ρ) IN OHM-CMS

FIG. 10.

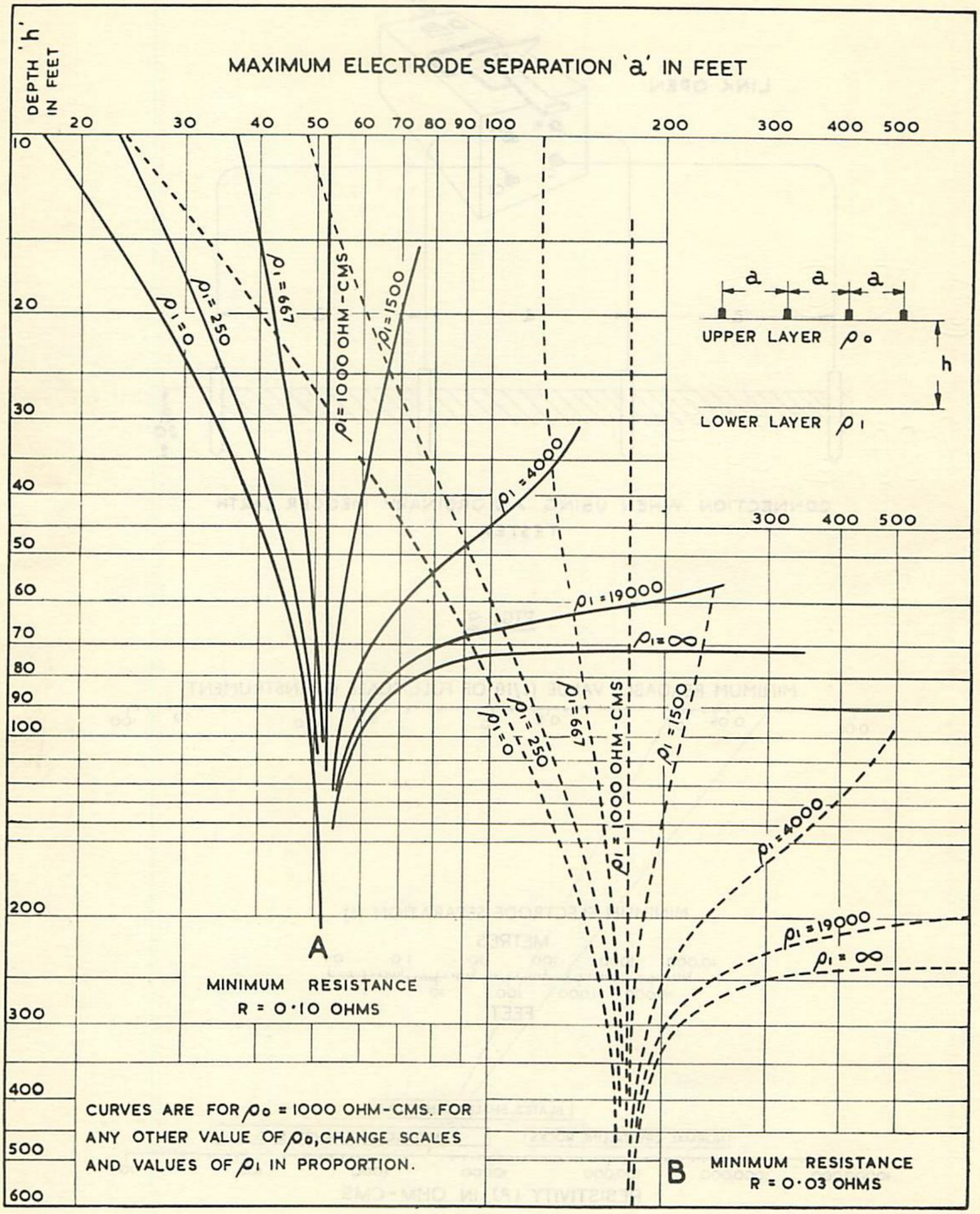

MAXIMUM ELECTRODE SEPARATION 'a' IN FEET
DEPTH 'h' IN FEET
20 30 40 50 60 70 80 90 100 200 300 400 500
10 20 30 40 50 60 70 80 90 100 200 300 400 500 600
ρ1 = 0
ρ1 = 250
ρ1 = 667
ρ1 = 1000 OHM-CMS
ρ1 = 1500
ρ1 = 4000
ρ1 = 19000
ρ1 = ∞
a a a
UPPER LAYER ρ0
h
LOWER LAYER ρ1
A
MINIMUM RESISTANCE
R = 0·10 OHMS
B
MINIMUM RESISTANCE
R = 0·03 OHMS
CURVES ARE FOR ρ0 = 1000 OHM-CMS. FOR ANY OTHER VALUE OF ρ0, CHANGE SCALES AND VALUES OF ρ1 IN PROPORTION.

