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ELECTRICAL PROTECTION GROUNDING FUNDAMENTALS

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1. GENERAL

1.1 This section provides to REA Borrowers, Engineers, and other interested parties technical information for use in the design, construction and operation of REA borrowers' telephone systems. The basic factors affecting earth resistivity and grounding are discussed. Information is also provided on the selection of an appropriate location for the installation of electrodes. Further, techniques are presented for measuring soil resistivity and resistance to ground of an electrode.

1.2 The term "ground", for the purposes of this practice, is defined as a conducting connection by which a circuit or equipment is connected to the earth. The connection is used for establishing and maintaining the potential of the earth, or approximately that potential, on the circuit or equipment connected to it. A "ground" consists of a grounding conductor, a bonding connector, its grounding electrode, and the soil in contact with the electrode.

1.3 Grounds have two basic uses in protection applications:

1.3.1 For natural phenomena, such as lightning, grounds are used to discharge the system of current before personnel can be injured or vulnerable system components can be damaged.

1.3.2 For foreign potentials due to faults in electric power systems with ground return, grounds aid in insuring rapid operation of the power system protective relays by providing additional low resistance fault current paths. This provides the means for the removal of the foreign potential as rapidly as possible. The ground should drain the foreign potential before personnel are injured or the telephone system damaged.

1.4 Ideally, a ground should be of zero ohms resistance. In reality, this value cannot be obtained due to the series resistances shown in Figure 1. Grounding theory and methods for obtaining a ground of the smallest practical resistance will be discussed in subsequent paragraphs.

2. PHENOMENA AFFECTING GROUND RESISTANCE

2.1 An electrode cannot be driven into the soil with the expectation of obtaining a good, low resistance ground. Many factors, both natural and man-made, may affect results. Some of the factors are described:

2.2 Earth Resistivity: The electrical resistivity of the earth (resistance of the earth to the flow of current) is of major importance. The unit of earth resistivity, the meter-ohm, is defined as the resistance, in ohms, between opposite faces of a cube of earth one cubic meter in volume. An alternate unit of measurement, the ohm-centimeter, is defined as the resistance in ohms, between opposite faces of a one-centimeter cube of earth. To convert meter-ohms to ohm-centimeters, multiply by the former by 100.

2.2.1 Earth resistivity varies over a considerable range. Within the United States it varies from a few meter-ohms along some coasts to many thousands of meter-ohms in rocky, mountainous country. Figure 2 provides very general data on average surface earth resistivity throughout the United States.

2.2.2 In addition to regional variations, earth resistivity may vary widely within very small distances due to local soil conditions. Table I lists typical ranges of earth resistivity for various soil types. This table should be useful in selecting locations at which a ground is to be constructed.

TABLE I: RESISTIVITY OF VARIOUS SOILS

SOIL	RESISTIVITY RANGE (meter-ohms)
Loam	5 - 50
Clay	4 - 100
Sand/Gravel	50 - 1,000
Limestone	5 - 10,000
Sandstone	20 - 2,000
Granite	1,000
Slates	600 - 5,000

2.3 Soil Moisture: Nearly any soil, with a zero moisture content, is an insulator. Fortunately, this condition is rarely encountered except in desert areas or during periods of extreme drought. Figure 3 illustrates the typical affect of moisture on soil resistivity. It should be noted that above 17% moisture by weight additional moisture has little effect. Below this figure resistivity rises rapidly until, at 2% moisture it reaches 100 times its value at 17% moisture. Thus, a good ground connection should always be in contact with soil having a ground water content in excess of 17%. Local well drillers should be able to provide information concerning the depth of the water table in their areas. Water content alone does not provide a good ground in many areas so do not be misled by moisture depth only.

2.4 Soil Mineral Content: Water with no mineral salt content is nearly as good an insulator as soil with no moisture content. Figure 4 illustrates the effect of mineral salt content on soil resistivity. Soils which lack adequate soluble mineral salts may be encountered from time to time. In this situation, chemically treating the soil surrounding the electrode may provide an acceptable ground. Refer to Appendix E.

2.5 Temperature: As the temperature of soil decreases, resistivity increases. When the soil temperature drops below the freezing point of water, resistivity increases rapidly, as shown in Figure 5.

3. CHARACTERISTICS OF VERTICAL ELECTRODES

3.1 Single Vertical Electrode Buried in Earth: The majority of ground electrodes installed in telecommunications systems consists of a single electrode driven vertically into the earth. An equation for calculating the approximate resistance to the flow of current away from the electrode is given in Appendix A, Paragraph 2.1. The resistance to ground with this type of electrode is dependent to a large degree upon the electrode length and to a lesser degree upon the electrode diameter.

3.2 Variation of Resistance With Depth: The theoretical resistance to ground for electrodes driven vertically into homogeneous soil has been calculated and plotted in Figure 6. These curves illustrate the resistance variation with length for electrodes of different diameters. The curves show that the electrode resistance to ground decreases rapidly during the first few feet it is driven into the earth. Theoretically there is little gained by driving an electrode more than 10 or 12 feet (3 to 3.7 meters). However, the earth resistivity sometimes decreases with increased depth since the earth is not homogeneous. Therefore, driving a deep test rod at the site of a proposed grounding system may sometimes provide valuable resistivity information. Electrodes should be driven well below the frost line so that the resistance to ground will not be greatly increased by freezing of the surrounding soil.

3.2.1 The condition of homogeneous soil is rarely encountered. The conditions illustrated in Figure 7 are more typical with soil that is in layers. Ground electrode resistance, under these conditions, will decrease with depth until the water table is reached. After that point the resistance decreases rapidly again as increasing lengths of rod are exposed to the moist soil.

3.2.2 The desirable electrode length is a balance between that which can be installed with reasonable effort and that which will produce the objective resistance value. The objective resistance for outside plant is typically 25 ohms or less, and for central offices 5 ohms or less. The possibility of electrode bending increases with electrode length.

3.2.3 Installation of 5-foot (1.5 meter) or 8-foot (2.4 meter) electrodes is normally easy. It may sometimes be more desirable to install several shorter electrodes, where space is available, than to attempt installation of one or more long electrodes (rods or pipes). Installation of multiple electrodes is likely to be the optimum choice at locations with rocky soil where frost or low water table are not a problem. Conversely, in areas of sand with a deep water table, a single long electrode might provide the best solution. The engineer should examine <u>all</u> factors and select the option best suited for a particular situation.

3.3 Variation of Resistance with Diameter: The theoretical resistance to ground of electrodes having different diameters and driven vertically into earth of homogenous soil has been calculated and plotted in Figure 8. These curves show the resistance variation with diameter for electrodes of different lengths. The curves show that the resistance decreases only slightly as the diameter of the electrode is increased. The volume of earth displaced as a ground electrode is driven into the earth increases as the square of the diameter. As a result, the effort required to install an electrode increases rapidly with increased diameter. Calculations show that two electrodes of equal diameter will provide a lower resistance to ground than a single electrode of twice that diameter. Based on this, an electrode of only sufficient diameter to withstand the strain of driving should be used.

3.4 Electrode Material: The material used for an electrode, based on the resistance to earth, is not important since almost all of the voltage drop is in the earth surrounding the electrode. Corrosion susceptibility of the material is a prime consideration. Studies show that copper will corrode less rapidly than iron. Further, corrosion of copper clad on galvanized iron is accelerated if the coating is imperfect or has become pitted so as to expose the iron. Base iron electrodes will be covered with a layer of oxide or rust within a short time. This layer of oxide or rust has been shown by test to be permeable to soil moisture and consists of particles forming the soil itself. The possibility of oxidization from the atmosphere is reduced when the electrodes are driven below the surface of the earth.

3.5 Multiple Vertical Electrodes Buried in Earth: There are locations where the objective resistance to earth is less than the value attainable with a single electrode. Among such locations might be the sites of carrier system repeaters, central office switching systems, remote switching terminals, concentrators, etc. <u>The installation of two or more electrodes connected in parallel provides a means of reducing the grounding system resistance</u>.

Multiple vertical electrode systems can be installed in a straight-line, circular, square, or rectangular configuration. The electrodes may be interconnected with either insulated or bare buried conductors. The specific grounding system design is usually based on the space available for installation and the desired objective.

3.6 Multiple Vertical Electrodes Buried in a Straight Line: Grounding systems of this type are typically used at locations in the field where installation must be completed along a road or within the limits of a narrow private right-of-way. Placing vertical ground electrodes with a separation of twice the electrode length will minimize the unwanted effect from the mutual resistance between electrodes on the grounding system.

3.6.1 Equations for calculating the approximate resistance to the flow of current away from two or more electrodes installed along a straight line are given in Paragraphs 2.2.1.1 and 2.2.1.2 of Appendices A (English) and B (Metric). The equation in Paragraph 2.2.1.1 should be used when the distance between the electrodes is equal to or greater than the electrode length. When the distance between electrodes is less than the electrode length the equation in Paragraph 2.2.1.2 should be used.

3.6.2 The approximate resistance (calculated for various numbers of multiple vertical ground electrodes in a straight line) due to spacing is illustrated in Figure 9. These curves provide the percentage of the single electrode resistance that can be expected by installing various numbers of vertical electrodes interconnected with insulated wire and separated by one-half, one, two and four times the electrode length. For example, a grounding system with a resistance to ground of 25 ohms or less is required at a carrier repeater location in an area having a mean earth resistivity of 200 meter-ohms. The grounding system will have to be placed in a straight line between the side of the road and the edge of the road right-of-way. The calculated approximate resistance to ground of a single 5/8 inch x 8 foot (1.6 cm x 2.4 m) electrode at the site is 79.8 ohms and of a single 5/8 inch x 16 foot (1.6 cm x 4.9 m) electrode is 44.4 ohms. The 25 ohm objective is 31.3 percent of the resistance to ground with a single 8 foot (2.4 m) electrode and 56.3 percent of a single 16 foot (4.9 m) electrode resistance to ground. The 31 percent horizontal line in Figure 9 intersects the 1ℓ curve between the vertical lines designating four and five electrodes. Thus, with a distance between the electrodes equal to the length of a single 8 foot (2.4 m) electrode, the installation of five electrodes in a straight line should provide a resistance to ground less than the 25 ohm objective. Extending the electrode separation to twice the single electrode length reduces the requirement to four since the 2ℓ curve is intersected between the three and four electrode vertical lines. This design would reduce the number of electrodes by one but increase the interconnecting wire required from 32 feet (9.75 m) to 48 feet (14.6 m). Following the same procedure for the 56.3 percent of a 16 foot (4.9 m) electrode shows there is some possibility that two electrodes with a separation equal to the electrode length will provide 25 ohms resistance to ground. If the measured resistance to ground after installation was greater than 25 ohms, addition of a third electrode with the same separation should produce an acceptable resistance to ground.

3.7 Multiple Vertical Electrodes Buried in a Ring: Ring grounding systems may be installed in a square, rectangular, or circular configuration. Systems of this type are typically installed at central office and other locations where sufficient area is available for installation of the grounding system. One form of ring ground is around the perimeter of a central office building. The perimeter ground configuration is also used for concentrators and remote switching terminals housed in buildings.

3.7.1 An equation for calculating the approximate resistance to the flow of current away from four or more electrodes installed in a ring configuration is given in Paragraph 2.2.2 of Appendices A (English) and B (Metric).

3.7.2 The approximate resistance variation due to spacing calculated for various numbers of vertical electrodes in a ring configuration is shown in Figure 10. These curves provide the percentage of the single electrode resistance that will be attained by installing various numbers of vertical electrodes interconnected with insulated wire and separated by various distances, i.e., one-half, or two times the electrode length. The curves are applied in the same manner as the curves of Figure 9 which were discussed in Paragraph 3.6.2.

3.8 Multiple Vertical Electrodes Buried in a Rod Bed: Ground systems of this type are usually installed to complement a horizontal grid of buried bare wire. The principal application of these systems is for grounding electrical power stations and substations where it is essential to provide a low resistance to ground and minimize voltage gradients along the earth's surface.

3.8.1 The equation for calculating the approximate resistance to ground for a multiple buried vertical electrode rod bed is given in Paragraph 2.2.4 of Appendices A (English) and B (Metric).

3.8.2 The approximate resistance to ground calculated for various numbers of vertical electrodes in rod beds of selected sizes is shown in Figure 11. The curves show the resistance to ground for electrodes interconnected with insulated wire. Points are identified on each curve indicating the number of electrodes that provides a perimeter ground and a full rod bed where the electrode separation is ten feet (three meters) or greater.

3.8.3 Study of the curves in Figure 11 shows that the maximum reduction in resistance to ground is nearly achieved when the electrodes are placed around the perimeter of an area. Placing additional rods inside the perimeter to complete the rod bed will reduce the overall resistance to ground four tenths of an ohm, or less. This provides confirmation that rod beds, while valuable for control of step and touch potentials along the earth's surface, do not provide significant improvement of the overall resistance to ground.

Note: Step potential is defined as the voltage differential between two points on the ground separated by the distance of one pace, which is assumed to be 3 feet (1 meter). Touch potential is defined as the voltage differential between both feet on the ground and an object that can be touched with a hand.

3.8.4 Increasing the area perimeter does not provide a significant improvement of the overall resistance to ground. For example, changing a 20 x 20 ft. (6 x 6 m) to a 30 x 30 ft. (9 x 9 m) square is a 125 percent increase in area which will reduce the resistance to ground by 26.5 percent. A significant improvement of the overall resistance to ground is defined as a reduction that lowers the resistance below the objective value. The final 5.2 ohms ground of this example will not meet the 5.0 ohm central office objective while the original 7.1 ohms is less than 25 ohms (See TE&CM Section 810).

4. CHARACTERISTICS OF HORIZONTAL ELECTRODES

4.1 Horizontal Electrode Buried in Earth: Installation of vertical ground electrodes is not always practical at locations where grounding systems are required. A horizontal ground electrode provides an effective alternative. The horizontal electrode might be a ground rod or, more typically, a length of bare copper wire buried in the earth. Where a horizontal electrode is used in lieu of a vertical electrode, burial depth should be below the deepest frost penetration. (Reference Paragraph 2.5). Horizontal electrodes are often used to interconnect a system of multiple vertical electrodes for further reduction of the overall system resistance to ground. A horizontal electrode configuration can be either a straight line, a ring, or perimeter (square, circular, or rectangular), a grid (square or rectangular), or a star radiating from a single point.

4.2 Horizontal Electrode Buried in a Straight Line: Grounding systems of this type are utilized at locations where vertical electrodes cannot be installed along a narrow path, such as a road right-of-way, due to a shallow rock substructure. (Another common configuration is the interconnection of a series of vertical electrodes installed in a straight line.) The equation for calculating the approximate resistance to ground of a horizontal electrode buried in a straight line is given in Paragraph 3.1 of Appendices A (English) and B (Metric). The approximate resistance to ground calculated for various lengths of #2 solid copper wire buried in a straight line is shown in Figure 12.

4.2.1 The electrode diameter has minimal effect on the resistance to ground of a buried horizontal electrode but is of major importance to the physical strength of the configuration. The calculated approximate resistance of straight horizontal electrodes of different lengths for different wire sizes is illustrated in Figure 13.

4.2.2 There is no significant reduction of the horizontal electrode resistance to ground from increased burial depth at the commonly used depths for buried wire grounding systems in the telecommunications industry.

Greater reduction can be attained with a deep buried horizontal electrode but this is neither practical nor economical. The calculated resistance of horizontal electrodes buried at various depths is shown in Figure 14.

4.3 Horizontal Electrode Buried in a Ring: A common application for a buried horizontal electrode in a ring configuration is the interconnection of a ring of buried vertical ground electrodes installed around the perimeter of a central office building. Two equations for calculating the approximate resistance to ground of a buried bare wire ring are given in Paragraphs 3.2.1 and 3.2.2 of Appendices A (English) and B (Metric). The equation from Paragraph 3.2.1 is convenient for calculating the resistance to ground of a square or rectangular ring configuration. Calculation of the resistance to ground with a circular ring configuration is more convenient by the equation given in Paragraph 3.2.2 of the Appendices.

4.3.1 The approximate resistance to ground calculated for buried wire rings with various perimeter lengths is shown in Figure 15. Curves for three wire sizes are provided to illustrate the small resistance variation relative to conductor size. Resistance to ground variations with burial depth for ring configurations are similar to those for straight horizontal electrodes discussed in Paragraph 4.2.2 and illustrated in Figure 14.

4.3.2 The resistance to ground of a buried wire ring is greater than that of a straight buried wire of the same length. This difference is illustrated in Figure 16. The resistance to ground of a wire ring with an 80 foot (24 meter) perimeter is about 9 percent greater than that of a straight wire of the same length.

4.4 Horizontal Electrodes Buried in a Radial Configuration: Buried radially extending bare wire grounding systems are employed typically for protecting radio antenna tower installations. These systems may also be used for protecting similar installations where it is convenient to extend the grounding conductors radially from a common point. Radial grounding systems have the advantage of a lower initial surge impedance to lightning surge currents (relative to the direct current resistance) than a single or group of parallel horizontal wires.

4.4.1 Equations for calculating the approximate resistance to ground for bare wires buried in a radial configuration are given in Paragraphs 3.4.1 thru 3.4.4, of Appendices A (English) and B (Metric). These provide for the calculations for the following:

Three-branched Star	- Paragraph 3.4.1
Four-branched Star	- Paragraph 3.4.2
Six-branched Star	- Paragraph 3.4.3
Six-or more branched Star	- Paragraph 3.4.4

4.4.2 The approximate resistance to ground calculated for buried bare wire radial ground systems with various numbers and lengths of conductors is shown in Figure 17. These curves show there is little advantage in designing a radial grounding system with more than six branches.

4.5 Horizontal Electrodes Buried in a Grid Configuration: Grounding systems of this design are commonly used at locations where it is essential to minimize voltage gradients along the earth's surface. The grid configuration is most frequently used for grounding systems associated with electric power stations and substations. A typical design consists of a grid of horizontal electrodes solidly connected at each crossing installed at or close to the earth's surface. The resistance to ground of a grid depends mainly on the area covered by the grid and to a lesser extent on the total length of wire used in constructing the grid.

4.5.1 The equation for calculating the approximate resistance to ground for a buried bare wire grid is given in Paragraph 3.3 of Appendix A (English) and Appendix B (Metric).

4.5.2 The approximate resistance to ground calculated for bare wire grid grounding systems for different grid sizes with various total wire lengths is illustrated in Figure 18. These curves show there is no significant reduction of the resistance to ground when a buried wire perimeter grounding system is converted to a grid system of the same area. For example, Curve E of Figure 18 is for a 900 square foot (84 square meter) buried wire grounding system. The perimeter ground conductor is 120 feet (37 meters) long and as shown by the X at the left end of the curve has a resistance to ground of about 6 ohms. Adding 300 feet (91 meters) of buried conductor will convert the perimeter ground to a grid of 5 foot (1.5 meter) squares. The resistance to ground will be about 5.5 ohms. The buried conductor length has been increased by 250 percent to obtain an 8 percent reduction in resistance to ground. The 0.5 ohm reduction will not significantly improve the performance of the grounding system so there is no justification for the additional wire.

5. MUTUAL RESISTANCE BETWEEN VERTICAL AND HORIZONTAL ELECTRODES

5.1 The vertical electrodes of a grounding system are usually interconnected with buried bare horizontal electrodes. The net combined resistance to ground of the vertical and horizontal electrodes will be greater than the calculated parallel resistance but less than the resistance of either electrode system alone. This is due to the interaction between the electrodes called mutual resistance. The contribution to total resistance from this mutual resistance is addressed in Paragraph 6.

5.2 Mutual Resistance, Vertical Electrodes in a Straight Line: The approximate mutual resistance between vertical ground electrodes placed in a straight line and an interconnecting buried bare wire may be calculated by the equation in Paragraph 4.2 of Appendices A (English) and B (Metric). The wire length for this equation is the total conductor distance between the first and last vertical electrode.

5.3 Mutual Resistance, Vertical Electrodes in a Ring: The equation for calculating the approximate mutual resistance between a ring of vertical ground electrodes and interconnecting buried bare wire is given in Paragraph 4.3 of Appendices A (English) and B (Metric). Wire length for this equation is the total length of the ring.

5.4 Mutual Resistance, Rod Bed of Vertical Electrodes: The equation for calculating the approximate mutual resistance between a rod bed of vertical electrodes and a grid of interconnecting buried bare wire is given in Paragraph 4.4 of Appendices A (English) and B (Metric). This equation does not include the insignificant influence of the horizontal electrode depth. The wire length is the total length required to form the grid.

6. COMBINED RESISTANCE OF VERTICAL AND HORIZONTAL ELECTRODES

6.1 The combined parallel resistance to ground for vertical electrodes interconnected with bare wire may be calculated by the equation in Paragraph 5.1 of Appendices A (English) and B (Metric). A guide is provided in Paragraph 5.2 of the Appendices showing the appropriate equations for calculating the resistance to ground with various grounding system configurations.

6.2 Combined Resistance of Vertical and Horizontal Electrodes in a Straight Line: The approximate resistance to ground variation calculated for multiple vertical ground electrodes placed in a straight line and interconnected with buried bare horizontal conductors is shown in Figure 19. The combined resistance is given as a percentage of the resistance to ground for a single electrode.

6.3 Combined Resistance of Vertical and Horizontal Electrodes in a Ring: The calculated approximate resistance to ground variation for multiple 1 in. x 10 ft. (2.54 cm x 3 m) vertical ground electrodes placed in a square, rectangular, or circular ring and interconnected with buried bare horizontal conductors is illustrated in Figure 20. The combined resistance is given as a percentage of the resistance to ground for a single electrode. A set of curves could not be produced that would apply to all electrode dimensions due to the effects of mutual resistance with ring configurations.

6.4 Combined Resistance of Vertical and Horizontal Electrodes in a Grid: The approximate resistance to ground calculated for rod beds of various area and interconnected with a grid of buried bare horizontal conductors is shown in Figure 21. The curves show that due to the mutual resistance effects adding vertical electrodes to a grounding grid does not produce a significant reduction of the overall resistance to ground. Grounding grids are usually installed near the earth's surface since the principal purpose is to control step and touch potentials. This location is well above the frost line in colder parts of the country. During the winter months the grid resistance to ground will increase significantly. Vertical electrodes installed to a depth well below the frost line in these areas will insure maintaining a low resistance during the periods when the ground is frozen.

7. DESIGN OF CENTRAL OFFICE GROUNDING SYSTEMS

7.1 The ground electrode system establishes the electrical connection between the central office facility and the earth. This connection is essential for lightning protection, power fault protection, and to a lesser degree, the minimization of noise. The system should be tailored for the physical characteristics of the site and the objective resistance to ground. A grounding system must be properly installed; follow-up action is essential to assure the system continues to provide a low resistance connection to ground throughout the office's life. The procedure for achieving these objectives is as follows: first, determine the physical and electrical properties of the site; second, design an electrode system appropriate for the site; third, install the system in accordance with recommended procedures, and; finally, measure the resistance to ground of the completed system to verify that the objectives have been met. Then periodically measure the resistance to ground of the completed system to insure the objectives continue to be met.

7.2 Site Survey: A thorough survey of the proposed grounding electrode system site should be conducted before starting the design. The survey should determine the soil resistivity and any significant geological features that might influence the design. Local climate effects should also be reviewed. If a building is already in place, review architectural and landscape features that might influence the system design. Ideally, this survey should be conducted before the final site selection so that troublesome locations can be avoided.

7.2.1 Soil Resistivity: The initial step of a site survey is the measurement of soil resistivity at <u>several</u> points in the area occupied by and surrounding the central office building. For small sites up to 2500 square feet (232 square meters), complete one measurement at the center of the site and at each of the four corners as shown in Figure 22. At each of the locations a measurement should be made with 12 foot (4 meter) and 22 foot (7 meter) probe spacing. The recorded results of the <u>five</u> readings with each probe spacing are averaged to obtain the soil resistivity for the site. The method for measurement of earth resistivity is discussed in Appendix C. For larger sites, divide the area into two or more smaller areas with sides of 50 feet (15.2 meters) or less. Complete earth resistivity measurements at each corner and at the center of each smaller area as described above. Two examples of larger sites are illustrated in Figure 23. Average the recorded results of all measurements for each probe spacing to obtain the soil resistivity for the site.

7.2.2 Geological Features: Attempt to identify the presence of geological features at the site that might influence the grounding system design. Such features include the distribution of major soil types, major rock formations, and depth of water table. Information relating to the geological structure of an area can be obtained from local construction companies, well drillers, utilities (gas, water, and power), and local maps and site inspections. Test borings can be utilized when adequate information is not available from other sources. Review this information to determine the presence of factors that may influence the design or installation of the grounding system.

7.2.3 Physical Features: Identify other physical features that might influence the location, shape or type of grounding system. Study the planned or existing location of the building(s) or structure(s) together with the location of existing and proposed parking lots, paved roadways, and sidewalks. Buried structures, such as pipes or tanks, should also be located.

7.2.4 Climate Conditions: Determine the annual amount and seasonal distribution of rainfall, the relative incidence of lightning, and the typical soil depth of freezing (frost line) for the area. Rainfall and frostline information is available from the local weather service. The relative lightning incidence can be obtained from the isoceraunic map in REA TE&CM Section 801.

7.3 Design Procedure

7.3.1 Grounding System Configuration: Determine the type of grounding system appropriate for the office building and property on which it is located. A perimeter grounding system, installed around the outside building walls, is recommended. Electrodes should be placed at a 3 feet (1 meter) or greater distance from the outside wall of the building foundation and outside the drip line to insure wetting of the earth surrounding the electrodes by precipitation. Major portions of the grounding system should not be located under paved areas such as roads, parking lots, or sidewalks. The location of the building relative to property lines may make installation of a perimeter ground impractical. The property should be studied further to determine the area available for installation of the grounding system and the configuration best suited to the area. As previously mentioned, perimeter configuration is recommended even if the proposed grounding system will not be installed around a building. Installation of additional ground rods to convert a perimeter to a rod bed grounding system will not produce a significant reduction of the overall resistance to ground. This is due to the increasing mutual effects between the electrodes as they are added inside the perimeter. For example, consider a grounding system of 16, 5/8 inch by 10 foot (1.6 centimeter by 3 meter) electrodes, interconnected with insulated wire, installed around the perimeter of a 1600 square foot (148.6 square meter) area. Assuming a 200 meter-ohm earth resistivity, the calculated resistance to ground is 8.2 ohms. Addition of 9 electrodes will convert the perimeter system to a square rod bed containing 25 electrodes with 10 foot (3 meter) separation between electrodes. The calculated resistance to ground for the rod bed is 7.2 ohms. This one ohm reduction of the resistance to ground generally would not justify the added cost of installing nine additional electrodes and the wire required to interconnect them. Further, if bare #2 conductors are utilized for interconnecting the electrodes, both configurations have a calculated resistance to ground of 7.2 ohms. Installation of a rod bed array should be limited to locations where control of step-potentials is required.

7.3.2 Calculation of Earth Resistance: Once the appropriate configuration is chosen, the number and size of electrodes should be determined for the initial calculation of the anticipated system resistance to ground. The minimum electrode diameter is 5/8 inch (1.6 centimeter). This is practical for most installations. Electrodes 1 inch (2.54 centimeters) in diameter are recommended, where the soil is extremely hard, to resist bending of the electrode during installation. The electrode length selected is based on three factors:

1. The depth of rock formations in the area determines the maximum depth that an electrode can be driven into the earth. The electrode length selected for the initial resistance to earth calculation will typically be shorter than this maximum depth. When an acceptable resistance to ground cannot be attained in the available area with electrodes driven to the rock depth, a well drilled through the rock formation is an alternative.

2. Where the depth of the water table is near the surface with only small variation from year to year, selection of an electrode length that will penetrate to a depth five feet (1.5 meters) below the lowest water table level is appropriate. This insures that the electrodes will be in contact with moist soil.

3. The frost line depth is an important factor for determination of electrode length. Earth resistivity will increase three to four hundred percent as the earth freezes (Reference Figure 5). For example, an electrode measuring 35 ohms to ground in the summer is located in an area where the frost line penetrates to a depth of one-half the electrode length. During the winter when the earth is frozen the resistance to ground will increase to about 87 ohms. The portion of total electrode length that extends below the frost line should have a calculated resistance to ground meeting the desired objective (when the portion of electrode length above the frost line is disregarded). Further, buried bare conductors interconnecting the vertical electrodes should not be included in calculations of resistance to ground in areas where the frost line exceeds a depth of 12 inches (30.5 centimeters). The goal is to provide a grounding system that will meet the objective resistance to ground during the entire year.

7.3.2.1 The initial calculation of the grounding system resistance to ground should, where possible, be based on a spacing between electrodes of twice the electrode length. If the calculated resistance to ground meets the design requirement, the design may be implemented. When the objective resistance to ground is not met, alternate configurations should be considered. There are two alternatives available when a spacing of twice the electrode length is used initially. One is to double the length of the electrode and the second is to add electrodes of the initial length to reduce the spacing to the electrode length. The average earth resistivity at depths equal to the proposed electrode lengths will determine the best alternative.

7.3.2.2 To illustrate this design procedure, assume that a 40 foot x 60 foot (12.2 meter x 18.3 meter) rectangular configuration, as shown in

Figure 24, will accommodate a perimeter grounding system around a proposed central office building. Also, assume that the soil resistivity measurements made during the site survey show an average resistivity of 600 meter-ohms to a depth of 12 feet (3.7 meters) and 200 meter-ohms to a depth of 22 feet (6.7 meters). In addition, the site survey indicated that all rock formations are at depths greater than 25 feet (7.6 meters); the water table never drops below 6 feet (1.8 meters); and the frost line extends only 1 foot (0.3 meters) below the surface. Therefore, 10 foot (3 meter) electrodes are selected for the initial evaluation. An electrode diameter of 5/8 inch (1.6 centimeter) may be used since the soil is soft. The design steps follow:

1. Determine the resistance to ground of a single ground electrode of the selected size from Figures 25, 26, or 27 depending on electrode size. The resistance to ground for a 5/8 inch x 10 foot (1.6 centimeter x 3 meter) electrode in 600 meter-ohm soil is obtained from Figure 26. Since the curve for 10 foot (3 meter) length does not intersect the 600 meter-ohm line, divide 600 by 10 and determine the resistance to ground for the electrode in 60 meter-ohm soil. This value is about 19.9 ohms, which, multiplied by 10, equals 199 ohms, the desired 600 meter-ohm value.

2. Assume an initial spacing of 20 feet (6.1 meter) or twice the electrode length between electrodes. Figure 24 shows that 10 electrodes are required to provide the perimeter ground. Use Figure 10 to determine the equivalent value of the resistance of one electrode that is produced by 10 electrodes in parallel. The answer is about 13 percent. Thus the expected resistance of 10 electrodes in 600 meter-ohm soil is:

$$R = 199 \times 0.13 = 25.9 \text{ ohms}$$

While the objective resistance to ground for a central office grounding system is 5 ohms or lower, a system with a resistance to ground of 25 ohms or lower is acceptable where the resistance cannot <u>economically</u> be reduced to meet the objective. This configuration exceeds 25 ohms so an alternate configuration should be considered.

3. There are <u>two</u> alternatives readily available based on the same physical dimensions. One is to place 10 additional electrodes, reducing the spacing to the electrode length. Figure 10 shows that 20 electrodes in 600 meter-ohm soil will have an expected resistance to ground of about 9.1 percent of that of a single electrode.

$$R = 199 \times 0.091 = 18.1 \text{ ohms}$$

The 18.1 ohms resistance to ground is less than 25 ohms and is acceptable <u>unless</u> there is a means to provide a lower resistance with essentially the <u>same</u> expenditures. The <u>second</u> alternative should <u>also</u> be studied before making a final decision.

4. The second alternative is to place electrodes twice the initial length providing a system of 10 electrodes with the spacing equal to the

length of the electrode. The earth resistivity at the greater depth is 200 meter-ohms and from Figure 26 the resistance to ground of a 5/8 inch x 20 feet (1.6 centimeter x 6.1 meter) electrode in 200 meter-ohm soil is 36.8 ohms. From Figure 10, the resistance to ground of 10 electrodes with spacing equal to the electrode length is about 16 percent that of a single electrode.

$$R = 36.8 \times 0.16 = 5.9 \text{ ohms}$$

The second alternative design will provide a grounding system having an expected resistance to ground near the 5 ohm objective. Since there should be little difference in the cost of installing either of the two alternative designs the second is recommended for installation.

7.3.3 Ideal sites will not always be encountered. For example, had the water table been deeper in the area of the illustration discussed in Paragraph 7.3.2.2 (causing higher earth resistivity) it would not have been possible to provide a grounding resistance of 25 ohms. Where there is not sufficient property available for enlarging the grounding system, it may be necessary to drill a well that extends below the lowest yearly water table level.

8. DESIGN OF ISOLATED GROUNDING SYSTEMS

8.1 An isolated ground electrode system establishes the electrical connection between electronic equipment and the earth. These systems are typically installed along cable routes at the location of span line and voice frequency repeaters, carrier terminal equipment, and small-enclosure mounted concentrator equipment. This grounding connection is vital for lightning and power fault protection. The system should be tailored for the physical characteristics of the site and the objective resistance to ground. A grounding system must be properly installed and periodic measurement is essential to assure the system continues to provide an acceptable connection to ground. The procedure for achieving the objectives are as follows: first, determine the physical and electrical properties of the site; second, design an electrode system appropriate for the site; third, install the system in accordance with recommended procedures, and; finally, measure the resistance to ground of the completed system to verify that the objectives have been met.

8.2 Site Survey: Before starting the design, a thorough survey should be conducted at the site where the ground electrode system is to be installed. This survey should determine the soil resistivity and any significant geological features that might influence the design. The majority of isolated grounding systems will be located along roadways or private right-of-ways. This limits the design options available.

8.2.1 Soil Resistivity: The initial step of the site survey is the measurement of soil resistivity at several points over the area available for the grounding system. Where the corridor along which the telecommunications cable is placed has a width of 10 feet (3 meters) or greater, two designs can be considered. One design is a four-branch star configuration of buried bare wire with a vertical electrode installed at the end of each branch. The second design is a straight line configuration with the vertical electrodes installed parallel to the right-of-way boundary. Earth resistivity measurements should be completed so that either design can be considered for implementation. At each point, measurements should be made with 12 foot (4 meter) and 22 foot (7 meter) probe spacing. The method for measuring earth resistivity is discussed in Appendix C.

8.2.2 Geological Features: Attempt to identify the presence of geological features at the site that might influence the grounding system design. Such features include the distribution of major soil types, major rock formations, and depth of water table. Information relating to the geological structure of an area can be obtained from local construction companies, well drillers, utilities (gas, water, and power), local maps, and site inspections. Review this information to determine the presence of factors that may influence the design or installation of the grounding system.

