UNITED STATES DEPARTMENT OF AGRICULTURE
Rural Electrification Administration

REA BULLETIN 1751F-802

SUBJECT: **Electrical Protection Grounding Fundamentals**

TO: All Telephone Borrowers
REA Telephone Staff

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FILING INSTRUCTIONS: Discard TE&CM Section 802 and replace with this bulletin. File this bulletin with 7 CFR 1751 and REANET.

PURPOSE: To provide 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.

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4/12/94
Date

TABLE OF CONTENTS

TABLE

APPENDIX FIGURES

APPENDIX TABLES

FIGURES SECTION (NOT AVAILABLE ON REANET)

INDEX:

Grounding
Grounding, Fundamentals
Protection, Electrical

DEFINITIONS

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Current *The time rate of change of charge.*

Electrode *An electric conductor for the transfer of charge between the external circuit and the electroactive species in the electrolyte.*

Fault Current *A current that flows from one conductor to ground or to another conductor owing to an abnormal connection (including an arc) between the two conductor.*
Note: A fault current flowing to ground may be called a ground fault current.

Grounding connector *The conductor that is used to establish a ground and that connects an equipment, device, wiring systems, or another connector (usually the neutral conductor) with the grounding electrode of electrodes.*

Grounding electrode *A conductor used to establish a ground.*

Lightning *An electric discharge that occurs in the atmosphere between clouds or between clouds and ground.*

Ohm *The unit of resistance (and of impedance) in the International System of Units (SI). The ohm is the resistance of a conductor such that a constant current of one ampere in it produces a voltage of one volt between its ends.*

Resistance *A property opposing flow of energy and involving loss of potential (voltage).*

Resistivity *The ability to resist the flow of current.*

1. GENERAL

1.1 Ground, 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 grounding electrode, a grounding connector which attaches the grounding conductor to the ground electrode, and the soil in contact with the ground electrode.

1.2 Using Grounds in Protection Applications:
1.2.1 For natural phenomena, such as lightning, grounds are used to discharge the system of current before customer or personnel can be injured or vulnerable system components can be damaged.

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

1.3 Ground Resistance: 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: Components of Resistance in a Ground Connection. 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 Introduction: A grounding electrode cannot be driven into the soil with the expectation of obtaining a good, low resistance, ground. Many factors, both natural and human, may affect results. Some of the factors include:

2.1.1 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 ohm·meter, is defined as the resistance, in ohms, between opposite faces of a cube of earth one cubic meter in volume. An alternative 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 ohm·meters to ohm·centimeters, multiply by the former by 100.

2.1.1.1 Earth resistivity varies over a considerable range. Within the United States it varies from a few ohm·meters along some coasts to many thousands of ohm·meters in rocky, mountainous country. Figure 2: Estimated Average Earth Resistivity in U.S. provides very general data on average surface earth resistivity throughout the United States.

2.1.1.2 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 installed.

TABLE I: RESISTIVITY OF VARIOUS SOILS

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

2.1.2 **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: Typical Variation of Soil Resistivity with Moisture 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. (See Soil Mineral Content section to follow).

2.1.3 **Soil Mineral Content**: Water with no mineral salt content is nearly as good an insulator as soil with no moisture content. Figure 4: Typical Effect of Mineral Salt on Earth Resistivity illustrates the effect of mineral salt content on soil resistivity. Soils which lack adequate soluble mineral salts may be encountered from time to time.

2.1.4 **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: Typical Variation of Soil Resistivity with Temperature.

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-ground of a vertically driven electrode is given in Appendix B, 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 of various electrodes driven vertically into homogeneous soil has been calculated and plotted in Figure 6: Resistance-to-Ground Variation with Electrode Depth. 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 fractions of a meter the electrode is driven into the earth. Theoretically there is little gained by driving an electrode more than 3 to 3.7 meters. However, earth resistivity sometimes decreases with increased depth since the earth may not always be 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 Homogeneous soil conditions are rarely encountered. The conditions illustrated in Figure 7: Resistance-to-Ground Variation in Multiple Soil Layers are more typical where multiple soil layers prevail. Ground electrode resistance, under these conditions, will decrease with depth until the water table is reached. Resistance decreases rapidly again as increasing lengths of rod are exposed to the moist soil as the electrode is driven deeper.

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. Additionally, it may 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 <u>Variation of Resistance with Diameter</u>: The calculated, theoretical resistance-to-ground of electrodes having different diameters and driven vertically into earth of homogeneous soil is plotted in Figure 8: Resistance-to-Ground Variation with Electrode Diameter. The curves in Figure 8 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 slight reduction in resistance seems even less productive when considering 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 significantly 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 <u>Electrode Material</u>: The material composition of a grounding electrode is based primarily on corrosion and strength (durability) concerns. As far as resistance-to-earth is concerned an electrode could be made of most any metal because the majority of the total resistance occurs in the <u>earth</u> immediately adjacent to the electrode surface. Corrosion studies have shown that copper performs well in most soils. Unfortunately, solid copper electrodes would be too soft for driving in most soils. As a result, copper is usually used as a cladding material over steel and mates strength with good corrosion performance.

Steel has also proven to be an effective grounding electrode. However, since steel corrodes more readily than copper, steel electrodes are almost always galvanized (coated) with a special formulation of zinc.

Because the exposure of steel to soil through a holiday (bare spot) on a copper-clad steel rod could result in rapid corrosion deterioration of the steel, REA insists that clad rods meet strict minimum and average copper thickness standards (13 mils minimum and 15 mils average). All REA listed copper-clad steel ground rods have been found to meet these thickness requirements.

3.5 <u>Multiple Vertical Electrodes Buried in Earth</u>: 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 resistance-to-ground objective.

3.6 <u>Multiple Vertical Electrodes Buried in a Straight Line</u>: Grounding systems of this type are typically used at installations have to be completed along a road or within the limits of a narrow right-of-way. Spacing of vertically installed electrodes is important. Close spacing will result in considerable mutual resistance which adds to the overall resultant parallel resistance of a multiple rod installation. 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-ground of two or more electrodes installed along a straight line are given in Paragraphs 2.2.1.1 and 2.2.1.2 of Appendix B. 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 has to be 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) for various electrode spacing is illustrated in Figure 9: Percent Resistance Variation Multiple Electrodes in a Straight Line Interconnected with Wire. These curves provide the percentage of the single electrode resistance that can be expected by installing various numbers of vertical electrodes interconnected by bare 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 ohm·meters. 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 10 foot (1.6 cm x 3.0 m) electrode at the site is 66.2 ohms and of a single 5/8 inch x 20 foot (1.6 cm x 6.1 m) electrode is 36.7 ohms. The 25 ohm objective is [(25/66.2)*100] 37.8 percent of the resistance-to-ground with a single 10 foot (3.0 m) electrode and [(25/36.7)*100] 68.1 percent of a single 20 foot (6.1 m) electrode resistance-to-ground. The 38 percent horizontal line in Figure 9 intersects the 1ℓ·curve between the vertical lines designating three and four electrodes. Thus, with a distance between the electrodes equal to the length of a single 10 foot (3.0 m) electrode, the installation of four electrodes in a straight line should provide a resistance-to-ground less than the 25 ohm objective. Extending the electrode separation to four times the single electrode length reduces the requirement to two since the 4ℓ curve is intersected between the one and two electrode vertical lines. This design would reduce the number of electrodes by one but increase the interconnecting wire required from 20 feet (6.1 m) to 40 feet (12.2 m). Following the same procedure for the 68.1 percent of a 20 foot (6.1 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-ground of four or more electrodes installed in a ring configuration is given in Paragraph 2.2.2 of Appendix B.

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: Percent Resistance Variation for a Ring of Multiple Electrodes Interconnected with Wire. These curves provide the percentage of the single electrode resistance that will be attained by installing various numbers of vertical electrodes interconnected with bare 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 (step and touch potentials).

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 Appendix B.

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: Resistance-to-Ground for Multiple

Electrodes in a Rod Bed. 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 (0.9 meters). 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. (6.1 x 6.1m) to a 30 x 30 ft. (9.1 x 9.1m) 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 (TE&CM Section 810, proposed conversion to 1751F-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 Appendix B. The approximate resistance-to-ground calculated for various lengths of #2 solid copper wire buried in a straight line is shown in Figure 12: Resistance-to-Ground Variation with Length of Horizontal Electrode.

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: Resistance-to-Ground Variation with Different Sized Hortizontal Electrodes.

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: Resistance-to-Ground Variation with Depth of Horizontal Electrodes.

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 Appendix B. 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 Appendix B.

4.3.1 The approximate resistance-to-ground calculated for buried wire rings with various perimeter lengths is shown in Figure 15: Resistance-to-Ground for Various Horizontal Rings. 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: Resistance-to-Ground Variation between Configuration. The resistance-to-ground of a wire ring with an 80 foot (24.4 meter) perimeter is about 9 percent greater than that of a straight wire of the same length.

4.4 <u>Horizontal Electrodes Buried in a Radial Configuration</u>:

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 Appendix B. These equations provide a calculation means for the calculations for the following types of installations:

Three-branched Star - Paragraph 3.4.1
Four-branched Star - Paragraph 3.4.2
Six-branched Star - Paragraph 3.4.3
Eight-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: Resistance-to-Ground Variation for Various Radial (Star) Configurations.

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 B.

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: Resistance-to-Ground Variation for Different Wire Grid Areas. 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 C of Figure 18 is for a 900 square foot (83.6 square meter) buried wire grounding system. The perimeter ground conductor is 120 feet (36.6 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 120 feet (36.6 meters) of buried conductor will convert the perimeter ground to a grid of 10 foot (3.0 meter) squares. The resistance-to-ground will be about 5.8 ohms. The buried conductor length has been increased by 100 percent to obtain an 6 percent reduction in resistance-to-ground. The 0.3 ohm reduction will not significantly improve the performance of the grounding system so there is no justification for the additional wire, except when needed for safety purpose to minimize step and touch potentials

5. MUTUAL RESISTANCE BETWEEN VERTICAL AND HORIZONTAL ELECTRODES

5.1 **Introduction**: Vertical electrodes of a grounding system are usually interconnected with buried bare horizontal wire. The net combined resistance-to-ground of the interconnected vertical and horizontal electrodes will be greater than the calculated parallel equivalent of each type's separate 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 using the equation in Paragraph 4.2 of Appendix B. 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 Appendix B. 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 Appendix B. The wire length is the total length required to form the grid.

6. COMBINED RESISTANCE OF VERTICAL AND HORIZONTAL ELECTRODES

6.1 Introduction: The combined parallel resistance-to-ground for vertical electrodes interconnected with bare wire may be calculated by the equation in Paragraph 5.1 of Appendix B. A guide is provided in Paragraph 5.2 of the Appendix 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 9.

The combined resistance is given as a percentage of the resistance-to-ground for a single electrode.

6.3 <u>Combined Resistance of Vertical and Horizontal Electrodes in a Ring</u>: The calculated approximate resistance-to-ground variation for multiple 5/8 inch x 10 foot (1.6 cm x 3.0 m) vertical ground electrodes placed in a square, rectangular, or circular ring and interconnected with buried bare horizontal conductors is illustrated in Figure 10. The combined resistance is given as a percentage of the resistance-to-ground for a single electrode. A set of curves that would apply to all electrode dimensions could not be produced due to the effects of mutual resistance with ring configurations.

6.4 <u>Combined Resistance of Vertical and Horizontal Electrodes in a Grid</u>: 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 19: Comparsion of Resistance-to-Ground between Wire Grids and Rodbeds. 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. The horizontal wire of 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. The vertical electrodes are installed to a depth well below the frost line in these areas and help to ensure maintaining a low resistance during the periods when the ground is frozen.

7. DESIGN OF CENTRAL OFFICE GROUNDING SYSTEMS

7.1 <u>Introduction</u>: 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 has to 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 ensure 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 several points in the area occupied by and surrounding the central office building. For small sites up to 2500 square feet (232.3 square meters), complete one measurement at the center of the site and at each of the four corners as shown in Figure 20: Soil Resistivity Site Survey, Small Site Less than 2500 Sq. Ft. (232 Sq m). At each of the locations a measurement should be made with 12 foot (3.7 meter) and 22 foot (6.7 meter) test probe spacing. The recorded results of the five 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 21: Soil Resistivity Site Survey, Large Site - More than 2500 Sq. Ft.(232 Sq. m). 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 frost line information is available from the local weather service. The relative lightning incidence can be obtained from the isokeraunic map in (TE&CM Section 801, proposed conversion to Bulletin 1751F-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 (0.9 meters) or greater distance from the outside wall of the building foundation and outside the roof drip line to ensure wetting of the earth surrounding the electrodes by precipitation. The conductor between electrodes should be the same size as the conductor that is to be used to connect the grounding system to the central office master ground bar (See TE&CM Section 810, proposed conversion to Bulletin 1751F-810). 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 3.0 meter) electrodes, interconnected with insulated wire, installed around the perimeter of a 1600 square foot (148.6 square meter) area.

Assuming a 200 ohm·meter earth resistivity, the calculated resistance-to-ground is 7.7 ohms. Addition of 9 electrodes will convert the perimeter system to a square rod bed containing 25 electrodes with 10 foot (3.0 meter) separation between electrodes. The calculated resistance-to-ground for the rod bed is 7.2 ohms. This one-half 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 and touch 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 1/2 inch (1.3 centimeter). This is practical for most installations. Electrodes 5/8 inch (1.6 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:

7.3.2.1 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 should 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 may prove to be an acceptable alternative.

7.3.2.2 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 5 feet (1.5 meters) below the lowest water table level is appropriate. This ensures that the electrodes will be in contact with moist soil most of the time.

7.3.2.3 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 centimeters). The goal is to provide a grounding system that will meet the objective resistance-to-ground during the entire year.

7.3.2.4 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, alternative 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 should indicate the best alternative.

7.3.2.5 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 22: Grounding System Design Example, 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 900 ohm·meters to a depth of 12 feet (3.7 meters) and 200 ohm·meters 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. Because of the high soil resistivity, 10 foot (3 meter) electrodes are selected for the initial evaluation. The design steps follow:

7.3.2.5.1 Determine the resistance-to-ground of a single ground electrode from Figure 23: Resistance-to-Ground of 10 Foot

Sectional Electrodes. The resistance-to-ground for a 5/8 inch x 10 foot (1.6 centimeter x 3.0 meter) electrode in 900 ohm·meter soil is obtained from Figure 23. Since the curve for 10 foot (3.0 meter) length does not intersect the 900 ohm·meter line, divide 900 by 10 and determine the resistance-to-ground for the electrode in 90 meter· ohm soil. This value is about 29.8 ohms, which, multiplied by 10, equals 298 ohms, the desired 900 ohm·meter value.

7.3.2.5.2 Assume an initial spacing of 20 feet (6.1 meter) or twice the electrode length between electrodes. Figure 22 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 9.3 percent. Thus the expected resistance of 10 electrodes in 900 ohm·meter soil is:

$R = 298 \times 0.093 = 27.7$ 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.

7.3.2.5.3 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 900 ohm·meter soil will have an expected resistance-to-ground of about 8.2 percent of that of a single electrode.

$R = 298 \times 0.082 = 24.4$ ohms

The 24.4 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.

7.3.2.5.4 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 ohm·meters and from Figure 23 the resistance-to-ground of a 5/8 inch x 20 feet (1.6 centimeter x 6.1 meter) electrode in 200 ohm·meter soil is 36.7 ohms. From Figure 10, the resistance-to-ground of 10 electrodes with spacing equal to the electrode length is about 14 percent that of a single electrode.

R = 36.7 x 0.14 = 5.1 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 Introduction: 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 has to 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 (3.0 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 (3.7 meter) and 22 foot (6.7 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 frost line information is available from the local weather service. The relative incidence of lightning can be obtained from the isokeraunic map in TE&CM Section 801 (proposed conversion to Bulletin 1751F-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 **<u>Calculation of Resistance-to-Ground:</u>** 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 1/2 inch (1.3 centimeter) (this is practical for most installations). When the soil is extremely hard, electrodes 5/8 inch (1.6 centimeter) in diameter are recommended to resist bending of the electrode during installation. The electrode length selected is based on <u>three</u> factors:

8.3.2.1 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.