FIG. 11.

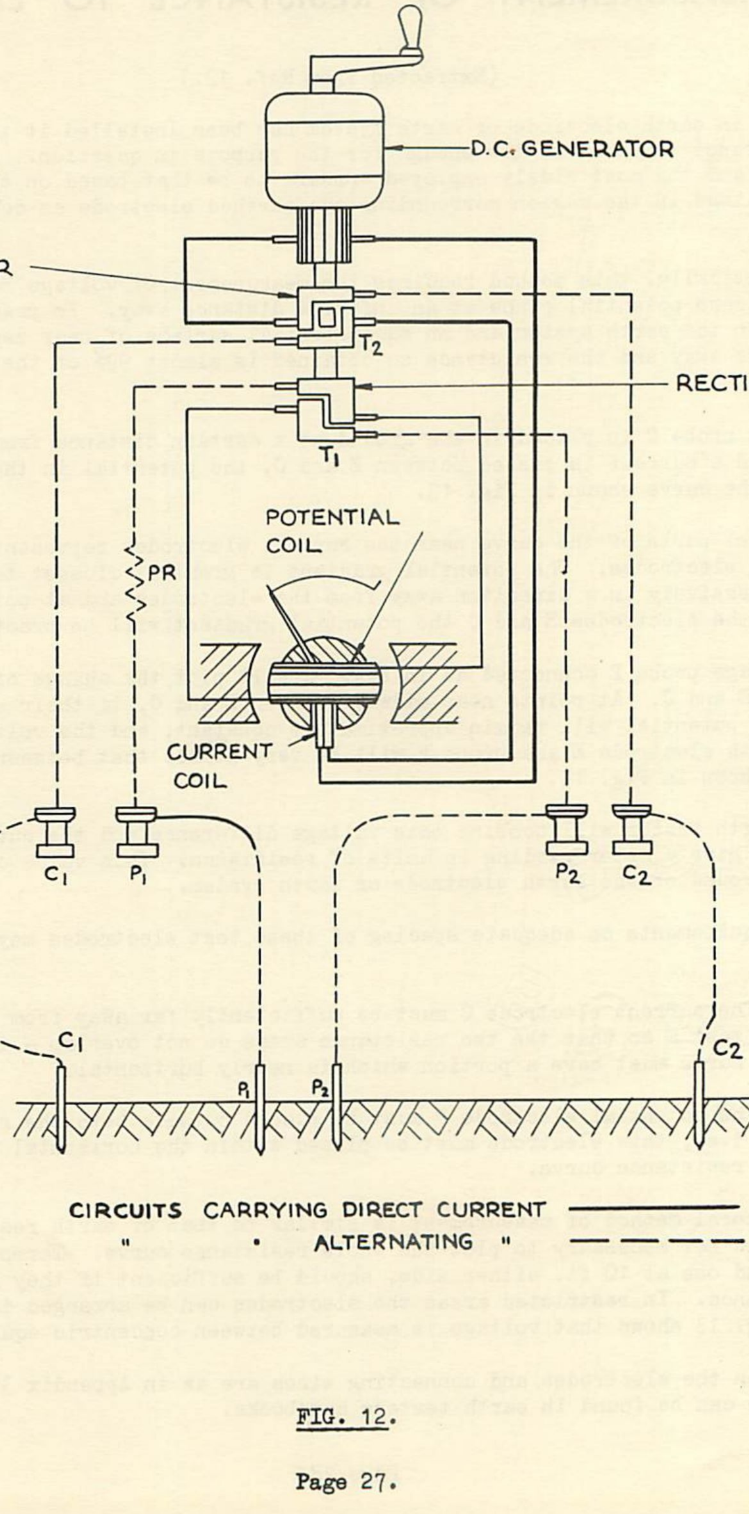

D.C. GENERATOR
CURRENT
REVERSER
T_2
RECTIFIER
T_1
POTENTIAL
COIL
PR
CURRENT
COIL
C_1
P_1
P_2
C_2
C_1
P_1
P_2
C_2
CIRCUITS CARRYING DIRECT CURRENT
" " ALTERNATING "

FIG. 12.

APPENDIX 4.