8.2.3 Physical Features: Identify other physical features that might influence the location, shape or type of grounding system. Study the location of existing or proposed roadways and drainage systems. Buried structures in the area, such as pipes, power conductors, and communication cables should be precisely located.

8.2.4 Climatic Conditions: Determine the annual amount and seasonal distribution of rainfall, the relative incidence of lightning, and the typical depth of freezing (frost line) for the area. Rainfall and frostline information is available from the local weather service. The relative incidence of lightning can be obtained from the isoceraunic map in REA TE&CM Section 801.

8.3 Design Procedure

8.3.1 Grounding System Configuration: Determine the type of grounding system appropriate for the area available for the installation. The area in which isolated grounding systems are typically installed limits design flexibility. Isolated grounding systems are usually required at points along a telecommunications cable route. These routes may be located along a roadway in either public or private right-of-way or along private right-of-way not adjacent to a traveled roadway. Thus, the use of some form of elongated system is indicated. A series of two or more vertical electrodes installed parallel to the public or private right-of-way may provide an acceptable grounding electrode. Although there exists no theoretical limit to the number of vertical electrodes that may be placed in a straight line, there may be some practical limits. Eight to ten electrodes is a reasonable maximum number of electrodes in a straight line. Where the width is 10 feet (3 meters) or greater, a rectangular configuration might be used. If the installation is adjacent to a roadway, the rectangular configuration should not be considered where one side would be placed at the edge of a drainage ditch (where it might be damaged during road maintenance). The specific grounding system will be determined during calculations of resistance to ground.

8.3.2 Calculation of Resistance to Ground: The first step in calculating the resistance to ground is to determine the number and size of electrodes that will provide the objective system resistance to ground. The minimum electrode diameter is 5/8 inch (1.6 centimeter) (this is practical for most installations). When the soil is extremely hard, electrodes 1 inch (2.54 centimeter) in diameter are recommended to resist bending of the electrode during installation. The electrode length selected is based on three factors:

1. The depth of rock formations in the area determine the maximum depth that an electrode can be driven into the earth. The initial electrode length selected will typically be less than the maximum available depth.

2. Where the water table is near the surface with only small variation from year to year, selection of an electrode length that will penetrate to a depth 5 feet (1.5 meters) below the lowest water table level is appropriate. This insures that the electrodes will be in contact with moist soil.

3. The frost line depth is an important factor for determination of electrode length. Earth resistivity will increase three to four hundred percent as the earth freezes (Reference Figure 5). Buried bare conductors interconnecting the vertical electrodes should not be included in calculations of resistance to ground in areas where the frost line exceeds a depth of 12 inches (30.5 centimeters). The goal is to provide a grounding system that will meet the objective resistance to ground during the entire year.

8.3.2.1 The objective resistance to ground for a grounding system protecting electronic equipment installed at a location remote from the central office is 25 ohms. The majority of isolated ground electrode systems will be located along road or private right-of-ways. This limits the design to a series of electrodes in a straight line along the right of way. The use of spacing between the electrodes equal to the electrode length is recommended.

8.3.2.2 To illustrate this design procedure, assume a grounding system for the protection of a span line repeater along a road right of way. Further, assume that soil resistivity measurements made during the site survey show an average resistivity of 400 meter-ohms to a depth of 12 feet (4 meters) and 250 meter-ohms to a depth of 22 feet (7 meters). In addition, the site survey indicated that no rock formation in the area will interfere with the installation of electrodes to either depth; the water table is about 30 feet (9 meters); and the frost line extends 1.5 feet (0.5 meter) below the surface. A 5/8 inch (1.6 centimeter) diameter electrode may be used since the soil is soft. A 10 foot (3 meter) electrode is selected for the initial calculation. The design steps follow:

1. Determine the resistance to ground of a single 5/8 inch x 10 foot (1.6 centimeter x 3 meter) electrode in 400 meter-ohm soil from Figure 26. Since the curve for a 10 foot (3 meter) length does not intersect the 400 meter-ohm line, divide 400 by 10 and determine the resistance to ground for the electrode in 40 meter-ohm soil. This value is about 13.2 ohms, which, multiplied by 10, equals 132 ohms, the desired 400 meter-ohm value.

2. Determine what percentage of the resistance to ground of a single electrode equals the objective resistance to ground (25/132 x 100 = 18.9%). Use Figure 9 to determine the number of 10 foot (3 meter) electrodes that will provide a resistance to ground of 25 ohms or less. The horizontal line representing 18.9 percent intersects the curve ($s = 1\ell$) just beyond the vertical line indicating 8 electrodes. This shows that a grounding system with 9 electrodes extended in a straight line is expected to provide a resistance to ground less than 25 ohms. The system would extend 80 feet (24 meters) and require at least that length of wire for interconnection. An alternate plan should be studied to determine if the system could be installed more economically.

3. Determine the resistance to ground of a single 5/8 inch x 20 foot (1.6 centimeter x 6 meter) electrode in 250 meter-ohm soil. From Figure 26, this is 46 ohms. The objective ground resistance is 100 times 25 divided by 46 equals 54.3 percent of the single electrode resistance to ground. Use Figure 9 to determine the number of 20 foot (6 meter) electrodes that will provide a resistance to ground of 25 ohms, or less. The horizontal line representing 54.3 percent intersects the curve between the vertical lines indicating two and three electrodes, respectively. Thus, a grounding system with three 20 foot (6 meter) electrodes extended in a straight line should provide a resistance to ground of less than 25 ohms. This system would extend 40 feet (12 meters) and require at least that length of wire for interconnection. This plan is more economical and should be recommended for installation.

8.3.3 Ideal sites for isolated grounding systems will not always be available. Since the location of the electronic equipment to be protected is determined by the transmission facility to which it is connected only minor relocation is possible. Thus, relocation to a more desirable site may be impossible. Where the expense of drilling a well cannot be justified, in extremely rocky terrain the burial of horizontal electrodes at a depth below the frost line may be the only means of providing adequate protection.

9. INSTALLATION PROCEDURES

9.1 The installation of the electrode system should be scheduled so that needed excavation, such as hole and trench digging, can be performed while other excavating associated with building construction is in progress. If the system is installed prior to other earth moving operations, necessary precautions should be taken to assure the components are not damaged.

9.2 Wire provided for interconnection of vertical electrodes should be buried at least 2 feet (0.6 meter) below grade level. The tops of the vertical electrodes should be a minimum of one foot (0.3 meter) below grade level. This will minimize resistance variations caused by surface drying of the soil. The possibility of mechanical damage will also be reduced. Resistance variations caused by freezing of the soil will be minimized in those areas where the frost line is one foot (0.3 meter) or less below grade level.

9.3 Access to the grounding system at a building site should be provided through the installation of a grounding well. This provides access for periodic resistance checks of the ground electrode system. Either clay pipe or poured concrete may be used, as illustrated in Figure 28, with a removable access cover.

9.4 All bonds in concealed locations must be brazed or welded. While the bonding of dissimilar metals should be avoided, there will be occasions where it becomes necessary. Any bonds between dissimilar metals, such as between a copper wire and cast iron on steel pipe, must be thoroughly sealed against moisture intrusion to minimize corrosion. Bolted clamp connections should be made only in manholes, handholes or grounding wells where they are readily available for verification of integrity.

9.5 Grounding electrodes should only be driven into undisturbed earth or thoroughly compacted filled areas. Electrodes and interconnecting conductors should be placed in the backfill around new building foundations only after the soil has been compacted or has had adequate time to settle. Electrodes should not be driven or laid in gravel beds which have been installed for drainage purposes unless the electrodes extend through such beds far enough to provide a minimum of 8 feet (2.5 meters) of contact with the undisturbed earth underneath. Horizontal bare interconnecting conductors should not be placed in such beds under any circumstances.

9.6 Electrodes may be driven either by hand sledging or with power drivers. Hand sledging may be preferable where only a limited number of electrodes are installed in earth of moderate compactness. Driving nuts should be used to prevent damage to the driven end, particularly, if two or more sections are to be joined. Deep driven electrodes or those driven into hard or rocky soil generally require the use of power drivers with special driving collars to prevent damage to the electrode.

9.7 The grounding system resistance to ground should be measured as soon as installation is completed by the measurement procedure outlined in Appendix D. This initial resistance to ground value will probably exceed the calculated values by as much as twenty percent since the disturbed soil has not had time to settle and provide good contact with electrode surfaces. Remeasurement on a monthly basis is recommended until a steady value is established.

9.8 After the resistance of the grounding system has stabilized, the resistance to ground should be remeasured annually to determine that the system is still adequate for protection purposes. Although resistance fluctuations will occur, any increase in the resistance to ground of 20 percent or more should be investigated and the necessary work completed to reduce it to the objective value.

10. REFERENCES

10.1 The publications listed below were utilized during the preparation of this practice. They are recommended for study to those individuals desiring further knowledge of grounding theory.

1. F. Wenner, "A Method of Measuring Earth Resistivity," Report No. 258, Bulletin of the Bureau of Standards, Volume 12, No. 3, October 11, 1915.

2. O. S. Peters, "Ground Connections for Electrical Systems," Technological Paper No. 108, Bureau of Standards, June 20, 1918.

3. H. B. Dwight, "Calculation of Resistance to Ground," Electrical Engineering, Volume 55, December 1936, pp. 1319-1328.

4. S. J. Schwarz, "Analytical Expressions for the Resistance of Grounding Systems," AIEE Transactions, Volume 73, Part III-B, 1954, pp. 1011-1016.

5. "Guide for Safety in Alternating-Current Substation Grounding," IEEE Standard 80-1961, IEEE, New York (R 1971).

6. E. D. Sunde, "Earth Conduction Effects in Transmission Systems," Dover Publications, Inc., New York, 1968.

7. G. F. Tagg, "Measurement of the Resistance of an Earth-Electrode System Covering a Large Area," IEE Proceedings, Volume 116, March 1969, pp. 475-479.

8. "Getting Down to Earth . . .," Manual 25T, James G. Biddle, Co., Plymouth Meeting, Pennsylvania, October 1970.

9. "Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System," IEEE Standard 81-1983, IEEE, New York.

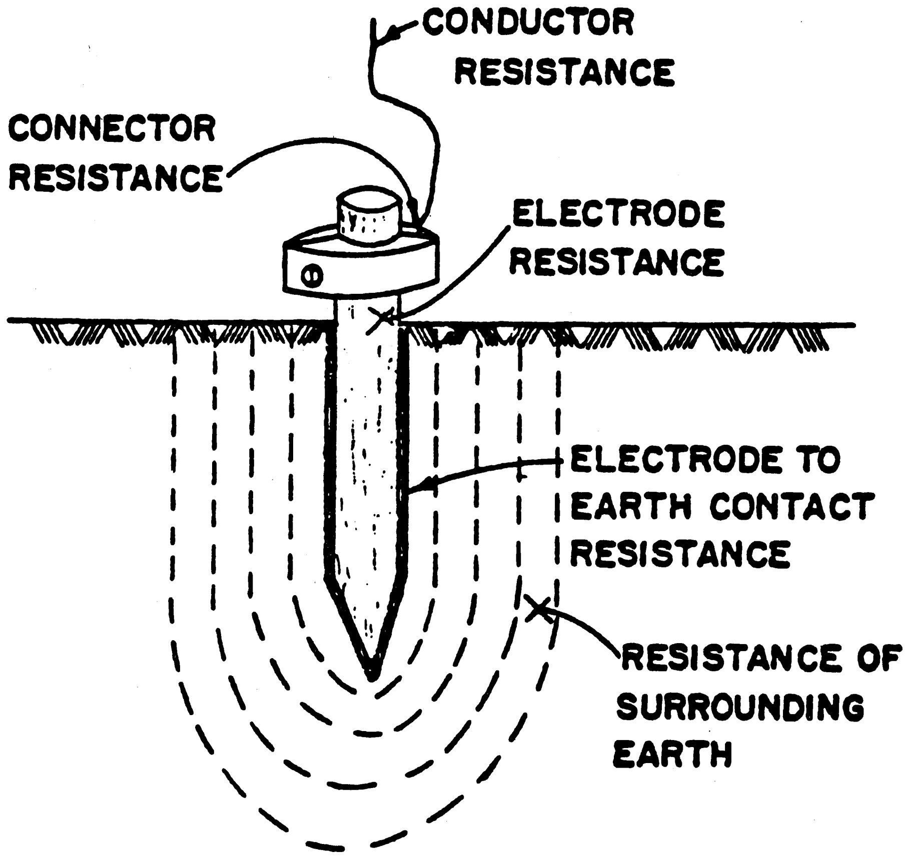


Fig. 1– COMPONENTS OF RESISTANCE
IN A GROUND CONNECTION

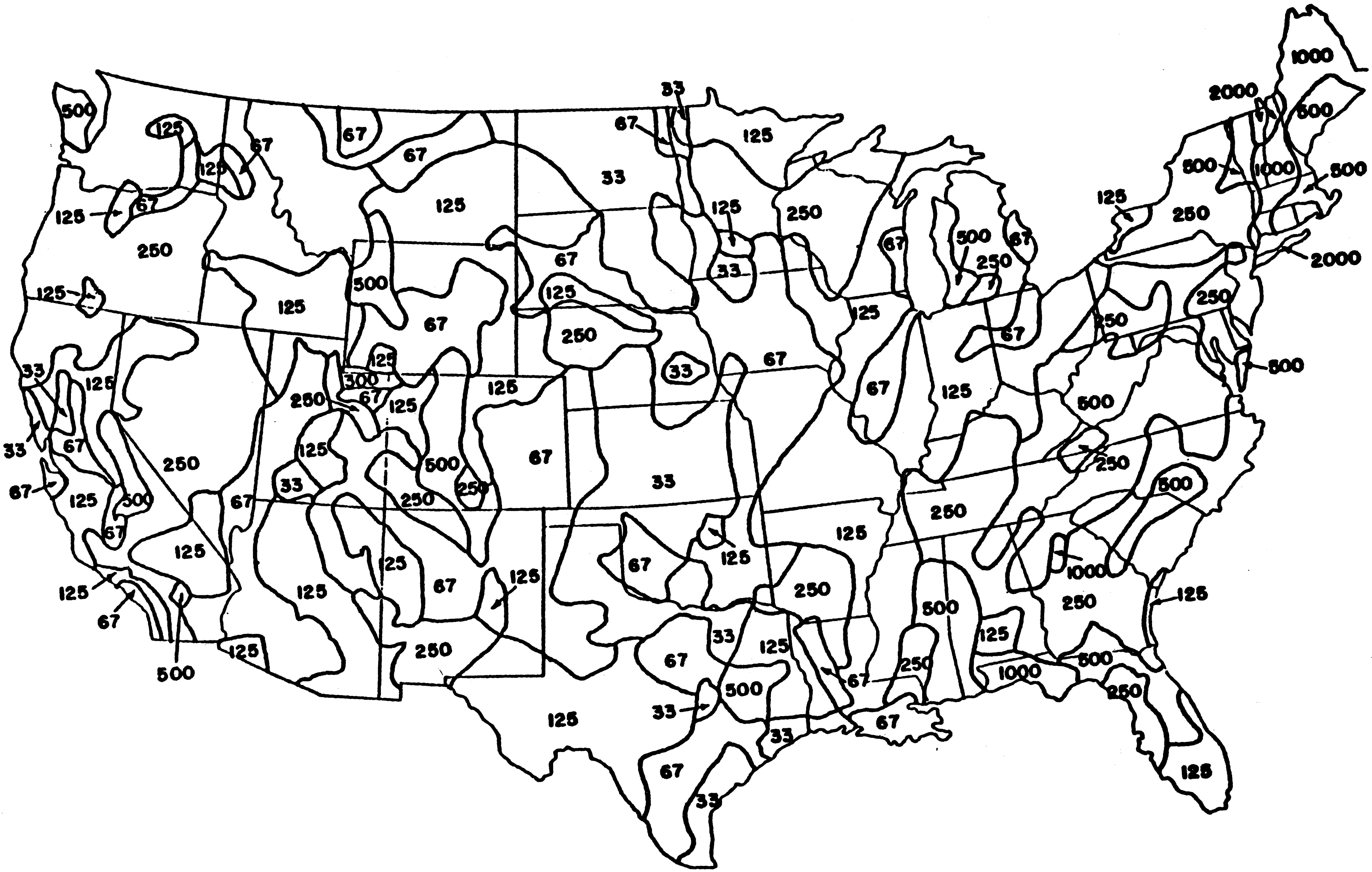


Fig. 2 ESTIMATED AVERAGE EARTH RESISTIVITY IN U.S.
(METER-OHMS)

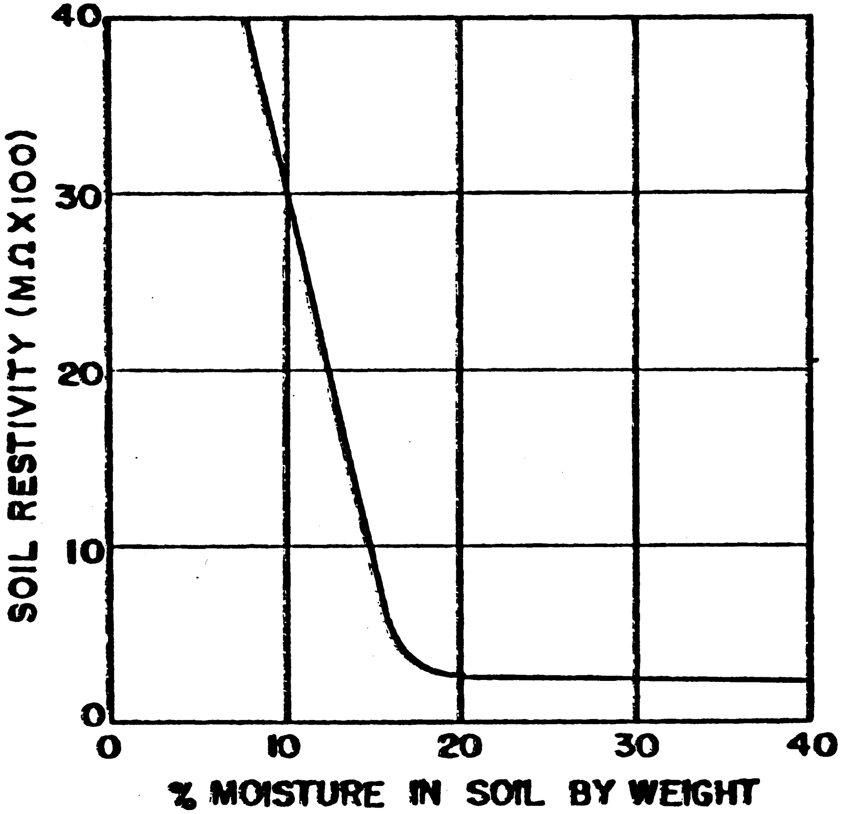


Fig.3-TYPICAL VARIATION OF SOIL RESISTIVITY WITH MOISTURE

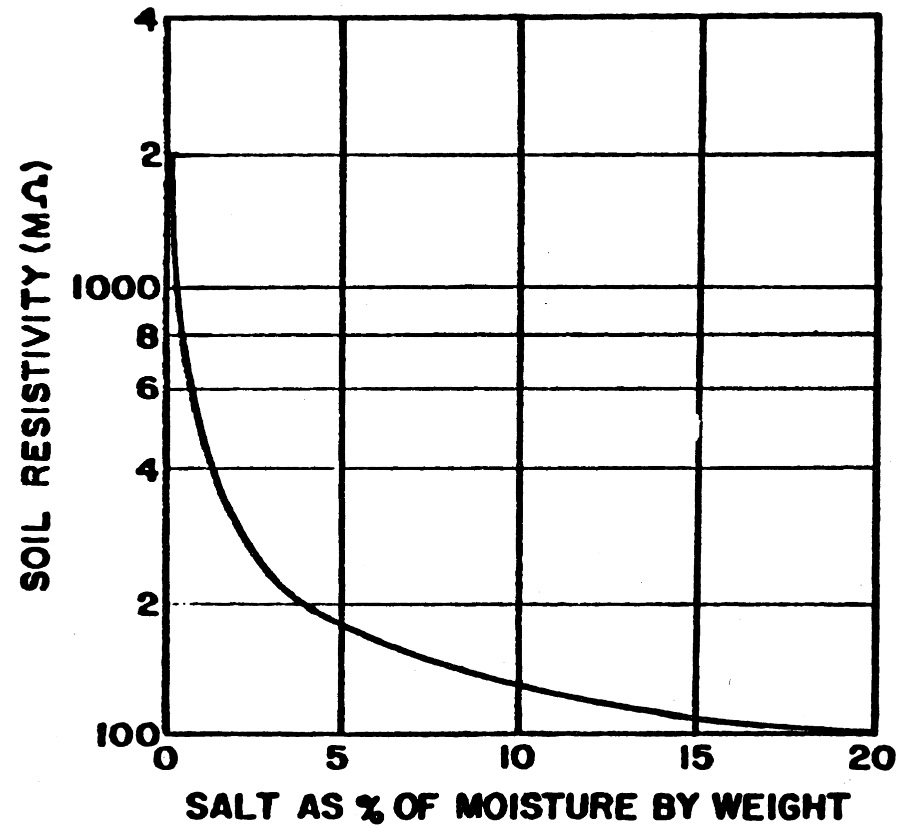


Fig. 4-TYPICAL EFFECT OF MINERAL SALT ON EARTH RESISTIVITY

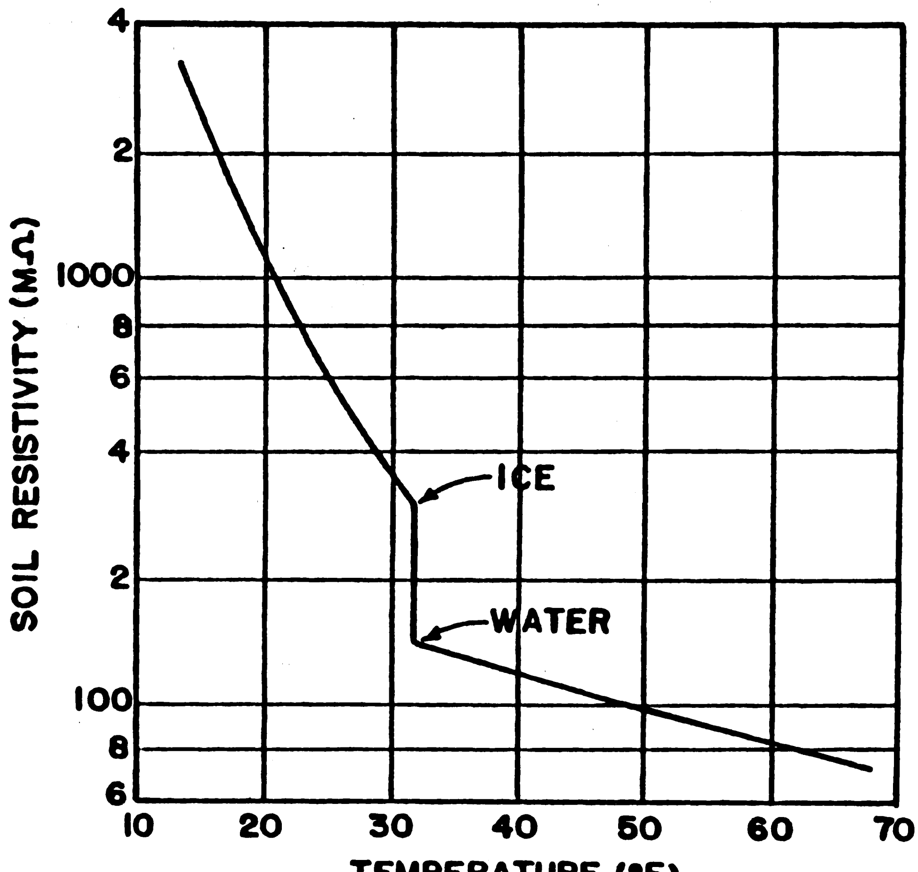
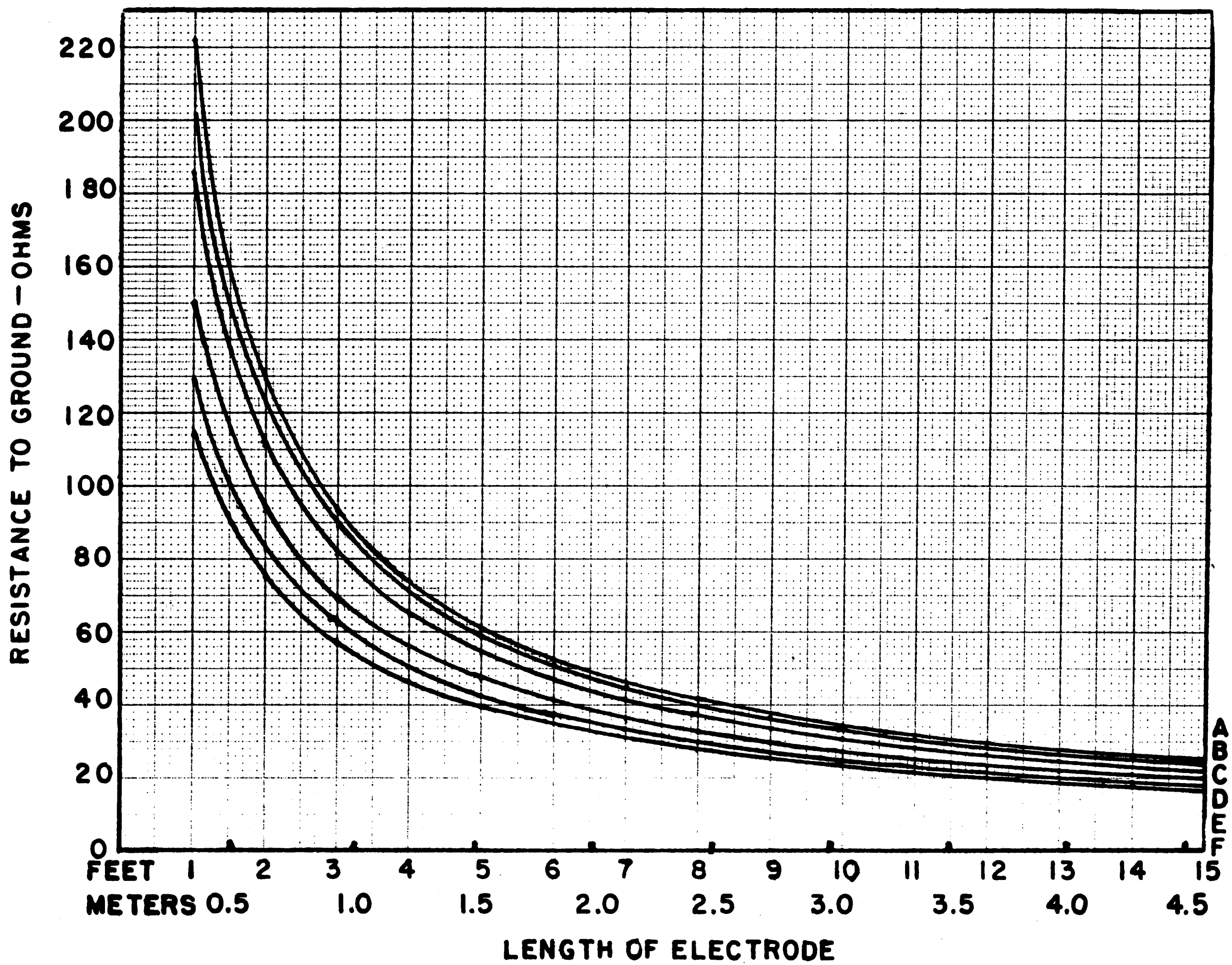


Fig. 5—TYPICAL VARIATION OF SOIL RESISTIVITY WITH TEMPERATURE



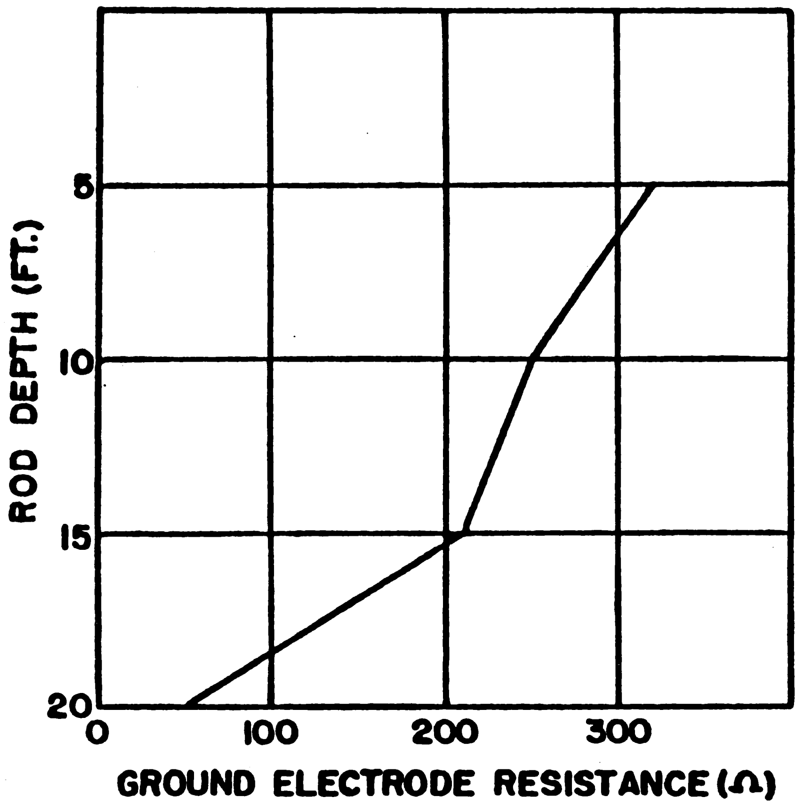
Diameter of Electrode

A - 0.5 inch (1.3 cm)
B - 0.625 inch (1.6 cm)
C - 1 inch (2.5 cm)
D - 2 inch (5.1 cm)
E - 3 inch (7.6 cm)
F - 4 inch (10.2 cm)

Soil Resistivity - 100 meter-ohms

FIGURE 6

Resistance to Ground Variation with Electrode Depth



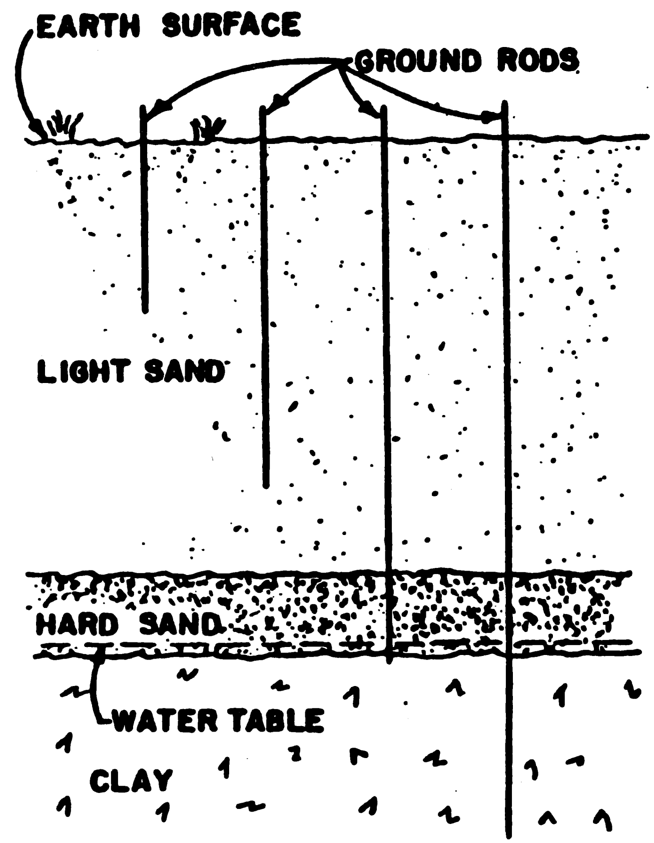
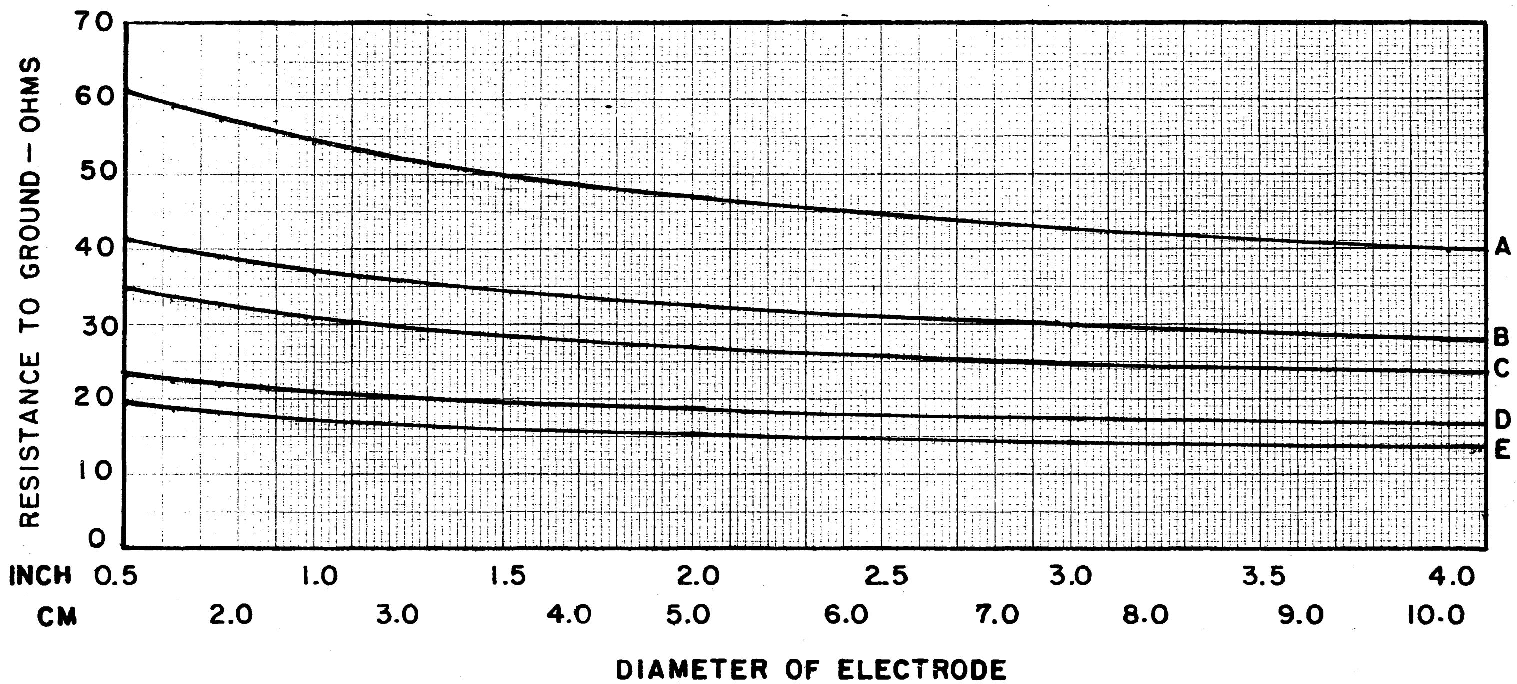