8.3.2.2 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 ensures that the electrodes will be in contact with moist soil.

8.3.2.3 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 centimeters).

The goal is to provide a grounding system that will meet the objective resistance-to-ground during the entire year.

8.3.2.4 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.

8.3.2.5 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 ohm·meters to a depth of 12 feet (3.7 meters) and 250 ohm·meters to a depth of 22 feet (6.7 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 (9.1 meters); and the frost line extends 1.5 feet (0.5 meter) below the surface. A 10 foot (3 meter) sectional electrode is selected for the initial calculation, to have the option of subsequently driving a 20 foot rod to take advantage of the lower resistivity at 12 feet (3.7 meters) to 22 feet (6.7 meters) below the surface. The design steps follow:

8.3.2.5.1 Determine the resistance-to-ground of a single 5/8 inch x 10 foot (1.6 centimeter x 3.0 meter) electrode in 400 ohm·meter soil from Figure 23. Since the curve for a 10 foot (3.0 meter) length does not intersect the 400 ohm·meter line, divide 400 by 10 and determine the resistance-to-ground for the electrode in 40 ohm·meter soil. This value is about 13.2 ohms, which, multiplied by 10, equals 132 ohms, the desired 400 ohm·meter value.

8.3.2.5.2 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 (3.0 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 before the vertical line indicating 7 electrodes. This shows that a grounding system with 7 electrodes extended in a straight line is expected to provide a resistance-to-ground less than 25 ohms.

The system would extend 60 feet (18.3 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.

8.3.2.5.3 Determine the resistance-to-ground of a single 5/8 inch x <u>20 foot</u> (1.6 centimeter x 6 meter) electrode in 250 ohm·meter soil. From <u>Figure 23</u>, this is 45.9 ohms. The objective ground resistance is 100 times 25 divided by 45.9 equals 54.5 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 one and two electrodes, respectively. Thus, a grounding system with two 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 20 feet (6.1 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 <u>Introduction</u>: 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 <u>Wire</u>: Wire provided for interconnection of vertical electrodes should be buried at least 2.5 feet (0.76 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 <u>Grounding Well</u>: Access to the grounding system at a building site should be provided through the installation of a hand hole or <u>grounding well</u>. 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 24: Typical Grounding Hand Hole, with a removable access cover.

9.4 <u>Bonds</u>: All Bonds in concealed locations have to 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, have to 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 the verification of integrity.

9.5 <u>Grounding Electrodes</u>: 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 (2.4 meters) of contact with the undisturbed earth underneath. Horizontal bare interconnecting conductors should not be placed in such beds under any circumstances.

9.6 <u>Driving Electrodes</u>: 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 <u>Measurements of the Grounding System Resistance-to-Ground</u>: Should be done as soon as installation is completed by using the procedure outlined in <u>Appendix D</u>.

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. Remeasuring on a monthly basis is recommended until a steady value is established.

9.8 Remeasuring the Grounding System: 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 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 80-1986, IEEE, New York.

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," IEEE 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.

10. "Standard Dictionary of Electrical and Electronics Terms" ANSI/IEEE Standard 100-1988, IEEE, New York.

APPENDIX A CONVERSION TABLES
(English to Metric)

1. GENERAL

1.1 Introduction: The tables provided in this Appendix may be used for converting measurements from English units to metric so converted values may be used in the equations found in Appendix B.

TABLE A1: COMMONLY USED MEASUREMENTS

English		Metric
1/2 inch	⟶	1.3 centimeters
5/8 inch	⟶	1.6 centimeters
5 feet	⟶	1.5 meters
8 feet	⟶	2.4 meters
10 feet	⟶	3.0 meters
20 feet	⟶	6.1 meters
30 feet	⟶	9.1 meters
40 feet	⟶	12.2 meters

TABLE A2: ENGLISH TO METRIC CONVERSIONS

To convert from	**Multiply by**	**To get**
Feet	0.3048	Meters
Inches	2.54	Centimeters
Square Feet	0.09290	Square Meters

1.2 Example: The following example illustrates how one can convert from English to Metric units and use the equations in Appendix B. A 30 x 40 foot rectangular ring configuration is installed. A site survey has been preformed and the soil resistivity has been measured at 100 ohm·meters. The ground rods used in this system are 5/8 inch x 10 feet and are spaced 10 feet apart. The rods are connected by #2 gauge wire, which has a diameter of 0.2576 inches. The grounding system is buried 2 feet deep.

1.2.1 Determining the resistance of the ground rods: Before one can use Equation B5 of Appendix B to find the resistance of the rods, one has to convert the electrode length, diameter, and spacing to Metric units. Using Table A1 one finds that the rods are 3.0 meters in length, have a diameter of 1.6 centimeters, and are spaced 3.0 meters apart. Now Equation 5 can be used to find that the resistance of the ground rods is 4.00 ohms.

1.2.2 Determining the buried wire resistance: Table A2 is used to convert the, English units wire length, diameter, and depth to metric units. To convert the wire length from English to Metric, multiplying the wire length, 140 feet, by 0.3048 to get 43 meters. Next, the wire diameter, 0.2576 inches, is multiplied by 2.54 to obtain 0.6543 centimeters. The wire depth, 2 feet, is converted in the same manner as wire length and found to be 0.6 meters. Next, these metric values are substituted into Equation B8 of Appendix B and one finds that the buried wire has a resistance of 2.30 ohms.

1.2.3 Determining the mutual and total resistance: Since the rod length and wire length have already been converted, one can go straight to Equation B16 of Appendix B to calculate the mutual resistance of the grounding system, 2.89 ohms. Using Equation B18 one can calculate the total resistance of the system, 1.59 ohms.

APPENDIX B GROUNDING EQUATIONS

1. GENERAL

1.1 <u>Introduction</u>: 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 <u>A Site Survey</u> should first be completed to determine the area available for installation of the grounding system. (Refer to Paragraph 7.2 of Bulletin text). 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 <u>The Equations</u> are derived from those published by Erling D. Sunde, "Earth Conduction Effects on Transmission Systems," Dover Publications, Inc., New York, 1968 and ANSI/IEEE Std. 80-1986. Equations have been simplified to permit use of electrode sizes in units commonly used for identification, i.e., 2.5 cm x 3 m. ground rod.

2. VERTICAL GROUND ELECTRODES (ROD OR PIPE)

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

$$R_r = \frac{\rho}{2\pi \ell r} \ln \frac{294.30\,\ell_r}{d_r} \qquad \text{(B1)}$$

Where: R_r = Electrode resistance-to-ground, ohms

ρ = Earth resistivity, ohmmeters

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 (B2), (B3), (B4) and (B5) 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 two possible conditions relative to parallel grounding electrodes in a straight line:

1. The distance between the electrodes is equal to or greater than the length of the electrodes.
2. 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:

$S = \ell_r$

$$R_R = \frac{1}{n}\left(R_r + \frac{\rho}{\pi S}(1/2 + 1/3 + \ldots + 1/n)\right) \qquad \text{(B2)}$$

Where: R_R = Parallel electrodes resistance-to-ground, ohms

n = Number of electrodes

R_r = Single electrode resistance-to-ground, ohms (From Equation (B1), Paragraph 2.1)

ρ = Earth resistivity, ohm·meters

ℓ_r = 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:

$S < \ell_r$

$$R_R = \frac{1}{n}(R_r + (n-1)\,R_m)\ ohms \tag{B3}$$

Where: R_R = Parallel electrodes resistance-to-ground, ohms

n = Number of electrodes

R_r = Single electrode resistance-to-ground, ohms (From Equation (B1), Paragraph 2.1)

R_m = Mutual resistance between electrodes, ohms (From Equation (B4) below)

ℓ_r = Electrode length, meters

The mutual resistance between two ground electrodes at a designated spacing for completing equation (B3) may be calculated by the following equation:

$$R_m = \frac{\rho}{2\pi\,\ell_r}\ln\frac{1.475\,\ell_r}{S} \tag{B4}$$

Where: R_m = Mutual resistance between electrodes, ohms

ρ = Earth resistivity, ohm·meters

ℓ_r = Electrode length, meters

S = Electrode spacing, meters

π = 3.1416

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

$$R_R = \frac{\rho}{2\pi n \ell_r}\left(\ln \frac{294.3\,\ell_r}{d_r} + \frac{2\ell_r}{S} + \ln \frac{2n}{\pi}\right) \qquad \text{(B5)}$$

Where: R_R = Parallel electrode resistance-to-ground, ohms

ρ = Earth resistivity, ohm·meters

n = Number of electrodes

ℓ_r = Electrode length, meters

d_r = Electrode diameter, centimeters

S = Electrode spacing, meters

π = 3.1416

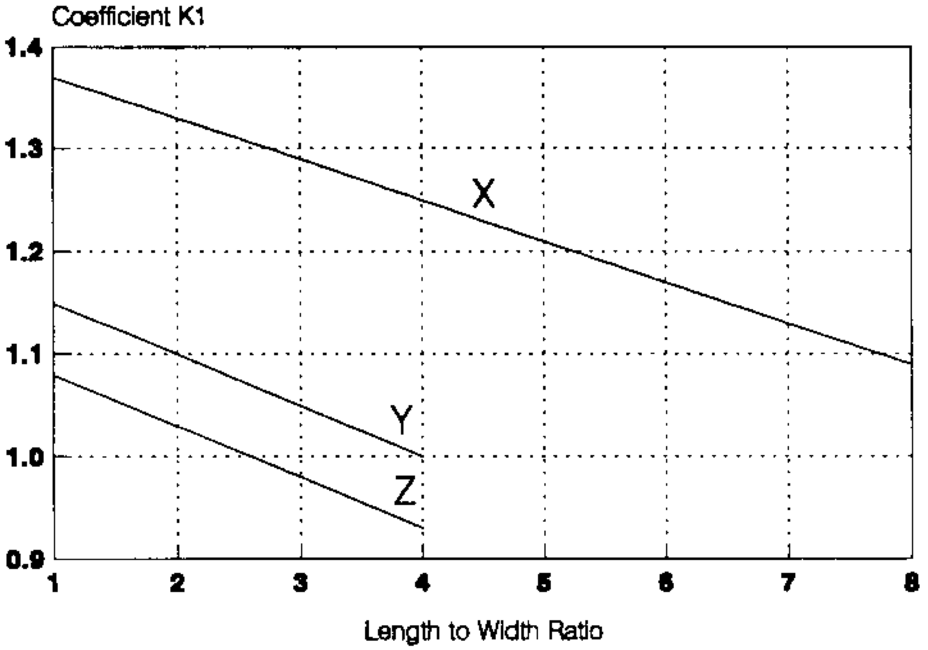
2.2.3 <u>Multiple Vertical Ground Electrodes in a Square or Rectangular Ring</u>: Calculation of resistance-to-ground for these configurations is the same as for a circular ring in Paragraph 2.2.2.

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

$$R_{GR} = \frac{\rho}{2\pi n \ell_r}\left(\ln \frac{294.30\,\ell_r}{d_r} + \frac{2K_1\ell_r}{\sqrt{A}}\left(\sqrt{n}-1\right)^2\right) \qquad \text{(B6)}$$

Where: R_{GR} = Parallel electrodes resistance-to-ground, ohms
ρ = Earth resistivity, ohm·meters
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 B1: Value of Coefficient K1



X - For Depth h ≈ 0
Y - For Depth h ≈ $0.1\sqrt{A}$
Z - For Depth h ≈ $0.17\sqrt{A}$

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:

$$R_w = \frac{\rho}{\pi \ell_w} \ln \frac{7.3576\, \ell_w}{\sqrt{d_w h}} \qquad \text{(B7)}$$

Where: R_W = Bare wire resistance-to-ground, ohms

ρ = Earth resistivity, ohm·meters

ℓ_W = Wire length, meters

d_W = 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 (B8), pertains to a square or rectangular ring since it is based on the wire length (perimeter of the ring). The second, Equation (B9), 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:

$$R_w = \frac{\rho}{\pi \ell_w} \ln \frac{12.732\, \ell_w}{\sqrt{d_w h}} \qquad \text{(B8)}$$

Where: R_W = Bare wire resistance-to-ground, ohms

ρ = Earth resistivity, ohm·meters

ℓ_W = Wire length, meters

d_W = Wire diameter, centimeters

h = Wire depth, meters

3.2.2 **<u>Bare wire in a circular ring</u>:** Another equation for calculating the approximate resistance-to-ground of a single bare wire buried in a ring is:

$$R_w = \frac{\rho}{2\pi^2 D}\left(\ln\frac{800D}{d_w} + \ln\frac{2D}{h}\right) \qquad \text{(B9)}$$

Where: R_W = Bare wire resistance-to-ground, ohms

D = Diameter of circular ring, meters

ρ = Earth resistivity, ohm·meters

d_W = Wire diameter, centimeters

h = Wire depth, meters

π = 3.1416

3.3 **<u>Bare Wire Buried in a Square or Rectangular Grid</u>:** 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:

$$R_w = \frac{\rho}{\pi \ell_w}\left(\ln\frac{20\ell_w}{\sqrt{d_w h}} + \frac{K_1 \ell_w}{\sqrt{K}} - K_2\right) \qquad \text{(B10)}$$

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

ρ = Earth resistivity, ohm·meters (Repeated on next pg.)

ρ = Earth resistivity, ohm·meters

ℓ_w = Total wire length in grid, meters

d_w = Wire diameter, centimeters

h = Wire depth, meters

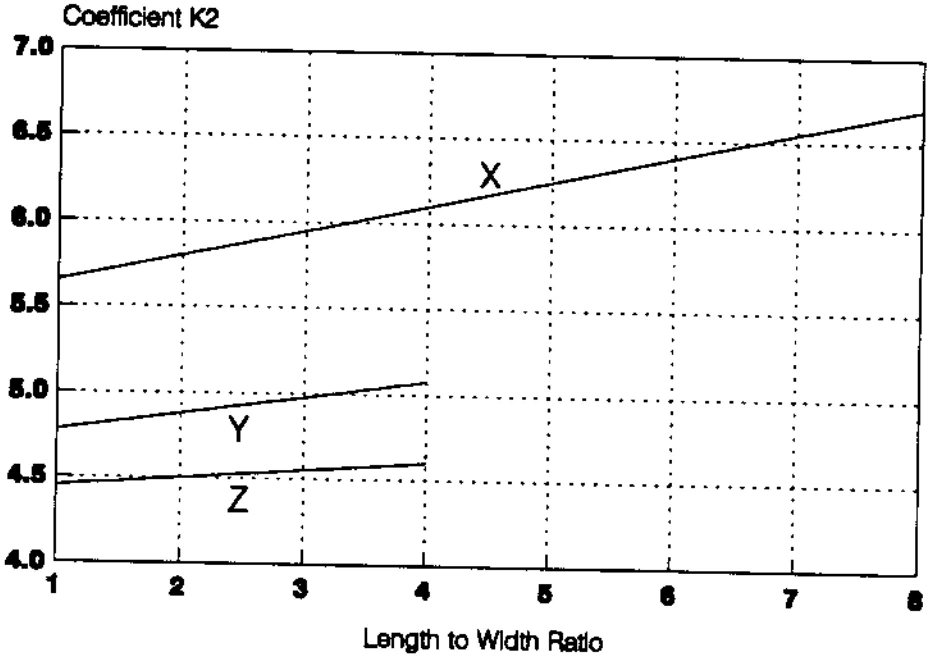
A = Area covered by wire, square meters

K_1 = Coefficient from Figure B1

K_2 = Coefficient from Figure B2, below

π = 3.1416

Figure B2: Value of Coefficient K2



X - For Depth $h \approx 0$
Y - For Depth $h \approx 0.1\sqrt{A}$
Z - For Depth $h \approx 0.17\sqrt{A}$