MEASUREMENT OF RESISTANCE TO EARTH.

(Extracted from Ref. 12.)

After an earth electrode or earth system has been installed it is necessary to check that its resistance to earth is low enough for the purpose in question. A number of methods have been used and the most widely employed appears to be that based on the measurement of current and voltage in the region surrounding the earthed electrode as defined by equation (1) of Appendix 2.

Theoretically, this method requires the measurement of voltage between the earth system and the zero potential plane at an infinite distance away. In practice voltage is measured between the earth system and an equipotential surface of near zero potential sufficiently far away and the resistance so obtained is almost 99% of the true resistance to earth.

When a probe C is placed in the ground at a certain distance from the earthed electrode E, and a current is passed between E and C, the potential in the ground will vary in accordance to the curve shown in Fig. 13.

The bent parts of the curve near the current electrodes represents the resistance area around the electrodes. The potential gradient is greatest closest to the electrodes and decreases progressively in a direction away from the electrodes and at points approximately midway between the electrodes E and C the potential gradient will be practically zero.

A voltage probe P connected as in Fig. 14 will plot the change of potential in the ground between E and C. At points near midway between E and C, if their separation is sufficient, the potential will remain approximately constant, and the voltage difference between the earth electrode E and probe P will be very nearly that between electrode E and true earth as shown in Fig. 15.

The earth tester will combine this voltage difference and the current through the electrode E and give a meter reading in units of resistance. This value could be taken as resistance to ground of the earth electrode or earth system.

The requirements on adequate spacing of these test electrodes may be stated as follows:-

(i) The current electrode C must be sufficiently far away from the electrode under test E so that the two resistance areas do not overlap - i.e., the resistance curve must have a portion which is nearly horizontal.

(ii) The potential electrode P must be placed outside both the resistance areas - i.e., this electrode must be placed within the horizontal portion of the resistance curve.

The general method of measurement is similar to that of earth resistivity measurements. In practice it is not necessary to plot the whole resistance curve. Three readings, one at the mid point and one at 10 ft. either side, should be sufficient if they give a constant value of resistance. In restricted areas the electrodes can be arranged in the form of a triangle, as Fig. 13 shows that voltage is measured between concentric equipotential shells.

Notes on the electrodes and connecting wires are as in Appendix 3 and details on field procedures can be found in earth testers handbooks.