Fig.7-TYPICAL ROD LENGTH VERSUS RESISTANCE



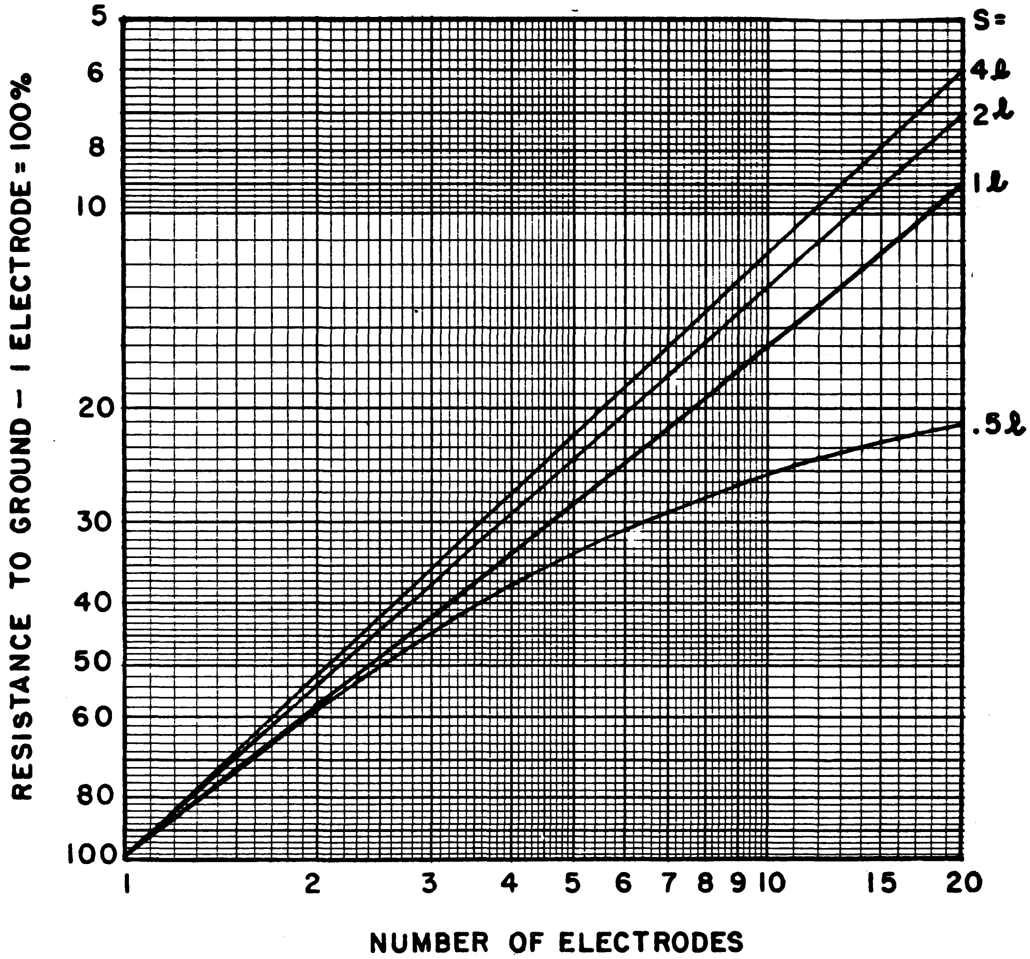
<u>Length of Electrode</u>

A - 5 Feet (1.5 meters)
B - 8 Feet (2.4 meters)
C - 10 Feet (3 meters)
D - 16 Feet (4.9 meters)
E - 20 Feet (6.1 meters)

Soil Resistivity - 100 Meter-Ohms

<u>FIGURE 8</u>

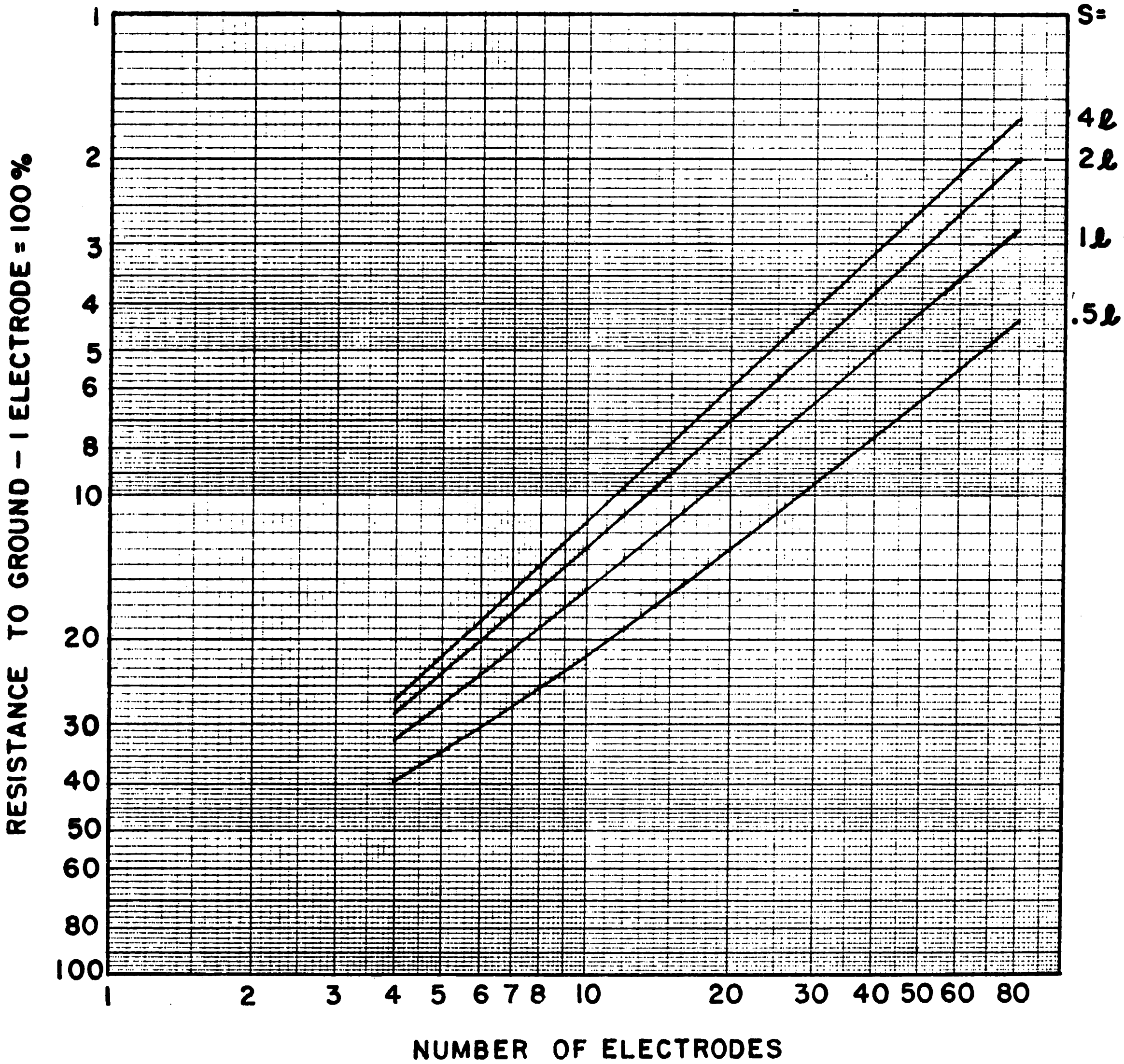
Resistance Variation to Ground with Electrode Diameter



S = Spacing between Electrodes
ℓ = Electrode Length

FIGURE 9

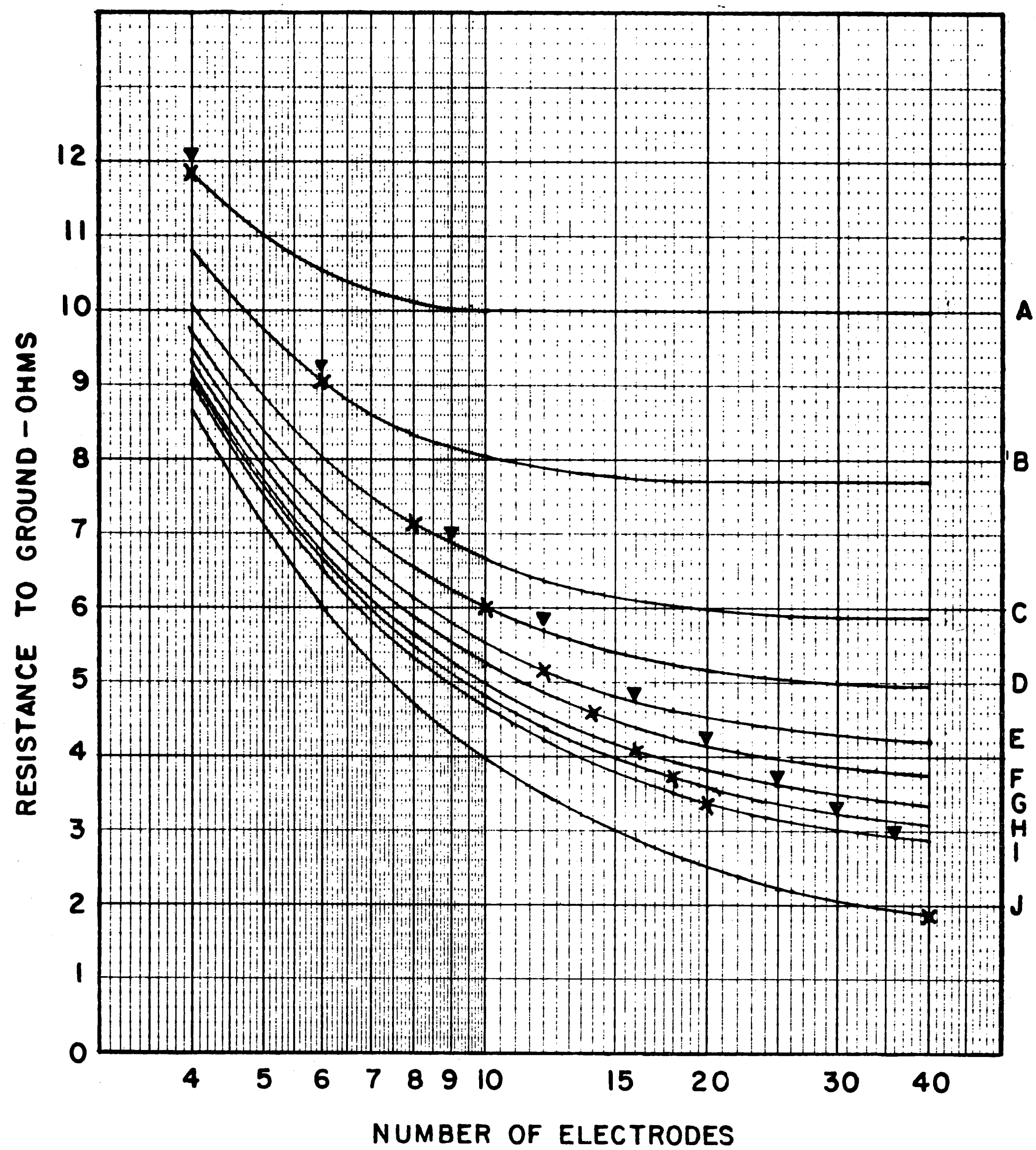
Resistance to Ground Variation with Multiple Electrodes in a Straight Line Interconnected with Insulated Wire



S = Spacing between Electrodes
ℓ = Electrode Length

FIGURE 10

Resistance to Ground Variation with a Ring of Multiple Electrodes Interconnected with Insulated Wire



<u>Total Area of Rod Bed</u>

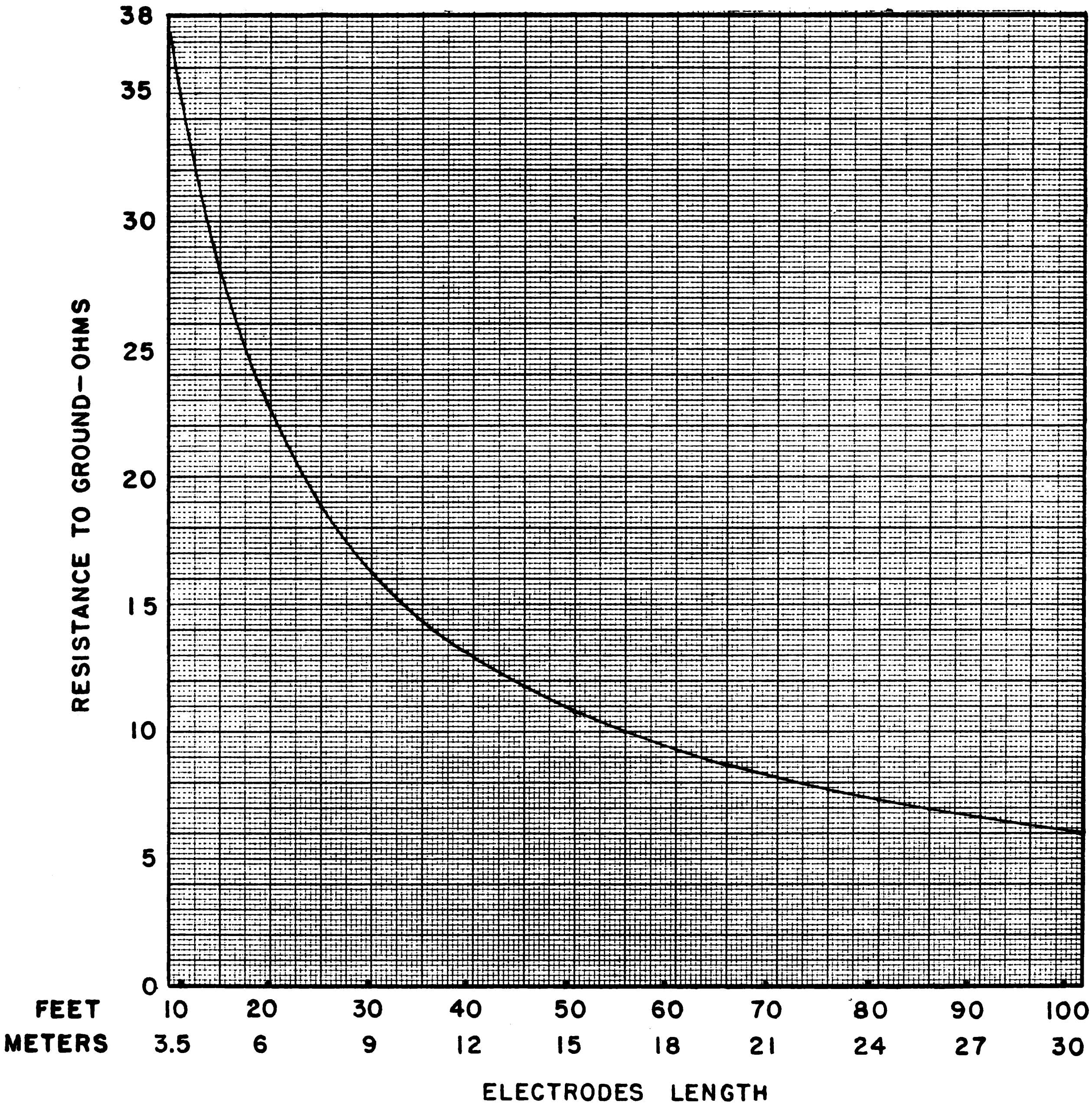
A - 100 Sq. Ft. (9 Sq. meters)
B - 200 Sq. Ft. (19 Sq. meters)
C - 400 Sq. Ft. (37 Sq. meters)
D - 600 Sq. Ft. (56 Sq. meters)
E - 900 Sq. Ft. (84 Sq. meters)
F - 1200 Sq. Ft. (112 Sq. meters)
G - 1600 Sq. Ft. (149 Sq. meters)
H - 2000 Sq. Ft. (186 Sq. meters)
I - 2500 Sq. Ft. (232 Sq. meters)
J - 10000 Sq. Ft. (929 Sq. meters)

X = Perimeter Ground
▼ = Rod Bed with Separation equal to Electrode Length

5/8 inch x 10 feet (1.6 cm x 3 meters) Electrodes
Earth Resistivity = 100 meter-ohms

FIGURE 11

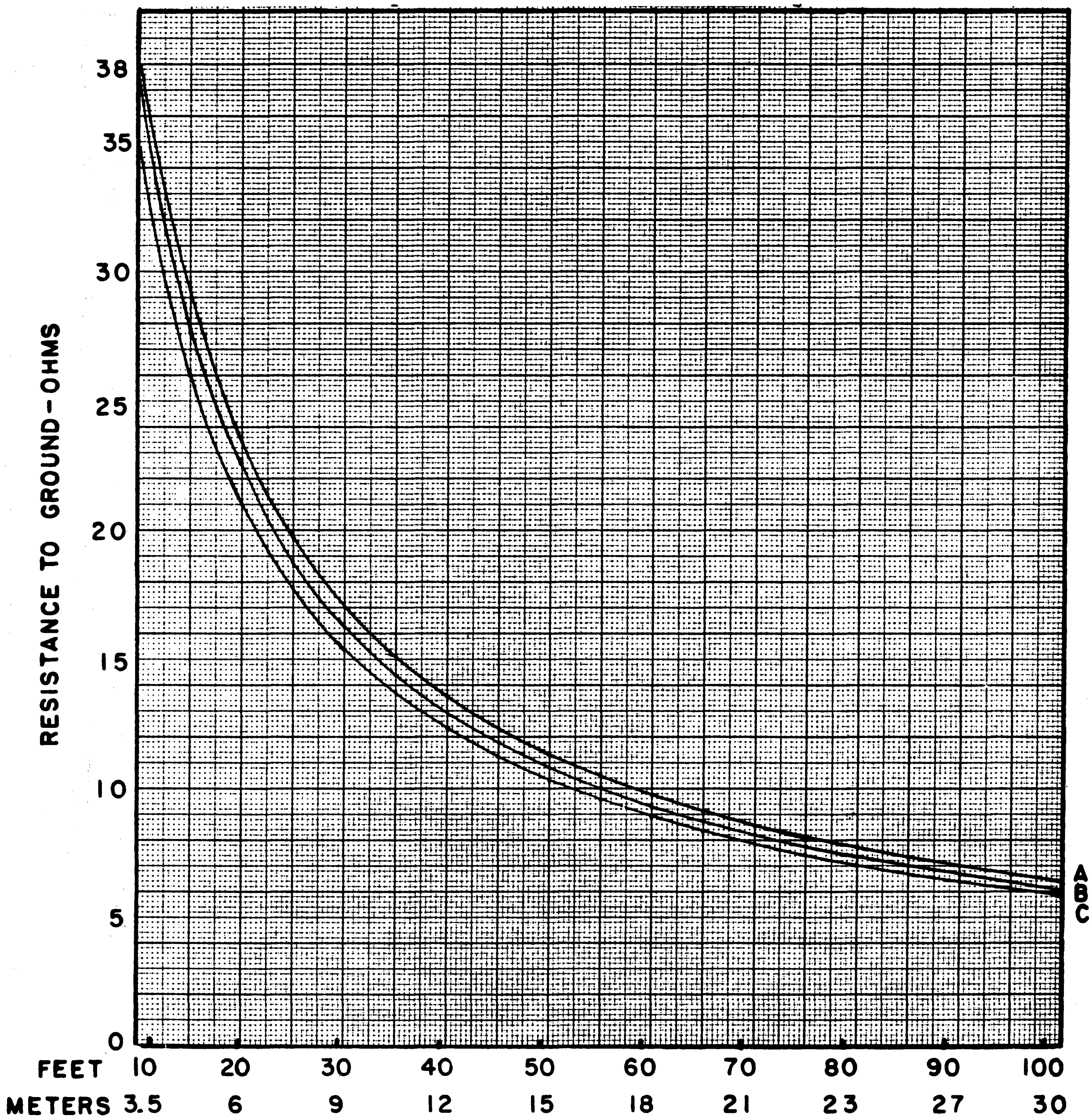
Resistance to Ground with Multiple Electrodes in a Rod Bed



Electrode Size = #2 Bare Copper Conductor
Depth = 2 Feet (0.6 meters)
Earth Resistivity = 100 meter-ohms

FIGURE 12

Resistance to Ground Variation with Length of Horizontal Electrode



ELECTRODES LENGTH

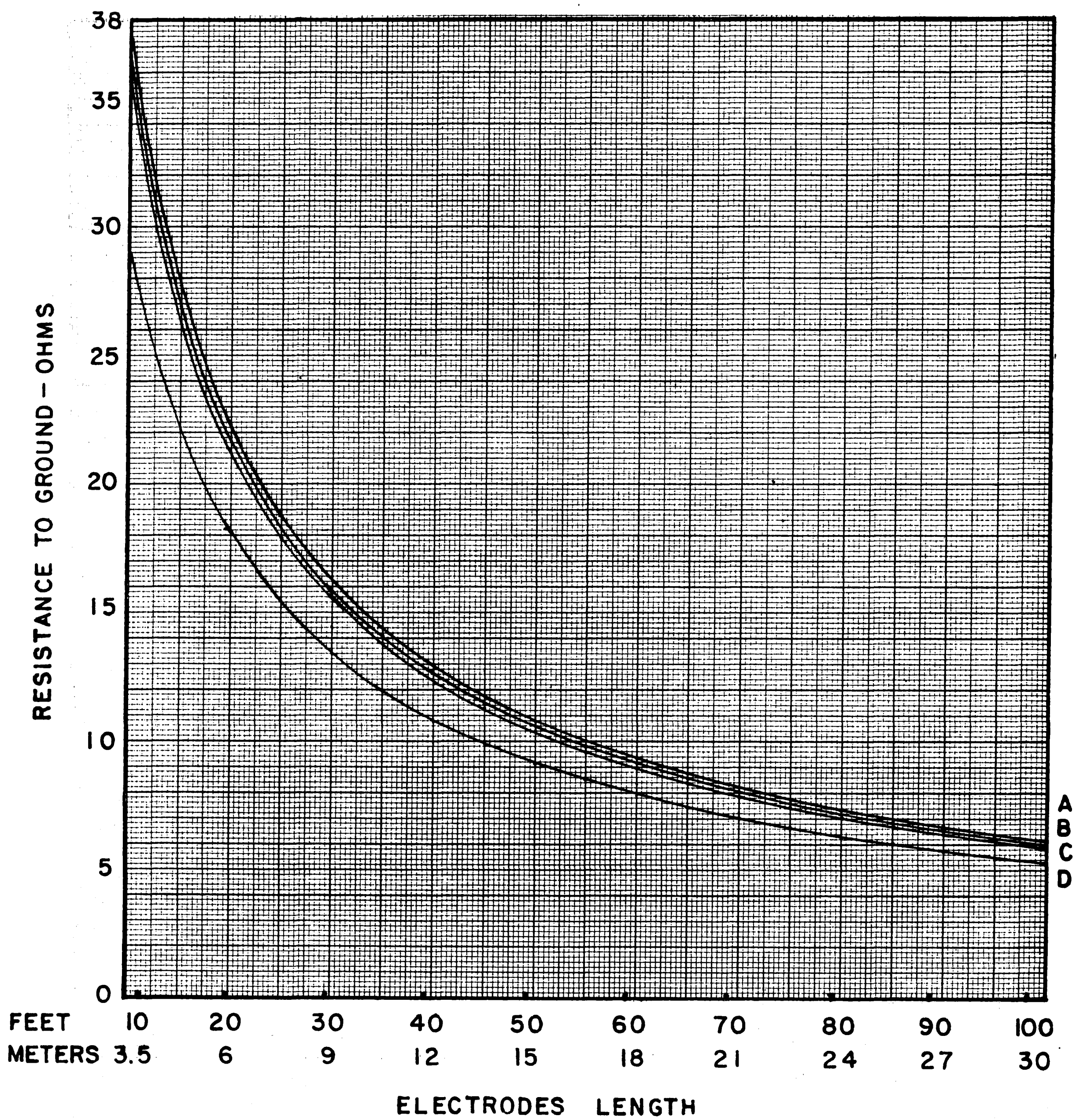
Electrode Size

A = #6 Conductor
B = #2 Coductor
C = 2/0 Conductor

Depth = 2 Feet (0.6 meters)
Earth Resistivity = 100 meter-ohms

FIGURE 13

Resistance to Ground Variation with Length of Horizontal Electrodes having Different Sizes



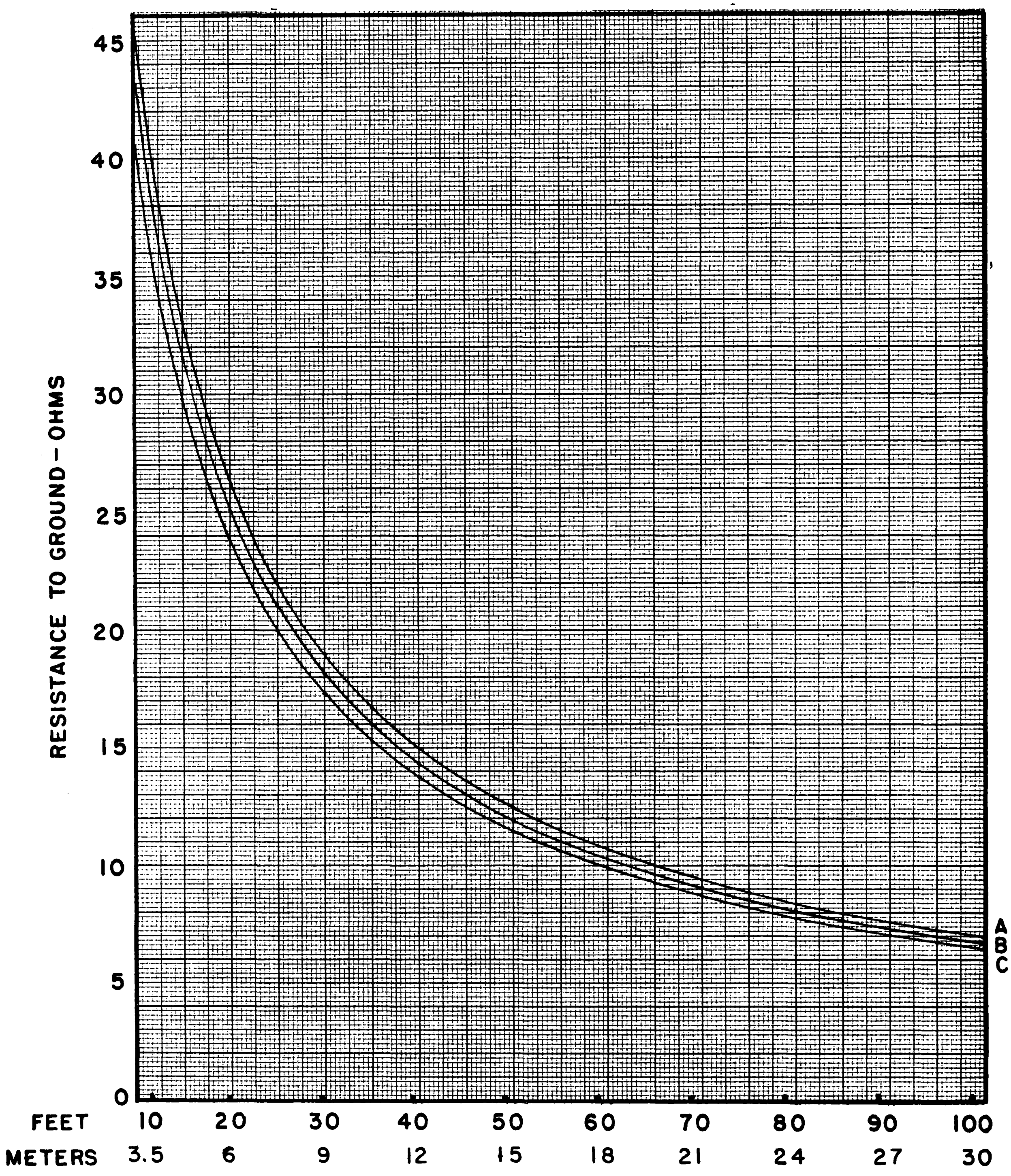
Electrode Depth

A - 2 Feet (0.6 meters)
B - 2.5 Feet (0.8 meters)
C - 3 Feet (0.9 meters)
D - 10 Feet (3 meters)

Electrode Size = #2 Bare Copper Conductor
Earth Resistivity = 100 meters-ohms

FIGURE 14

Resistance to Ground Variation with Length of Horizontal Electrodes Buried at Different Depths



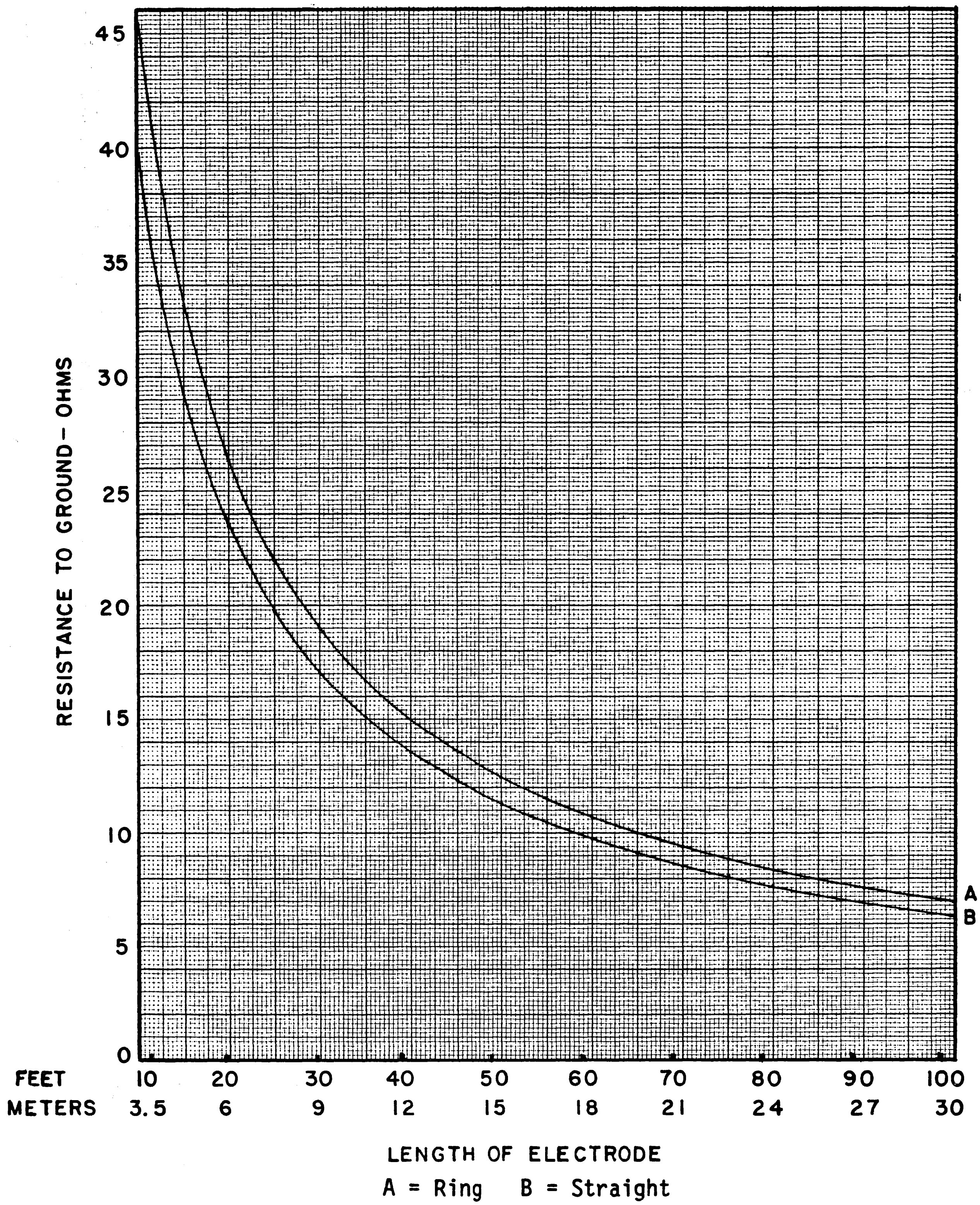
Electrode Size

A = #6 Conductor
B = #2 Conductor
C = 2/0 Conductor

Depth = 2 Feet (0.6 meters)
Earth Resistivity = 100 meter-ohms

FIGURE 15

Resistance to Ground Variation with Length of Horizontal Ring Having Different Conductor Sizes