3.4 **<u>Radial Bare Buried Wires</u>:** 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:

$$R_{WN} = \frac{\rho}{18.85\,\ell_w}\left(\ln\frac{1154.5\,\ell_w^2}{d_w h}\right) \tag{B11}$$

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

ρ = Earth resistivity, ohm·meters

ℓ_w = Wire length of single radial branch, meters

d_w = 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:

$$R_{WN} = \frac{\rho}{25.133\,\ell_w}\left(\ln\frac{7416.5\,\ell_w^2}{d_w h}\right) \tag{B12}$$

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

ρ = Earth resistivity, ohm·meters

ℓ_w = Wire length, meters

d_w = 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:

$$R_{WN} = \frac{\rho}{37.70\,\ell_w}\left(\ln \frac{381356\,\ell_w^2}{d_w h}\right)$$

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

ρ = Earth resistivity, ohm·meters

ℓ_w = Wire length, meters

d_w = 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:

$$R_{WN} = \frac{\rho}{n\pi\,\ell_w}\left(\ln \frac{7.3576\,\ell_w}{\sqrt{d_w h}} + 1.228(n-1) - \ln n\right)$$

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

ρ = Earth resistivity, ohm·meters

n = Number of radial wires

ℓ_w = Wire length of single radial branch, meters

d_w = Wire diameter, centimeters

h = Wire depth, meters
π = 3.1416

4. MUTUAL RESISTANCE

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

$$R_{WR} = \frac{\rho}{\pi \ell_w} \ln \frac{2\ell_w}{\ell_r} \qquad \text{(B15)}$$

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

ρ = Earth resistivity, ohm·meters

ℓ_w = Interconnecting wire length, meters

ℓ_r = Electrode length, meters

π = 3.1416

4.3 <u>Multiple Vertical Ground Electrodes in a Ring</u>: 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:

$$R_{WR} = \frac{\rho}{\pi \ell_w} \ln \frac{3.461\ell_w}{\ell_r} \qquad \text{(B16)}$$

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

π = Earth resistivity, ohm·meters

ℓ_w = 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 rod bed of multiple vertical ground electrodes and an interconnecting grid of bare buried conductors may be calculated by the following equation:

$$R_{GWR} = \frac{\rho}{\pi \ell_w}\left(\ln \frac{5.4366\,\ell_w}{\ell_r} + \frac{K_1 \ell_w}{\sqrt{A}} - K_2\right) \qquad \text{(B17)}$$

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

ρ = Earth resistivity, ohm·meters

ℓ_w = Total wire length in grid, meters

ℓ_r = Electrode length, meters

K_1 = Coefficient from Figure B1

K_2 = Coefficient from Figure B2

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:

$$R_T = \frac{R_W R_R - R_{WR}^2}{R_W + R_R} \qquad \text{(B18)}$$

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

R_W = Bare wire resistance-to-ground, ohms (From Equations (B7), (B8), (B9), or (B10), as appropriate)

R_R = Parallel vertical electrodes resistance to ground, ohms (From Equations (B2), (B3), (B5), or (B6), as appropriate)

R_{WR} = Mutual resistance between wire and electrodes, ohms (From Equations (B15), (B16), or (B17), as appropriate)

5.2 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	(B7)	(B8), (B9)	(B8)	(B10)
Find R_R from Equation	(B2), (B3)	(B5)	(B5)	(B6)
Find R_{WR} from Equation	(B15)	(B16)	(B16)	(B17)
Find R_T from Equation	(B18)	(B18)	(B18)	(B18)

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 C1: "Four-Terminal" Method for Measurement of Soil Resistivity). 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: q = 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

Note: Divide ohm·centimeters by 100 to convert to ohm·meters.

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 Objectives of Soil Resistivity Measurements: 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 Introduction: 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 C2: "Four-Terminal" Method for Measuring soil Resistivity. 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 C-I.

TABLE C-I

Test Electrode Depths for Various Distances Between Electrodes

Distance Between Electrodes (A)		Test Electrode Depth (B)	
Feet	Meters	Inches	Centimeters
5	1.52	3.0	8
8	2.44	5.0	13
10	3.05	6.0	15
16	4.88	10.0	25
20	6.10	12.0	30
30	9.14	18.0	46
40	12.19	24.0	61
50	15.4	30.0	76

2.2 Performing the Measurement: 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.

APPENDIX D MEASUREMENT OF RESISTANCE-TO-GROUND

1. GENERAL

1.1 Introduction: 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 Remeasuring Existing Grounding Systems: 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 Introduction: 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 D1: Triangulation Method for Measuring the Resistance of a Ground Electrode. The unknown resistance can then be calculated by the formula:

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

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 have to 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 driven electrode, should be 10m or more. For larger areas the minimum spacing should be on the order of the dimensions of the grounds.

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 D2: Direct Method for Measuting the Resistance of a Ground Electrode. (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 has to be extensive enough to have only negligible resistance-to-ground. The water-pipe system has to be entirely metallic without insulating couplings or flanges. The electrode being tested has to 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 ± 10 percent.

2.4 **Fall-of-Potential Method (Three terminal)**: The three-terminal test, illustrated in Figure D3: Fall of Potential Method, 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 D4: Example of Earth Resistance Curve. 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 D5: Effect with C_2 Located far from Earth Electrode. 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 D6: Effect with C_2 Located Close to Earth Electrode, 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 D1 (see next page) 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. The maximum dimension is determined as follows: 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. The maximum dimension for a grounding system containing electrodes in a circular ring configuration is the diameter of the circle. 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 **Problems with Measuring Grounding System**: 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.

TABLE D-I

REFERENCE ELECTRODE LOCATION

Maximum Dimension, Ft. (Meters)	Distance to P_2 Ft. (Meters) C_2,	Distance to Ft. (Meters)
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)
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)

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 the Technique is to obtain ground resistance curves for several reference electrode spacings. Then, 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 0 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 0. A curve such as abc in Figure D7: Earth Resistance Curve for Large Area Example 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 0. 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 0, 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 (0, 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 extends 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 D8: Earth Resistance Curve for Large Area Example. Applying the described method produced the intersection curves given in Figure D9: Intersection Curves for Figure D8. 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 from C_1 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.

APPENDIX E CONCRETE ENCASED ELECTRODES

1. GENERAL

1.1 Introduction: 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 Preventing Structural Damage: 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 Avoid Moisture Barriers: 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 Equation: The approximate resistance-to-ground for a grounding electrode encased in the concrete footing of a building may be calculated in Metric units by the equation:

$$R_c = \frac{1}{\pi \ell_w}\left(\rho_0 \ln \frac{12.732\,\ell_w}{\sqrt{d_w h}} - \rho_0 \ln \frac{12.732\,\ell_w}{\sqrt{d_c h}} + \rho_1 \ln \frac{12.732\,\ell_w}{\sqrt{d_c h}} \right)$$

Where: R_C = Resistance of Ufer ground, ohms.
ρ_0 = Resistivity of concrete, ohm·meters.
ρ_1 = Resistivity of soil, ohm·meters.
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.
π = 3.1416

2.3 **<u>Resistance of Various Sized Areas</u>:** The calculated approximate resistance-to-ground of concrete encased ring systems surrounding differently sized areas with various soil resistivities is shown in Figure E1: Concrete Encased Electrodes in a Square Ring Configuration. 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 **<u>Resistivity of Concrete</u>:** The resistivity of concrete has been estimated to be in the range of 30 to 300 ohm·meters, according to values published by several investigators. The majority of them favor a range from 30 to 100 ohm·meters. A value of 50 ohm·meters is recommended for calculations where the actual concrete resistivity is unknown.

3.2 **<u>Diameter of Concrete</u>:** A typical building footing is illustrated in Figure E2: Concrete Footing. 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 E3: Basic Elements for Calculation.

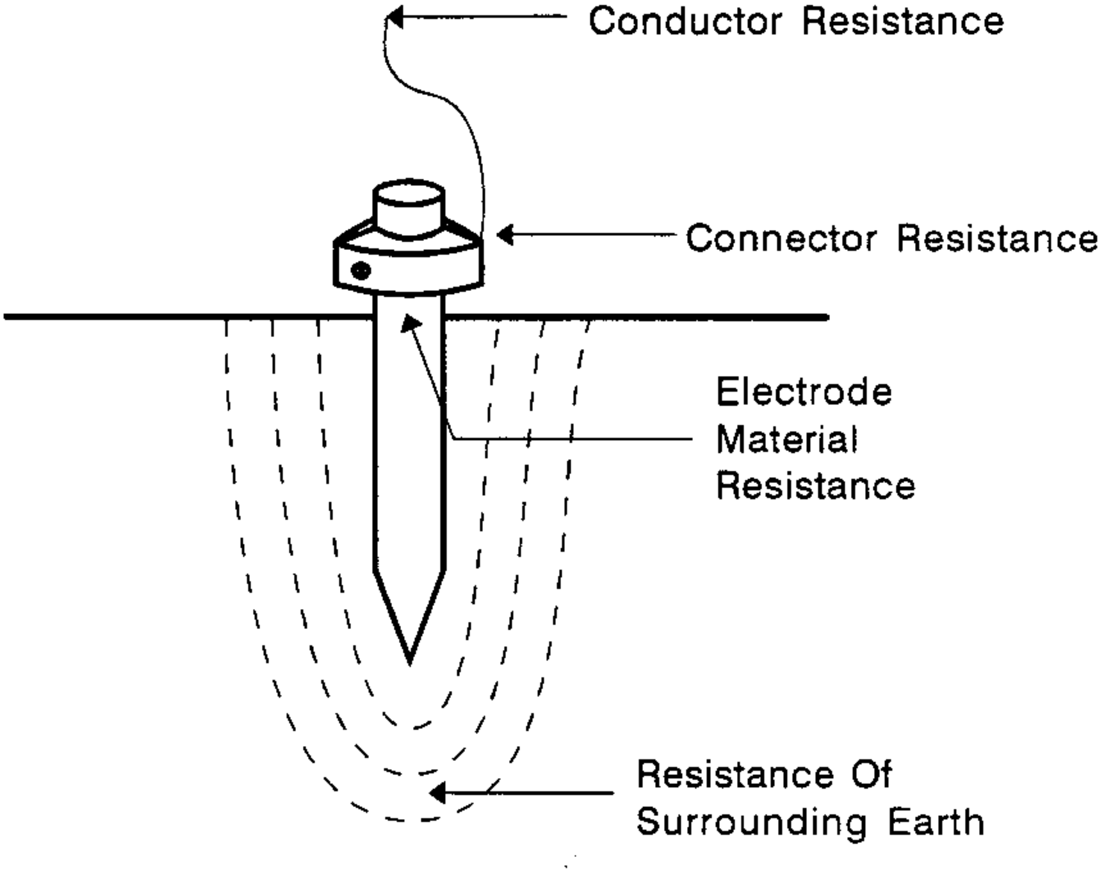
3.3 **<u>The Size of the Encased Conductor</u>** is not a major factor in the resulting resistance-to-ground with an encased electrode. Results of calculations, using #2 and 2/0 conductors in encased grounding systems, have been plotted in Figure E4: Variation with Wire Size. The curves show the ground resistance with a 2/0 conductor is only slightly 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 E5: Variation with Depth for Concrete Encased Electrodes shows plotted curves of calculated resistance-to-ground for a #2 encased grounding conductor buried at depths of 2, 4, and 10 feet (0.6, 1.2 and 3.0 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 Between Concrete Encased Electrode and Direct-Buried Electrode:** 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 E6: Comparsion between Encased and Direct Buried Electrodes with Different Concrete Resistivities 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 Effect of Concrete Footing Size:** The curves in Figure E7: Variation with concrete Diameter for Concrete Encased Electrodes 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.

Figure 1: Components of Resistance in a Ground Connection



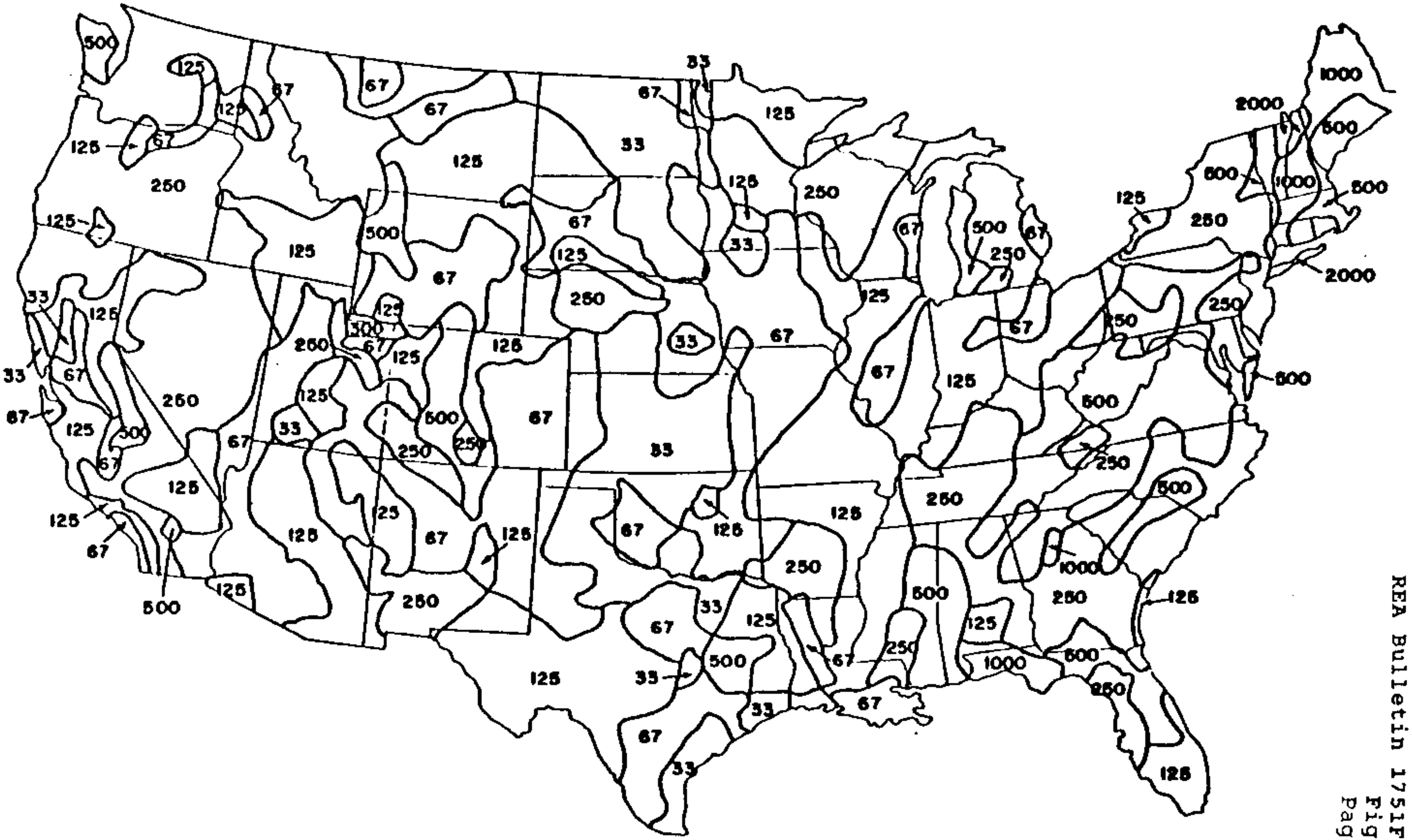


FIGURE 2

Estimated Average Earth Resistivity in U.S. (ohm·meters)