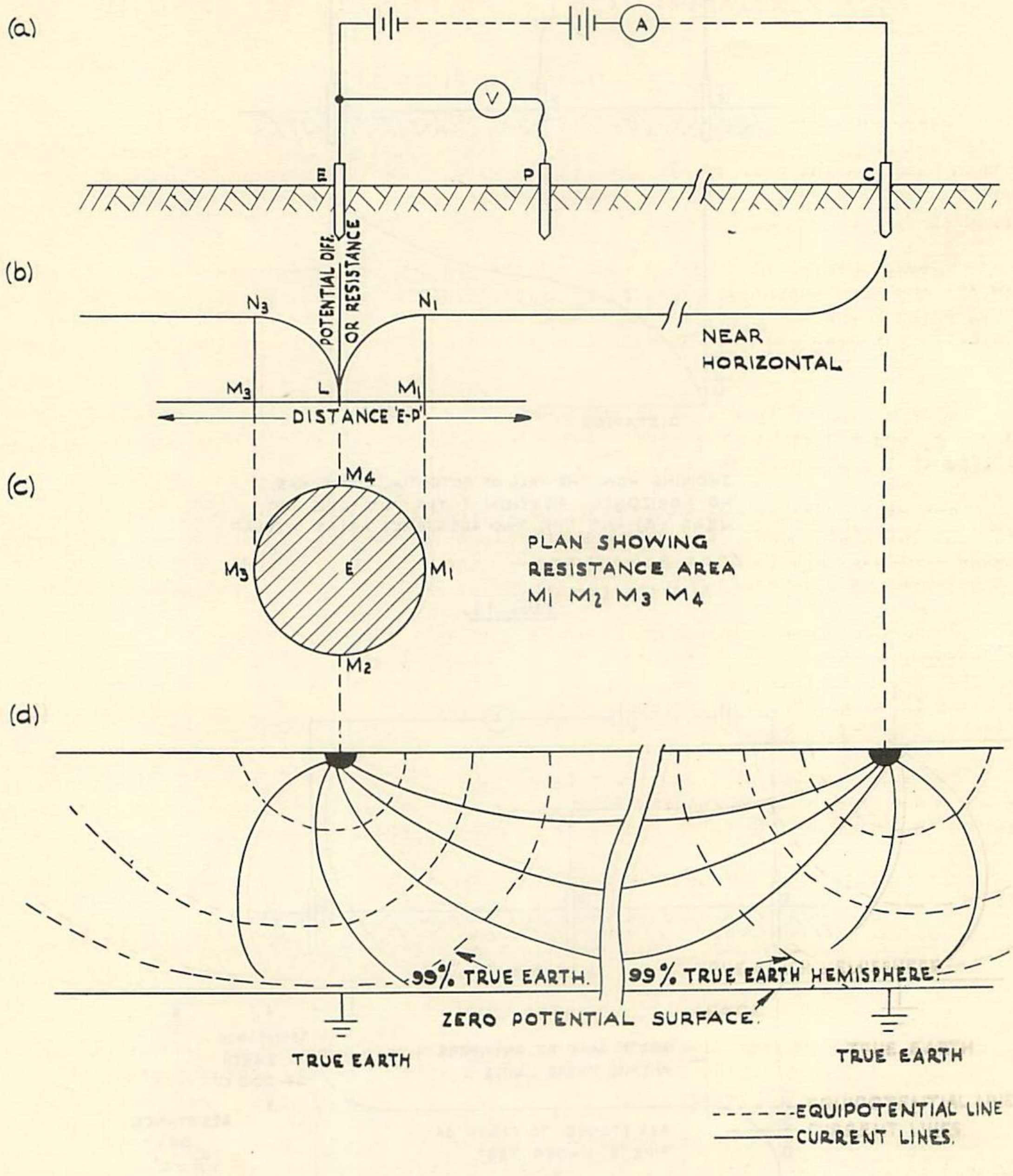
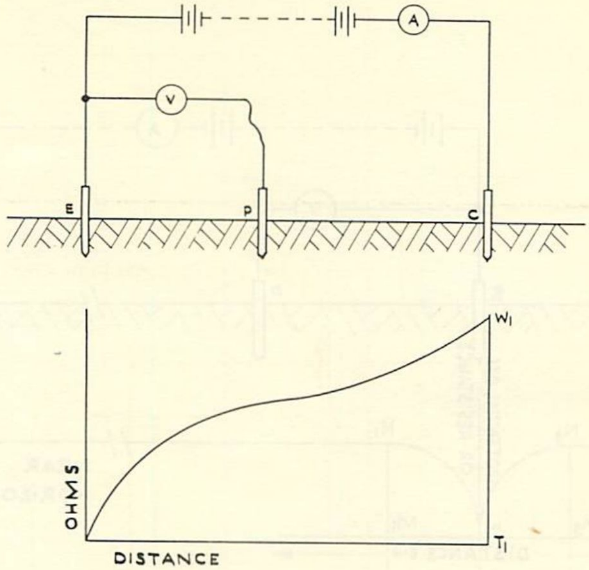
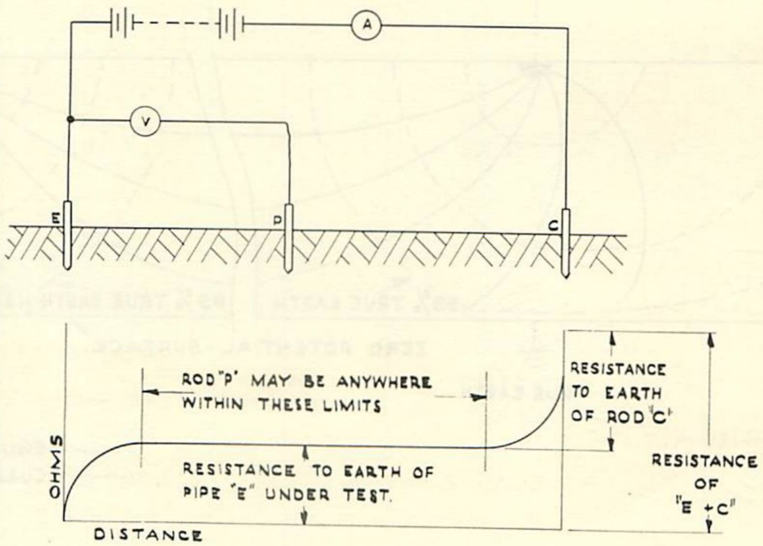

(a)
A
V
E
P
C
(b)
POTENTIAL DIFF. OR RESISTANCE
N3
N1
NEAR HORIZONTAL
M3
L
M1
DISTANCE 'E-P'
(c)
M4
M3
E
M1
M2
PLAN SHOWING RESISTANCE AREA M1 M2 M3 M4
(d)
99% TRUE EARTH.
99% TRUE EARTH HEMISPHERE.
ZERO POTENTIAL SURFACE.
TRUE EARTH
TRUE EARTH
EQUIPOTENTIAL LINE
CURRENT LINES.