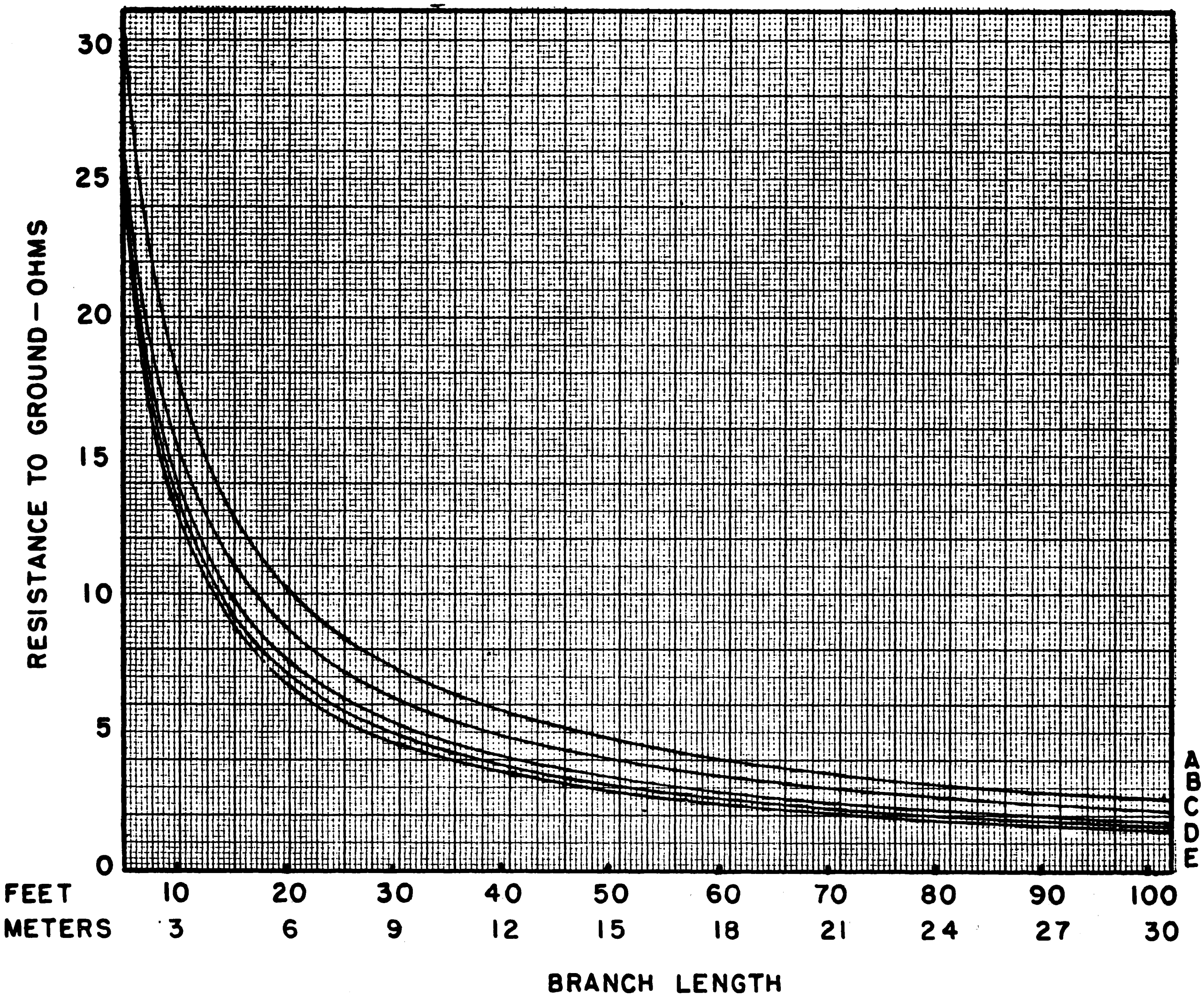


A = Ring B = Straight

Electrode Size = #6 Bare Copper Conductor
Depth = 2 Feet (0.6 meter)
Earth Resistivity = 100 meter-ohms

FIGURE 16

Resistance to Ground Variation with Length Between Horizontal Electrode in Ring and Straight Configuration



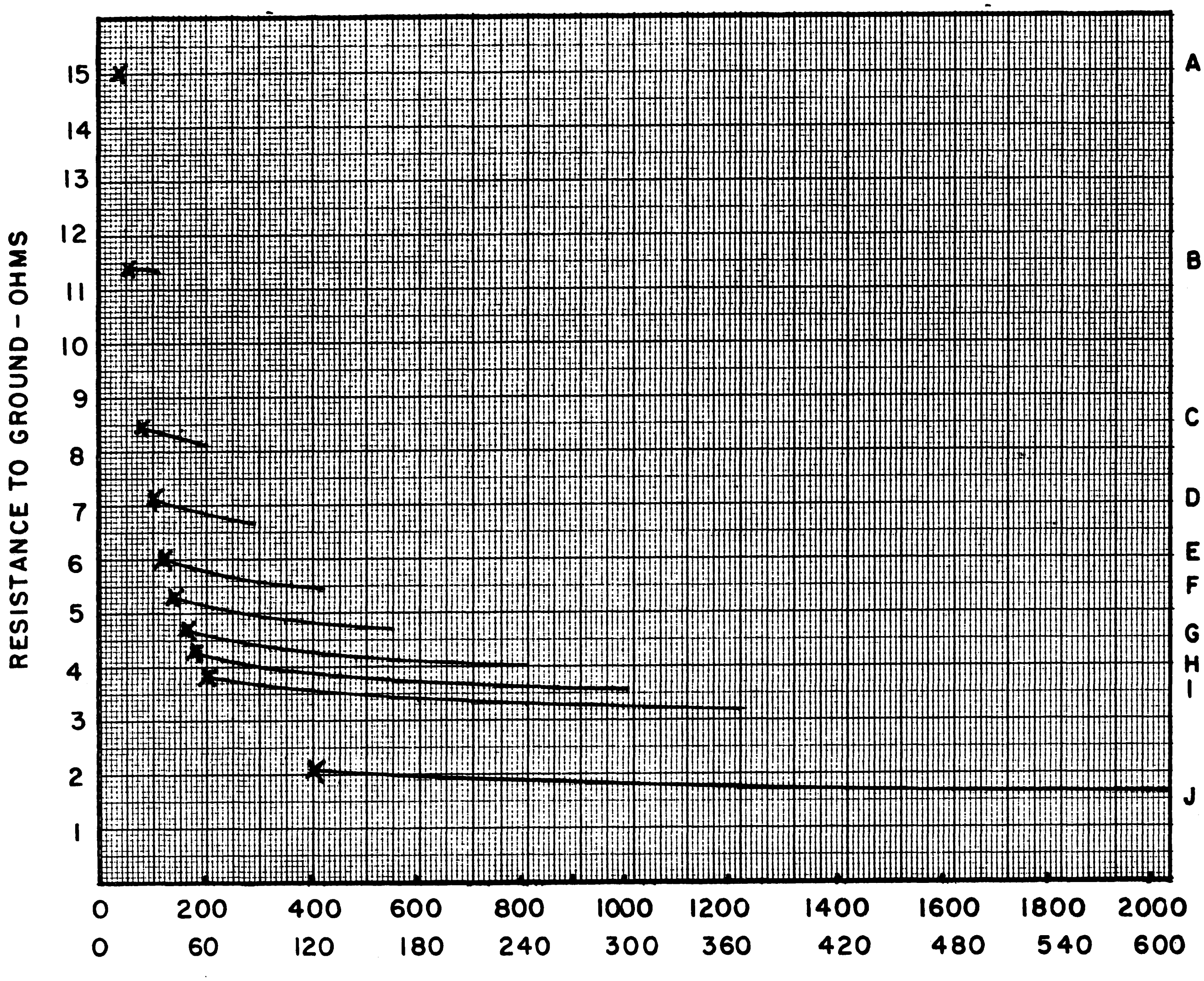
Star Size

A - 3 Branch Star
B - 4 Branch Star
C - 6 Branch Star
D - 8 Branch Star
E - 12 Branch Star

Conductor Size = #2 Bare Copper
Depth = 2 Feet (0.6 meters)
Earth Resistivity = 100 meter-ohms

FIGURE 17

Resistance to Ground Variation with Branch Length
For Different Star Configurations



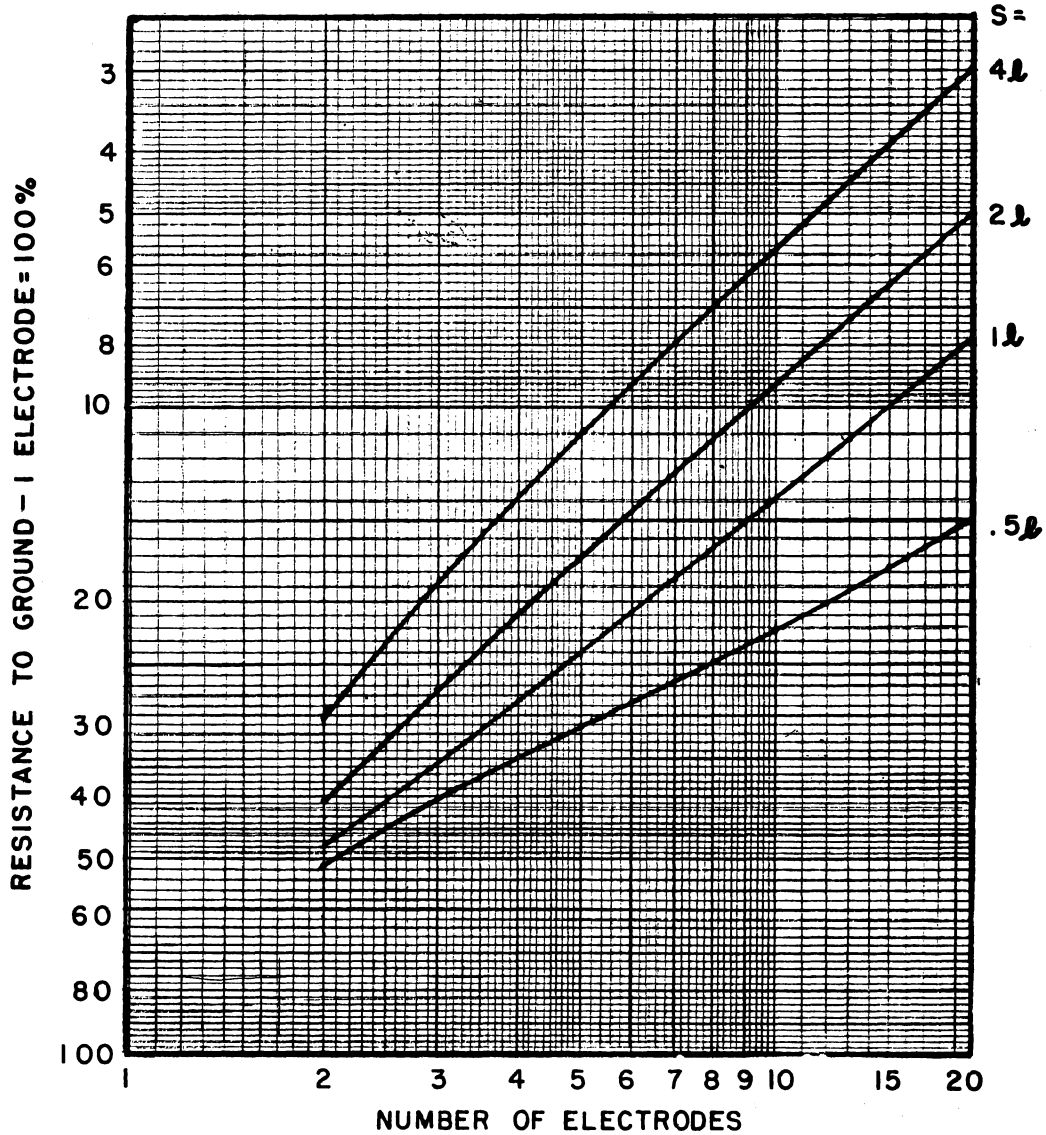
Total Area of Wire Grid

A - 100 Sq. Ft. (9 Sq. meters)
B - 200 Sq. Ft. (19 Sq. meters)
C - 400 Sq. Ft. (37 Sq. meters)
D - 600 Sq. Ft. (56 Sq. meters)
E - 900 Sq. Ft. (84 Sq. meters)
F - 1200 Sq. Ft. (112 Sq. meters)
G - 1600 Sq. Ft. (149 Sq. meters)
H - 2000 Sq. Ft. (186 Sq. meters)
I - 2500 Sq. Ft. (232 Sq. meters)
J - 10000 Sq. Ft. (929 Sq. meters)

X = Perimeter Ground
Conductor Size = #2 Bare Copper
Depth = 2 Feet (0.6 meters)
Earth Resistivity = 100 meter-ohms

FIGURE 18

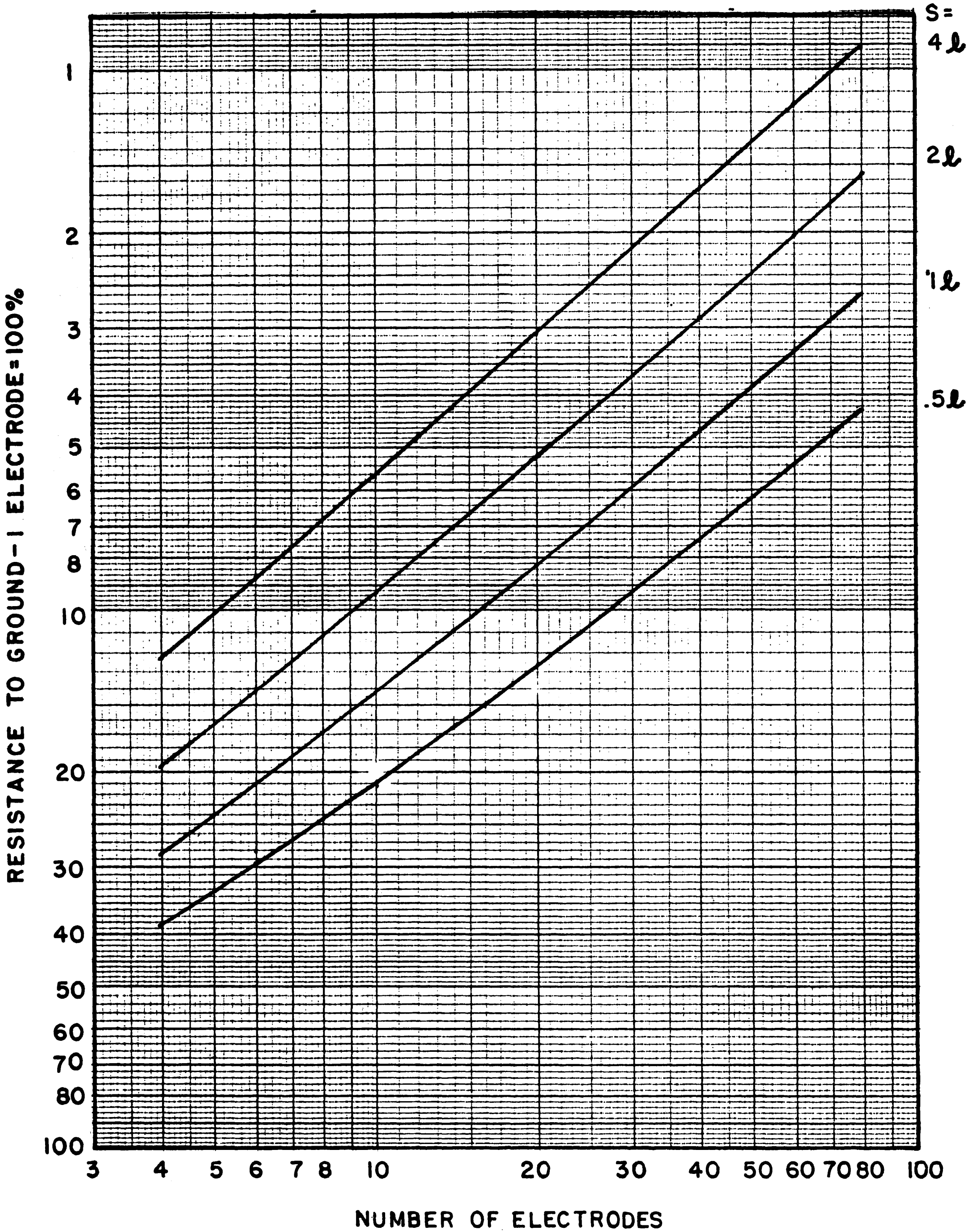
Resistance to Ground Variation with Total Wire Length for Different Wire Grid Areas



S = Electrode Spacing
ℓ = Electrode Length

FIGURE 19

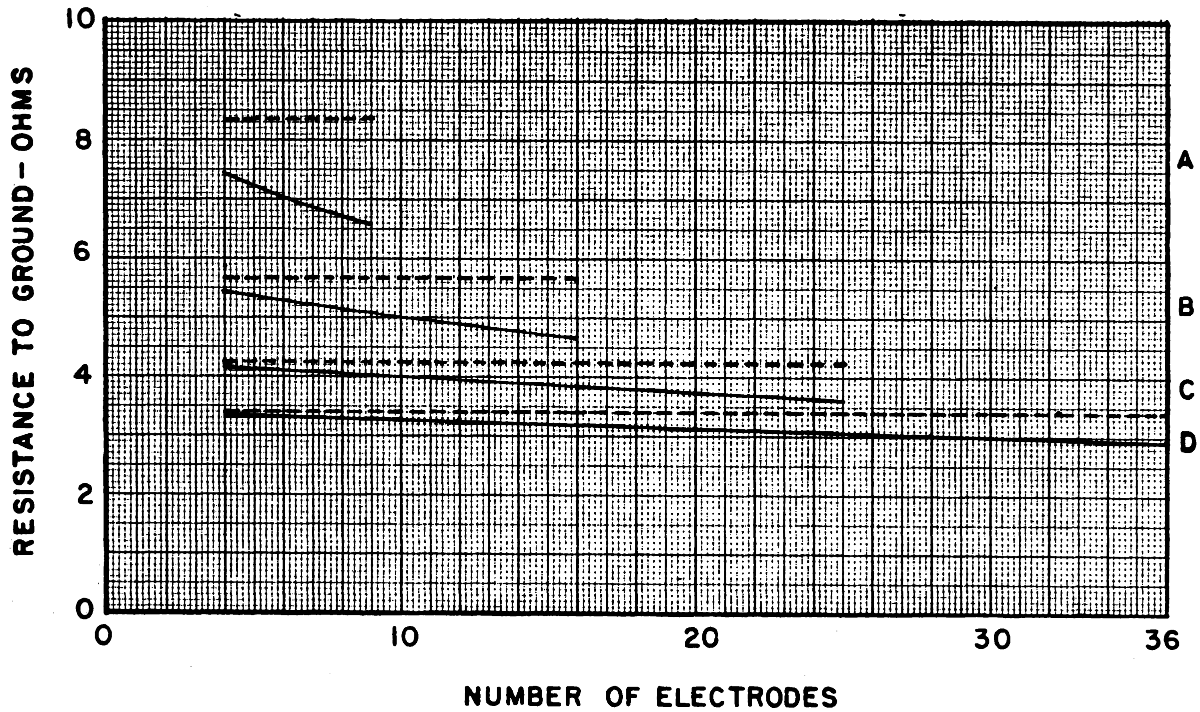
Resistance to Ground Variations with Number of Electrodes for a Straight Line of Multiple Electrodes Interconnected with Bare Wire



S = Electrode Spacing
ℓ = Electrode Length

FIGURE 20

Resistance to Ground Variation with Number of Electrodes for a Ring of Multiple Electrodes Interconnected with Bare Wire



---------- Wire Grid
__________ Combined Wire Grid and Rod Bed

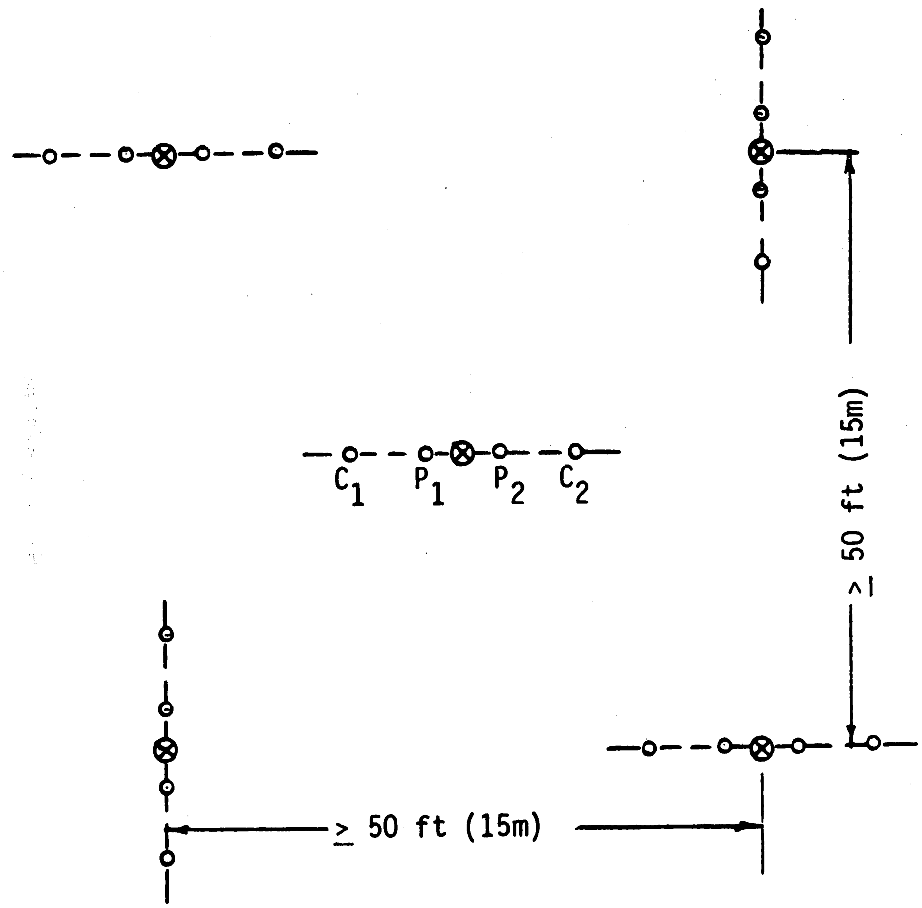
<u>Total Area of Grid</u>

A - 400 Sq. Ft. (37 Sq. meters)
B - 900 Sq. Ft. (84 Sq. meters)
C - 1600 Sq. Ft. (149 Sq. meters)
D - 2500 Sq. Ft. (232 Sq. meters)

Vertical Electrode = 5/8 inch x 10 Foot (1.6 cm x 3 meter)
Horizontal Electrode = #2 Bare copper conductor
Depth = 2 Feet (0.6 meters)
Resistivity = 100 meter-ohms

<u>FIGURE 21</u>

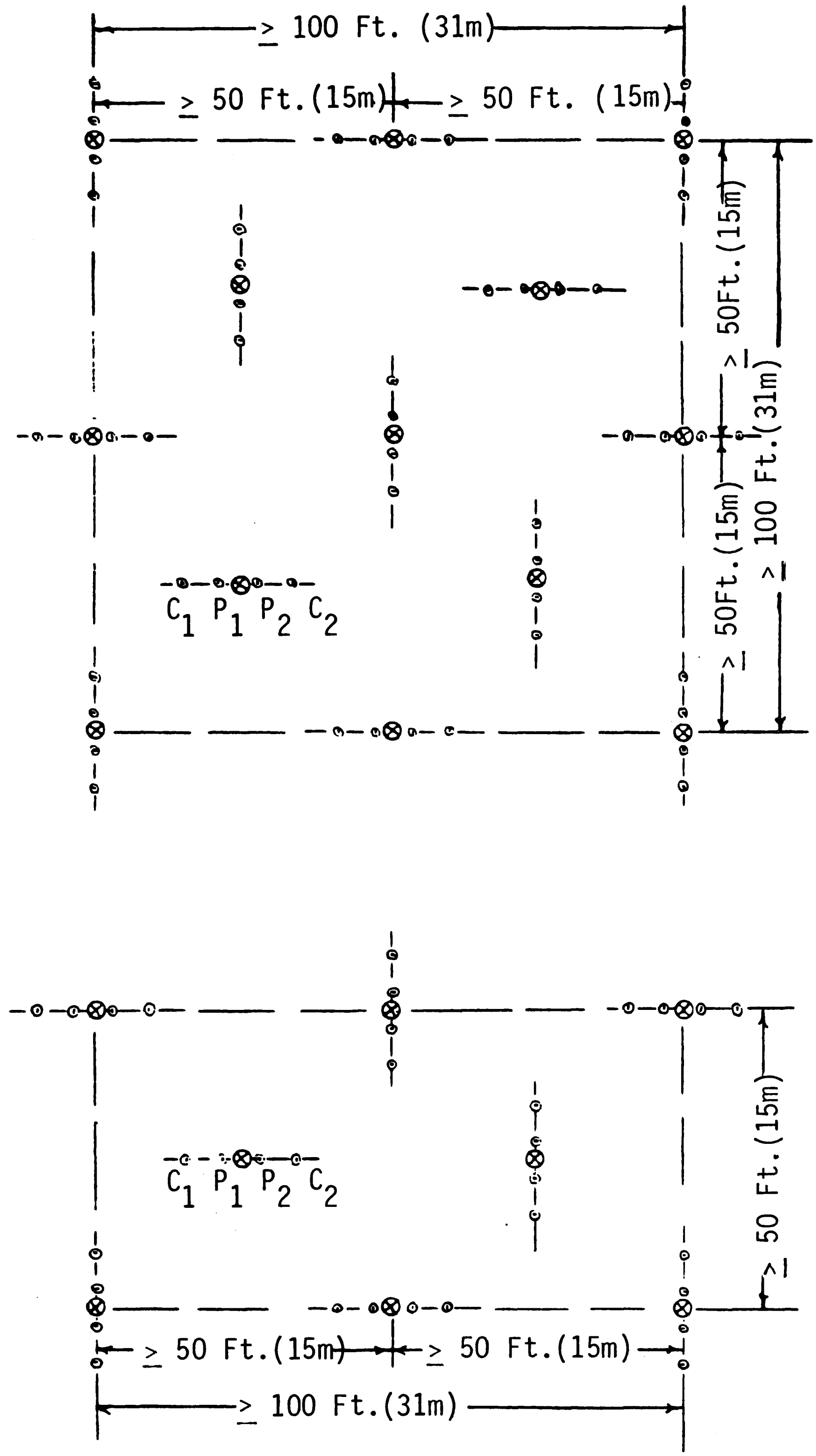
Resistance to Ground of Various Size Wire Grids Compared to Combined Grids and Rod Beds with Different Numbers of Electrodes



C_1, P_1, P_2, C_2 = Test Set Terminals (See Appendix C)

FIGURE 22

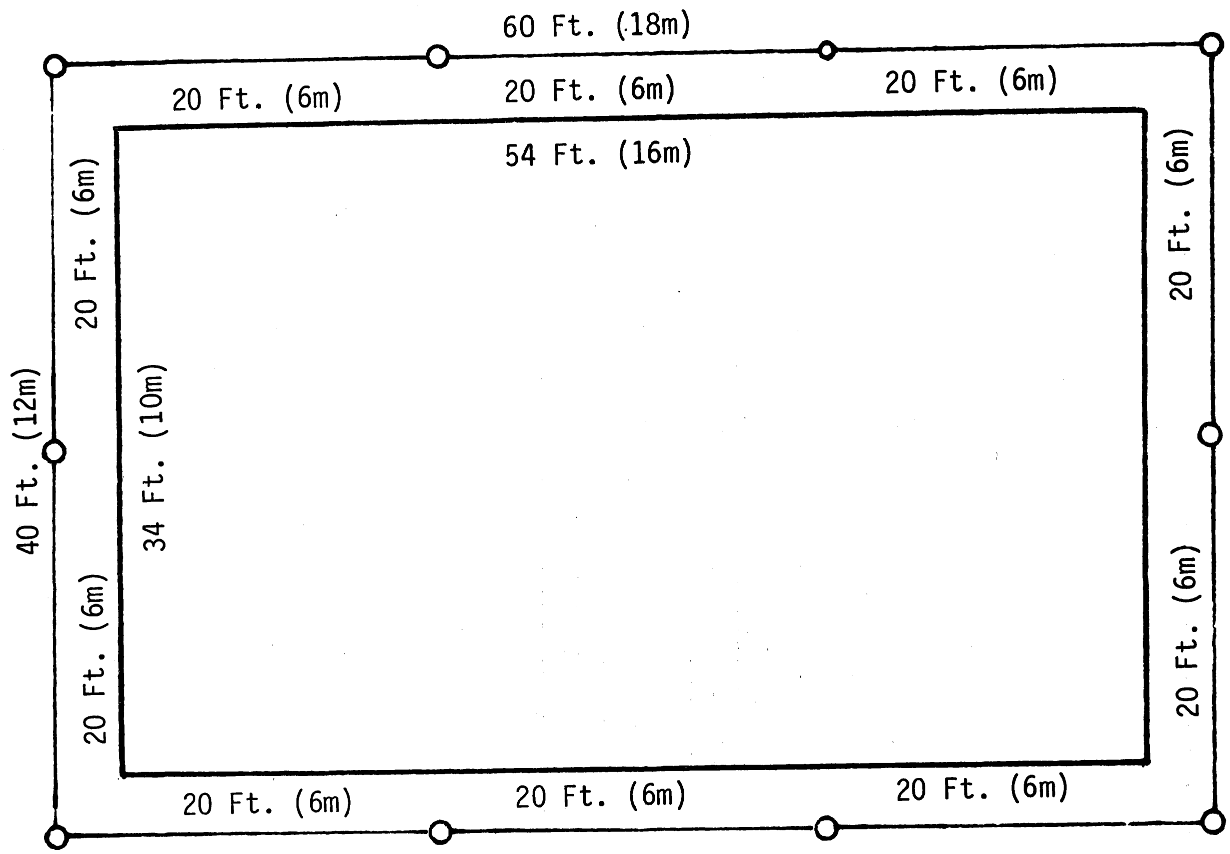
Soil Resistivity Site Survey
Small Site - Less than 2500 Sq. Ft. (232 Sq. meters)



C_1, P_1, P_2, C_2 = Test Set Terminals (See Appendix C)

FIGURE 23

Soil Resistivity Site Survey
Large Site - More than 2500 Sq. Ft. (232 Sq. meters)

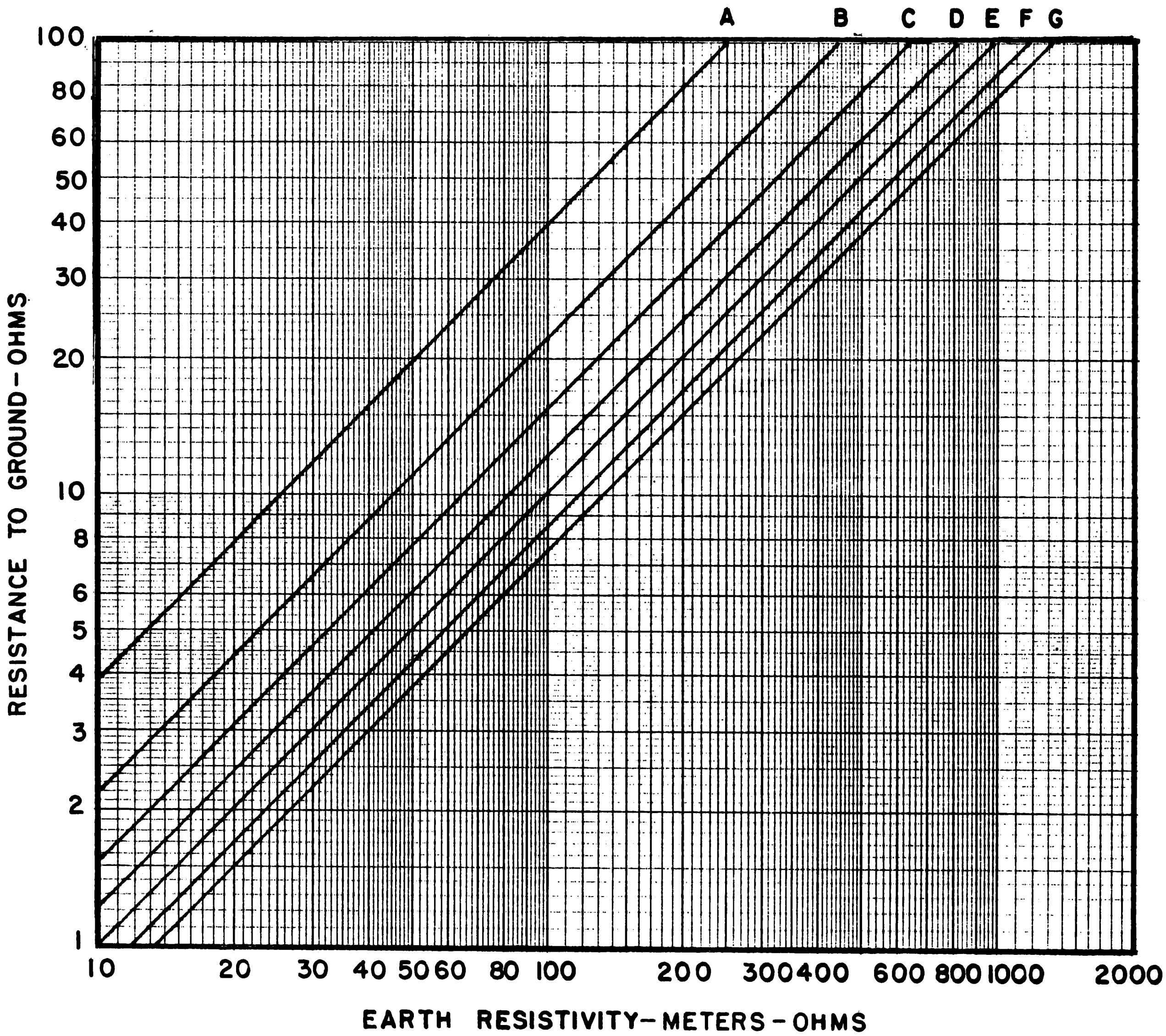


<u>Average Soil Resistivity</u>

12 Foot (4 meter) Depth = 600 meter-ohms
22 Foot (7 meter) Depth = 200 meter-ohms

<u>FIGURE 24</u>

Grounding System Design Example



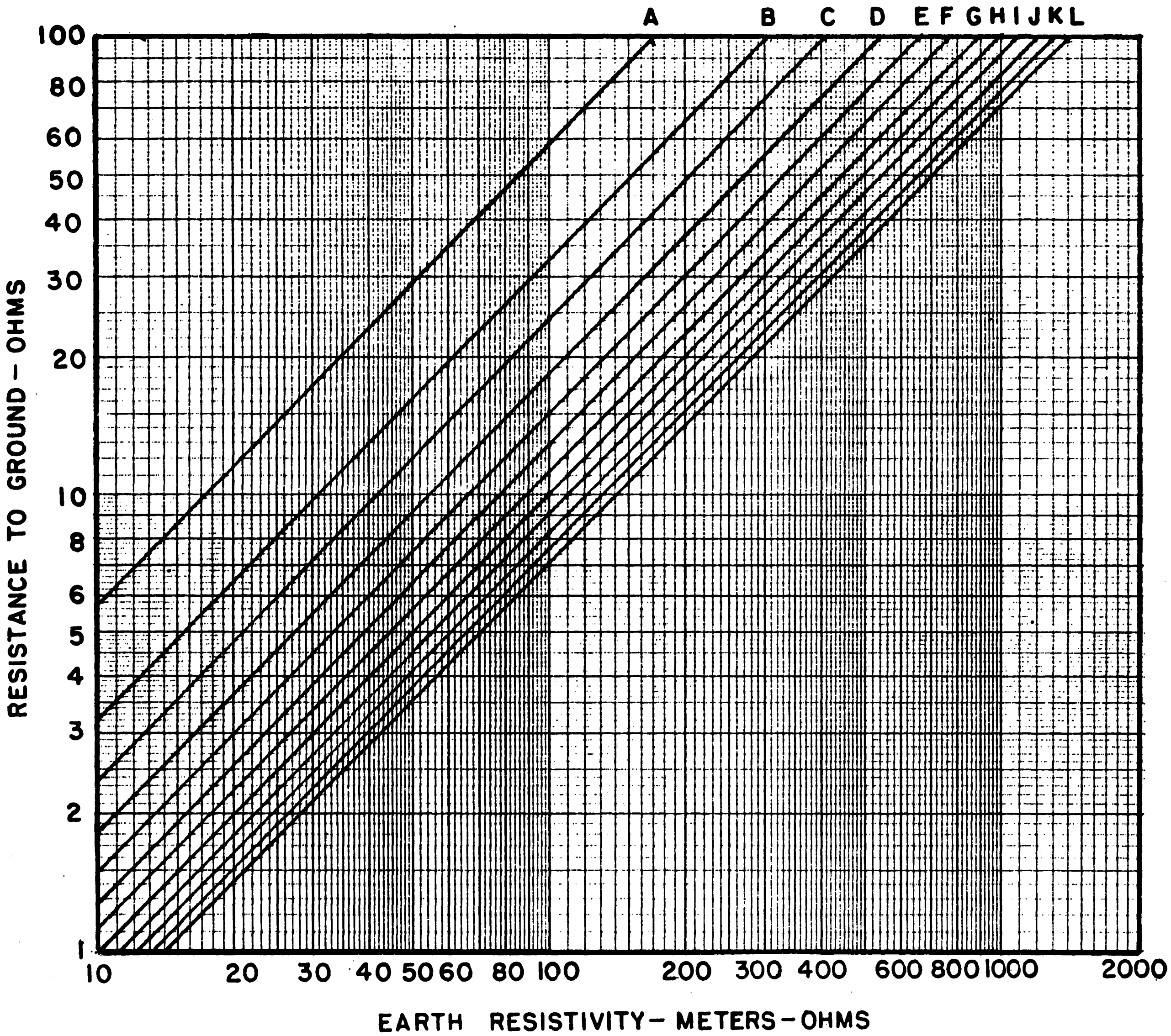
Total Length - 8 Foot Sectional Electrodes