Figure 3: Typical Variation of Soil Resistivity with Moisture

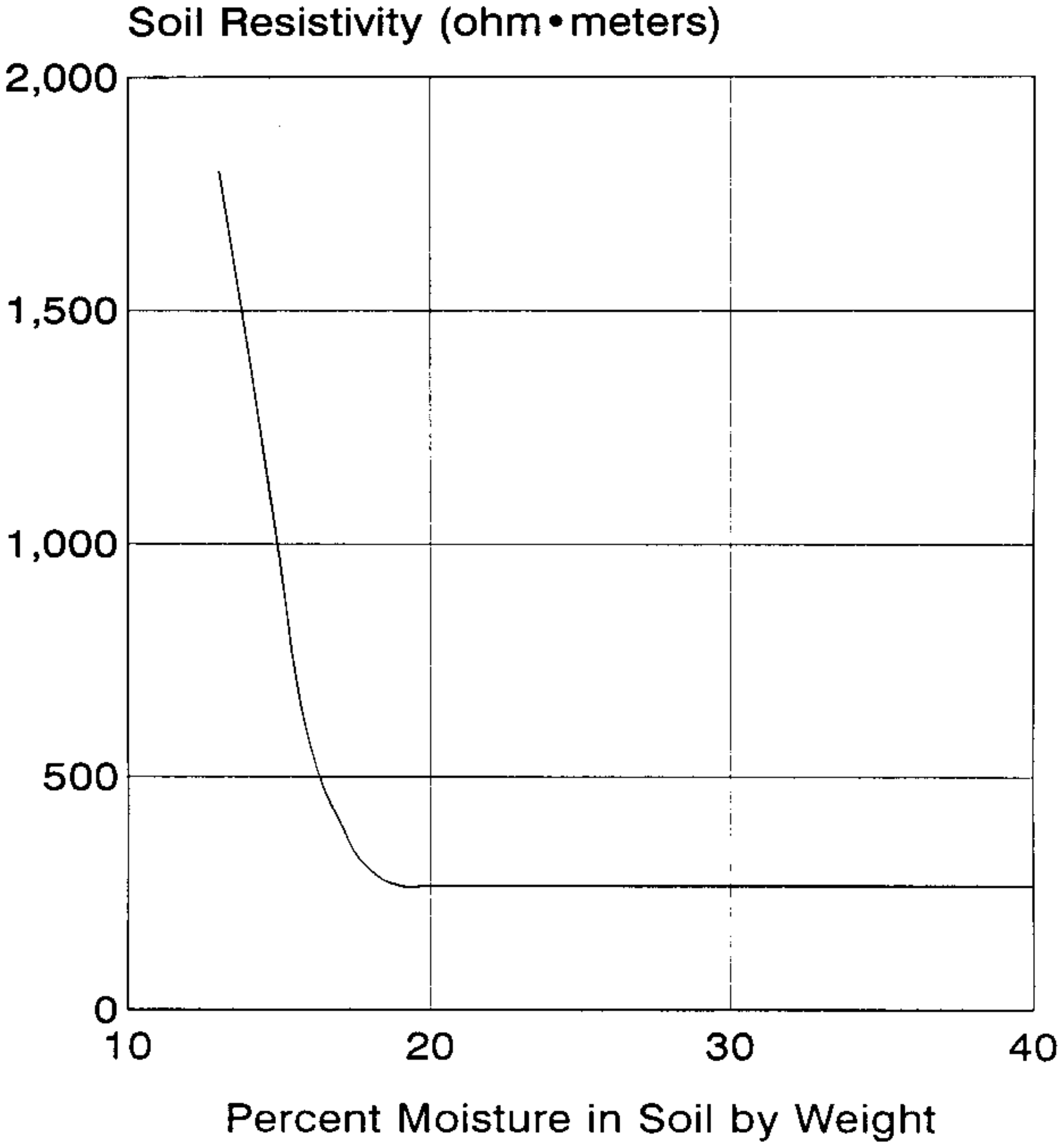


Figure 4: Typical Effect of Mineral Salt on Earth Resistivity

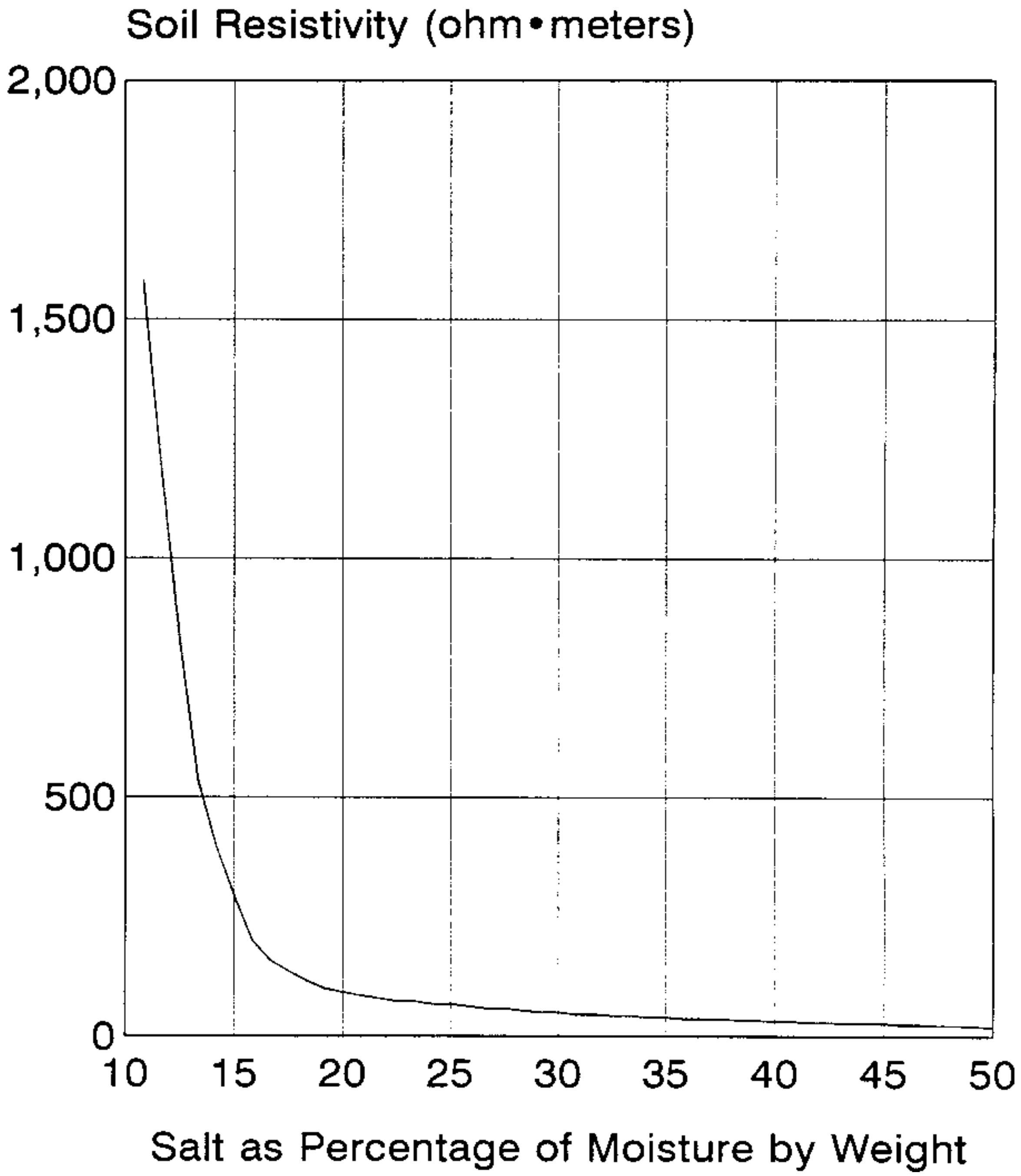


Figure 5: Typical Variation of Soil Resistivity with Temperature

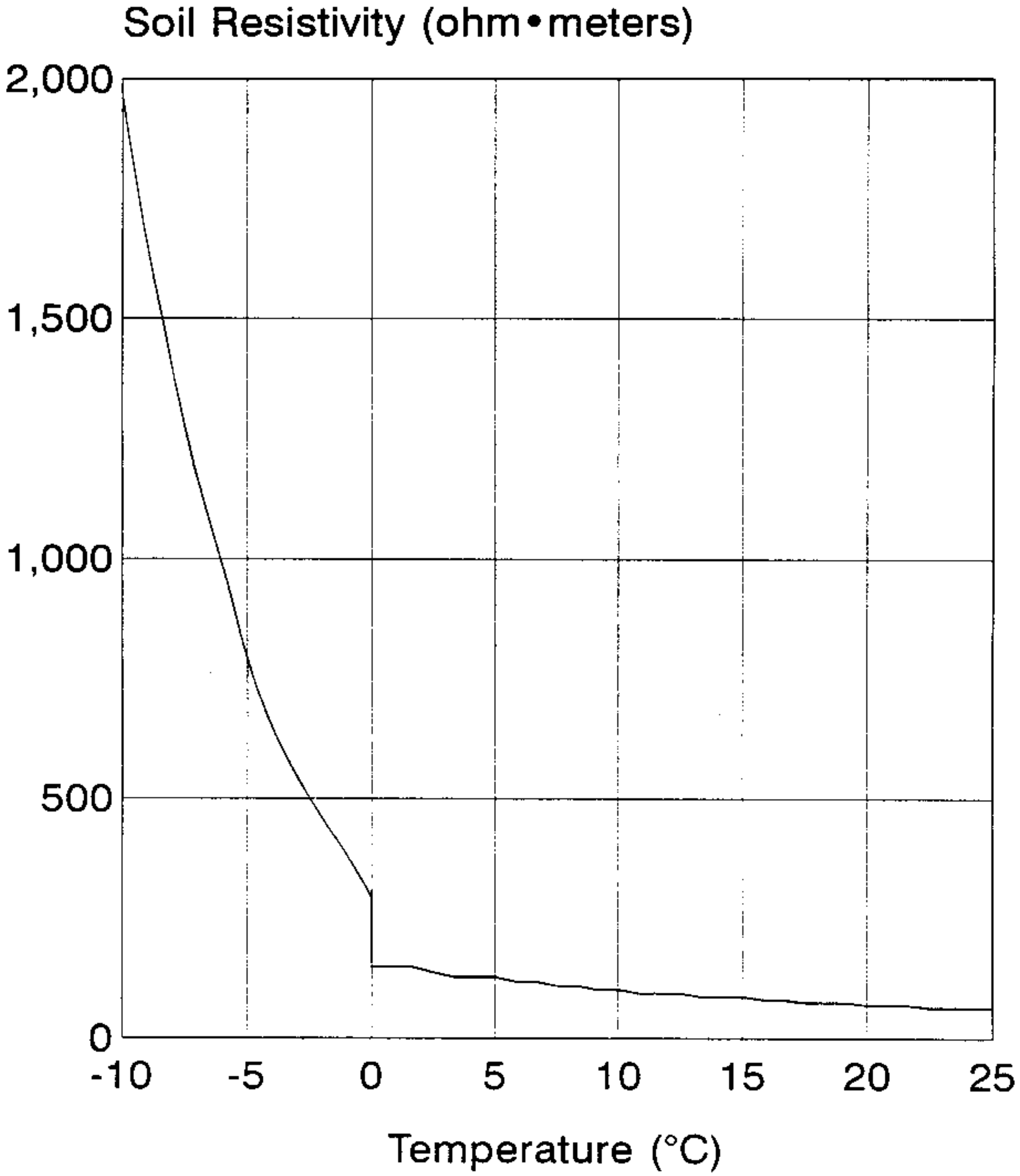
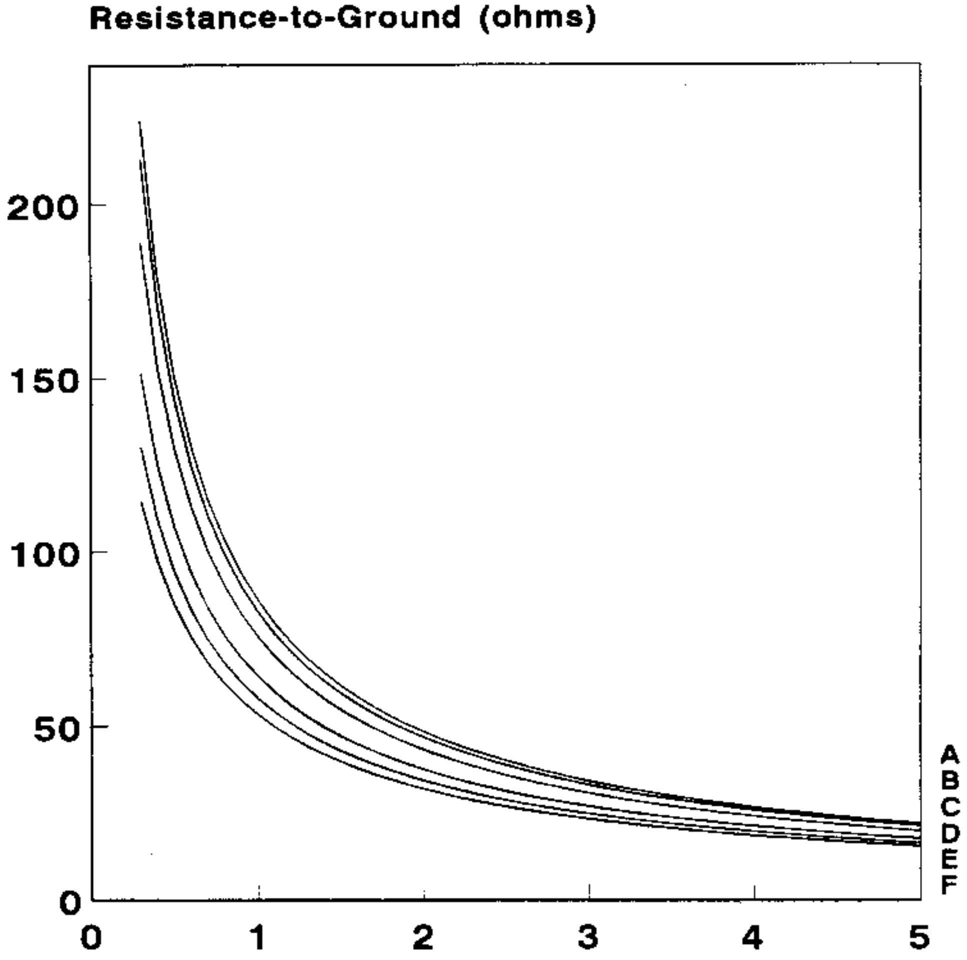


Figure 6: Resistance-to-Ground Variation with Electrode Depth



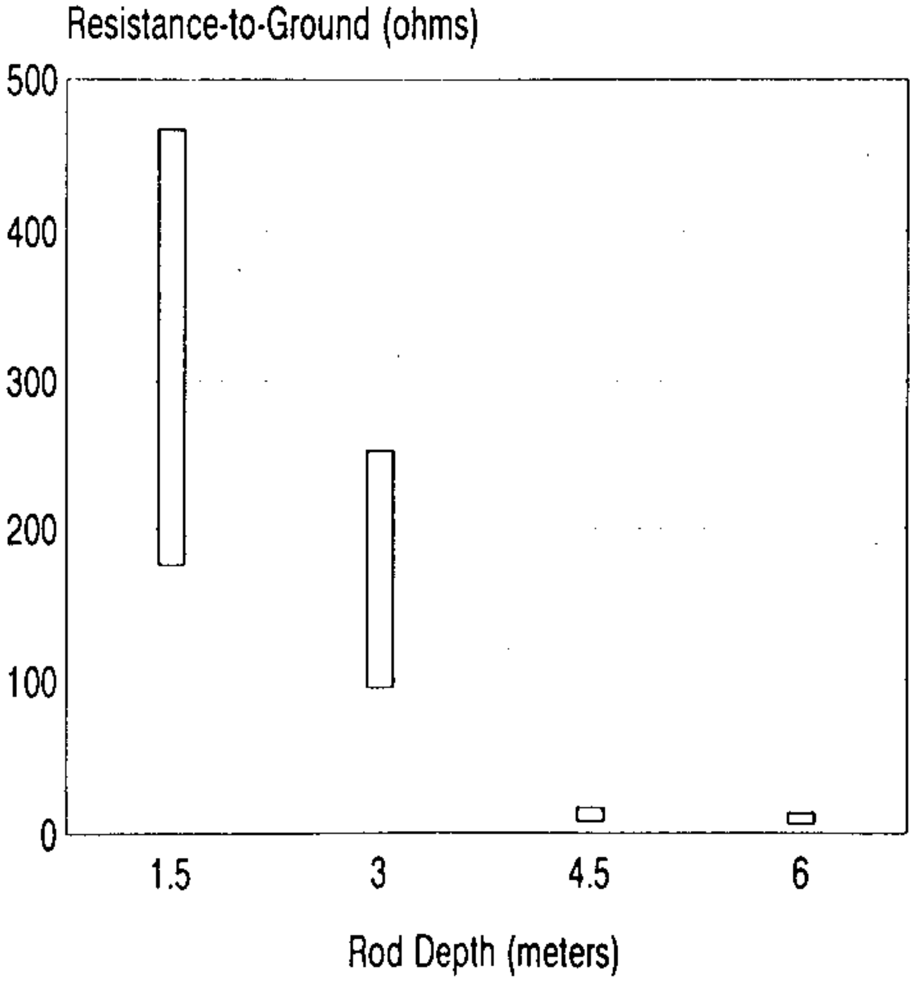
Length of Electrode (meters)