FIG. 13.



SHOWING HOW THE FALL OF POTENTIAL CURVE HAS NO HORIZONTAL PORTION IF THE ROD (C) IS TOO NEAR (E) AND THE TWO RESISTANCE AREAS OVERLAP

FIG. 14.



EFFECT OF THE RESISTANCE AREA OF THE DISTANT ROD (C) ON THE FALL OF POTENTIAL CURVE.

FIG. 15.

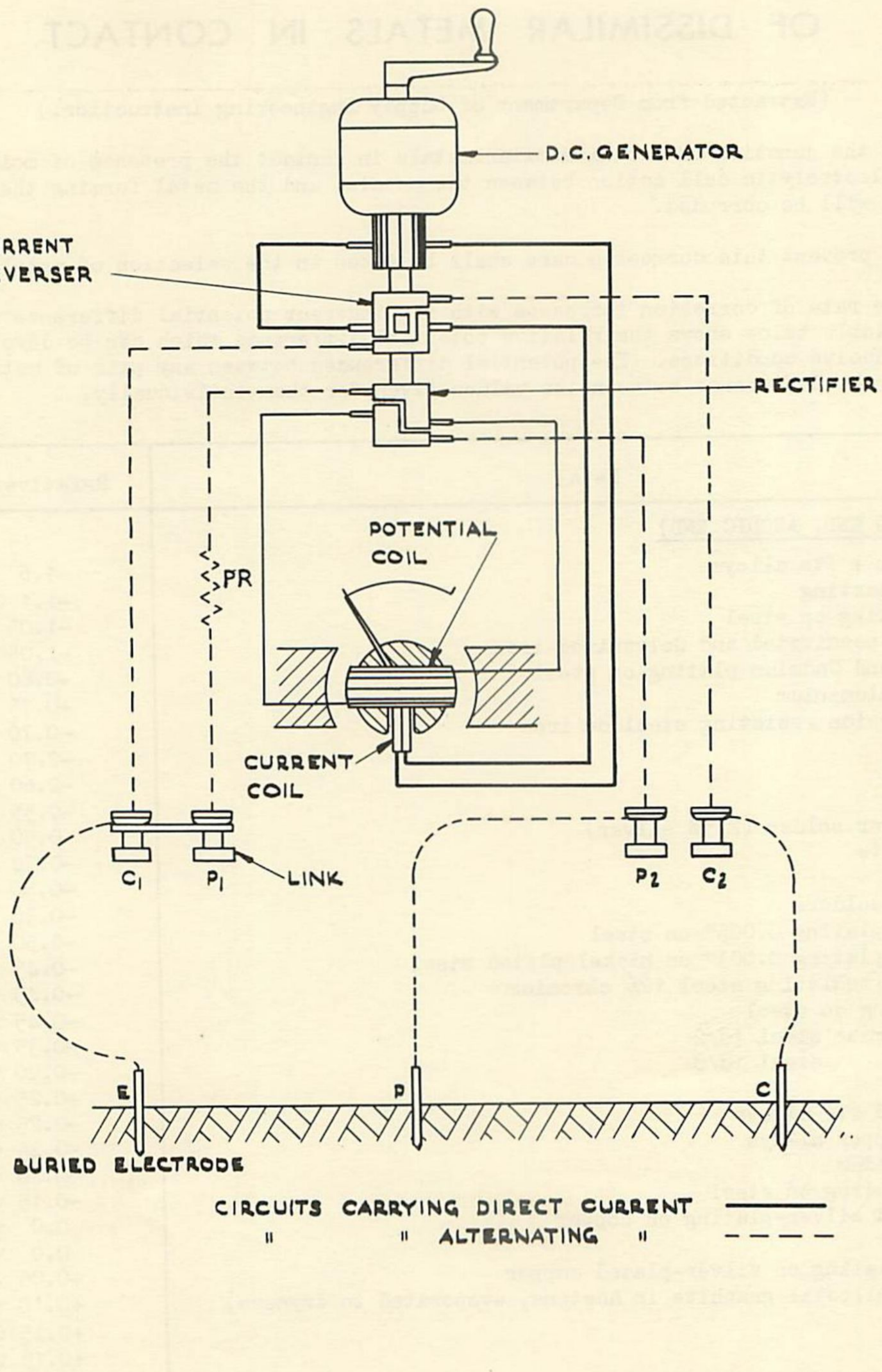

D.C. GENERATOR
CURRENT
REVERSER
RECTIFIER
POTENTIAL
COIL
PR
CURRENT
COIL
C1
P1
LINK
P2
C2
E
P
C
BURIED ELECTRODE
CIRCUITS CARRYING DIRECT CURRENT
" " ALTERNATING "

FIG. 16.