A - 8 Feet (2.4 meters)
B - 16 Feet (4.9 meters)
C - 24 Feet (7.3 meters)
D - 32 Feet (9.8 meters)
E - 40 Feet (12.2 meters)
F - 48 Feet (14.6 meters)
G - 56 Feet (17.1 meters)

All Diameters - 5/8 inch (1.6 cm)

FIGURE 25

Resistance to Ground of Vertical Electrodes



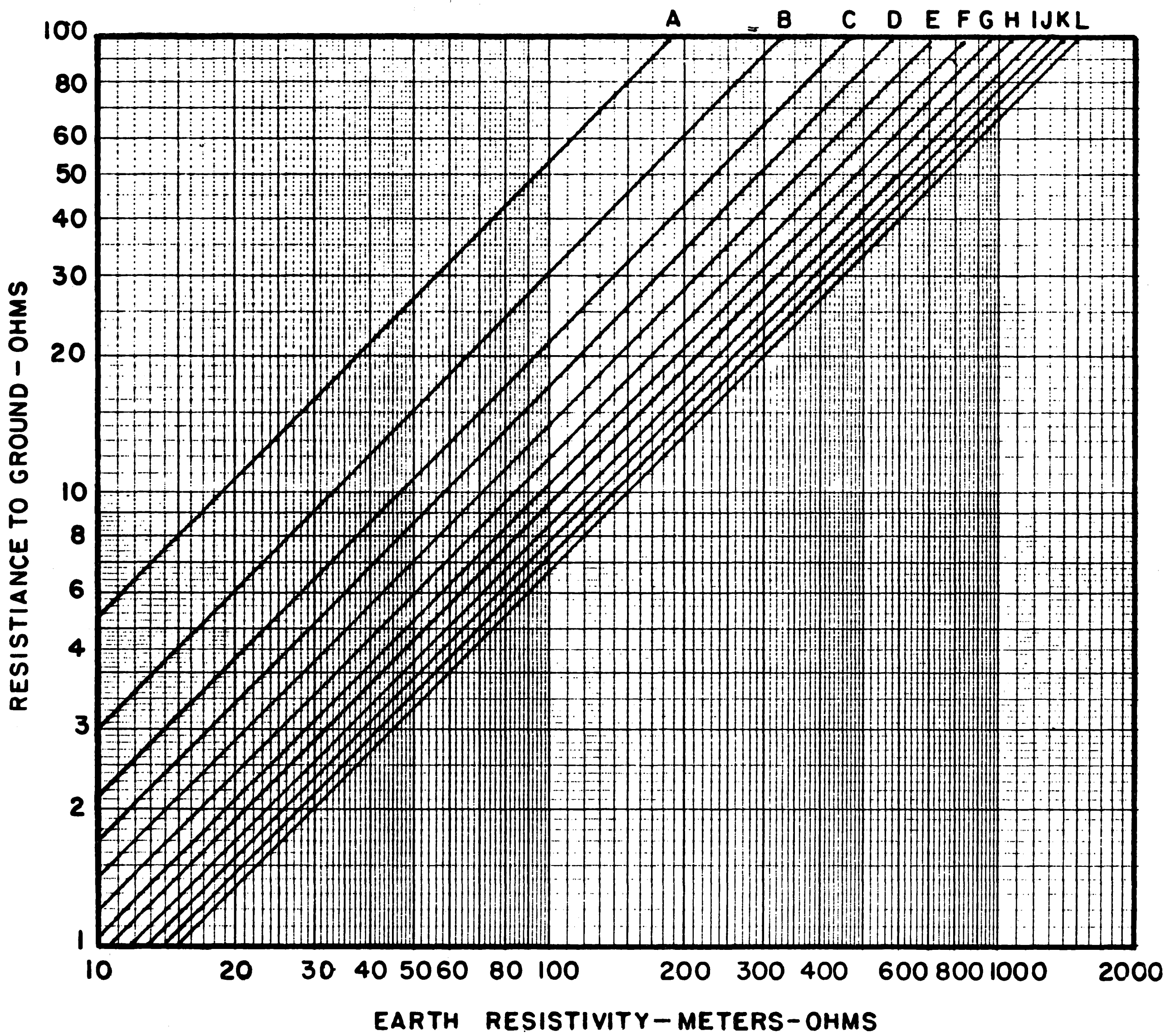
<u>Total Length - 5 Foot Sectional Electrodes</u>

A - 5 Feet (1.5 meters)
B - 10 Feet (3 meters)
C - 15 Feet (4.6 meters)
D - 20 Feet (6.1 meters)
E - 25 Feet (7.6 meters)
F - 30 Feet (9.1 meters)
G - 35 Feet (10.7 meters)
H - 40 Feet (12.2 meters)
I - 45 Feet (13.7 meters)
J - 50 Feet (15.2 meters)
K - 55 Feet (16.8 meters)
L - 60 Feet (18.3 meters)

All Diameters - 5/8 inch (1.6 cm)

<u>FIGURE 26</u>

Resistance to Ground of Vertical Electrodes



Total Length - 5 Foot Sectional Electrodes

A - 5 Feet (1.5 meters)
B - 10 Feet (3 meters)
C - 15 Feet (4.6 meters)
D - 20 Feet (6.1 meters)
E - 25 Feet (7.6 meters)
F - 30 Feet (9.1 meters)
G - 35 Feet (10.7 meters)
H - 40 Feet (12.2 meters)
I - 45 Feet (13.7 meters)
J - 50 Feet (15.2 meters)
K - 55 Feet (16.8 meters)
L - 60 Feet (18.3 meters)

All Diameters - 1 inch (2.5 cm)

FIGURE 27

Resistance to Ground of Vertical Electrodes

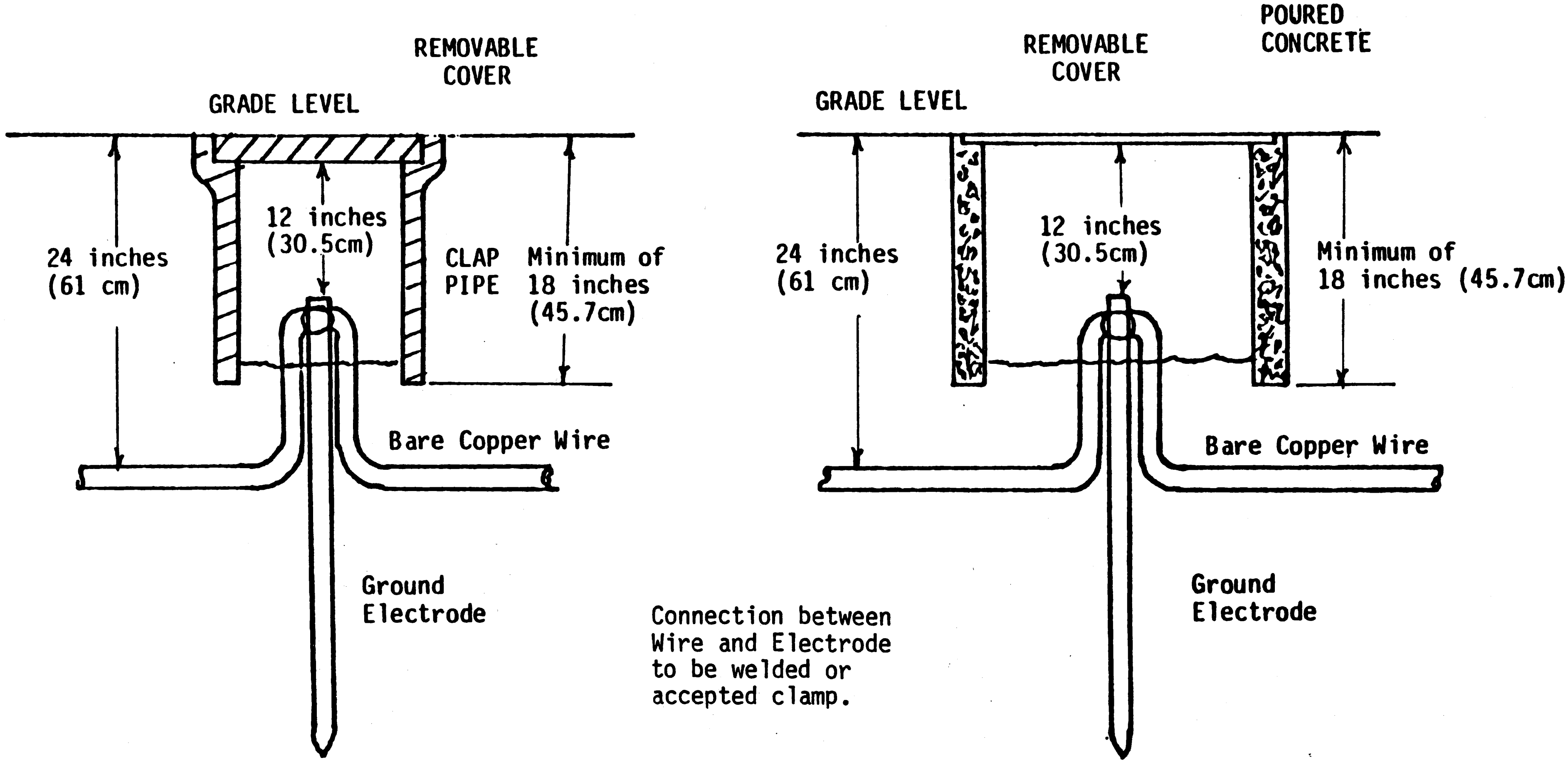


FIGURE 28

Typical Grounding Well

APPENDIX A

GROUNDING EQUATIONS
(English Units)

1. GENERAL

1.1 The equations provided in this Appendix may be used for calculating the approximate anticipated resistance to ground of various grounding configurations. These calculations allow an engineer to determine the probability for obtaining the desired objective resistance to ground at a location prior to electrode installation. The equations are based on the assumption that the soil is homogeneous. Even though soil is seldom of uniform resistivity, the calculation results are close enough to determine if additional electrodes should be driven or another design studied.

1.2 A site survey should first be completed to determine the area available for installation of the grounding system. Measurement of soil resistivity throughout the available area provides the average resistivity of the soil for use in the calculations. (See Appendix C).

1.3 The equations are derived from those published by Erling D. Sunde, "Earth Conduction Effects on Transmission Systems," 1968, D. Van Nostrand Company, Inc. Equations have been simplified to permit use of electrode sizes in units commonly used for identification, i.e., 5/8 inch x 8 foot ground rod.

2. VERTICAL GROUND ELECTRODES (ROD OR PIPE)

2.1 Single Vertical Ground Electrode: The equation for calculating the approximate resistance to ground of a single vertical ground electrode driven into the earth is:

$$R_r = \frac{\rho}{1.9151\,\ell_r} \log_e \frac{35.316\,\ell_r}{d_r} \text{ ohms} \qquad (1)$$

Where: R_r = Electrode resistance to ground, ohms

ρ = Earth resistivity, meter-ohms

ℓ_r = Electrode length, feet

d_r = Electrode diameter, inches

2.2 Multiple Vertical Ground Electrodes: Multiple ground electrode systems can be placed in several configurations, such as straight line, circular or rectangular ring, or rectangular bed. The individual electrodes contained in a system may be interconnected with either insulated or bare conductors. Equations (2), (3), (4) and (5) apply to multiple electrode systems interconnected with insulated conductors. The equations are based on the assumption that the electrodes are uniformly spaced.

2.2.1 Multiple vertical ground electrodes in a straight line: There are three possible conditions relative to parallel grounding electrodes in a straight line:

1. Distance between the electrodes is equal to the length of the electrodes.

2. Distance between the electrodes is greater than the length of the electrodes

3. Distance between the electrodes is less than the length of the electrode.

Because of these conditions there are two equations for calculating the resistance to ground for multiple electrodes placed in a straight line.

2.2.1.1 When the distance between the electrodes (S) is equal to or greater than the length (ℓ) of the electrode, the approximate resistance to ground may be calculated by the following equation:

$$S \geq \ell$$

$$R_R = \frac{1}{n}\left[R_r + \frac{\bar{\rho}}{0.9576\ S}(1/2 + 1/3 + \cdots + 1/n)\right] \text{ohms} \quad (2)$$

Where:

R_R = Parallel electrodes resistance to ground, ohms.

n = Number of electrodes

R_r = Single electrode resistance to ground, ohms (From Equation (1), Paragraph 2.1)

$\bar{\rho}$ = Mean earth resistivity, meter-ohms, measured over site area

S = Spacing between electrodes, feet

ℓ = Electrode length, feet

2.2.1.2 The approximate parallel resistance to ground, where the distance (S) between the electrodes is less than the length (ℓ) of the electrodes may be calculated by the following equation:

$$S < \ell$$

$$R_R = \frac{1}{n}(R_r + (n-1)R_m) \text{ ohms} \quad (3)$$

Where: R_R = Parallel electrodes resistance to ground, ohms

n = Number of electrodes

R_r = Single electrode resistance to ground, ohms (From Equation (1), Paragraph 2.1)

R_m = Mutual resistance between electrodes, ohms (From Equation (4) below)

ℓ = Electrode length, feet

The mutual resistance between two ground electrodes at a designated spacing for completing Equation (3) may be calculated by the following equation:

$$R_m = \frac{\bar{\rho}}{1.9151 \ell_r} \log_e \frac{1.4715 \ell_r}{S} \text{ ohms} \quad (4)$$

Where: R_m = Mutual resistance between electrodes, ohms

$\bar{\rho}$ = Mean earth resistivity, meter-ohms

ℓ_r = Electrode length, feet

S = Electrode spacing, feet

2.2.2 Multiple Vertical Ground Electrodes in a Circular Ring: The equation for calculating the approximate resistance to ground of a grounding system with multiple vertical ground electrodes placed in a circle is:

$$R_R = \frac{\bar{\rho}}{1.9151 n \ell_r} \left(\log_e \frac{35.316 \ell_r}{d_r} + \frac{2 \ell_r}{S} \log_e \frac{2n}{\pi} \right) \text{ ohms} \quad (5)$$

Where: R_R = Parallel electrode resistance to ground, ohms

$\bar{\rho}$ = Mean earth resistivity, meter-ohms

n = Number of electrodes

ℓ_r = Electrode length, feet

d_r = Electrode diameter, inches

S = Spacing between electrodes, feet

π = 3.1416

2.2.3 Multiple Vertical Ground Electrodes in a Square or Rectangular Ring: Calculation of resistance to ground for these configuration is the same as for a circular ring in Paragraph 2.2.2.

2.2.4 Multiple Vertical Ground Electrodes in a Rod bed: The approximate resistance to ground of a grounding system with multiple vertical ground electrodes arranged in a rod bed may be calculated by:

$$R_{GR} = \frac{\bar{\rho}}{1.9151 n \ell_r}\left(\log_e \frac{35.316\,\ell_r}{d_r} + \frac{2K_1 \ell_r}{\sqrt{A}}\left(\sqrt{n}-1\right)^2\right) \text{ ohms} \qquad (6)$$

Where: R_{GR} = Parallel electrodes resistance to ground, ohms

$\bar{\rho}$ = Mean earth resistivity, meter-ohms

n = Number of electrodes

ℓ_r = Electrode length, feet

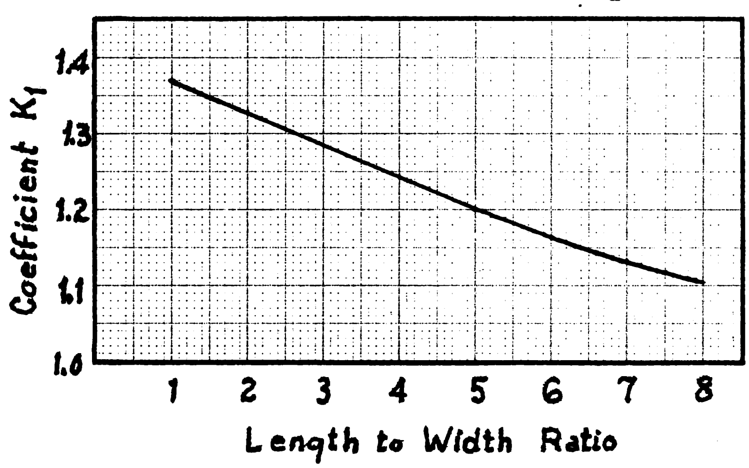
d_r = Electrode diameter, inches

A = Area covered by electrodes, square feet

K_1 = Coefficient from Figure 1, below

FIGURE 1

Values of Coefficient K_1



3. BURIED BARE WIRE

3.1 Bare Wire Buried in a Straight Line: The equation for calculating the approximate resistance to ground of a single bare wire buried in a straight line is:

$$R_w = \frac{\bar{\rho}}{0.9576\,\ell_w} \log_e \frac{2.5487\,\ell_w}{\sqrt{d_w h}} \text{ ohms} \tag{7}$$

Where: R_w = Bare wire resistance to ground, ohms

$\bar{\rho}$ = Mean earth resistivity, meter-ohms

ℓ_w = Wire length, feet

d_w = Wire diameter, inches

h = Wire depth, feet

3.2 Bare Wire Buried in a Ring Configuration: There are two equations available for calculation of the approximate resistance to ground for a bare wire buried in a ring configuration. The equations produce identical results when the same parameter values are used. Both equations are included in this practice. One, Equation (8), pertains to a square or rectangular ring since it is based on the wire length (perimeter of the ring). The second, Equation (9), pertains to a circular configuration since it is based on the ring diameter.

3.2.1 Bare wire buried in a square or rectangular ring: The approximate resistance to ground of a single bare wire buried in a ring may be calculated by the following equation:

$$R_w = \frac{\bar{\rho}}{0.9576\,\ell_w} \log_e \frac{4.4106\,\ell_w}{\sqrt{d_w h}} \text{ ohms} \tag{8}$$

Where: R_w = Bare wire resistance to ground, ohms

$\bar{\rho}$ = Mean earth resistivity, meter-ohms

ℓ_w = Wire length, feet

d_w = Wire diameter, inches

h = Wire depth, feet

3.2.2 Bare Wire Buried in a Circular Ring: Another equation for calculating the approximate resistance to ground of a single bare wire buried in a ring is:

$$R_w = \frac{\bar{\rho}}{6.0165\,D}\left(\log_e \frac{96D}{d_w} + \log_e \frac{2D}{h}\right) \text{ ohms} \tag{9}$$

Where: R_W = Bare wire resistance to ground, ohms

$\bar{\rho}$ = Earth resistivity, meter-ohms

D = Diameter of ring, feet

d_W = Wire diameter, inches

h = Wire depth, feet

3.3 Bare Wire Buried in a Square or Rectangular Grid: The approximate resistance to ground of a grounding system with bare wire buried in a square or rectangular grid can be calculated by the following equation:

$$R_{GW} = \frac{\bar{\rho}}{0.9576\, \ell_W}\left(\log_e \frac{6.9282\, \ell_W}{\sqrt{d_W h}} + \frac{K_1 \ell_W}{\sqrt{A}} - K_2\right) \text{ ohms} \qquad (10)$$

Where: R_{WG} = Bare wire resistance to ground, ohms

$\bar{\rho}$ = Mean earth resistivity, meter-ohms

ℓ_W = Total wire length in grid, feet

d_W = Wire diameter, inches

h = Wire depth, feet

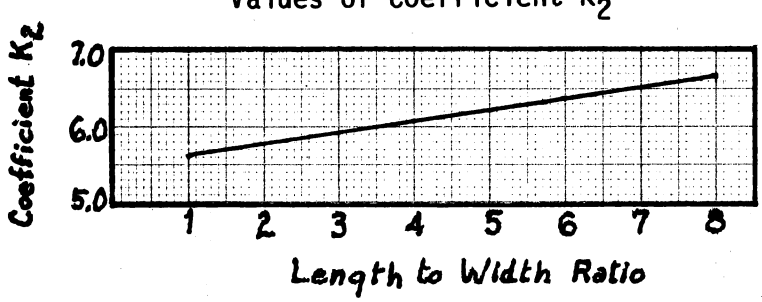
A = Area covered by wire, square feet

K_1 = Coefficient from Figure 1, below Paragraph 2.2.4

K_2 = Coefficient from Figure 2, below

FIGURE 2

Values of Coefficient K_2



3.4 Radial Bare Buried Wires: There are a series of equations for calculating the resistance to ground of radial wire grounding systems. The equations are for three-branched, four-branched, six-branched, and six-or more branched systems.

3.4.1 Radial Bare Buried Wires, Three-Branched Star: The equation for calculating the approximate resistance to ground of a grounding system with three bare buried wires extending radially from a point is:

$$R_{wn} = \frac{\bar{\rho}}{5.7453\,\ell_w}\left(\log_e \frac{48\,\ell_w^2}{d_w h} + 1.071 - 0.4145\frac{h}{\ell_w}\right) \text{ ohms} \qquad (11)$$

Where: R_{wn} = Radial bare wire resistance to ground, ohms

$\bar{\rho}$ = Mean earth resistivity, meter-ohms

ℓ_w = Wire length of single radial branch, feet

dw = Wire diameter, inches

h = Wire depth, feet

3.4.2 Radial Bare Buried Wires, Four-Branched Star: The approximate resistance to ground of a grounding system with four bare buried wires extending radially from a point may be calculated by the following equation:

$$R_{wn} = \frac{\bar{\rho}}{7.66\,\ell_w}\left(\log_e \frac{48\,\ell_w^2}{d_w h} + 2.9128 - 2.1414\frac{h}{\ell_w}\right) \text{ ohms} \qquad (12)$$

Where: R_{wn} = Radial bare wire resistance to ground, ohms

$\bar{\rho}$ = Mean earth resistivity, meter-ohms

ℓ_w = Wire length of single radial branch, feet

dw = Wire diameter, inches

h = Wire depth, feet

3.4.3 Radial Bare Buried Wires, Six-Branched Star: The equation for calculating the approximate resistance to ground of a grounding system with six bare buried wires extending radially from a point is:

$$R_{wn} = \frac{\bar{\rho}}{11.491\,\ell_w}\left(\log_e \frac{48\,\ell_w^2}{d_w h} + 6.8617 - 3.1315\frac{h}{\ell_w}\right) \text{ ohms} \qquad (13)$$

Where: R_{wn} = Radial bare wire resistance to ground, ohms

$\overline{\rho}$ = Mean earth resistivity, meter-ohms

ℓ_w = Wire length of single radial branch, feet

dw = Wire diameter, inches

h = Wire depth, feet

3.4.4 Radial Bare Buried Wires, Six- and Greater Branched Stars: The equation for calculating the approximate resistance to ground of a grounding system with six or more bare buried wires extending radially from a point is:

$$R_{wn} = \frac{\overline{\rho}}{0.9576 n \ell_w}\left(\log_e \frac{2.5487 \ell_w}{\sqrt{d_w h}} + 1.228(n-1) - \log_e n\right) \text{ ohms} \tag{14}$$

Where: R_{wn} = Radial bare wire resistance to ground, ohms

$\overline{\rho}$ = Mean earth resistivity, meter-ohms

n = Number of radial wires

ℓ_w = Wire length of single radial branch, feet

dw = Wire diameter, inches

h = Wire depth, feet

4. MUTUAL RESISTANCE

4.1 When a multiple vertical ground electrode system is interconnected with bare buried conductors, the total resistance to ground (R_T) is influenced by the mutual resistance (R_{WR}) between the vertical electrodes and the bare wire.

4.2 Multiple Vertical Ground Electrodes in a Straight Line: The mutual resistance between multiple vertical ground electrodes in a straight line and bare buried interconnecting conductors may be calculated by the equation:

$$R_{WR} = \frac{\overline{\rho}}{0.9576 \ell_w} \log_e \frac{2 \ell_w}{\ell_r} \text{ ohms} \tag{15}$$

Where: R_{WR} = Mutual resistance between electrodes and wires, ohms

$\bar{\rho}$ = Mean earth resistivity, meter-ohms

ℓ_w = Interconnecting Wire length, feet

ℓ_r = Electrode length, feet

4.3 Multiple Vertical Ground Electrodes in a Ring: The equation for calculating the mutual resistance between multiple vertical ground electrodes in a circular, square or rectangular ring and a bare buried interconnecting conductor is:

$$R_{WR} = \frac{\bar{\rho}}{0.9576\,\ell_w} \log_e \frac{3.461\,\ell_w}{\ell_r} \quad \text{ohms} \qquad (16)$$

Where: R_{WR} = Mutual resistance between electrodes and wire, ohms

$\bar{\rho}$ = Mean earth resistivity, meter-ohms

ℓ_w = Interconnecting Wire length, feet

ℓ_r = Electrode length, feet

4.4 Multiple Vertical Ground Electrodes in a Rod bed: The mutual resistance between a rod bed of multiple vertical ground electrodes and an interconnecting grid of bare buried conductors may be calculated by the following equation:

$$R_{GWR} = \frac{\bar{\rho}}{0.9576\,\ell_w}\left(\log_e \frac{5.4366\,\ell_w}{\ell_r} + \frac{K_1 \ell_w}{\sqrt{A}} - K_2\right) \text{ohms} \qquad (17)$$

Where: R_{GWR} = Mutual resistance between electrodes and wire, ohms

$\bar{\rho}$ = Mean earth resistivity, meter-ohms

ℓ_w = Total wire length in grid, feet

ℓ_r = Electrode length, feet

K_1 = Coefficient from Figure 1, below Paragraph 2.2.4

K_2 = Coefficient from Figure 2, below Paragraph 3.3

A = Area covered by wire, square feet

5. COMBINED RESISTANCE, VERTICAL AND HORIZONTAL ELECTRODES

5.1 The equation for calculating the approximate combined resistance to ground of a grounding system with multiple vertical electrodes interconnected by bare buried wire is:

$$R_T = \frac{R_W R_R - R_{WR}^2}{R_W + R_R - 2R_{WR}} \text{ ohms} \tag{18}$$

Where: R_T = Aggregate resistance of wire and electrodes, ohms

R_W = Bare wire resistance to ground, ohms. (From Equations (7), (8), (9), or (10) as appropriate)

R_R = Parallel vertical electrodes resistance to ground, ohms (From Equations (2), (3), (5), or (6), as appropriate)

R_{WR} = Mutual resistance between wire and electrodes, ohms (From Equations (15), (16), or (17), as appropriate)

5.2 Following is a guide for calculating the approximate resistance to ground of various ground system configurations:

Electrode Configuration	Straight Line	Circular	Square or Rectangular	Rod bed and Grid
Find R_W from Equation	(7)	(8) or (9)	(8)	(10)
Find R_R from Equation	(2) or (3)	(5)	(5)	(6)
Find R_{WR} from Equation	(15)	(16)	(16)	(17)
Find R_T from Equation	(18)	(18)	(18)	(18)

APPENDIX B

GROUNDING EQUATIONS

SI Units (Metric-Meter, Kilogram, Second)

1. GENERAL

1.1 The equations provided in this Appendix may be used for calculating the approximate anticipated resistance to ground of various grounding configurations. These calculations allow an engineer to determine the probability for obtaining the desired objective resistance to ground at a location prior to electrode installation. The equations are based on the assumption that the soil is homogeneous. Even though soil is seldom of uniform resistivity, the calculated results are close enough to determine if additional electrodes should be driven or another design studied.

1.2 A site survey should first be completed to determine the area available for installation of the grounding system. (Refer Paragraph 7.2 of TE&CM Section 802). Measurement of soil resistivity throughout the available area provides the average resistivity of the soil for use in the calculations. (Refer to Appendix C).

1.3 The equations are derived from those published by Erling D. Sunde, "Earth Conduction Effects on Transmission Systems," Dover Publications, Inc., New York, 1968. Equations have been simplified to permit use of electrode sizes in units commonly used for identification, i.e., 2.54 cm x 3 m. ground rod.

2. VERTICAL GROUND ELECTRODES (ROD OR PIPE)

2.1 Single Vertical Ground Electrode: The equation for calculating the approximate resistance to ground of a single vertical ground electrode driven into the earth is:

$$R_r = \frac{\rho}{2\pi \ell_r} \log_e \frac{294.32\,\ell_r}{d_r} \quad \text{ohms} \qquad (1)$$

Where:

R_r = Electrode resistance to ground, ohms

ρ = Earth resistivity, meter-ohms

ℓ_r = Electrode length, meters

d_r = Electrode diameter, centimeters

π = 3.1416

2.2 Multiple Vertical Ground Electrodes: Multiple ground electrode systems can be placed in several configurations, such as straight line, circular or rectangular ring, or rectangular bed. The individual electrodes contained in a system may be interconnected with either insulated or bare conductors. Equations (2), (3), (4) and (5) apply to multiple electrode systems interconnected with insulated conductors. The equations are based on the assumption that the electrodes are uniformly spaced.

2.2.1 Multiple vertical ground electrodes in a straight line: There are three possible conditions relative to parallel grounding electrodes in a straight line:

1. The distance between the electrodes is equal to the length of the electrodes.
2. The distance between the electrodes is greater than the length of the electrodes.
3. The distance between the electrodes is less than the length of the electrodes.

Because of these conditions there are two equations for calculating the resistance to ground for multiple electrodes in a straight line.

2.2.1.1 When the distance between the electrode (S) is equal to or greater than (ℓ) the length of the electrode, the approximate resistance to ground may be calculated by the following equation:

$$S \geq \ell$$

$$R_R = \frac{1}{n}\left[R_r + \frac{\bar{\rho}}{\pi S}\left(1/2 + 1/3 + \cdots + 1/n\right)\right] \text{ ohms} \qquad (2)$$

Where: R_R = Parallel electrodes resistance to ground, ohms

n = Number of electrodes

R_r = Single electrode resistance to ground, ohms (From Equation (1), Paragraph 2.1)

$\bar{\rho}$ = Mean earth resistivity, meter-ohms

ℓ = Electrode Length, meters

S = Spacing between electrodes, meters

π = 3.1416

2.2.1.2 The approximate parallel resistance to ground, where the distance (S) between the electrodes is less than the length (ℓ) of the electrode may be calculated by the following equation:

$$S < \ell$$

$$R_R = \frac{1}{n}\left(R_r + (n-1)\,R_m\right) \text{ ohms} \qquad (3)$$

Where: R_R = Parallel electrodes resistance to ground, ohms

n = Number of electrodes

R_r = Single electrode resistance to ground, ohms (From Equation (1), Paragraph 2.1)

R_m = Mutual resistance between electrodes, ohms (From Equation (4) below)

ℓ = Electrode length, meters

The mutual resistance between two ground electrodes at a designated spacing for completing equation (3) may be calculated by the following equation:

$$R_m = \frac{\bar{\rho}}{2\pi \ell_r} \log_e \frac{1.4715\,\ell_r}{S} \text{ ohms} \qquad (4)$$

Where: R_m = Mutual resistance between electrodes, ohms

$\bar{\rho}$ = Mean earth resistivity, meter-ohms

ℓ_r = Electrode length, meters

S = Electrode spacing, meters

π = 3.1416

2.2.2 Multiple Vertical Ground Electrodes in a Circular Ring: The equation for calculating the approximate resistance to ground of a grounding system with multiple vertical ground electrodes placed in a circle is:

$$R_R = \frac{\bar{\rho}}{2\pi n \ell_r}\left(\log_e \frac{294.32\,\ell_r}{d_r} + \frac{2\ell_r}{S} \log_e \frac{2n}{\pi}\right) \text{ ohms} \qquad (5)$$

Where: R_R = Parallel electrode resistance to ground, ohms

$\overline{\rho}$ = Mean earth resistivity, meter-ohms

n = Number of electrodes

ℓ_r = Electrode length, meters

d_r = Electrode diameter, centimeters

S = Electrode spacing, meters

π = 3.1416

2.2.3 Multiple Vertical Ground Electrodes in a Square or Rectangular Ring: Calculation of resistance to ground for these configurations is the same as for a circular ring in Paragraph 2.2.2.