Diameter of Electrode

A - 1/2 inch (1.3 cm)
B - 5/8 inch (1.6 cm)
C - 1 inch (2.5cm)
D - 2 inch (5.1 cm)
E - 3 inch (7.6 cm)
F - 4 inch (10.2 cm)

Soil Resistivity - 100 ohm•meters

Figure 7: Resistance-to-Ground Variation in Multiple Soil Layers



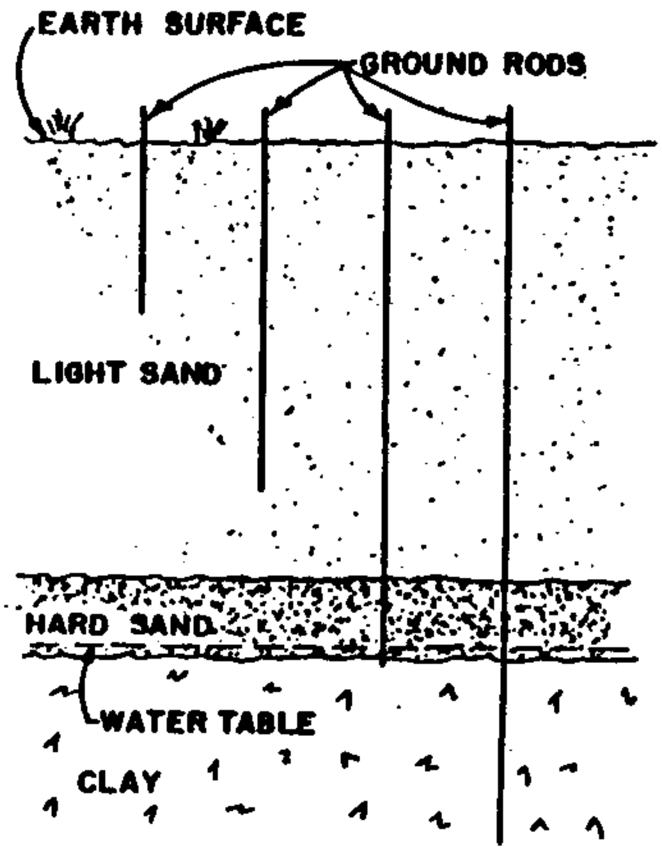
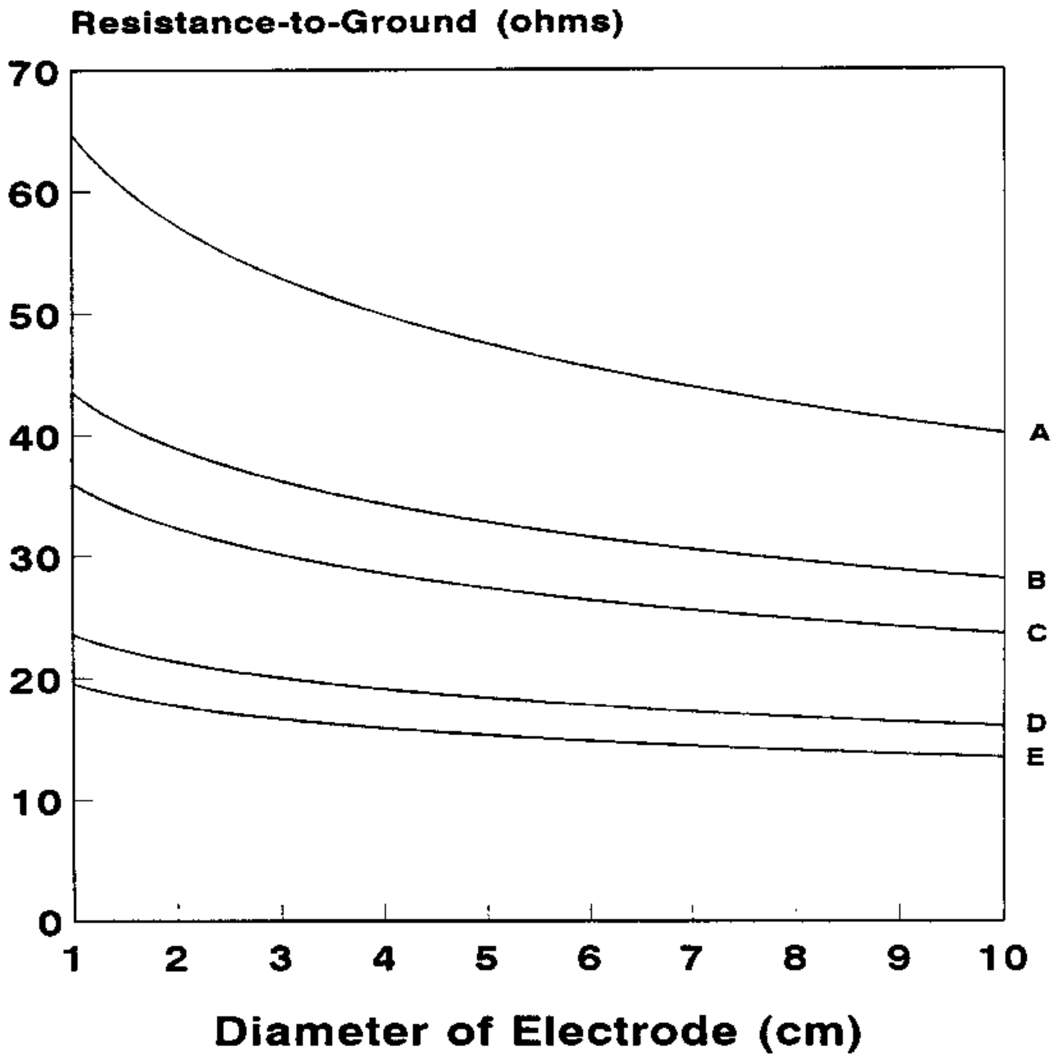


Figure 8: Resistance-to-Ground Variation with Electrode Diameter

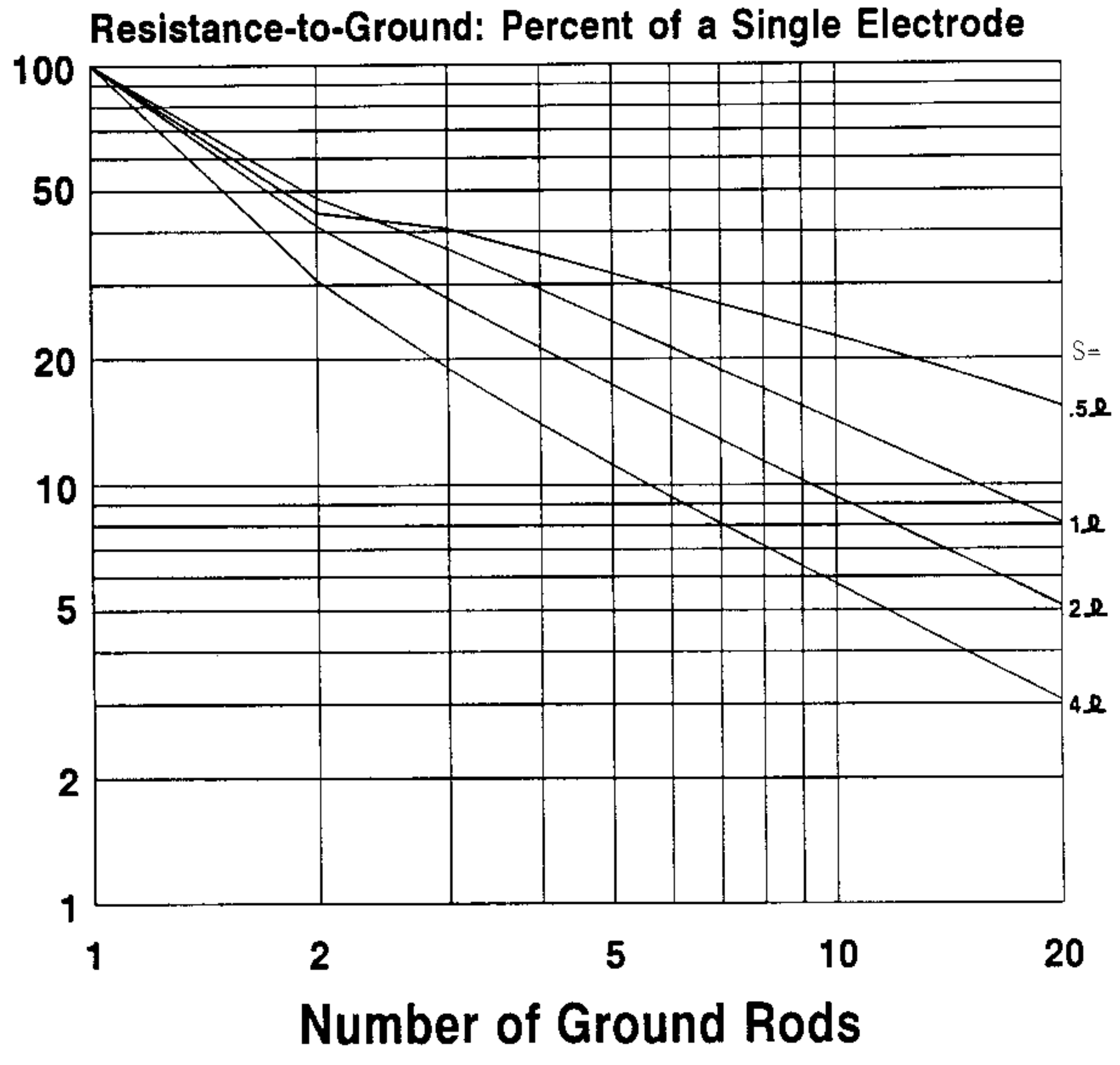


Length of Electrode

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 ohm•meters

Figure 9: Percent Resistance Variation Multiple Electrodes in a Straight Line Interconnected with Wire



S = Spacing between Electrodes
ℓ = Electrode Length

Figure 10: Percent Resistance Variation for a Ring of Multiple Electrodes Interconnected with Wire

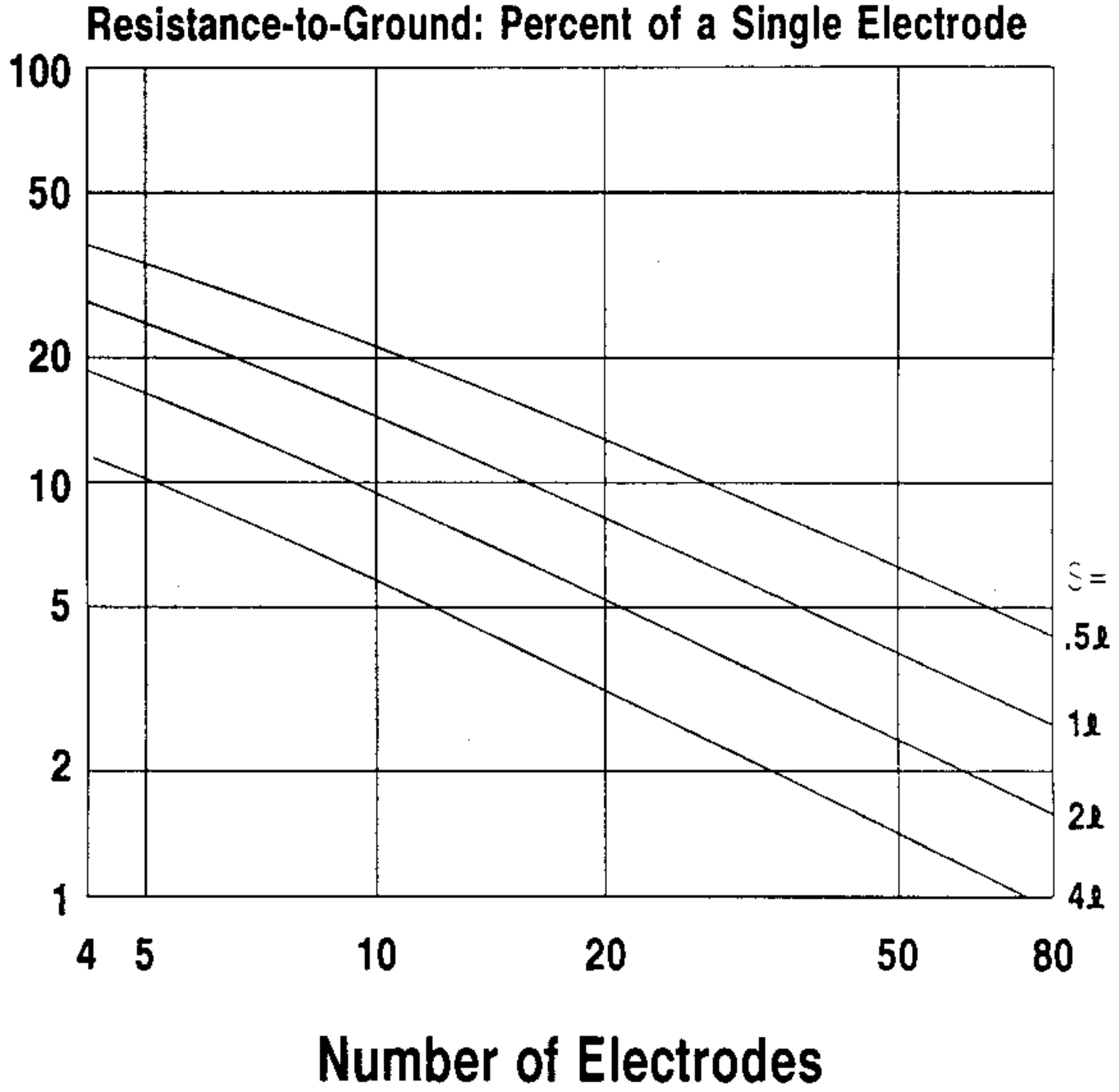
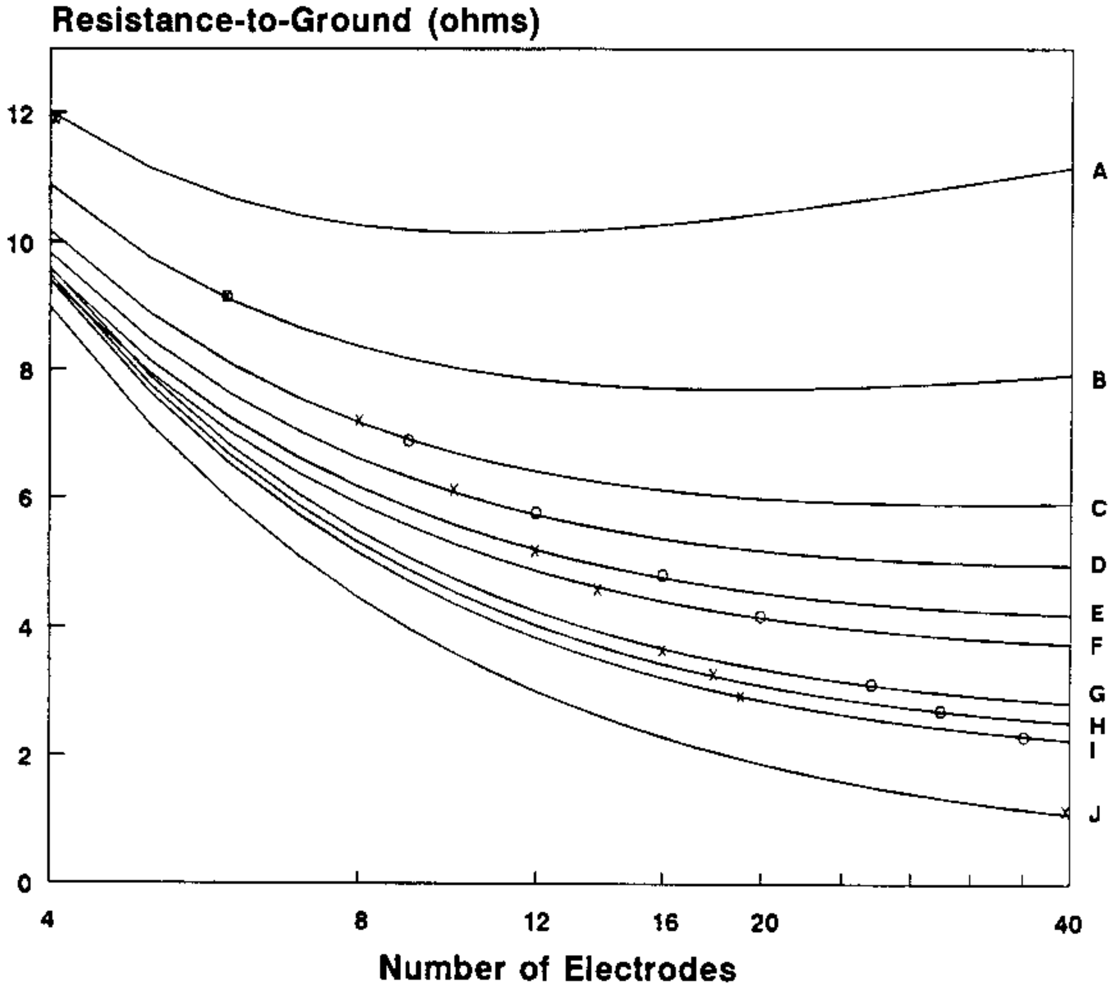