APPENDIX 5.

GALVANIC CORROSION CHARACTERISTICS OF DISSIMILAR METALS IN CONTACT.

(Extracted from Department of Supply Engineering Instruction.)

At the junction of two dissimilar metals in contact the presence of moisture will set up an electrolytic cell action between the metals, and the metal forming the anodic end of the cell will be corroded.

To prevent this corrosion care shall be taken in the selection of metals in contact.

The rate of corrosion increases with the inherent potential difference set up in the cell. The table below shows the relative potential difference which can be developed under certain conducive conditions. The potential differences between any pair of metals in contact is equal to the difference between the values given for them individually.

Metal	Relative Potential
(CORRODED END, ANODIC END)	
Magnesium + its alloys	-1.6 volts
Zinc diecasting	-1.1 volts
Zinc plating on steel	-1.05 volts
Chromate passivated and Galvanised iron	-1.05 volts
Cadmium and Cadmium plating on steel	-0.80 volts
Wrought aluminium	-0.75 volts
Non-corrosion resisting steel or iron	-0.70 volts
Cast iron	-0.70 volts
Duralumium	-0.60 volts
Lead	-0.55 volts
Lead-silver solder (2.5% silver)	-0.50 volts
Terne plate	-0.50 volts
Tin-plate	-0.50 volts
Tin lead solders	-0.50 volts
Chromium plating 0.005" on steel	-0.50 volts
Chromium plating 0.003" on nickel-plated steel	-0.45 volts
Corrosion resisting steel 12% chromium	-0.45 volts
Tin-plating on steel	-0.45 volts
High chromium steel 18/2	-0.35 volts
" " steel 18/8	-0.20 volts
Brasses	-0.25 volts
Copper and its alloys	-0.25 volts
Nickel-copper alloys	-0.25 volts
Silver solder	-0.20 volts
Nickel-plating on steel	-0.15 volts
Silver and silver-plating on copper	0.0 volts
Titanium	0.0 volts
Rhodium plating on silver-plated copper	+0.05 volts
Carbon (collòdial graphite in acetone, evaporated to dryness)	+0.10 volts
Gold	+0.15 volts
Platinium	+0.15 volts
(PROTECTED END, CATHODIC END)	

APPENDIX 6.

CORROSION CHARACTERISTICS OF CONNECTED EARTH SYSTEMS OF DISSIMILAR METALS.

(Based on Denki Kogyo Co., Japan, Tender Information for Phase 3 Stations.)

Metal B / Metal A	Area of Surfaces	Zinc	Aluminium	Iron	Brass	Copper
Zinc	Area of A < Area of B Area of A = Area of B Area of A > Area of B	(slight corrosion direction indefinite)	Marked in zinc Moderate in zinc Slight in zinc			
Aluminium	Area of A < Area of B Area of A = Area of B Area of A > Area of B	negligible in Al. negligible in Al. slight in Al.	(slight corrosion direction indefinite)	Marked in aluminium Moderate in aluminium Slight in aluminium		
Iron	Area of A < Area of B Area of A = Area of B Area of A > Area of B	negligible in Fe. negligible in Fe. slight in Fe.		(slight corrosion direction indefinite)	Marked in iron Moderate in iron Slight in iron	
Brass	Area of A < Area of B Area of A = Area of B Area of A > Area of B	negligible in brass negligible in brass slight in brass			(slight corrosion direction indefinite)	Marked in brass Moderate in brass Slight in brass
Copper	Area of A < Area of B Area of A = Area of B Area of A > Area of B	negligible in Cu. negligible in Cu. slight in Cu.				(slight corrosion direction indefinite)

NOTE:- As in Appendix 5, the two dissimilar metals will form an electrolytic cell, and the metal that will corrode is indicated in the table. The rate of corrosion will depend on the relative potential as well as the exposed area forming the electrodes of the cell.

END.