2.2.4 Multiple Vertical Ground Electrodes in a Rod Bed: The approximate resistance to ground of a grounding system with multiple vertical ground electrodes arranged in a rod bed may be calculated by:

$$R_{GR} = \frac{\overline{\rho}}{2\pi n \ell_r}\left(\log_e \frac{294.32\,\ell_r}{d_r} + \frac{2K_1\ell_r}{\sqrt{A}}\left(\sqrt{n}-1\right)^2\right) \text{ ohms} \qquad (6)$$

Where: R_{GR} = Parallel electrodes resistance to ground, ohms

$\overline{\rho}$ = Mean earth resistivity, meter-ohms

n = Number of electrodes

ℓ_r = Electrode length, meters

d_r = Electrode diameter, centimeters

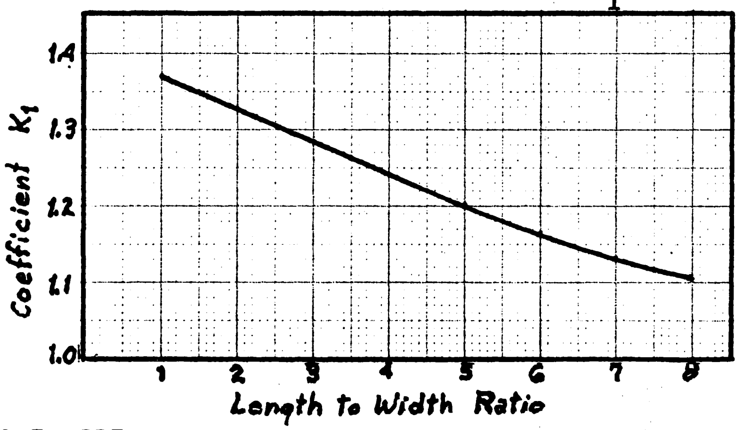
A = Area covered by electrodes, square meters

K_1 = Coefficient from Figure 1, below

π = 3.1416

FIGURE 1

Values of Coefficient K_1



3. BURIED BARE WIRE

3.1 Bare Wire Buried in a Straight Line: The equation for calculating the approximate resistance to ground of a single bare wire buried in a straight line is:

$$R_W = \frac{\bar{\rho}}{\pi \ell_w} \log_e \frac{7.3576\, \ell_w}{\sqrt{d_w h}} \text{ ohms} \qquad (7)$$

Where: R_W = Bare wire resistance to ground, ohms

$\bar{\rho}$ = Mean earth resistivity, meter-ohms

ℓw = Wire length, meters

dw = Wire diameter, centimeters

h = Wire depth, meters

π = 3.1416

3.2 Bare Wire Buried in a Ring Configuration: There are two equations available for calculation of the approximate resistance to ground for a bare wire buried in a ring configuration. The equations produce identical results when the same parameter values are used. Both equations are included in this practice. One, Equation (8), pertains to a square or rectangular ring since it is based on the wire length (perimeter of the ring). The second, Equation (9), pertains to a circular configuration since it is based on the ring diameter.

3.2.1 Bare wire buried in a square or rectangular ring: The approximate resistance to ground of a single bare wire buried in a ring may be calculated by the following equation:

$$R_W = \frac{\bar{\rho}}{\pi \ell_w} \log_e \frac{12.732 \ell_w}{\sqrt{d_w h}} \quad ohms \qquad (8)$$

Where: R_W = Bare wire resistance to ground, ohms

$\bar{\rho}$ = Mean earth resistivity, meter-ohms

ℓw = Wire length, meters

dw = Wire diameter, centimeters

h = Wire depth, meters

3.2.2 Bare wire in a circular ring: Another equation for calculating the approximate resistance to ground of a single bare wire buried in a ring is:

$$R_W = \frac{\bar{\rho}}{2\pi^2 D}\left(\log_e \frac{800D}{d_w} + \log_e \frac{2D}{h}\right) ohms \qquad (9)$$

Where: R_W = Bare wire resistance to ground, ohms

$\bar{\rho}$ = Mean earth resistivity, meter-ohms

D = Ring Diameter, meters

dw = Wire diameter, centimeters

h = Wire depth, meters

π = 3.1416

3.3 Bare Wire Buried in a Square or Rectangular Grid: The approximate resistance to ground of a grounding system with bare wire buried in a square or rectangular grid can be calculated by the following equation:

$$R_{GW} = \frac{\bar{\rho}}{\pi \ell_w}\left(\log_e \frac{20\ell_w}{\sqrt{d_w h}} + \frac{K_1 \ell_w}{\sqrt{A}} - K_2\right) \text{ ohms} \qquad (10)$$

Where: R_{WG} = Bare wire resistance to ground, ohms

$\bar{\rho}$ = Mean earth resistivity, meter-ohms

ℓw = Total wire length in grid, meters

dw = Wire diameter, centimeters

h = Wire depth, meters

A = Area covered by wire, square meters

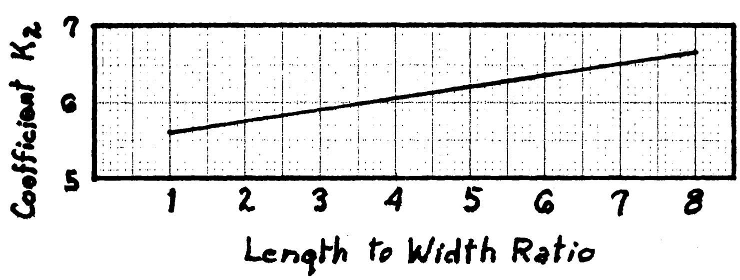
K_1 = Coefficient from Figure 1, below Paragraph 2.2.4

K_2 = Coefficient from Figure 2, below

π = 3.1416

FIGURE B2

Values of Coefficient K_2



3.4 Radial Bare Buried Wires: There are a series of equations for calculating the resistance to ground of radial wire grounding systems. The equations are for three-branched, four-branched, six-branched, and six- or more branched stars.

3.4.1 Radial Bare Buried Wires: Three-Branched Star: The equation for calculating the approximate resistance to ground of a grounding system with three bare buried wires extending radially from a point is:

$$R_{Wn} = \frac{\bar{\rho}}{18.85\,\ell_w}\left(\log_e \frac{400\,\ell_w^2}{d_w h} + 1.071 - 0.4145\frac{h}{\ell_w}\right) \text{ ohms} \qquad (11)$$

Where: R_{wn} = Radial bare wire resistance to ground, ohms

$\bar{\rho}$ = Mean earth resistivity, meter-ohms

ℓw = Wire length of single radial branch, meters

dw = Wire diameter, centimeters

h = Wire depth, meters

3.4.2 Radial Bare Buried Wires, Four-Branched Star: The approximate resistance to ground of a grounding system with four bare buried wires extending radially from a point may be calculated by the following equation:

$$R_{Wn} = \frac{\bar{\rho}}{25.133\,\ell_w}\left(\log_e \frac{400\,\ell_w^2}{d_w h} + 2.9128 - 2.1414\frac{h}{\ell_w}\right) \text{ ohms} \qquad (12)$$

Where: R_{wn} = Radial bare wire resistance to ground, ohms

$\bar{\rho}$ = Mean earth resistivity, meter-ohms

ℓw = Wire length, meters

dw = Wire diameter, centimeters

h = Wire depth, meters

3.4.3 Radial Bare Buried Wires, Six-Branched Star: The equation for calculating the approximate resistance to ground of a grounding system with six bare buried wires extending radially from a point is:

$$R_{Wn} = \frac{\bar{\rho}}{37.699\,\ell_w}\left(\log_e \frac{400\,\ell_w^2}{d_w h} + 6.8617 - 3.1315\frac{h}{\ell_w}\right) \text{ ohms} \qquad (13)$$

Where: R_{wn} = Radial bare wire resistance to ground, ohms

$\bar{\rho}$ = Mean earth resistivity, meter-ohms

ℓw = Wire length, meters

dw = Wire diameter, centimeters

h = Wire depth, meters

3.4.4 Radial Bare Buried Wires, Six- and Greater Branched Stars: The equation for calculating the approximate resistance to ground of a grounding system with six or more bare buried wires extending radially from a point is:

$$R_{Wn} = \frac{\bar{\rho}}{\pi n \ell_w}\left(\log_e \frac{7.3576\,\ell_w}{d_w h} + 1.228(n-1) - \log_e n\right) \text{ohms} \qquad (14)$$

Where: R_{wn} = Radial bare wire resistance to ground, ohms

$\bar{\rho}$ = Mean earth resistivity, meter-ohms

n = Number of radial wires

ℓw = Wire length of single radial branch, meters

dw = Wire diameter, centimeters

h = Wire depth, meters

π = 3.1416

4. MUTUAL RESISTANCE

4.1 When a multiple vertical ground electrode system is interconnected with bare buried conductors, the total resistance to ground (R_T) is influenced by the mutual resistance (R_{WR}) between the vertical electrodes and the bare wire.

4.2 Multiple Vertical Ground Electrodes in a Straight Line: The mutual resistance between multiple vertical ground electrodes in a straight line and bare buried interconnecting conductors may be calculated by the equation:

$$R_{WR} = \frac{\bar{\rho}}{\pi \ell_w} \log_e \frac{2\ell_w}{\ell_r} \quad \text{ohms} \tag{15}$$

Where: R_{WR} = Mutual resistance between electrodes and wire, ohms

$\bar{\rho}$ = Mean earth resistivity, meter-ohms

ℓw = Interconnecting wire length, meters

ℓ_r = Electrode length, meters

π = 3.1416

4.3 Multiple Vertical Ground Electrodes in a Ring: The equation for calculating the mutual resistance between multiple vertical ground electrodes in a circular, square or rectangular ring and a bare buried interconnecting conductor is:

$$R_{WR} = \frac{\bar{\rho}}{\pi \ell_w} \log_e \frac{3.461\,\ell_w}{\ell_r} \quad \text{ohms} \tag{16}$$

Where: R_{WR} = Mutual resistance between electrodes and wire, ohms

$\bar{\rho}$ = Mean earth resistivity, meter-ohms

ℓw = Interconnecting wire length, meters

ℓ_r = Electrode length, meters

π = 3.1416

4.4 Multiple Vertical Ground Electrodes in a Rod Bed: The mutual resistance between a rodbed of multiple vertical ground electrodes and an interconnecting grid of bare buried conductors may be calculated by the following equation:

$$R_{WGR} = \frac{\bar{\rho}}{\pi \ell_w} \left(\log_e \frac{5.4366\,\ell_w}{\ell_r} + \frac{K_1 \ell_w}{\sqrt{A}} - K_2 \right) \text{ohms} \tag{17}$$

Where: R_{WGR} = Mutual resistance between electrodes and wire, ohms

$\bar{\rho}$ = Mean earth resistivity, meter-ohms

ℓw = Total wire length in grid, meters

ℓ_r = Electrode length, meters

K_1 = Coefficient from Figure 1, below Paragraph 2.2.4

K_2 = Coefficient from Figure 2, below Paragraph 3.3

A = Area covered by wire, square meters

π = 3.1416

5. COMBINED RESISTANCE, VERTICAL AND HORIZONTAL ELECTRODES

5.1 The equation for calculating the approximate combined resistance to ground of a grounding system with multiple vertical electrodes interconnected by bare buried wire is:

$$R_T = \frac{R_W R_R - R_{WR}^2}{R_W + R_R - 2R_{WR}} \text{ ohms} \quad (18)$$

Where: R_T = Aggregate resistance of wire and electrodes, ohms

R_W = Bare wire resistance to ground, ohms (From Equations (7), (8), (9), or (10), as appropriate)

R_T = Parallel vertical electrodes resistance to gound, ohms (From Equations (2), (3), (5), or (6), as appropriate)

R_{WR} = Mutual resistance between wire and electrodes, ohms (From Equations (15), (16), or (17), as appropriate)

5.2 Following is a guide for calculating the approximate resistance to ground of various grounding system configurations:

Electrode Configuration	Straight Line	Circular	Square or Rectangle	Rod bed and Grid
Find R_W from Equation	(7)	(8) or (9)	(8)	(10)
Find R_R from Equation	(2) or (3)	(5)	(5)	(6)
Find R_{WR} from Equation	(15)	(16)	(16)	(17)
Find R_T from Equation	(18)	(18)	(18)	(18)

APPENDIX C

MEASUREMENT OF SOIL RESISTIVITY

1. GENERAL

1.1 Soil resistivity measurements are commonly made with a test instrument that uses the four-terminal fall of potential method. The test instrument has four terminals that are connected to four electrodes arranged at equal distances along a straight line (shown in Figure 1C). Internally the instrument contains a current circuit and a voltage circuit. The current source can be a hand-driven a.c. generator or a voltage reversing vibrator that causes a current to flow between the two outer electrodes (Terminals C_1 and C_2). A potential is measured between the inner electrodes (Terminals P_1 and P_2). The voltage and current circuits are coupled within the test set to provide a reading in ohms.

1.2 The theory for this measurement was developed by Dr. Frank Wenner of the U.S. Bureau of Standards in 1915 and published in Report No. 258, Bulletin of Bureau of Standards, Vol. 12, No. 3, October 11, 1915, "A Method of Measuring Earth Resistivity." Dr. Wenner established that, if the test electrode depth is small compared to the distance between the electrodes, the following equation applies to determine the average soil resistivity to a depth equal to the distance between the electrodes:

$$\rho = 2\pi \ AR = 6.28AR$$

Where: ρ = Average soil resistivity to depth equal to A, in ohm-centimeters
π = 3.1416
A = Distance between electrodes, in centimeters
R = Test instrument resistance reading, in ohms

The calculations may be conveniently completed using English Units of measurement with the following equation:

$$\rho = 191.51AR$$

Where: ρ = Average soil resistivity to depth equal to A, in ohm-centimeters,
A = Distance between electrodes, in feet
R = Test instrument resistance reading, in ohms

Note: Divide ohm-centimeters by 100 to convert to meter-ohms.

1.3 Ground test instruments generally use an alternating voltage source with a frequency not related to power system fundamental frequencies or their harmonics. This avoids the effects of polarization and foreign earth currents which could produce erroneous results.

1.4 Measurement of soil resistivity has two basic objectives. The first is to determine the type of earth connection required to provide the objective resistance to earth. The second is to define any geological limitations that might be present, such as a rock layer, that would restrict installation of the grounding system.

2. BASIC SOIL RESISTIVITY MEASUREMENT

2.1 The depth to which the average soil resistivity is desired determines the distance (A) between the test electrodes. This distance will typically be the length of the ground electrode to be installed plus the depth below the earth's surface to which it will be driven. A measurement should be taken with test electrode spacings of one-half, one, two and four times the length of the proposed ground electrode. This will identify the presence of large deviations in the soil resistivity. Place four test electrodes along a base line in relation to the proposed vertical ground electrode location as shown in Figure 2C. The test electrodes should be driven into the soil to a depth equal to A/20. Depths for test electrodes for various distances (A) are shown in Table I.

TABLE I

Test Electrode Depths for Various Distances Between Electrodes

Distance Between Electrodes (A)		Test Electrode Depth (B)	
Feet	Centimeters	Inches	Centimeters
5	152	3.0	8
8	244	5.0	13
10	305	6.0	15
16	488	10.0	25
20	610	12.0	30
30	914	18.0	46
40	1219	24.0	61
50	1524	30.0	76

2.2 Connect the leads from the four test electrodes to the proper terminals on the test set, C_1, P_1, P_2 and C_2. Complete the measurement as described by the manufacturer of the test equipment. Calculate the soil resistivity by the equation in Paragraph 1.2 and record results.

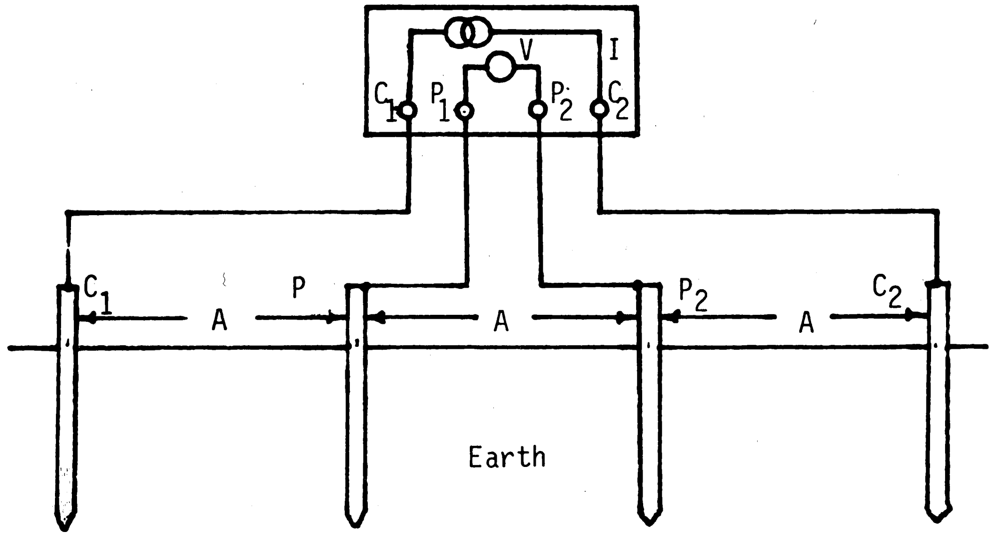
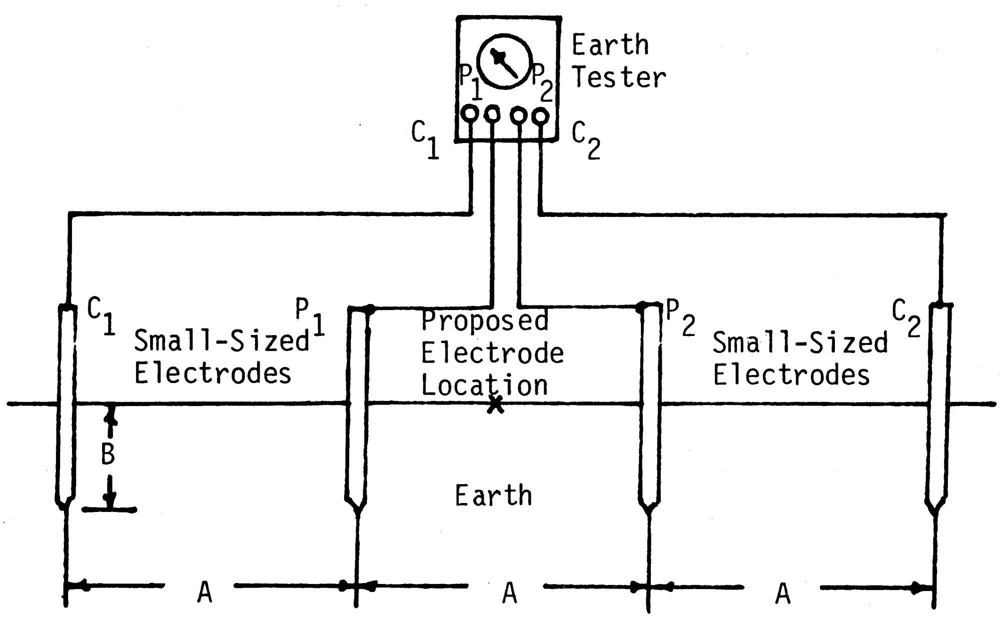


FIGURE 1C

"Four-Terminal" Method for Measurement of Soil Resistivity



A = 20 B (Approximately)

FIGURE 2C

"Four-Terminal" Method for Measuring Soil Resistivity

APPENDIX D

MEASUREMENT OF RESISTANCE TO GROUND

1. GENERAL

1.1 Measurement of a new grounding system's resistance to ground is needed to determine if the design criteria have been met. Measurement is essential when the grounding system has been installed for the protection of sensitive electronic equipment, such as, digital central offices, line concentrators, carrier terminals and carrier repeaters.

1.2 The resistance to ground of existing grounding systems should be periodically measured to determine if the system continues to meet the original design limits. Where the resistance to ground is found to have increased significantly, expansion of the system may be desirable to restore the original effectiveness.

2. METHODS

2.1 There are three methods for measuring grounding system resistance to ground. They are the triangulation, direct (two terminal), and fall-of-potential (three terminal) methods.

2.2 Triangulation method: The series resistance of the electrode under test (R_x) and the auxiliary electrodes (R_a, R_b) are measured two at a time as illustrated in Figure 1D. The unknown resistance can then be calculated by the formula:

$$Rx = \frac{(R_x + R_a) + (R_x + R_b) - (R_a + R_b)}{2}$$

The series resistances may be measured with a bridge, ohmmeter, or a voltmeter. The current source may be either alternating or direct current. The auxiliary electrodes should have a resistance to ground on the same order of magnitude as the unknown for accuracy. The electrodes must be some distance apart to avoid errors, such as zero or negative resistances, in the calculations. The recommended distance between each pair of the three separate ground electrodes, when measuring a single 10-foot (3.0 meter) driven electrode, should be at least 15 feet (4.6 meters), (a preferable spacing is 25 feet (7.6 meters)).

2.3 Direct method (two terminal): This technique utilizes an instrument with four terminals (P_1, P_2, C_1, C_2) for ground resistance tests. The instrument includes: (1) a voltage source, (2) an ohmmeter to measure resistance directly, and (3) a switch or switches to change the resistance range. The voltage source can be either a hand-driven a.c. generator or a voltage reversing vibrator. Connect terminals P_1 and C_1 to the ground electrode to be measured and connect terminals P_2 and C_2 to an all-metallic water-pipe system as illustrated in Figure 2D. (The resistance to ground of a metallic water system covering a large area should be less than one ohm.) The instrument reading can be accepted as being the resistance to ground of the electrode under test.

Although the direct method of measuring two electrodes in series is the simplest way to make a ground resistance test, it has important limitations. The water-pipe system must be extensive enough to have only negligible resistance to ground. The water-pipe system must be entirely metallic without insulating couplings or flanges. The electrode being tested must be located far enough from the water-pipe system to be outside its sphere of influence.

NOTE: "Getting Down-to-Earth", Manual on Earth-Resistance Testing for the Practical Man, published by the James G. Biddle Company indicates the distance from the electrode to the water-pipe system should be about ten times the radius of the electrode or grid to provide a measurement accuracy of $\pm$ 10 percent.

2.4 Fall-of-Potential Method (Three terminal): The three-terminal test, illustrated in Figure 3D, is the method most commonly used to measure the electrode resistance to ground. The P_1 and C_1 terminals of the test instrument are connected together and to the electrode being tested. A reference electrode C_2 should be driven into earth as far as practical from the electrode being tested. The distance between the electrode under test and the reference electrode may be limited by the length of wire available or the physical characteristics of the surrounding area. Reference electrode P_2 is then driven at a number of points along a straight line between the ground electrode and C_2. Resistance readings are taken and recorded for each point. A curve of resistance to ground versus distance can then be plotted similar to Figure 4D. The correct resistance to ground is shown on the curve at a distance about 62 percent of the total distance from the ground electrode to C_2.

2.4.1 Reference electrode location: The distance between the reference electrode C_2 and the electrode being tested determines the accuracy of the test results. When the electrodes are located far enough apart so that the earth shells surrounding them do not overlap the resistance versus distance curve will flatten as shown in Figure 5D. A value very close to the actual resistance to ground can be found at the point within this plateau along the curve representing 62 percent of the total distance. The value will be erroneous only where soil conditions at the 62 percent point vary significantly from those at other points. The objective is to get a degree of flatness along the curve that will provide easy identification of such variations.

When the electrodes are located so close that the earth shells overlap, as illustrated in Figure 6D, the leveling of the curve does not occur. The shells surrounding reference electrode (C_2) add to the shells around the ground electrode and the resistance increases linearly.

2.4.2 Table I provides the minimum distance between the reference electrode (C_2) and the ground electrode system. The distance from the ground electrode to reference electrode (P_2) that is about 62 percent of the distance to C_2 is also shown.

TABLE I

REFERENCE ELECTRODE LOCATION

Maximum Dimension, Ft. (Meters)	Distance to P_2 Ft. (Meters)	Distance to C_2, Ft. (Meters)
2 (0.6)	40 (12.2)	70 (21.3)
4 (1.2)	60 (18.3)	100 (30.5)
6 (1.8)	80 (24.4)	125 (38.1)
8 (2.4)	90 (27.4)	140 (42.7)
10 (3.0)	100 (30.5)	160 (48.8)
12 (3.7)	105 (32.0)	170 (51.8)
14 (4.3)	120 (36.6)	190 (57.9)
16 (4.9)	125 (38.1)	200 (61.0)
18 (5.5)	130 (39.6)	210 (64.0)
20 (6.1)	140 (42.7)	220 (67.1)
40 (12.2)	200 (61.0)	320 (97.5)
60 (18.3)	240 (73.2)	390 (118.9)
80 (24.4)	280 (85.3)	450 (137.2)
100 (30.5	310 (94.5)	500 (152.4)
120 (36.6)	340 (103.6)	550 (167.6)
140 (42.7)	365 (111.3)	590 (179.8)
160 (48.8)	400 (121.9)	640 (195.1)
180 (54.9)	420 (128.0)	680 (207.3)
200 (61.0)	440 (134.1)	710 (216.3)

The maximum dimension is determined as follows:

1. When the grounding system contains two or more electrodes along a straight line, the maximum dimension is the distance between the first and last electrode.

2. The maximum dimension for a grounding system containing electrodes in a circular ring configuration is the diameter of the circle.

3. The diagonal distance across a grounding system having a square or rectangular form is the maximum dimension.

3. GROUNDING SYSTEMS OF LARGE AREA

3.1 There are problems when attempting to measure the resistance to ground of a grounding system that is spread over a large area. The primary problem is the need for placing the reference electrode (C_2) at a considerable distance from the ground electrode system. In addition to the necessity of transporting sufficient wire to reach this electrode and the corresponding length for reference electrode (P_2) there is often difficulty in findings clear path of the required length from the grounding system. G.F. Tagg developed a technique for these measurements in which such long leads are not necessary.

3.2 The measurement method is presented in this practice since there may be locations where it will be desirable to use it when measuring systems of moderate area. Depending on the location of the grounding system, a clear path may not be available for the reference electrodes and associated wire. The technique described below may be utilized to complete the desired measurements.

3.3 The basis of this technique is to obtain ground resistance curves for several reference electrode spacings. Then, be assuming a number of successive positions for the electrical center of the system, intersection curves are constructed which will give the earth resistance and the position of the electrical center.

3.3.1 Assume that all measurements are made from an arbitrary starting point O along the perimeter of the grounding system. The distance C to the reference electrode (C_2) and the variable distance P to the reference electrode (P_2) are measured from point O. A curve such as abc in Figure 7D can be constructed giving the measured resistance against the value of P. Further, assume the electrical center of the ground electrode system is point D, at distance X from point O. The true distance from the center to C_2 is then C + X and the true resistance is obtained when P_2 is at a distance 0.618(C+X) from D. Thus, the value of P, measured from O, is 0.618(C+X)-X. If X is given a number of values the corresponding values of P can be calculated and the resistance read off the curve. These resistances can be plotted against the values of X in another curve. When this procedure is repeated for a different value of C, and another curve of resistance against X plotted, the two curves should intersect at the required resistance. The procedure can be repeated for a third value of C as a check. These curves are called intersection curves. The electrical center (D) is assumed to be an extension of the testing line (O, C_2). Even where this is not the case only a small error results which is not important.

3.3.2 Large Area Example: The ground system covers an area 300 ft. X 250 ft. (91 m X 76 m) and consists of a number of ground electrodes bonded together by copper cables. The testing line extended from a point approximately halfway along one side with reference electrode placed at a distance of 400 (122), 600 (183), 800 (244), and 1000 (305) feet (meters). The resulting curves are shown in Figure 8D. Applying the described method produced the intersection curves given in Figure 9D. The center of the triangle formed by these curves gives the ground resistance as about 0.146 ohms.

3.4 The purpose of this method is to reduce the distance to reference electrode C_2 which appears to have been achieved. There are some additional points to be noted. The distance to electrode C_2 has certain limits. If the grounding system is in the form of a square, the minimum distance to C_2 should not be less than the side of the square. On the other hand, the maximum distance should not be too great or the resulting curve is very flat and the intersection point will be rather indefinite. Again, for a square system, the maximum distance should not exceed twice the side of the square. For other shapes of ground electrode systems, suitable minimum and maximum values for the distance to C_2 are based on judgement.