Figure 11: Resistance-to-Ground for Multiple Electrodes in a Rod Bed

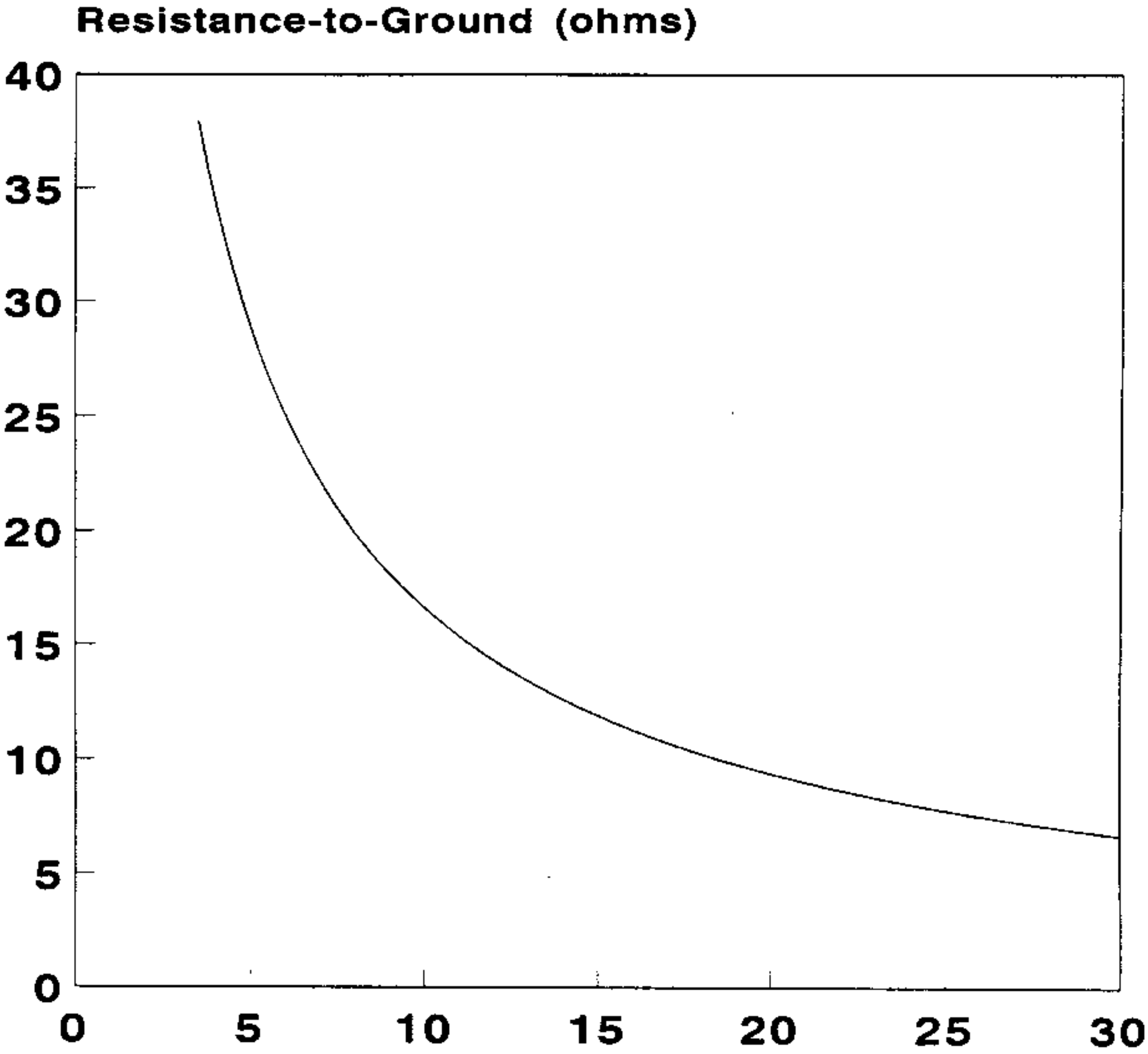


Total Area of Rod Bed

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
O = Rod Bed with Separation equal to Electrode Length
5/8 inch x 10 feet (1.6 cm x 3.0 m) Electrodes
Earth Resistivity = 100 ohm meters

Figure 12: Resistance-to-Ground Variation with Length of Horizontal Electrode



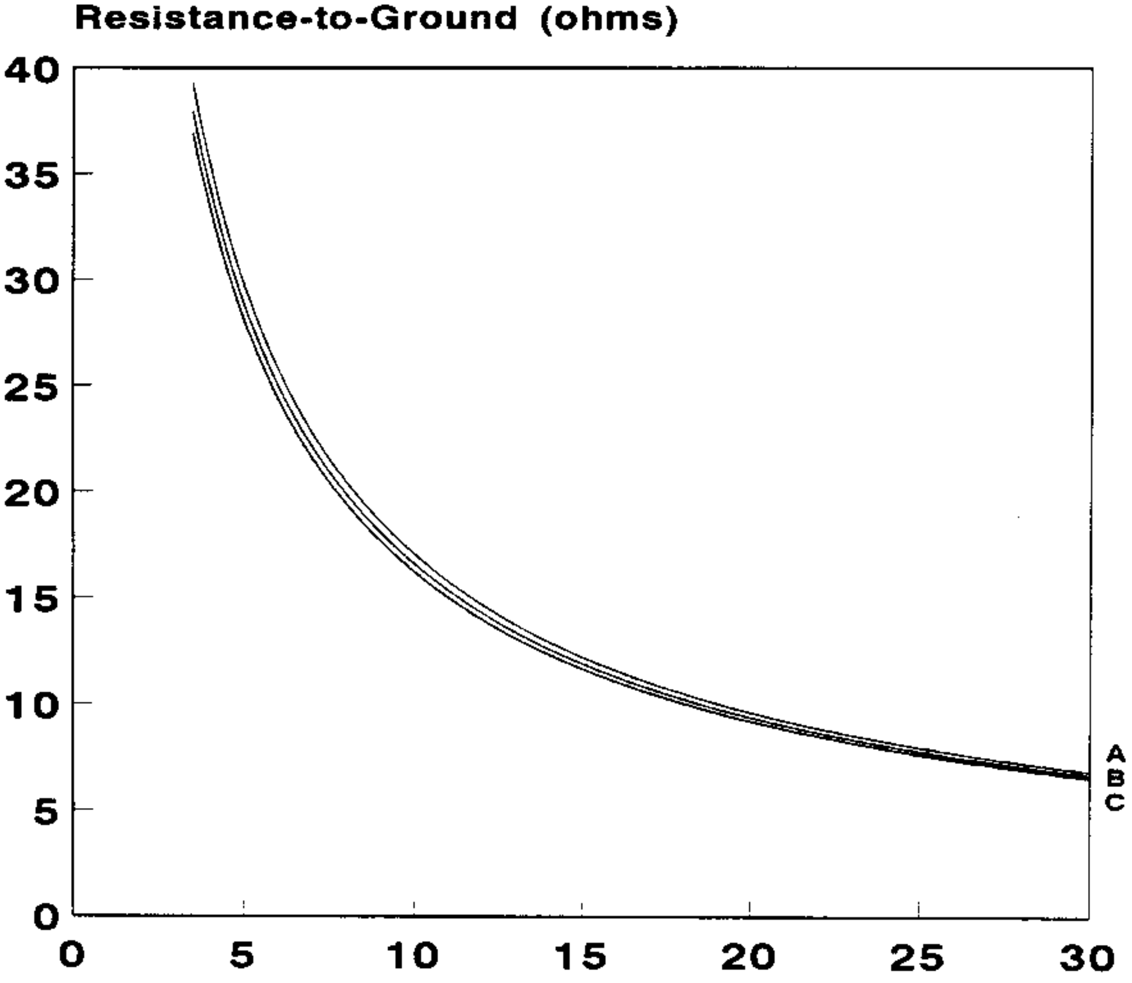
Electrode Length (meters)

Electrode Size = #2 Bare Copper Conductor

Depth = 2 Feet (0.6 meters)

Earth Resistivity = 100 ohm•meters

Figure 13: Resistance-to-Ground Variation with Different Sized Horizontal Electrodes