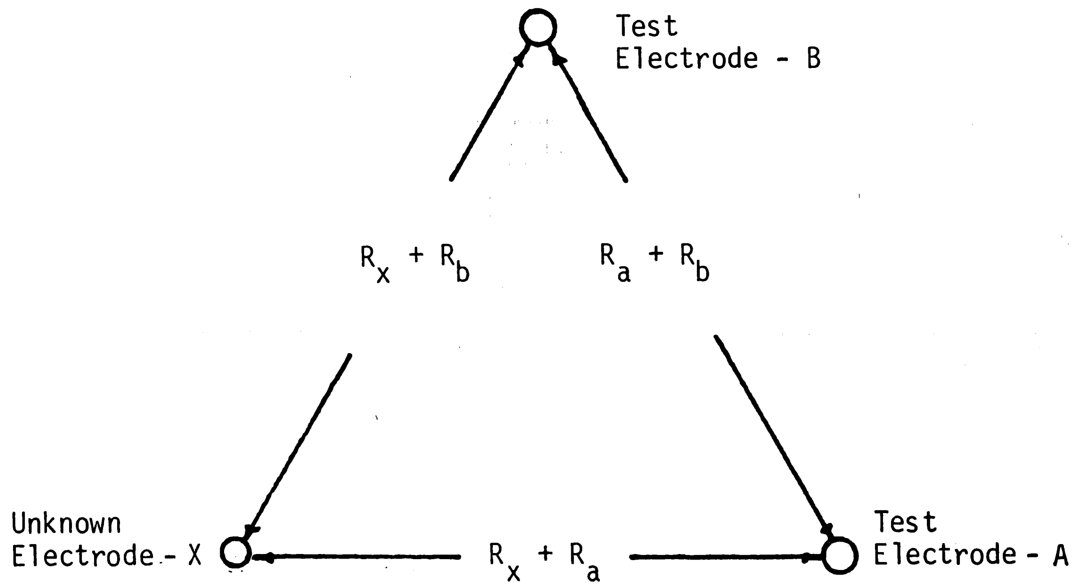


FIGURE 1D

Triangulation Method for Measuring the Resistance of a Ground Electrode

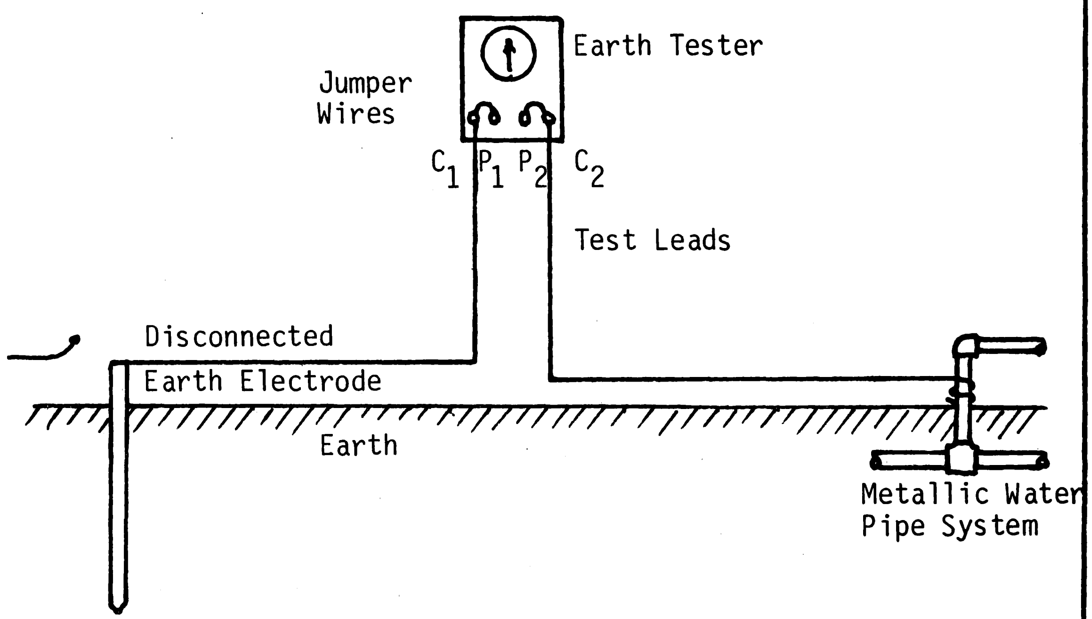


FIGURE 2D

Direct Method for Measuring the Resistance of a Ground Electrode

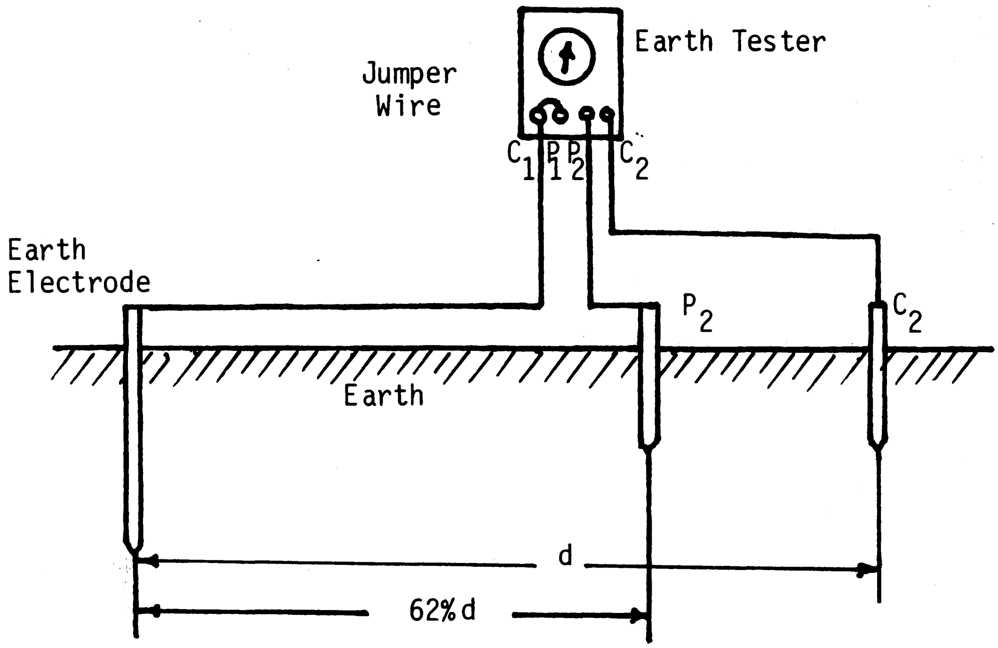


FIGURE 3D

Fall of Potential Method

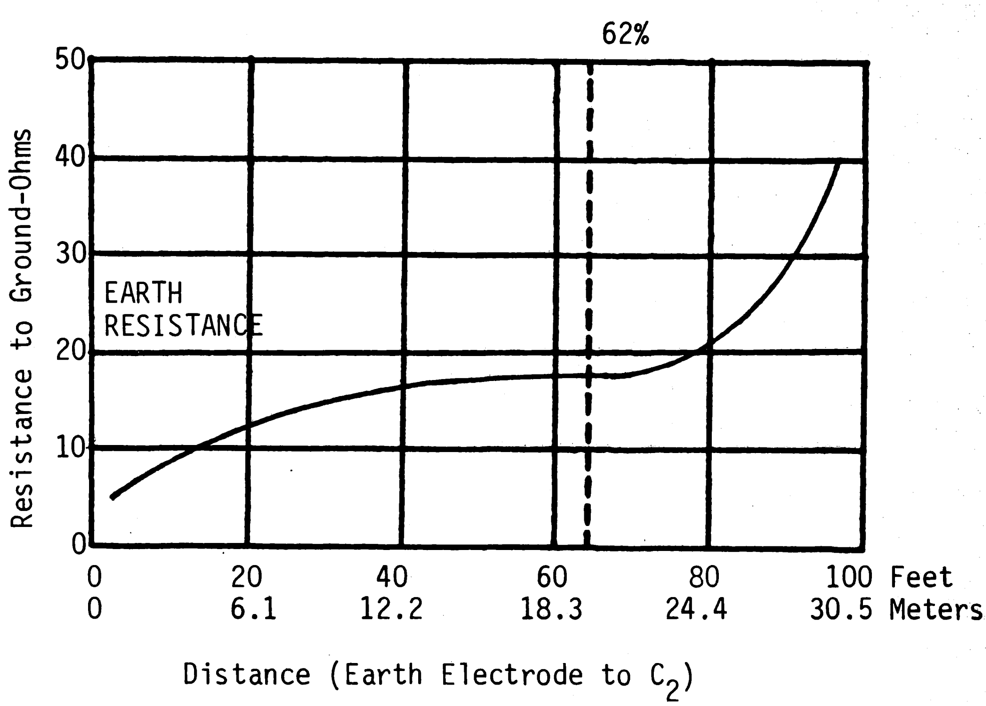


FIGURE 4D

Example of Earth Resistance Curve

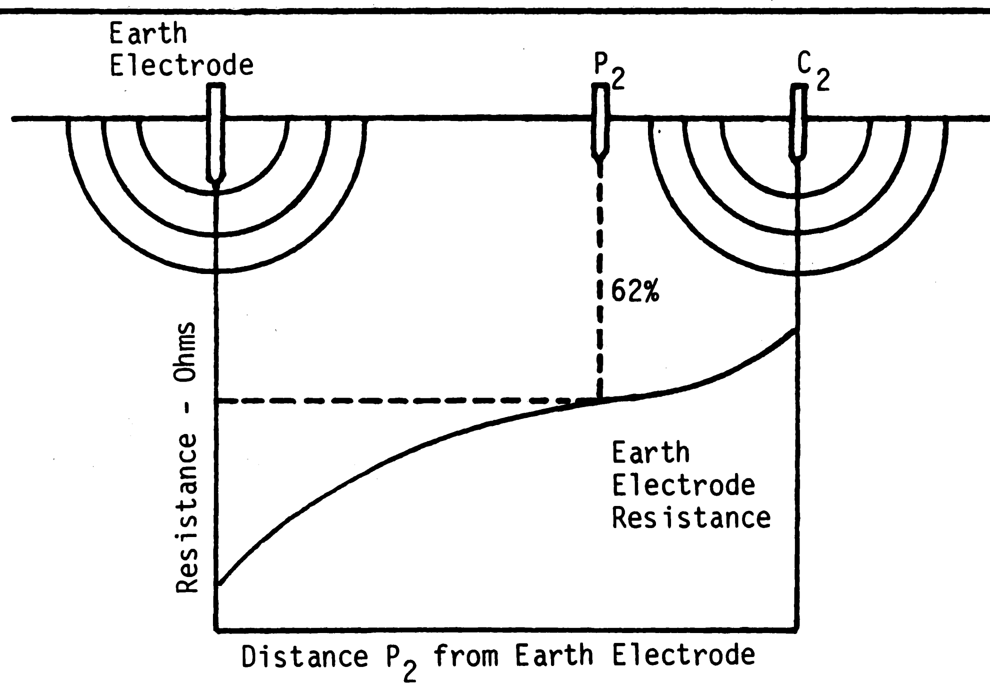


FIGURE 5D

Effect with C_2 Located Far From Earth Electrode

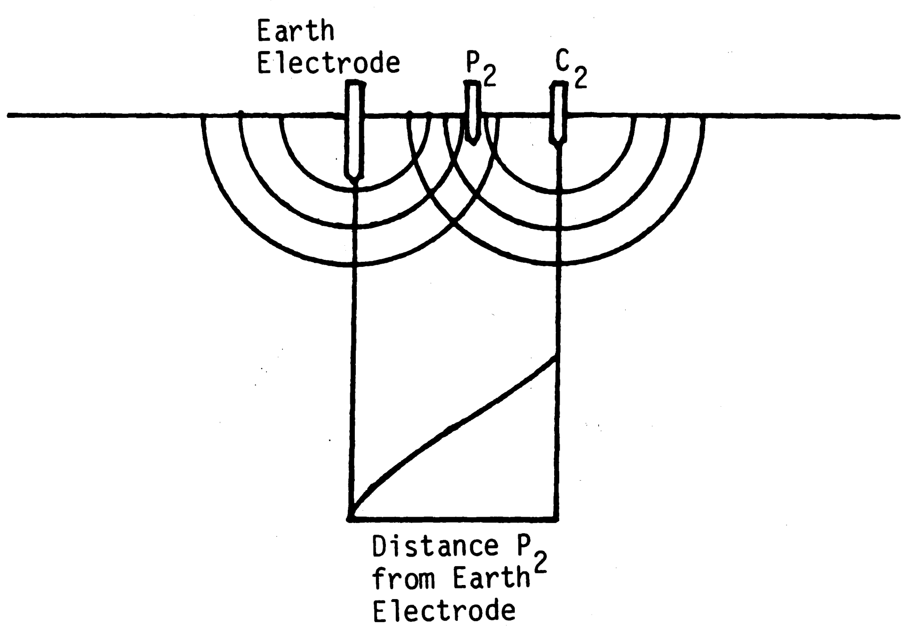


FIGURE 6D

Effect with C_2 Located Close to Earth Electrode

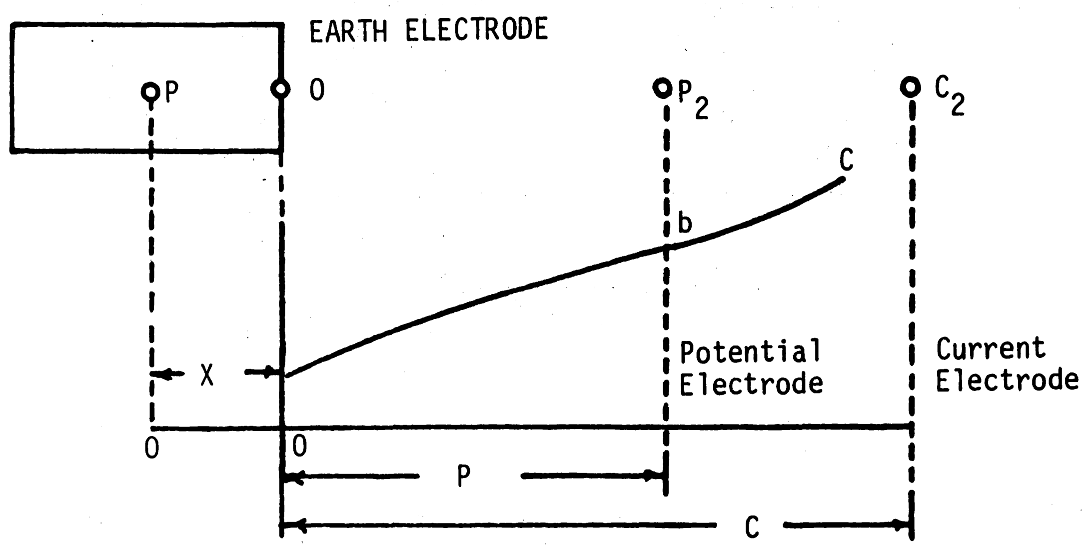


FIGURE 7D

Earth Resistance Curve for Large Area Example

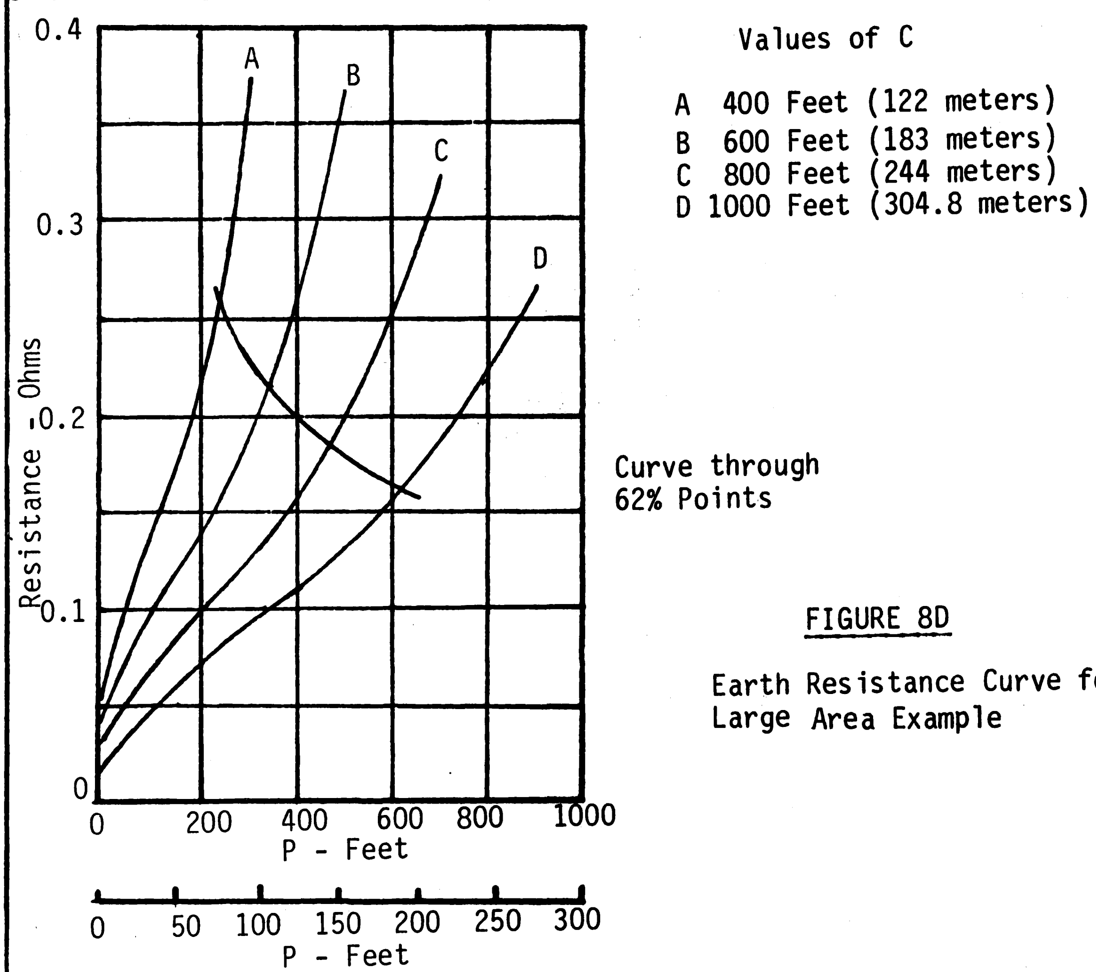
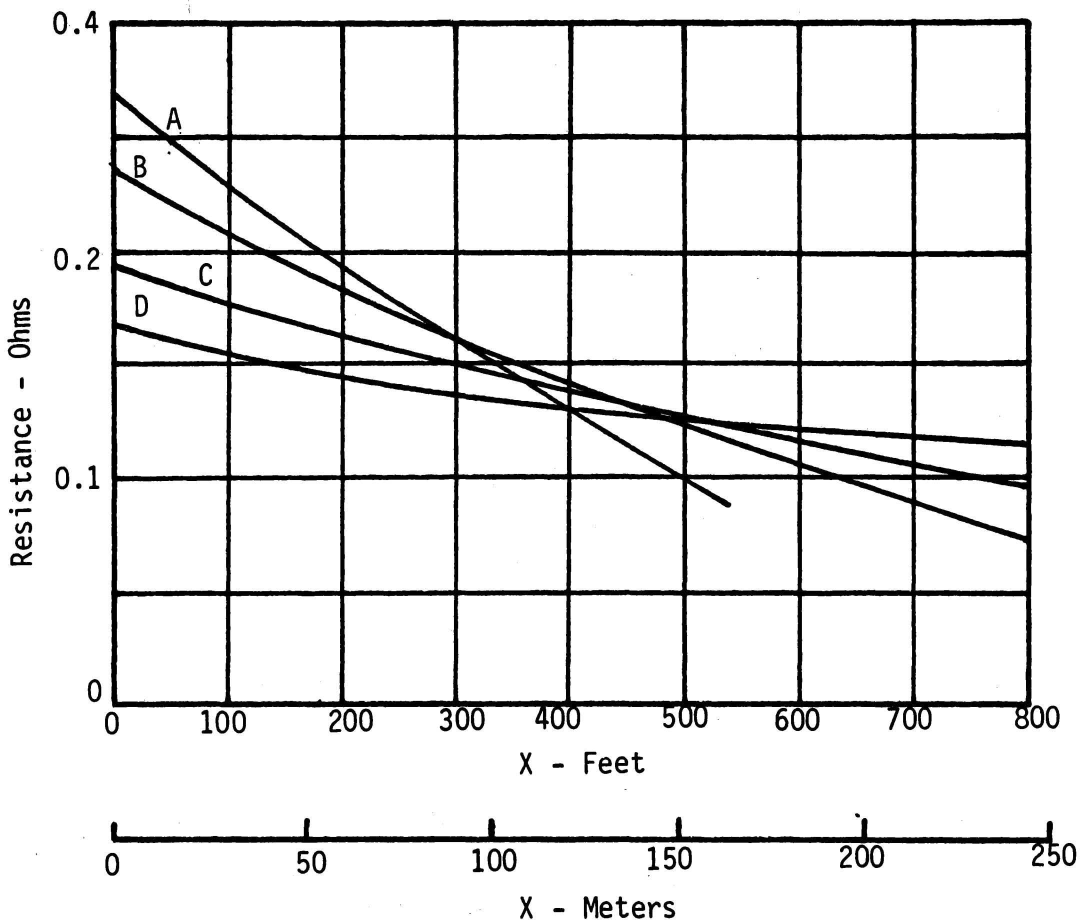


FIGURE 8D

Earth Resistance Curve for Large Area Example



Values of C

A 400 Feet (122 meters)
B 600 Feet (183 meters)
C 800 Feet (244 meters)
D 1000 Feet (304.8 meters)

FIGURE 9D

Intersection Curves for Figure 8D

APPENDIX E

CHEMICAL TREATMENT

1. GENERAL

1.1 There will be locations where the maximum number of electrodes that can be installed in the area available will not provide the desired objective resistance to ground. Chemical treatment of the soil around the electrodes to enhance the soil resistivity may be necessary in these situations to lower the overall resistance. The treatment is not a permanent means of improving ground electrode resistance since the chemicals are gradually washed away by rainfall and natural drainage through the soil.

1.2 The resistance to ground of an electrode is directly proportional to the soil resistivity and inversely proportional to the total area of contact between the surface and the soil. Installation of additional electrodes (vertical or horizontal) in grounding systems occupying fixed areas will produce diminishing reductions because of increased mutual coupling effects. Refer to the main section of this TE&CM for a discussion of mutual resistance. The most effective method for reducing electrode resistance to ground in such situations is to lower the soil resistivity.

1.3 Factors which strongly affect soil resistivity are the moisture content, ionizable salt content, and soil porosity. The soil porosity determines the moisture retention property of the soil.

There are two recommended techniques for reducing soil resistivity: improving the water retention, and chemical treatment. Salts that are essential for high soil conductivity are leeched out by overdrainage and deeper soil layers are consequently dried out, increasing the resistivity. Surface drainage in the area of the grounding system should be channeled so as to keep the electrodes moist. Planting of ground covers, such as legumes, to retard runoff and elevate the natural production of salts in the soil, can be beneficial. Keeping the earth moist over the entire area of the grounding system will keep the salts in solution as ions.

1.4 Chemical treatment involves the addition of ion-producing material to the soil in the area of an electrode system to improve soil conductivity. The effect of this material is to increase the effective radius of the ground electrode. Experience shows that large reductions in the resistance to ground of ground electrodes can be expected following chemical treatment. The percentage reduction will generally be greater with higher initial electrode resistance values. This relationship is not universally applicable since soil variations also affect the final resistance values. The initial effectiveness of chemical treatment is greatest where the soil is somewhat porous because the solution permeates a considerable volume of earth, thereby increasing the effective size of the electrode. Chemical treatment will not be as immediately effective in more compact soils since the material tends to remain in its original location for a longer period of time. A significant initial reduction of electrode resistance to ground is obtained through chemical treatment plus stabilization of resitance variations. Further, seasonal variation and the freezing point of surrounding soil are limited. (See curves of Figure 1E.)

1.5 Chemical treatment should only be considered after all other alternatives have been proven impractical. The treatment is not a permanent means of improving ground electrode resistance since the chemicals are gradually washed away by rainfall and natural drainage through the soil. The time span before replacement varies, depending on the soil porosity and the amount of rainfall. Typical long term variation for treated and untreated electrodes is shown in Figure 2E. This shows that after about four years the resistance of the treated electrode has increased to essentially the same value as the untreated electrode. The chemicals should be replenished when the electrode resitance to ground has increased by twenty percent. Assuming measurement of electrode resistance to ground is repeated at six month intervals for the treated electrode of Figure 2E, chemicals would require replenishment at the end of one year. Measurement of electrode resistance to ground at regular intervals is essential after chemical treatment if the effectiveness of the grounding system is to be maintained.

2. CHEMICAL MATERIALS

2.1 The better known chemicals for reduction of electrode resitance to ground, in the order of preference are as follows:

a. Magnesium sulphate (M_gSO_4) - epsom salts

b. Copper sulphate (C_uSO_4) - blue vitriol

c. Calcium chloride ($CaCl_2$)

d. Sodium chloride ($NaCl_2$) - common salt

e. Potassium nitrate (KNO_3) - saltpeter

2.2 Magnesium sulphate is the most common material used for ground connection enhancement, even though it is the least conductive of the materials available. This material combines a reasonable conductivity with low cost and the least corrosion effects. The use of common salt or saltpeter is not recommend since greater care must be given to protect against corrosion. Nearby metal objects that are not a part of the grounding system will also have to be protected against corrosion when either common salt or saltpeter are used. These materials should be used only where absolutely necessary to meet maximum resistance objectives.

3. METHODS OF CHEMICAL TREATMENT

3.1 Trenching: The simplest method for chemically treating the earth around a vertical ground electrode is by trenching. A circular trench is dug about one foot (0.3 meter) deep around the electrode as shown in Figure 3E. The trench is filed with the desired quantity of soil treating material and then covered with earth. To provide the best treating material distribution with the least corrosive effect, the chemical material should not come into direct contact with the electrode.

3.1.1 When the percentage of moisture in the soil is known, the weight of chemical material required to achieve a six percent (by weight) concentration may be calculated by the following equations:

a. Epsom Salts $W_s=0.5727P_w l^3$

b. Blue Vitriol $W_s=0.1292P_w l^3$

c. Common Salt $W_s=0.1145_w l^3$

Where: W_s = Weight of chemical material.
P_w = Percent moisture in soil.
l = Length of electrode in feet.

3.1.2 When the moisture content of the soil is not known, forty to ninety pounds of chemical generally will be required to maintain the effectiveness for two or three years. An initial application of fifty pounds is recommend in this situation. The amount can be adjusted when it becomes necessary to replenish the chemicals if the elapsed time since the initial application is too short.

3.1.3 The chemicals will be depleted by precipitation and underground water flow since they are all water soluble. Measure the resistance at predetermined intervals (at least every six months) and replenish the chemicals when the resistance increases twenty percent. Each replenishment extends the effectiveness for a longer period so that subsequent treatments are required less frequently.

3.2 Single Grounding Well: The chemical treatment of a vertical electrode by means of a single grounding well provides an alternative to trenching. A well provides a more permanent arrangement which facilitates replenishment of depleted chemicals. Install an aproximately two foot (0.6 meter) length of 8-inch (20-centimeter) diameter tile pipe in the earth surrounding the electrode as shown in in Figure 4E. Fill the pipe to within one foot (0.3 meter) of grade level with magnesium sulfate (epsom salts) and water thoroughly after installation. The tile pipe should have a cover with holes. Use only magnesium sulfate with this method since the chemical is in direct contact with the electrode increasing the corrosive effects.

3.3 Multiple Grounding Well: A better alternative to either trenching or single grounding well vertical electrode treatment is provided by multiple grounding wells. This not only provides a more permanent arrangement facilitating replenishment of chemicals but keeps the chemicals from coming into direct contact with the surface of the electrode. This method is more expensive so that costs should be weighed against the final results provided.

Provide four wells arranged symmetrically around the electrode to a depth of at least one-half the length of the electrode as shown in Figure 5E. Locate the wells three to four feet from the electrode. Lining of the wells with perforated pipe is recommended, especially where there is porous soil. Install an approximately two foot (0.6 meter) length of 8-inch (20-centimeter) diameter tile pipe at each well as shown in Figure 5E. Install the same sized tile pipe in the soil surrounding the electrode. This provides a means for accessing the electrode for periodic measurement of the resistance to ground. Fill each of the wells with chemical, preferably magnesium sulfate, watering thoroughly after installation. Measure the resistance to ground after three or four days to determine that the chemical treatment is having the desired effect. All of the wells should be covered with a cover containing holes. Follow the procedures presented in Paragraph 3.1.3 for determining when it will be necessary to replenish the chemicals.

3.4 Gel Treatment: There are several gel compounds which are said to be longer lasting than the chemical treatments described above. Since all of these contain toxic materials that are dangerous to handle, their use is not recommended. There is some doubt as to the safety of some of these substances since they could find a path into water supplies.

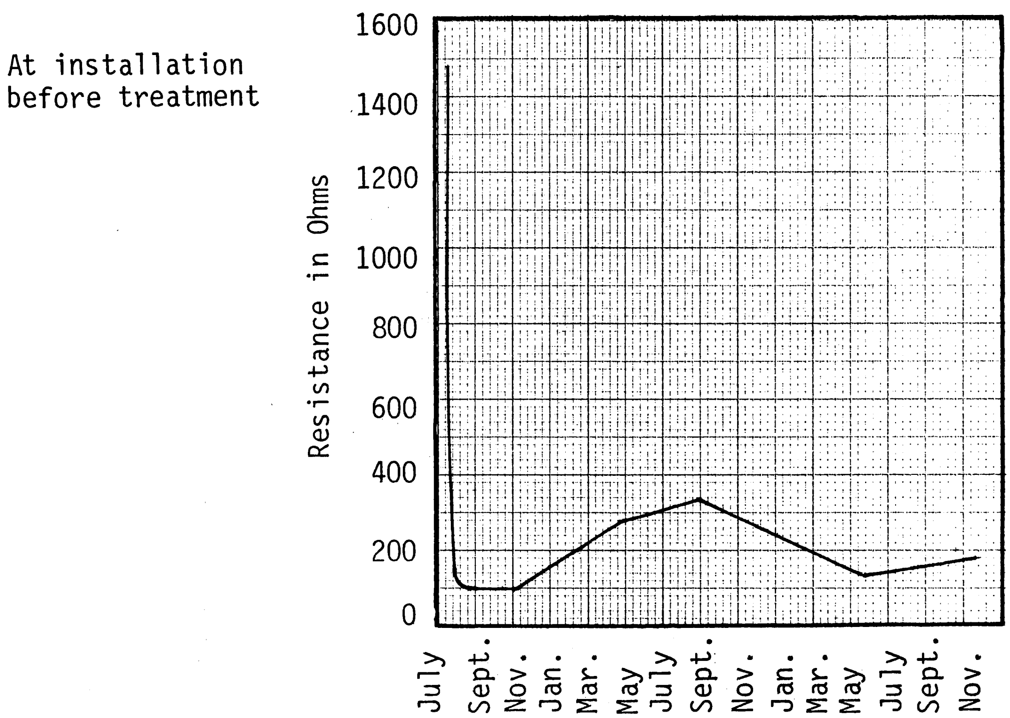


FIGURE 1E

Effect of Chemical Treatment on Resistance of Ground Rod

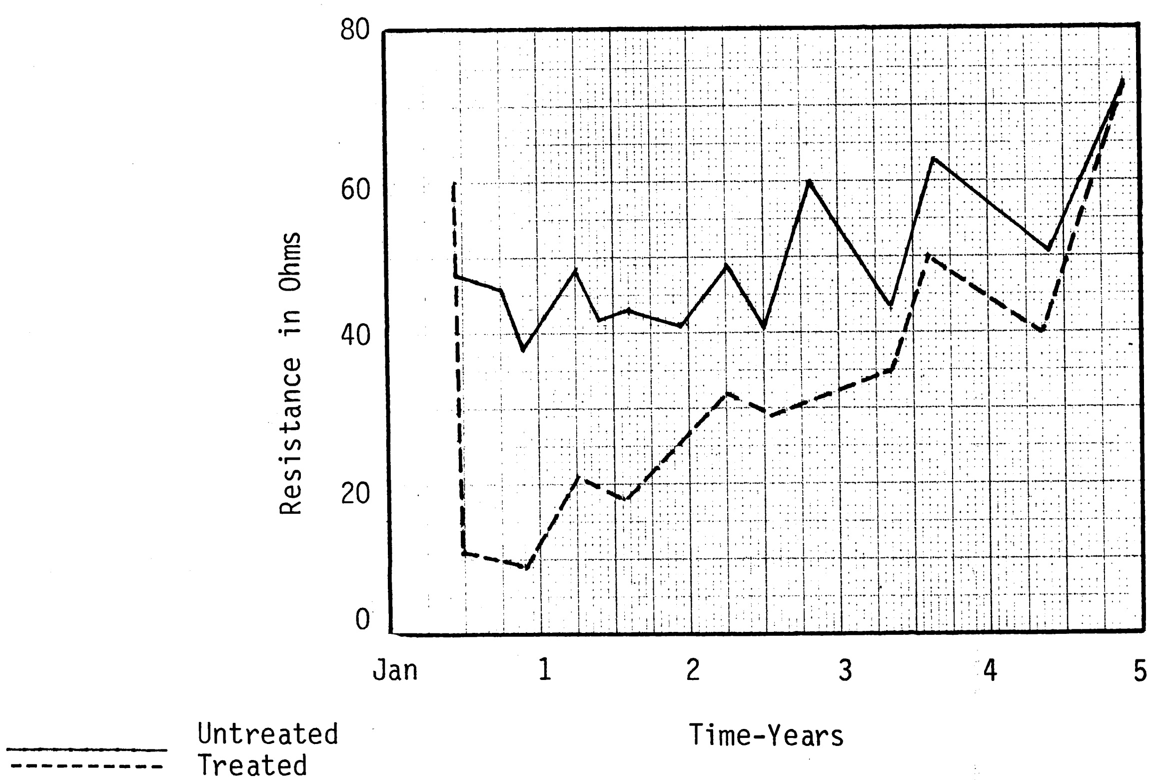


Figure 2E

Variations of Resistance to Ground vs. Time of Adjacent Electrodes

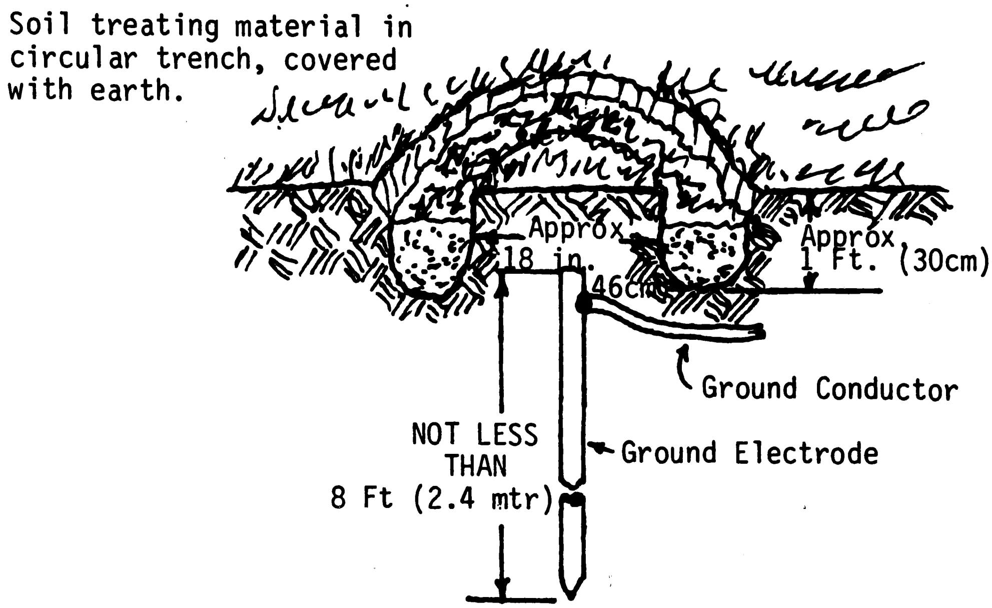


FIGURE 3E

Trench Method of Soil Treatment

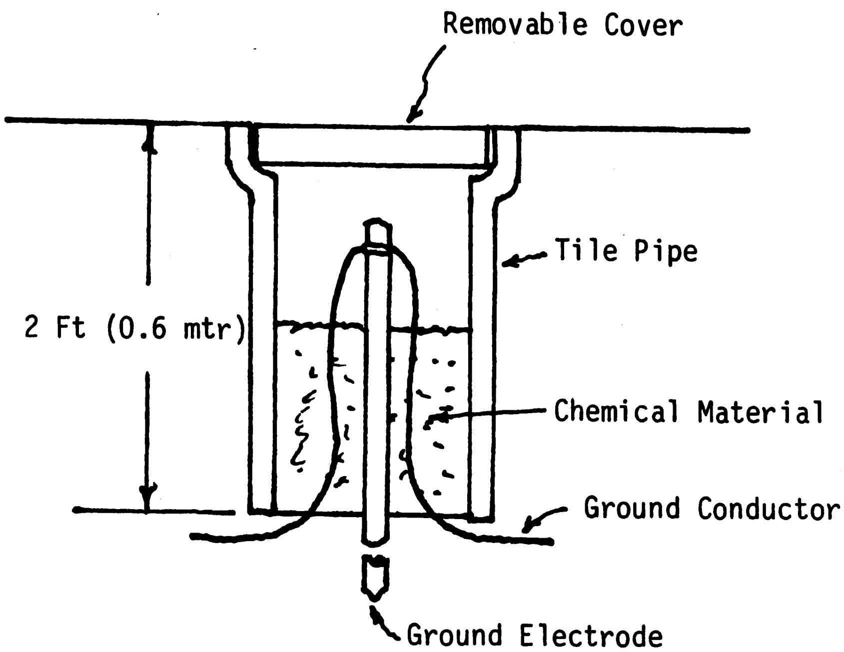
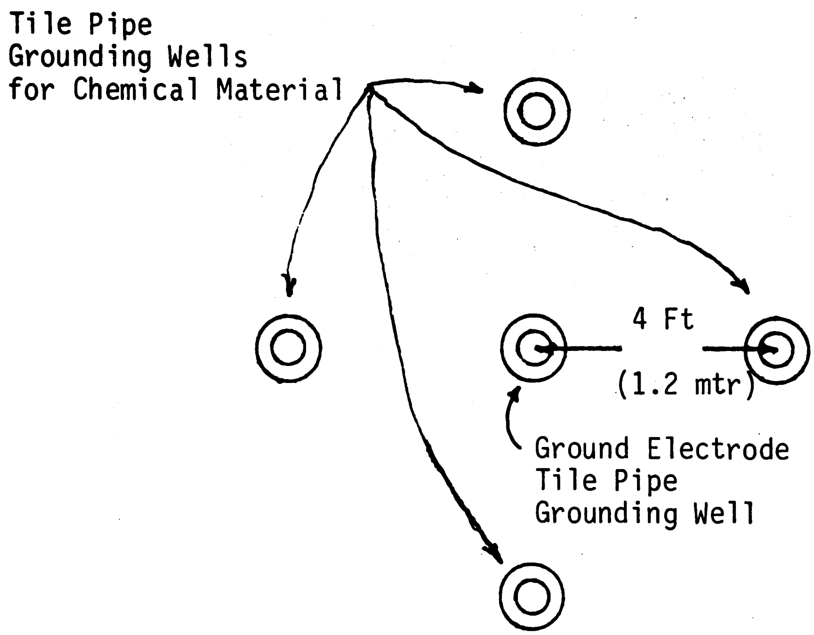
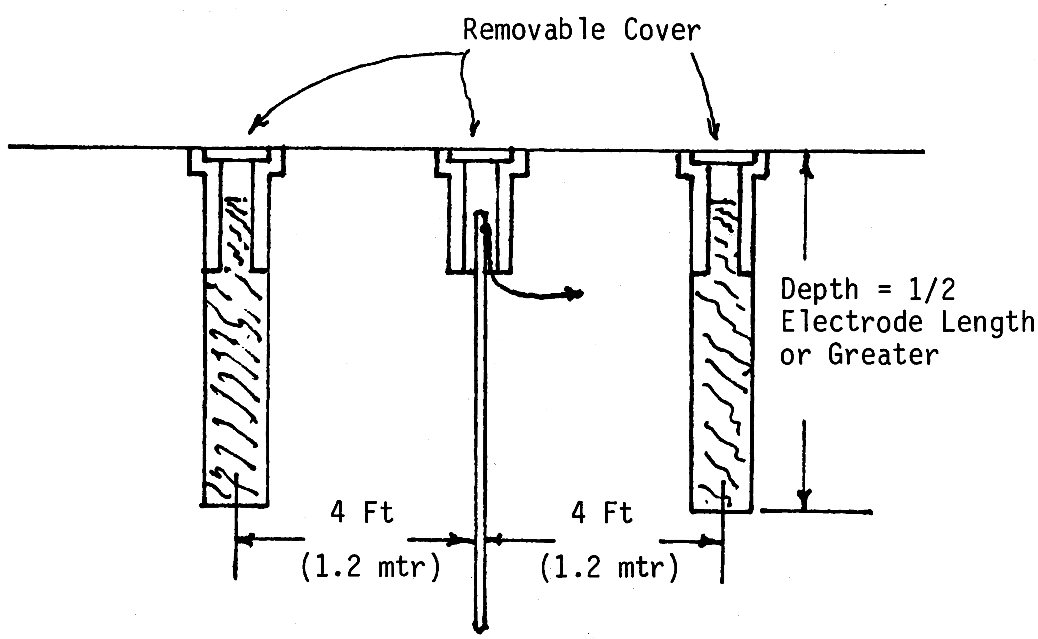


FIGURE 4E

Single Grounding Well Method of Soil Treatment



Plan View



<u>FIGURE 5E</u>

Multiple Grounding Well Method of Soil Treatment

APPENDIX F

CONCRETE ENCASED ELECTRODES

1. GENERAL

1.1 A grounding conductor encased in the concrete footing of a small central office building may provide an effective grounding system. This type grounding system is sometimes called a "Ufer" ground. Encased conductors should be considered at locations where there is not sufficient space available for installation of a ring ground outside the building. They also provide an alternative where a rock substructure will not permit installation of vertical electrodes.