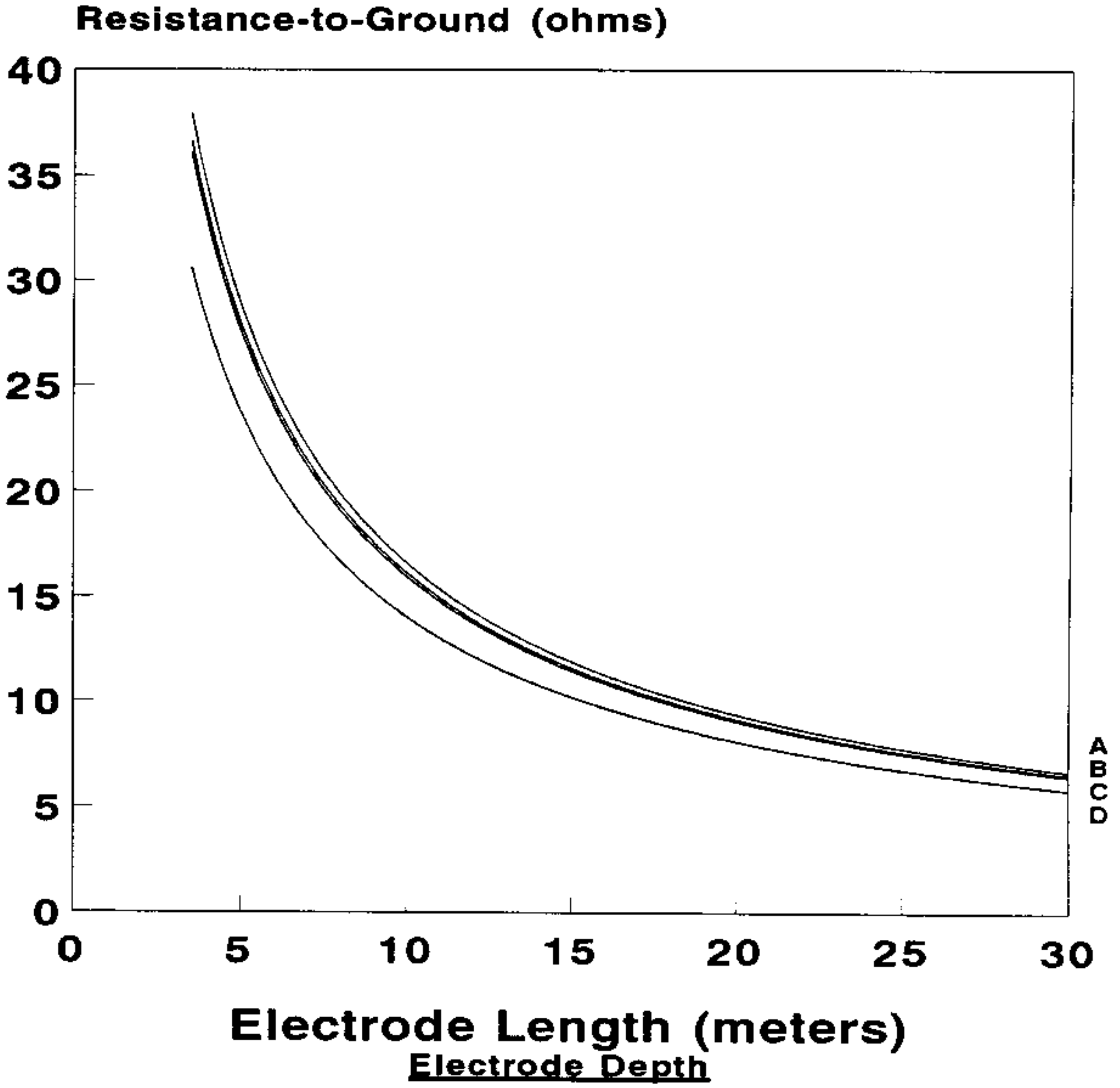


Electrode Size

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

Depth = 2 Feet (0.6 meters)
Earth Resistivity = 100 ohm•meters

Figure 14: Resistance-to-Ground Variation with Depth of Horizontal Electrodes

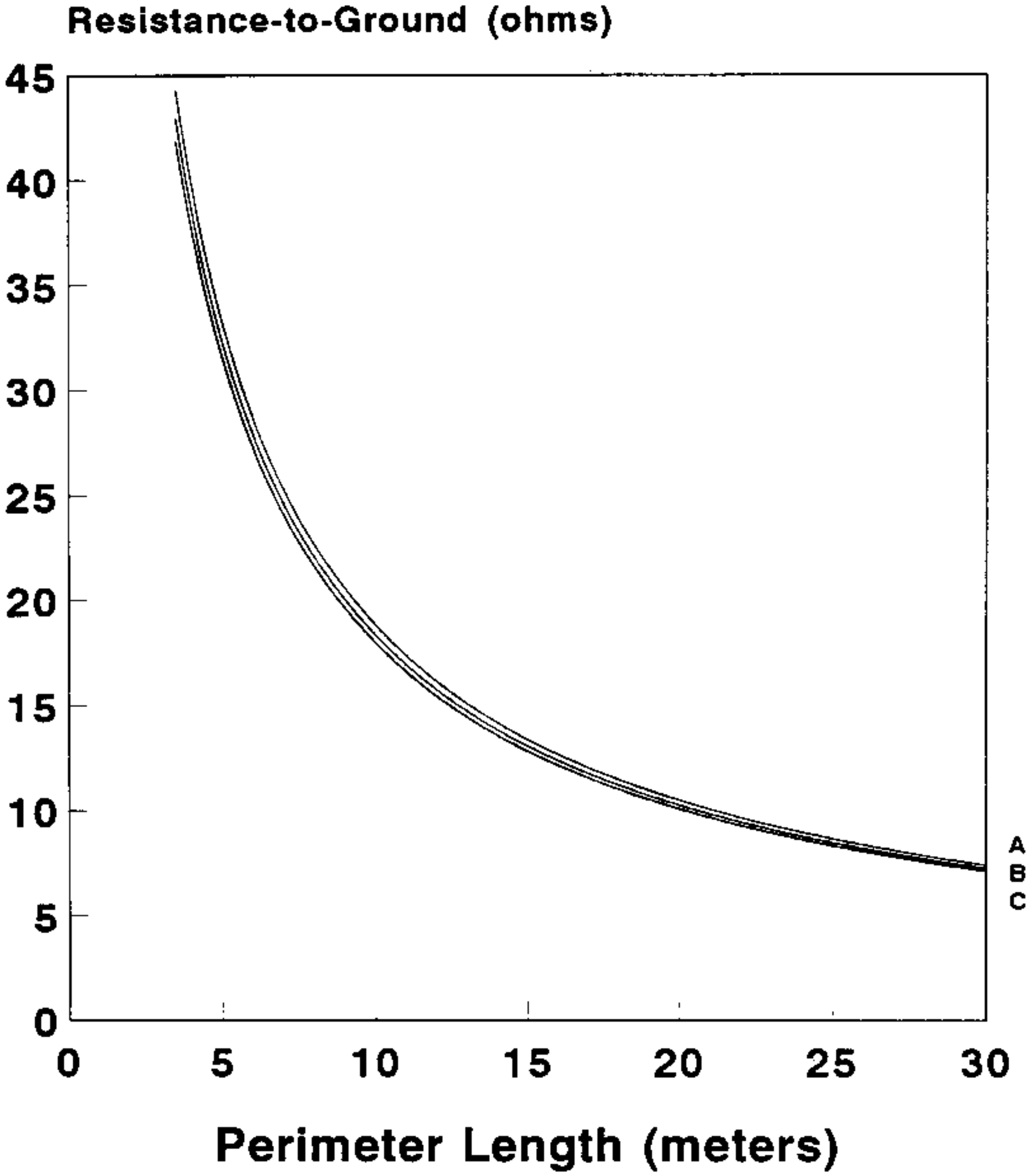


Electrode Depth

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 ohm•meters

Figure 15: Resistance-to-Ground for Various Horizontal Rings

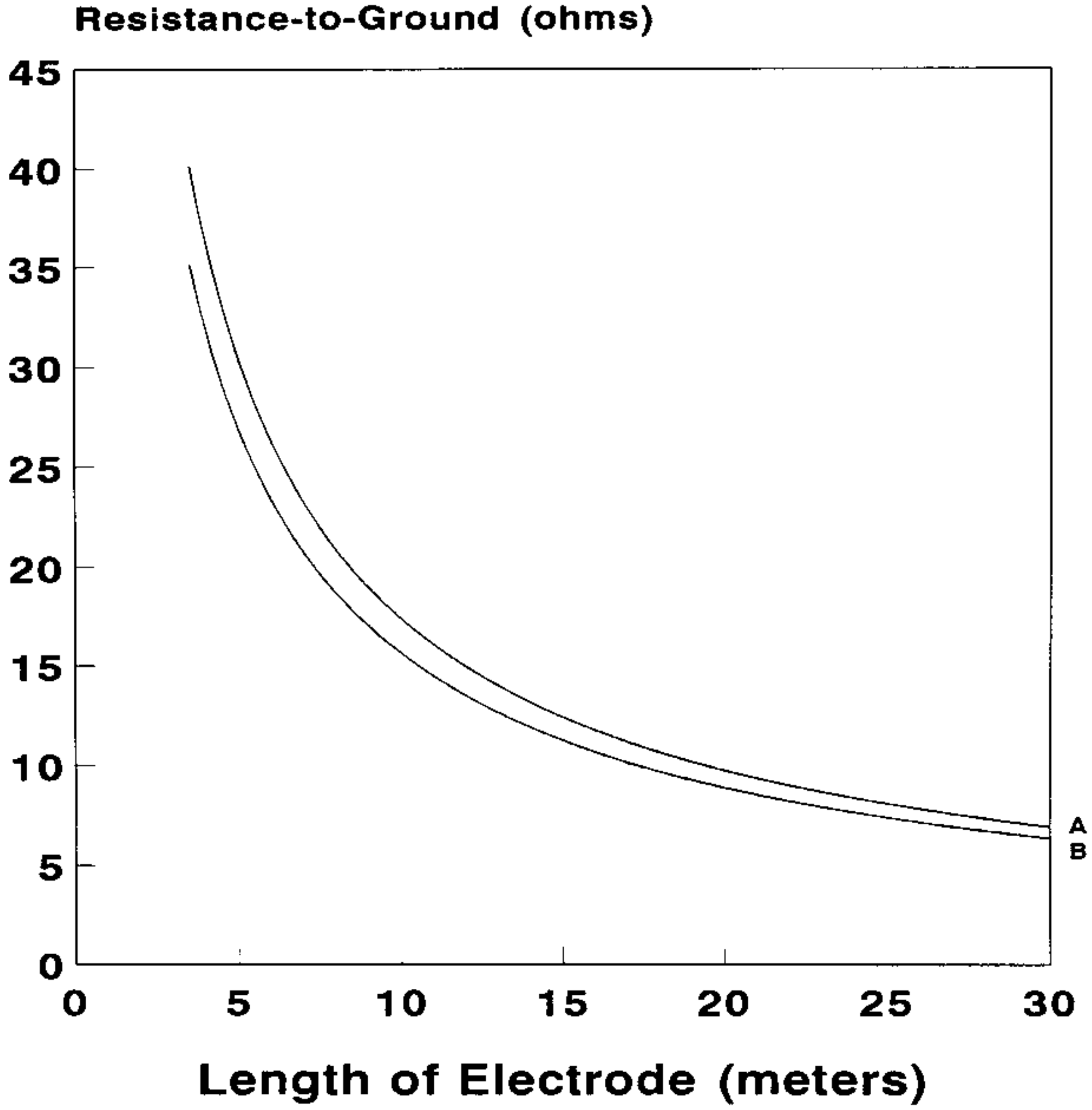


Electrode Size

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

Depth = 2 Feet (0.6 meters)
Earth Resistivity = 100 ohm•meters

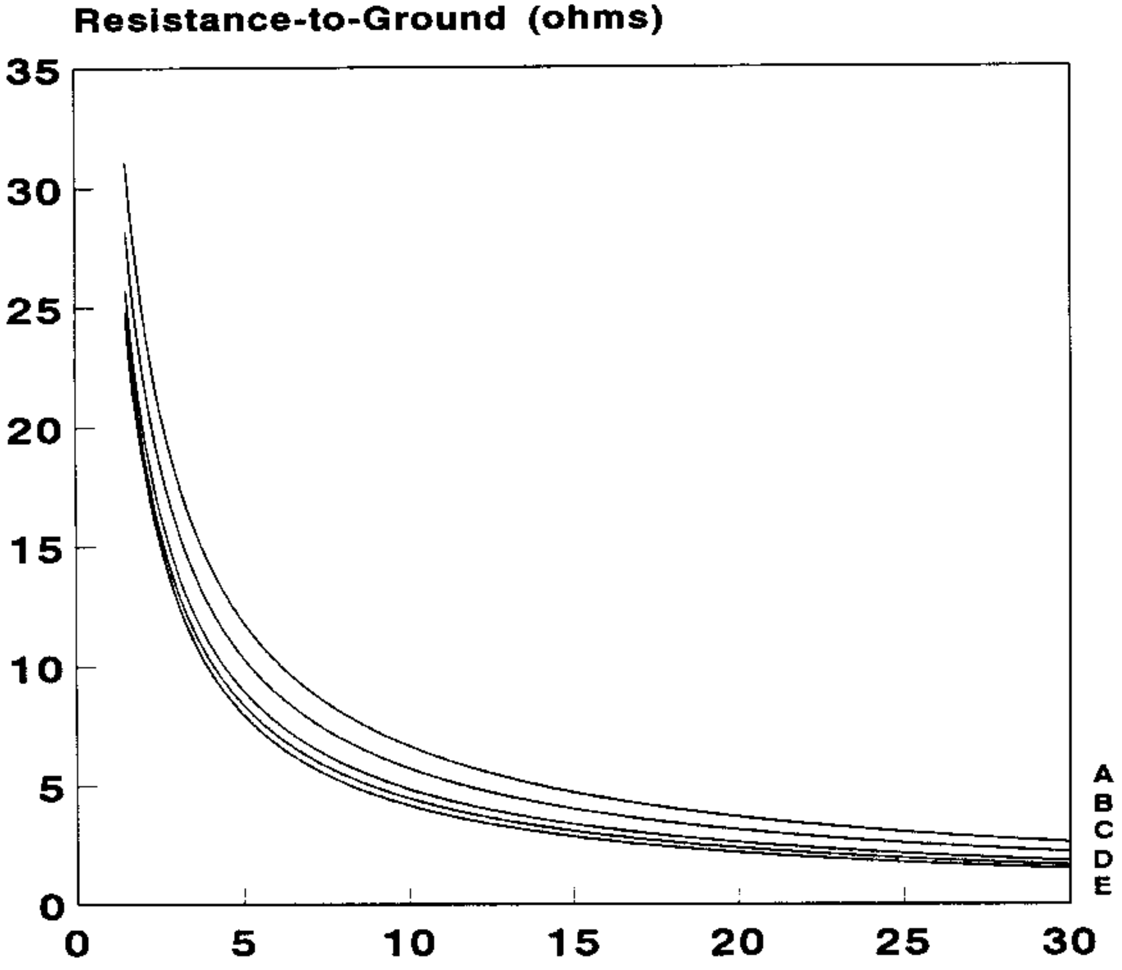
Figure 16: Resistance-to-Ground Variation between Configurations



A = Ring B = Straight

Electrode Size = #6 Bare Copper Conductor
Depth = 2 Feet (0.6 meters)
Earth Resistivity = 100 ohm•meters

Figure 17: Resistance-to-Ground Variation for Various Radial (Star) Configurations



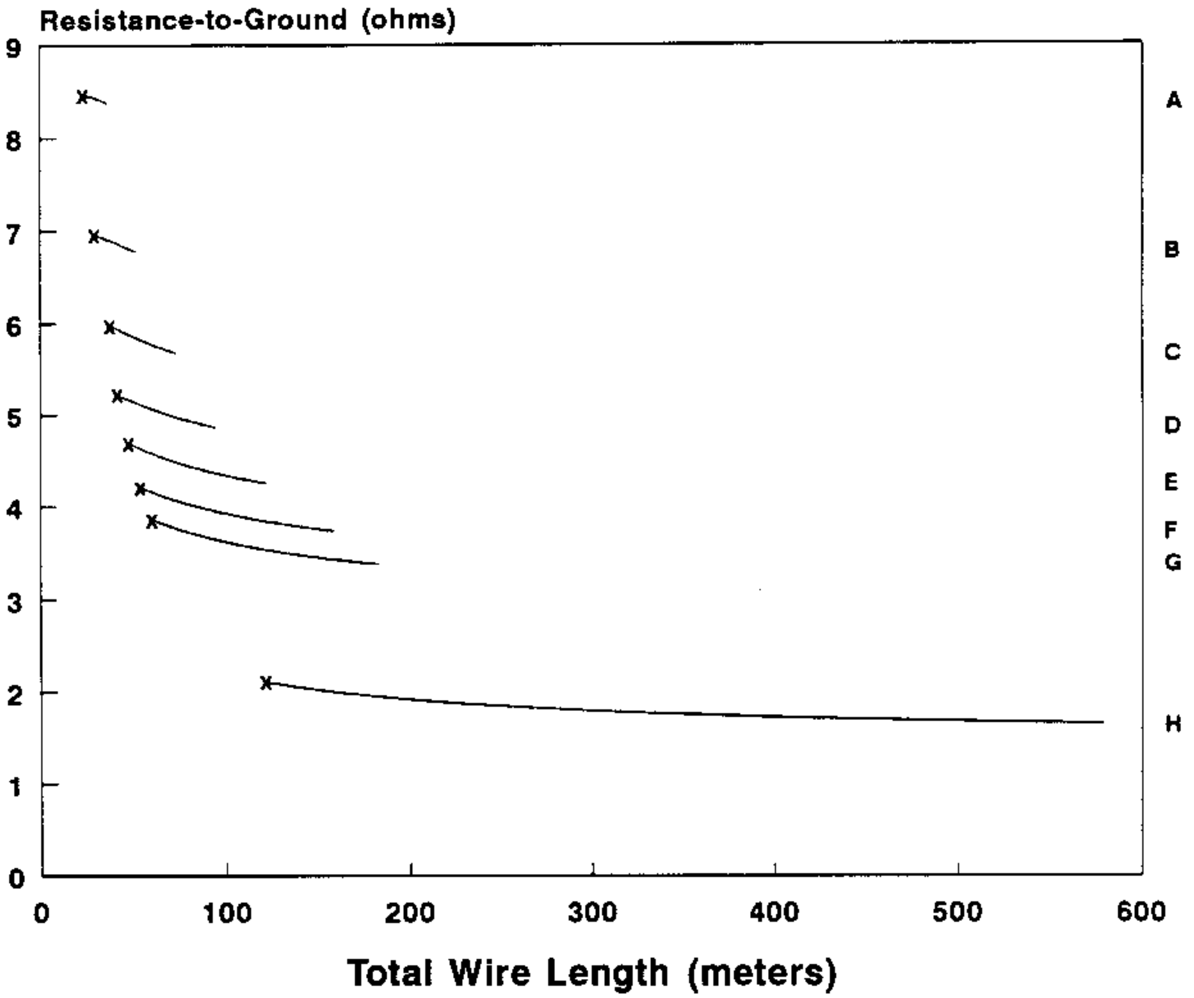
Branch Length (meters)

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 ohm•meters

Figure 18: Resistance-to-Ground Variation for Different Wire Grid Areas

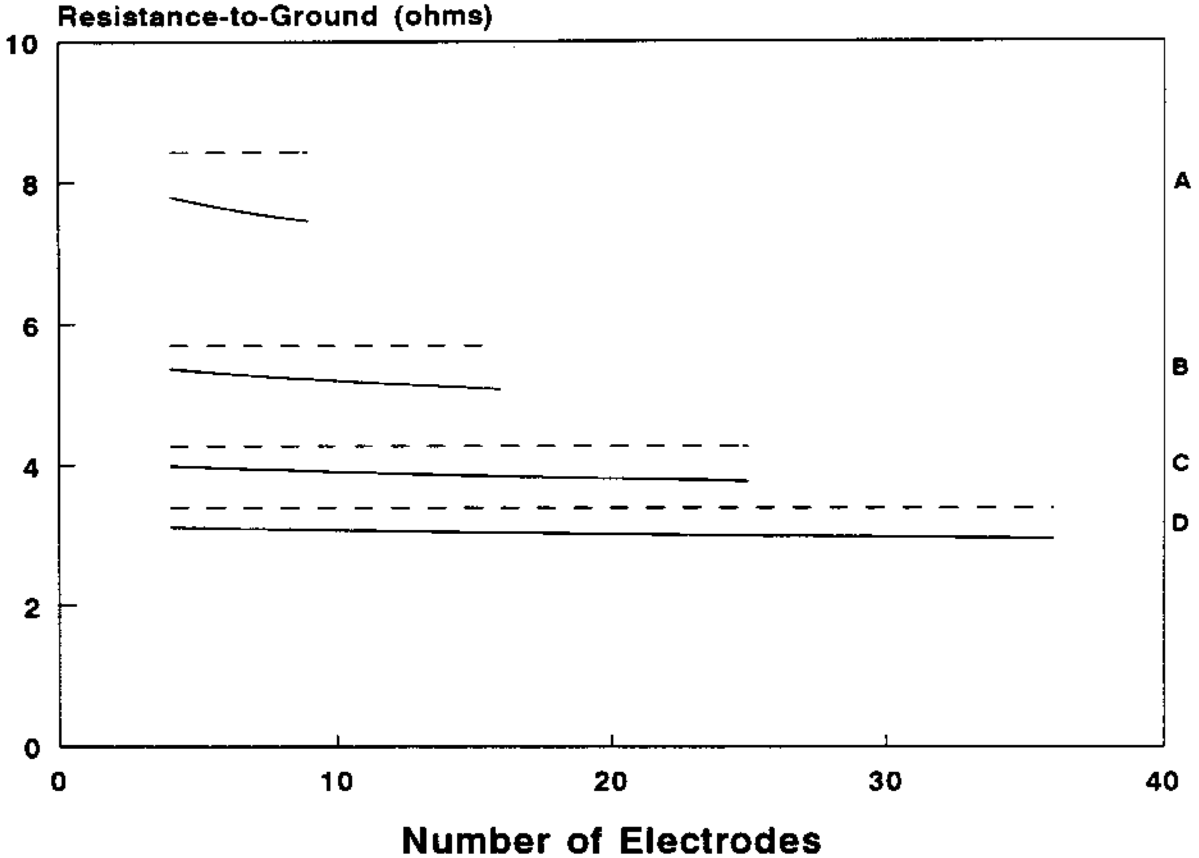


<u>Total Area of Wire Grid</u>

A - 400 Sq. Ft. (37 Sq. m)	E - 1600 Sq. Ft. (149 Sq. m)
B - 600 Sq. Ft. (56 Sq. m)	F - 2000 Sq. Ft. (186 Sq. m)
C - 900 Sq. Ft. (84 Sq. m)	G - 2500 Sq. Ft. (232 Sq. m)
D -1200 Sq. Ft. (112 Sq. m)	H -10000 Sq. Ft. (929 Sq. m)