1.2 The grounding conductor may be a copper wire, which is placed in the concrete footing specifically for grounding, or the reinforcing steel bars provided in the footing for strength. Reinforcing bars should be used only where the electrical continuity of the entire reinforcing steel network has been assured by metal fusing techniques at all contact points. Failure to provide these solid bonds can result in structural damage during a lightning stroke due to side flash between the bars.

1.3 There should be no moisture barrier between the concrete footing and the surrounding earth. Such a barrier will interrupt the path to remote earth and severely degrade the grounding system.

1.4 Another path to ground is provided through the steel reinforcing bars in the concrete floor of a building. Since these bars are usually near the earth's surface in a single story building, they will not be as effective as those in the building footings, which are deeper. Further, the mutual effects between the bars in the floor and in the footings will almost offset the benefits gained in resistance to ground from the floor bars.

2. CALCULATION OF RESISTANCE TO GROUND

2.1 The approximate resistance to ground for a grounding electrode encased in the concrete footing of a building may be calculated in English units of measure by the equation:

$$R_c = \frac{\rho_0}{0.9576\,\ell_w} \log_e \frac{4.4106\,\ell_w}{\sqrt{d_w h}} - \frac{\rho_0}{0.9576\,\ell_w} \log_e \frac{4.4106\,\ell_w}{\sqrt{d_c h}} + \frac{\rho_1}{0.9576\,\ell_w} \log_e \frac{4.4106\,\ell_w}{\sqrt{d_c h}}$$

Where:
- R_c = Resistance of Ufer ground, ohms.
- ρ_0 = Resistivity of concrete, meter-ohms.
- ρ_1 = Resistivity of soil, meter-ohms
- ℓ_w = Length of grounding conductor, feet.
- d_w = Diameter of grounding conductor, inches.
- d_c = Diameter of concrete cylinder, inches
- h = Depth of grounding conductor, feet.

2.2 The approximate resistance to ground for a grounding electrode encased in the concrete footing of a building may be calculated in Standard International Units of Measure by the equation:

$$R_c = \frac{\rho_0}{\pi \ell_w} \log_e \frac{12.732 \ell_w}{\sqrt{d_w h}} - \frac{\rho_0}{\pi \ell_w} \log_e \frac{12.732 \ell_w}{\sqrt{d_c h}} + \frac{\rho_1}{\pi \ell_w} \log_e \frac{12.732 \ell_w}{\sqrt{d_c h}}$$

Where: R_c = Resistance of Ufer ground, ohms.
ρ_0 = Resistivity of concrete, meter-ohms.
ρ_1 = Resistivity of soil, meter-ohms.
ℓ_w = Length of grounding conductor, meters.
d_w = Diameter of grounding conductor, centimeters.
d_c = Diameter of concrete cylinder, centimeters.
h = Depth of grounding conductor, meters.

2.3 The calculated approximate resistance to ground of concrete encased ring systems surrounding differently sized areas with various soil resistivities is shown in Figure 1F. These curves may be used to determine if a Ufer ground in the concrete footing of a new building will meet the resistance objectives when the building area and average soil resistivity are known.

3. CHARACTERISTICS

3.1 Resistivity of concrete: The resistivity of concrete has been estimated to be in the range of 30 to 300 meter-ohms, according to values published by several investigators. The majority of them favor a range from 30 to 100 meter-ohms. A value of 50 meter-ohms is recommended for calculations where the actual concrete resistivity is unknown.

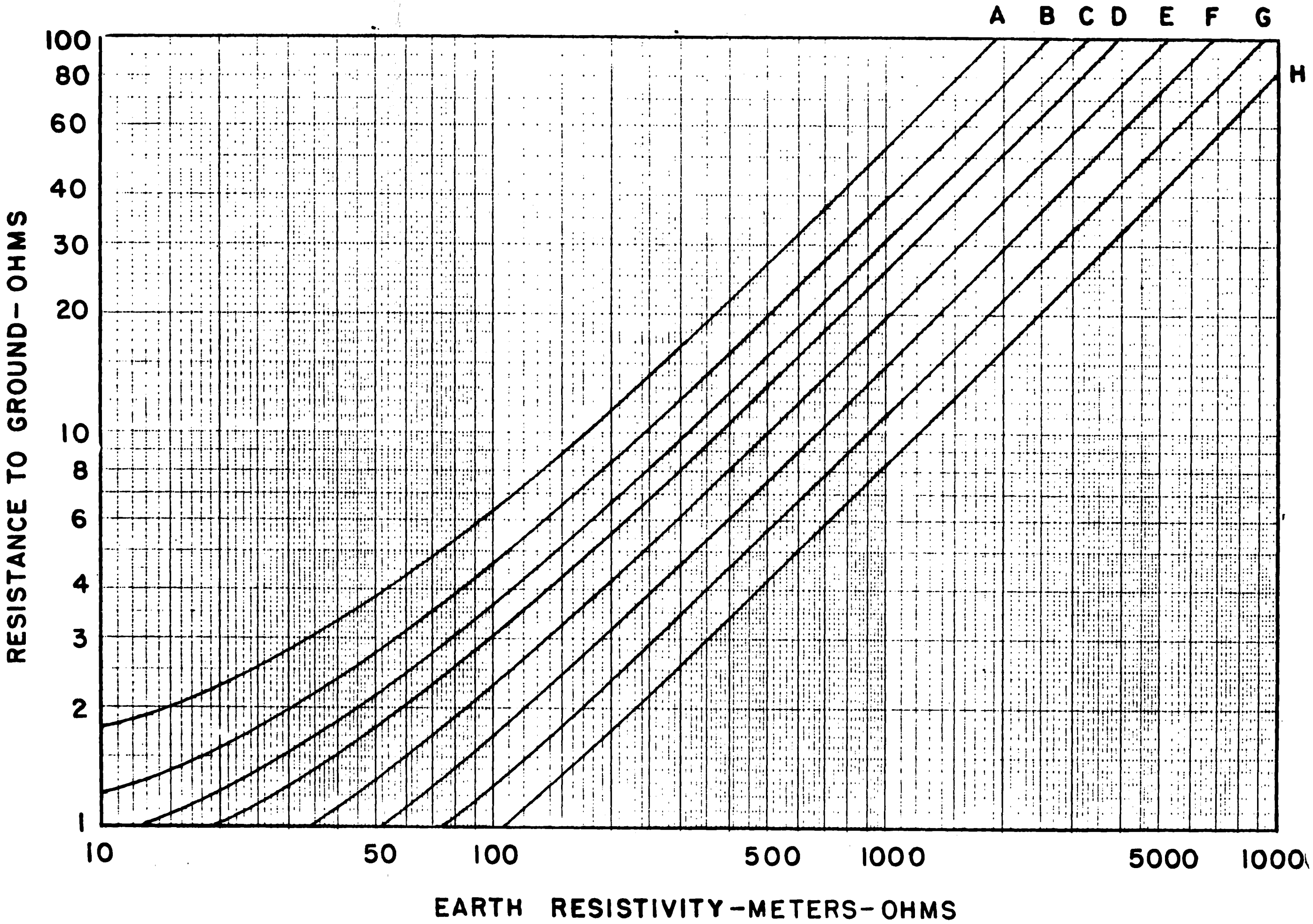
3.2 Diameter of concrete: A typical building footing is illustrated in Figure 2F. For clarity only a single horizontal wire is shown in the footing. For purposes of approximation, the effective surface of the concrete is assumed to be equivalent to a cylinder having a diameter equal to the shortest measurement, height or width, of the footing. The basic elements for calculating the resistance to ground of a concrete encased ring electrode are shown in Figure 3F.

3.3 The size of the encased conductor is not a major factor in the resulting resistance to ground with an encased electrode. Results of calculations, using #2 and 2/0 conductors in encased grounding systems, have been plotted in Figure 4F. The curves show the ground resistance with a 2/0 conductor is only about 2.0 ohms lower than that of a #2 conductor for all values of soil resistivity. The installation of a 2/0 conductor thus cannot be justified for reduction of the resistance to ground.

3.4 Depth of burial is also not a significant factor in the value of resistance to ground with encased electrodes. Figure 5F shows plotted curves of calculated resistance to ground for a #2 encased grounding conductor buried at depths of 2, 4, and 10 feet (0.61, 1.22 and 3.05 meters). The lower resistance to ground obtainable with deeper burial is considered significant only where the reduction will provide a grounding system meeting the desired objective. The curves show that this is not the case for most values of soil resistivity.

3.5 Comparison of the calculated resistance to ground of a concrete encased electrode and calculated resistance to ground of an electrode buried directly in the earth is given in Figure 6F. The resistance to ground of the direct-buried electrode is lower than that of the encased electrode when the soil resistivity is lower than the concrete's resistivity and vice versa. When the resistivity of both soil and concrete are the same, the resistance to ground of both electrodes will be the same. The concrete encased electrode is the preferred design in areas of higher soil resistivity. The curves in Figure 7F illustrate the comparison of resistances to ground between an electrode buried directly in the earth and concrete encased electrodes with different concrete resistivities. These curves show that at the higher concrete resistivity values the difference between the resistance to ground of a direct buried and concrete encased electrode is significant.

3.6 The curves in Figure 8F provide a comparison of the calculated resistance to ground between electrodes encased in differently sized concrete footings. The curves show that when the concrete's resistivity and that of the surrounding earth are identical, the resistance to ground of all four configurations is the same. When the resistivity of the surrounding soil is less than that of the concrete, the conductor encased in concrete of the least volume will have the lowest resistance to ground. Conversely the conductor encased in concrete having the greatest volume will have the lowest resistance to ground when the resistivity of the surrounding soil is higher than that of the concrete footing.



	Area of Ring	Conductor Length
A -	400 Feet^2 (37 meters^2)	80 Feet (24 meters)
B	900 Feet^2 (84 meters^2)	120 Feet (37 meters)
C -	1600 Feet^2 (149 meters^2)	160 Feet (49 meters)
D -	2500 Feet^2 (232 meters^2)	200 Feet (61 meters)
E -	5000 Feet^2 (465 meters^2)	283 Feet (86 meters)
F -	10000 Feet^2 (929 meters^2)	400 Feet (122 meters)
G -	20000 Feet^2 (1858 meters^2)	566 Feet (173 meters)
H -	40000 Feet^2 (3716 meters^2)	800 Feet (244 meters)

Conductor Size - #2 Concrete Resistivity - 50 Meter-Ohms
Conductor Depth - 4 Feet (1.2 meters) Concrete Diameter - 1 Foot (0.3 meters)

FIGURE 1F

Concrete Encased Electrodes in a Square Ring Configuration

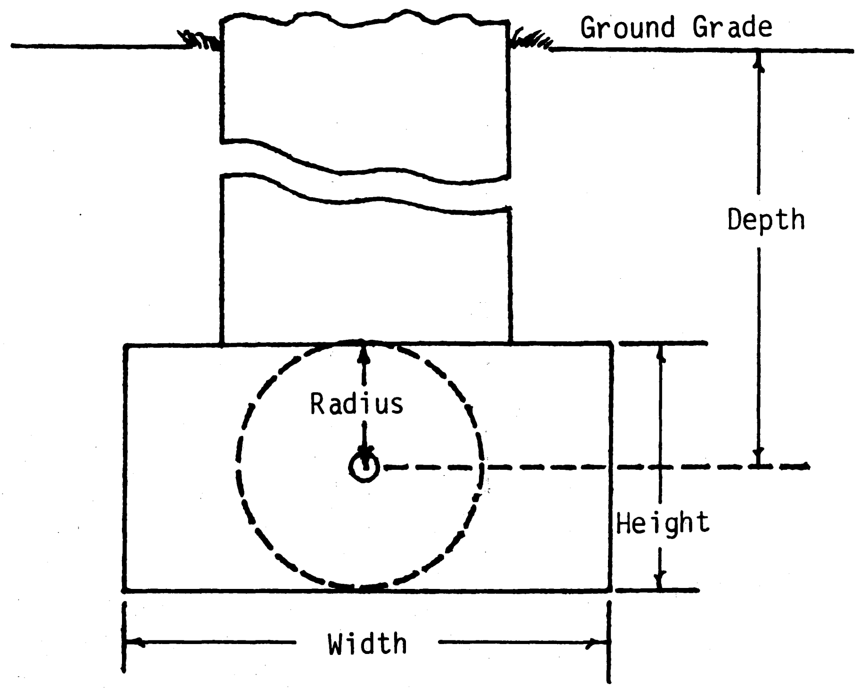


FIGURE 2F

Concrete Footing

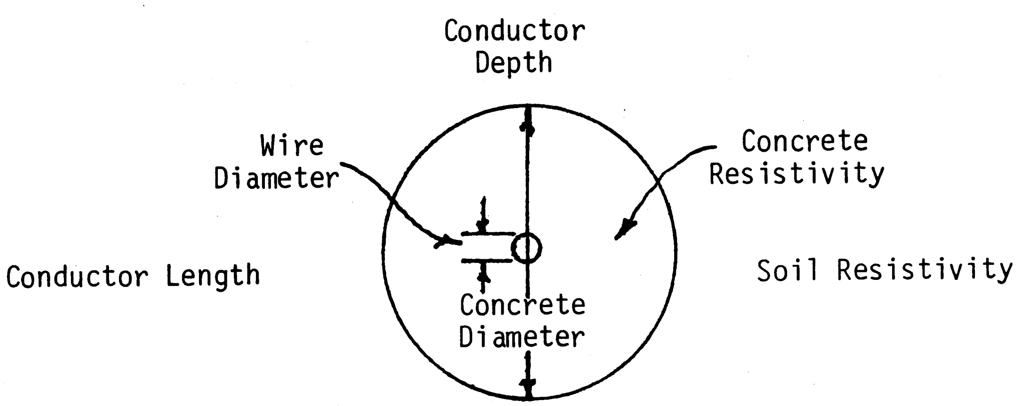
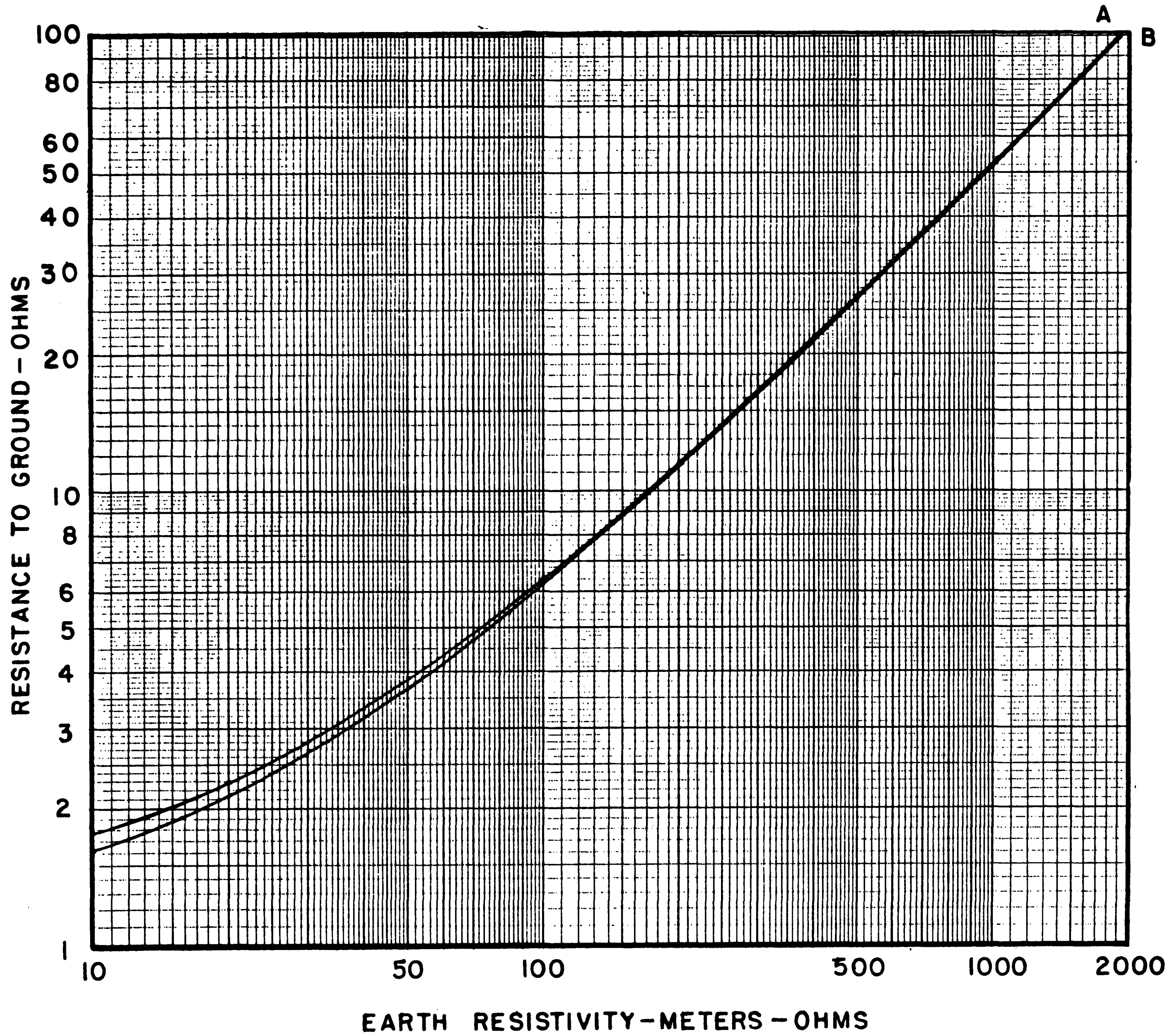


FIGURE 3F

Basic Elements for Calculation



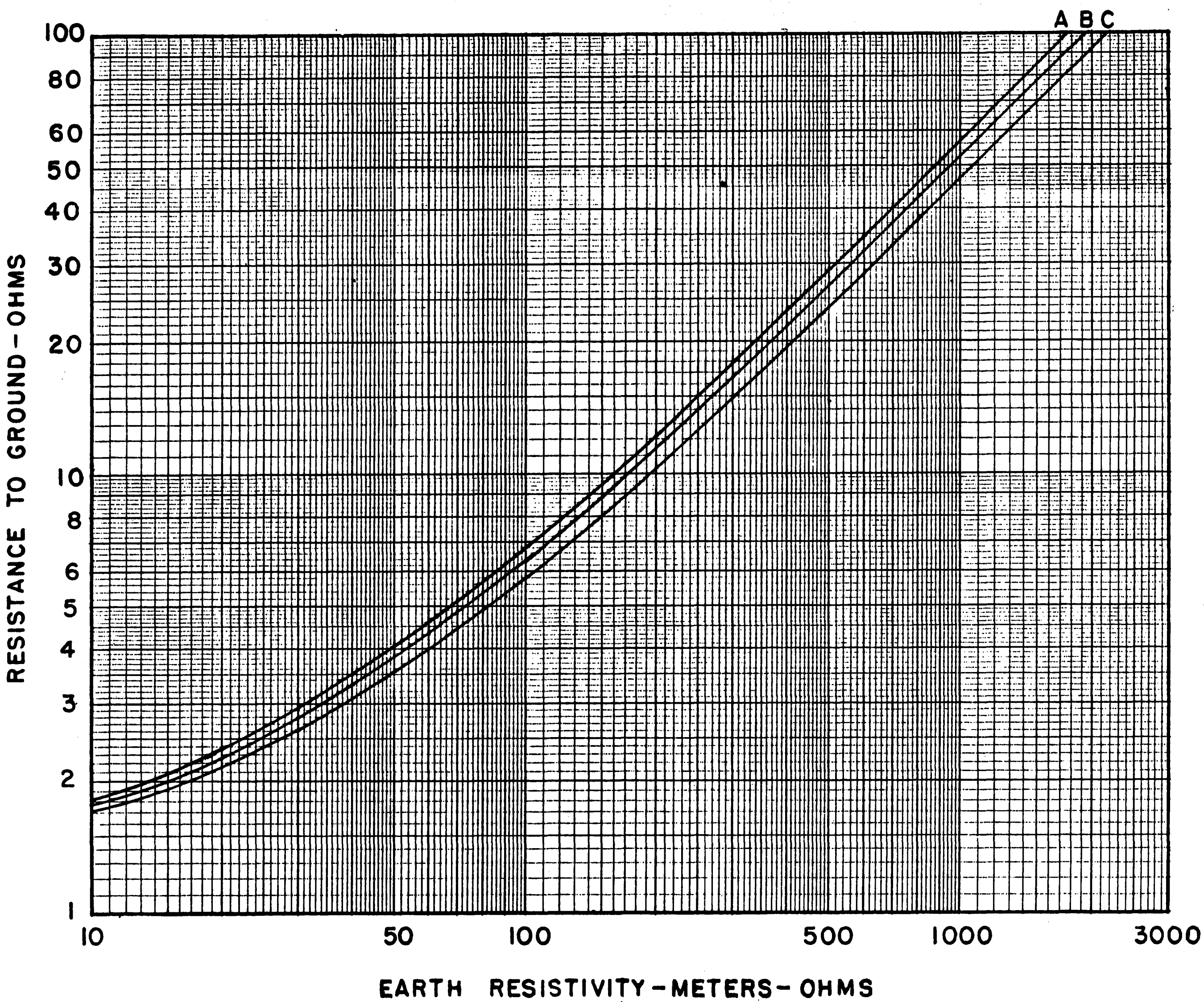
Conductor Size & Diameter

A- #2 - 0.2576 inch (0.7 centimeter)
B-2/0 - 0.419 inch (1.1 centimeter)

Ring Size - 400 feet^2 (37 meters^2)
Concrete Resistivity - 50 meter-ohms
Concrete Diameter - 1 foot (31 centimeters)
Conductor Depth - 4 feet (1.2 meters)

FIGURE 4F

Variation with Wire Size



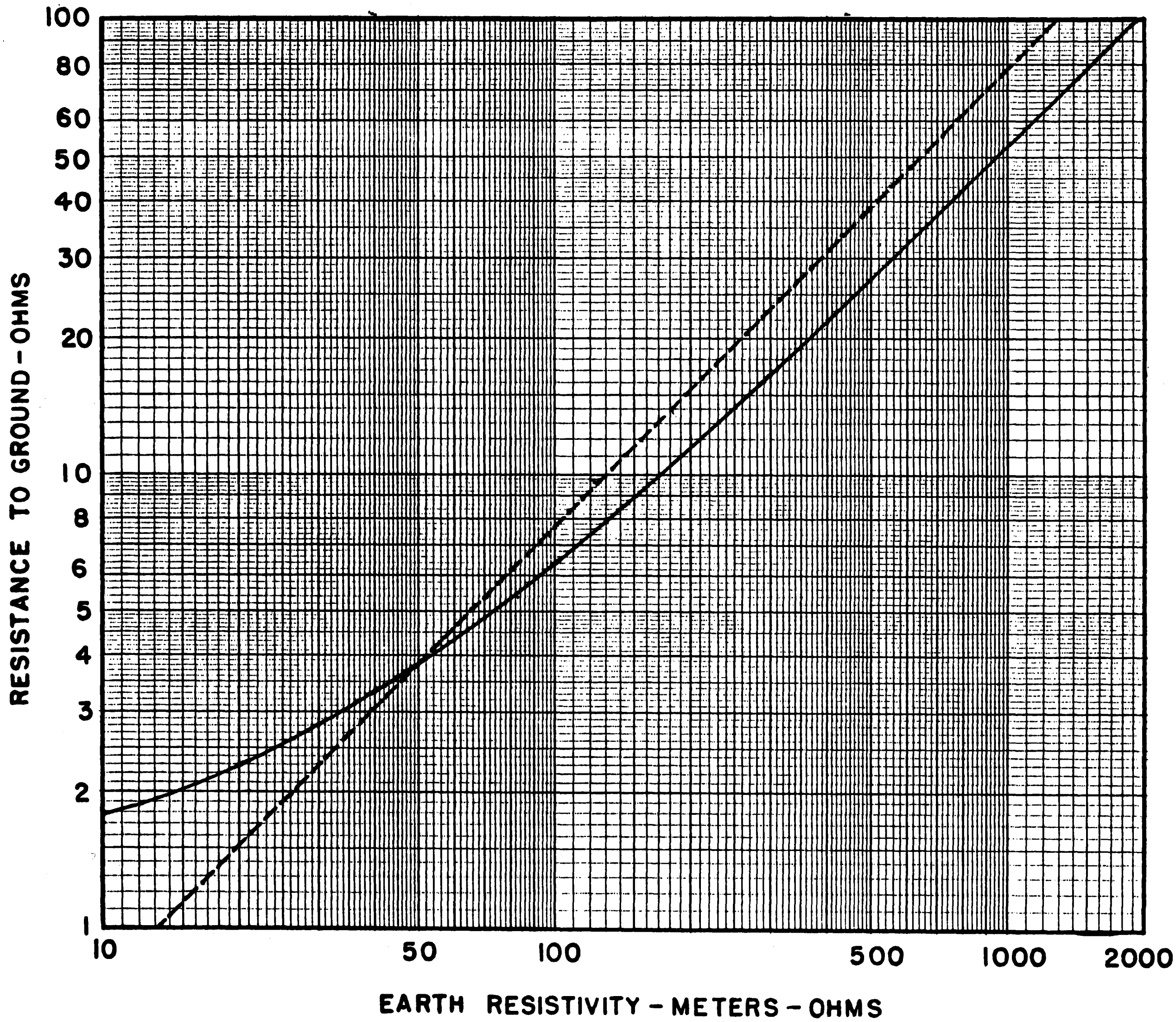
<u>Conductor Depth</u>

A - 2 feet (0.6 meters)
B - 4 feet (1.2 meters)
C - 10 feet (3.0 meters)

Ring Size - 400 feet^2 (37 meters^2)
Conductor Size - #2
Concrete Resistivity - 50 meter-ohms
Concrete Diameter - 1 feet (31 centimeters)

<u>FIGURE 5F</u>

Variation with Depth



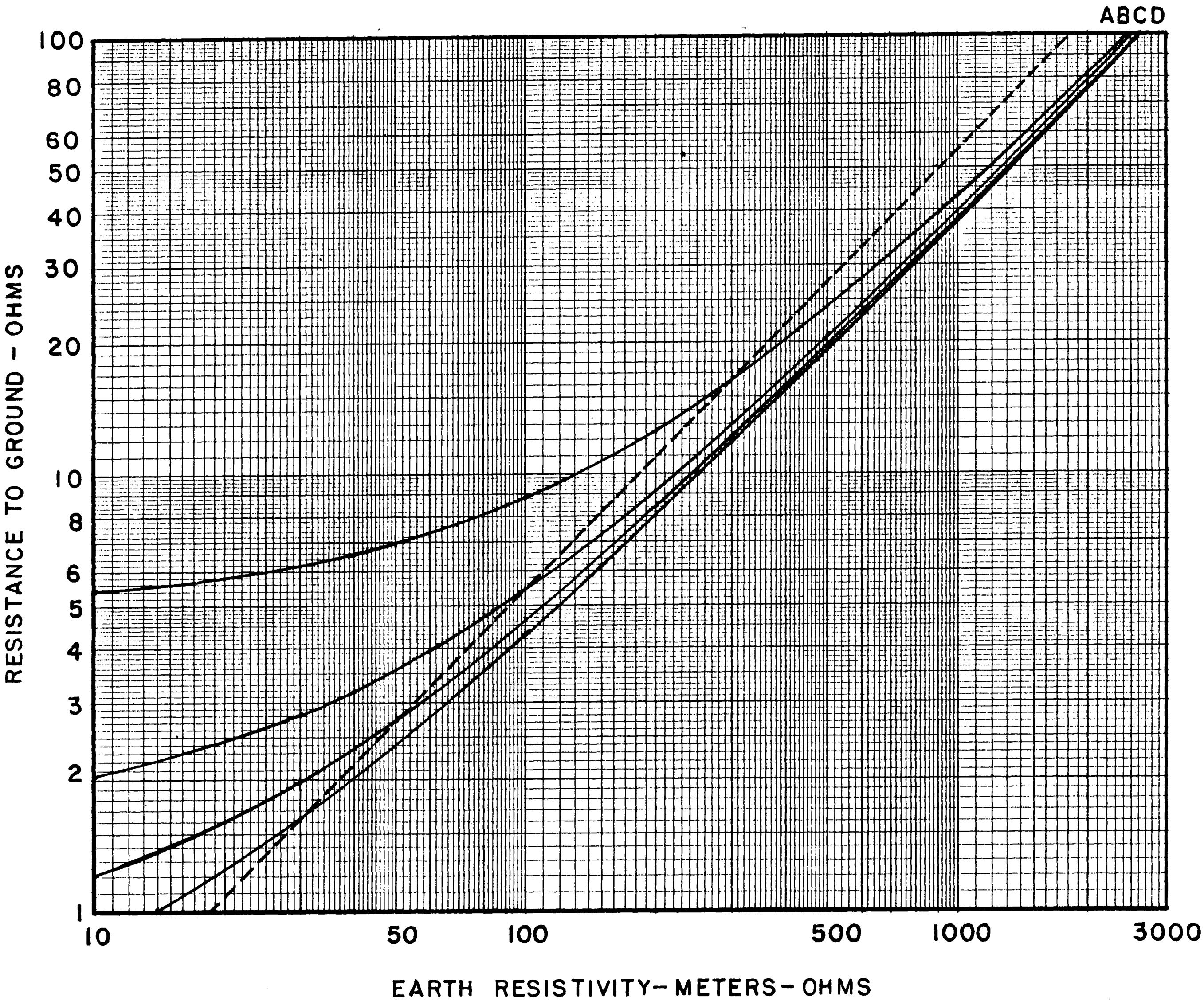
Horizontal Electrode

___________ Concrete Encased
----------- Direct Buried

Ring Size 400 feet^2 (37 meters^2)
Conductor Size - #2
Conductor Depth - 4 feet (1.2 meter)
Concrete Resistivity - 50 meter-ohms
Concrete Diameter - 1 foot (31 centimeters)

Figure 6F

Comparison Between Concrete Encased and Direct Buried Electrode



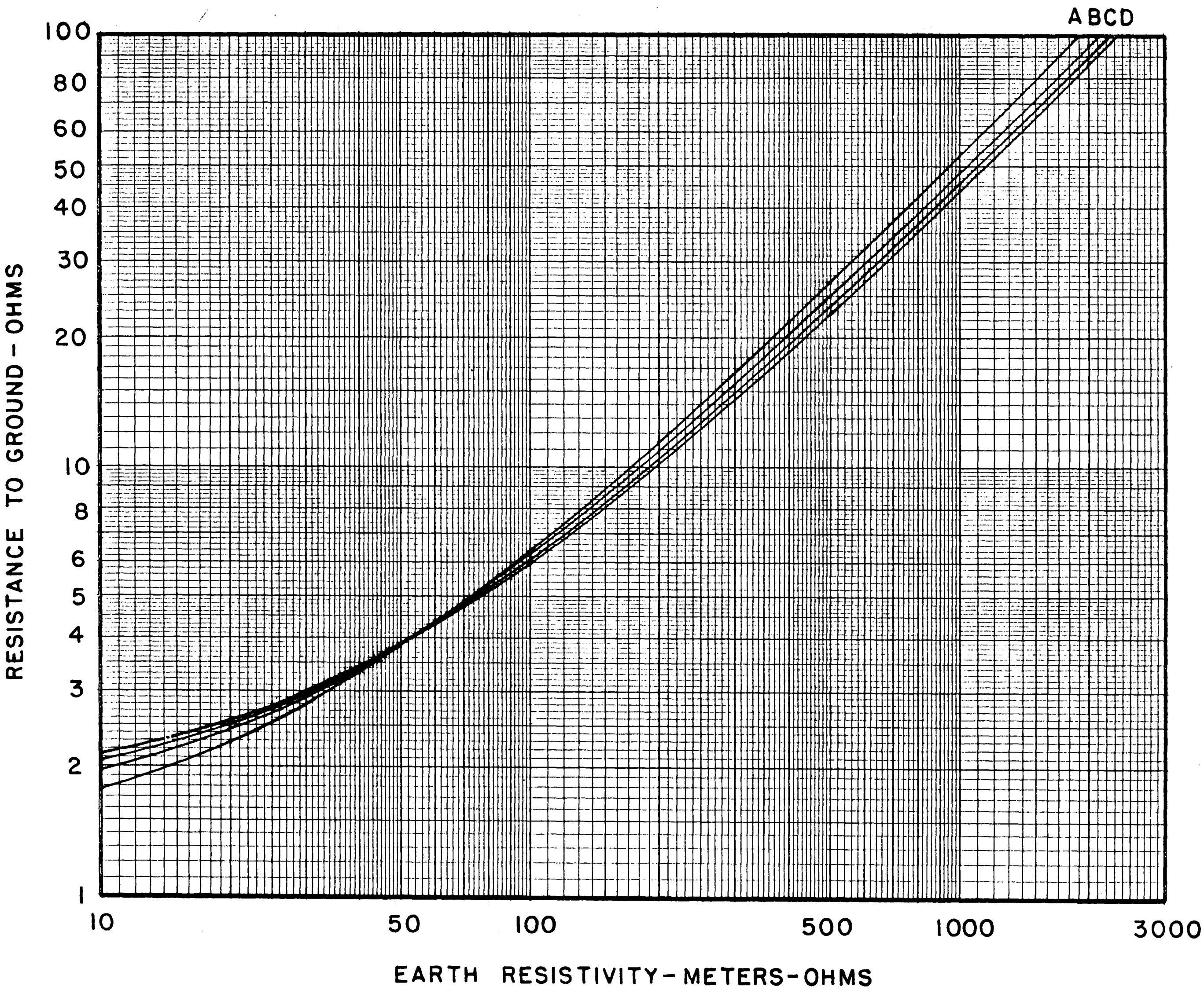
Horizontal Electrode
_____ Concrete Encased
----- Direct Buried

Concrete Resistivity
A - 300 meter-ohms
B - 100 meter-ohms
C - 50 meter-ohms
D - 30 meter-ohms

Ring Size 900 feet^2 (84 meters^2)
Conductor Size - #2
Conductor Depth - 4 feet (1.2 meters)
Conductor Diameter - 1 foot (31 centimeters)

FIGURE 7F

Comparison Between Concrete Encased and Direct Buried Electrode with Different Concrete Resistivities



Concrete Diameter

A-1 foot (31 centimeters)
B-2 feet (61 centimeters)
C-3 feet (91 centimeters)
D-4 feet (1.2 meters)

Ring Size - 400 feet^2 (37 meters^2)
Conductor Size #2
Conductor Depth - 4 feet (1.2 meters)
Concrete Resistivity - 50 meter-ohms

FIGURE 8F

Variation with Concrete Diameter

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