X = Perimeter Ground
Conductor Size = #2 Bare Copper
Depth = 2 Feet (0.6 meters)
Earth Resistivity = 100 ohm•meters

Figure 19: Comparison
of Resistance-to-Ground between Wire Grids and Rodbeds



- - - - - - Wire Grid
———— Combined Wire Grid and Rod Bed

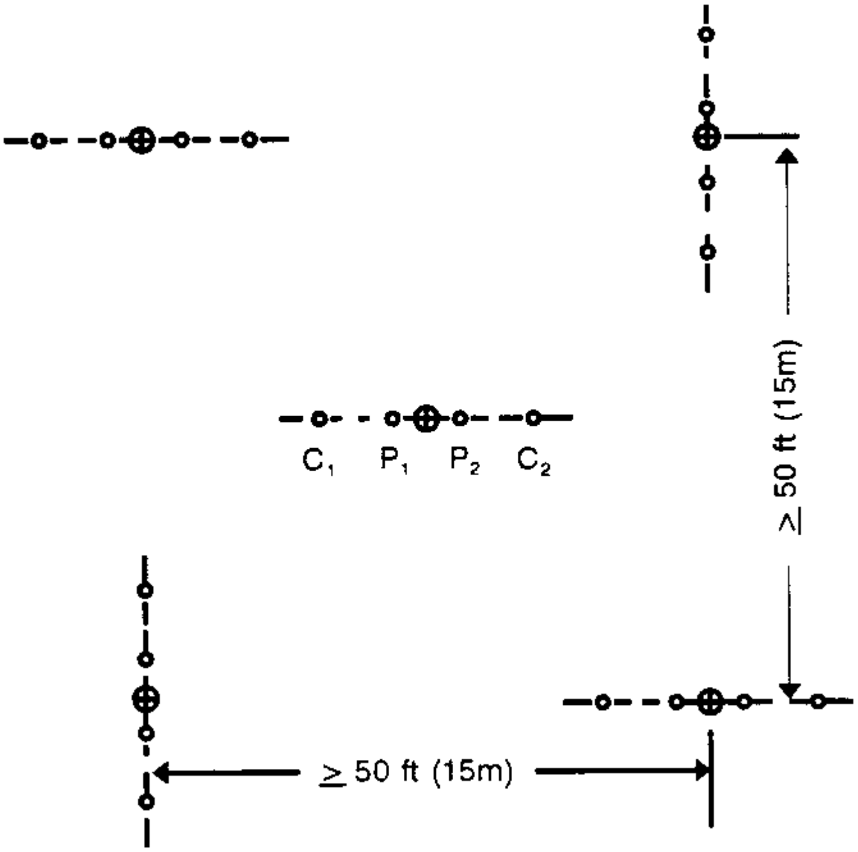
Total Area of Grid

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)

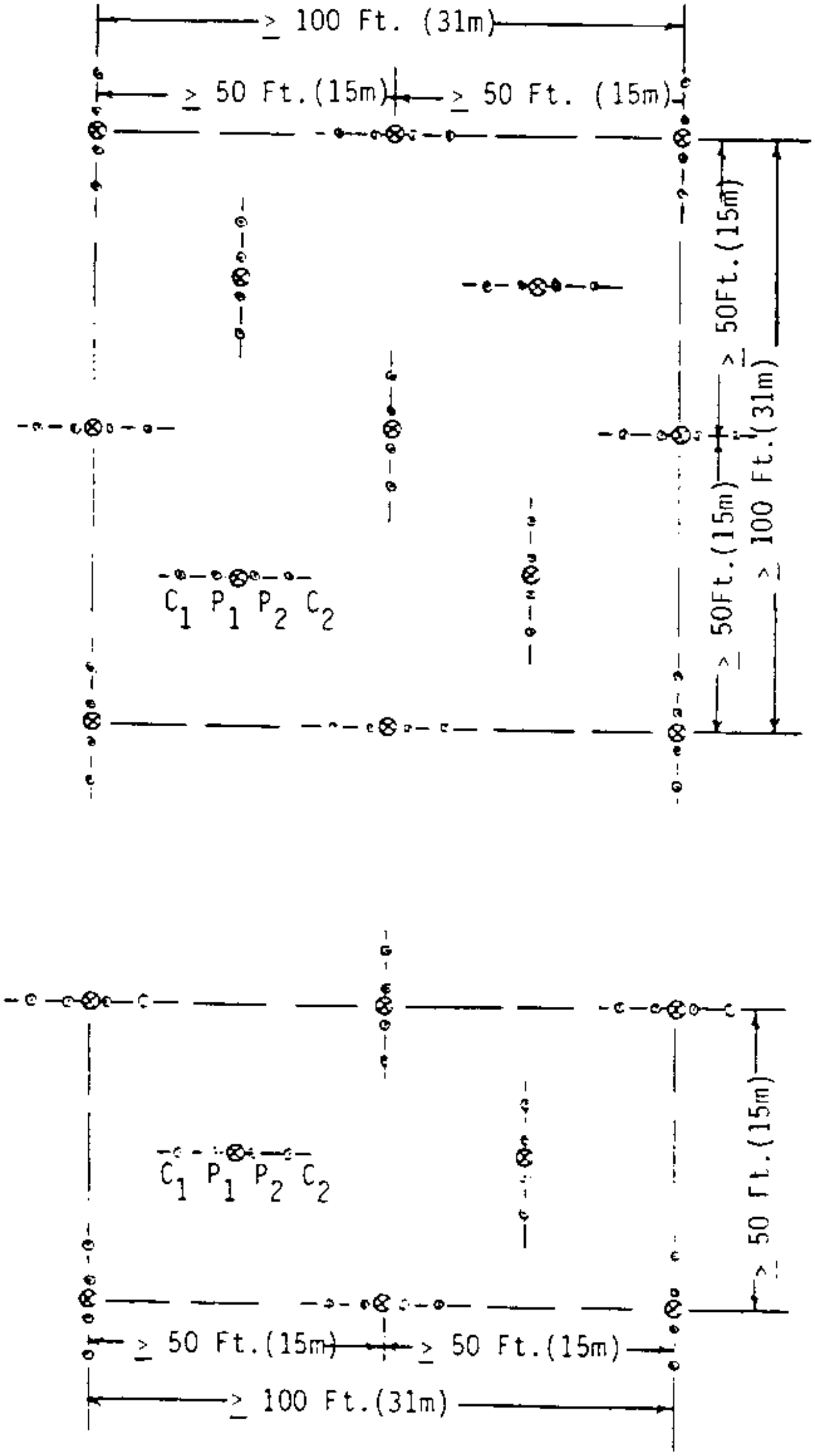
Vertical Electrode = 5/8 inch x 10 Foot (1.6 cm x 3 meter)
Horizontal Electrode = #2 Bare copper conductor
Depth = 2 Feet (0.6 meters)
Resistivity = 100 ohm•meters

Figure 20

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



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



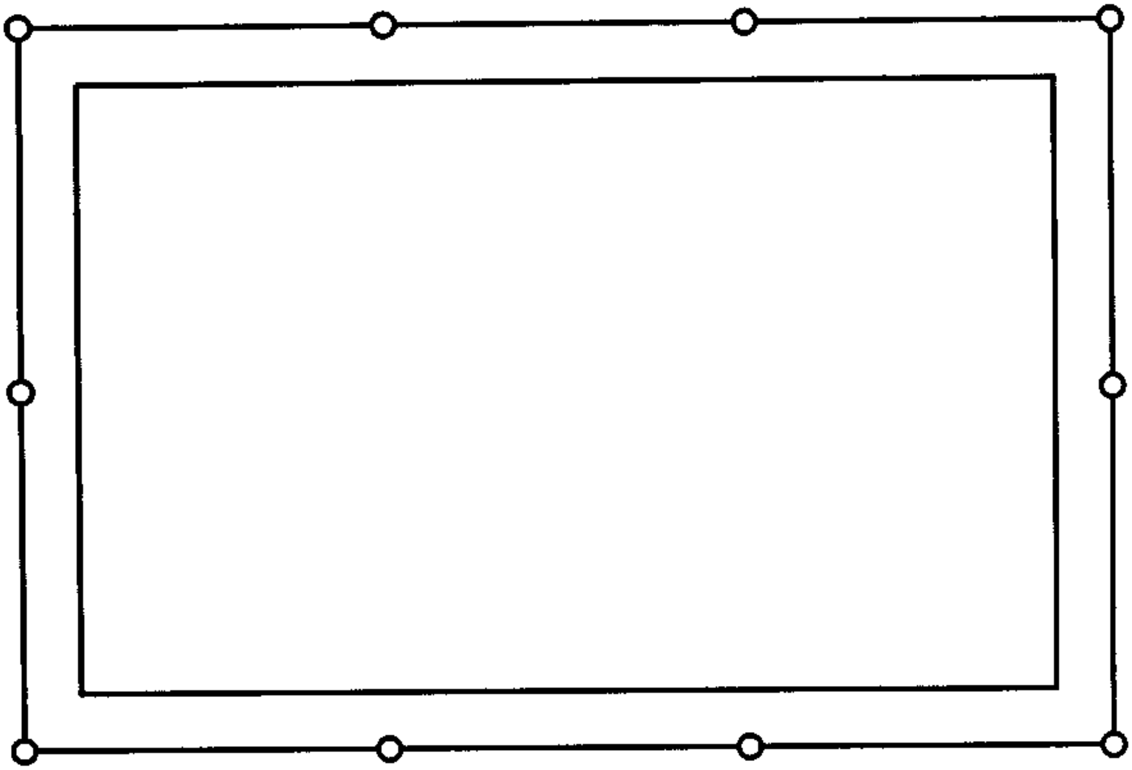
C_1, P_1, P_2, C_2 = Test Set Terminals (See Appendix C)

FIGURE 21

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

Figure 22: Grounding System Design Example

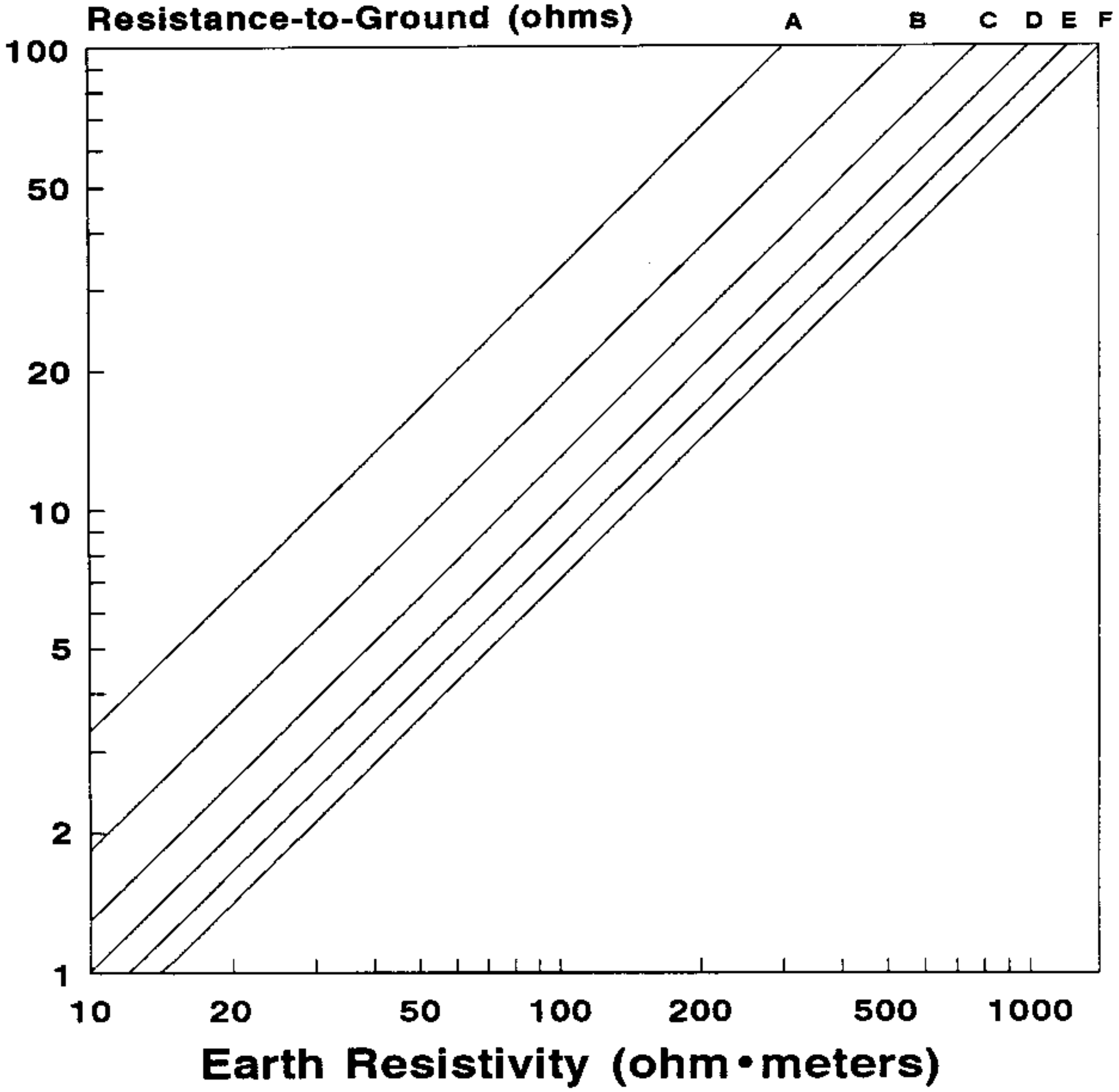
Grounding system area:
40 ft. x 60 ft. (12m x 18m)
Distance between electrodes:
20 ft. (6m)



Average Soil Resistivity

12 ft. (4m) Depth = 900 ohm-meters
22 ft. (7m) Depth = 200 ohm-meters

Figure 23: Resistance-to-Ground of 10 Foot Sectional Electrodes



Total Length - 10 Foot Sectional Electrodes

A - 10 Feet (3.0 meters)
B - 20 Feet (6.1 meters)
C - 30 Feet (9.1 meters)
D - 40 Feet (12.2 meters)
E - 50 Feet (15.2 meters)
F - 60 Feet (18.3 meters)

All Diameters - 5/8 inch (1.6 cm)

Figure 24: Typical Grounding Hand Hole

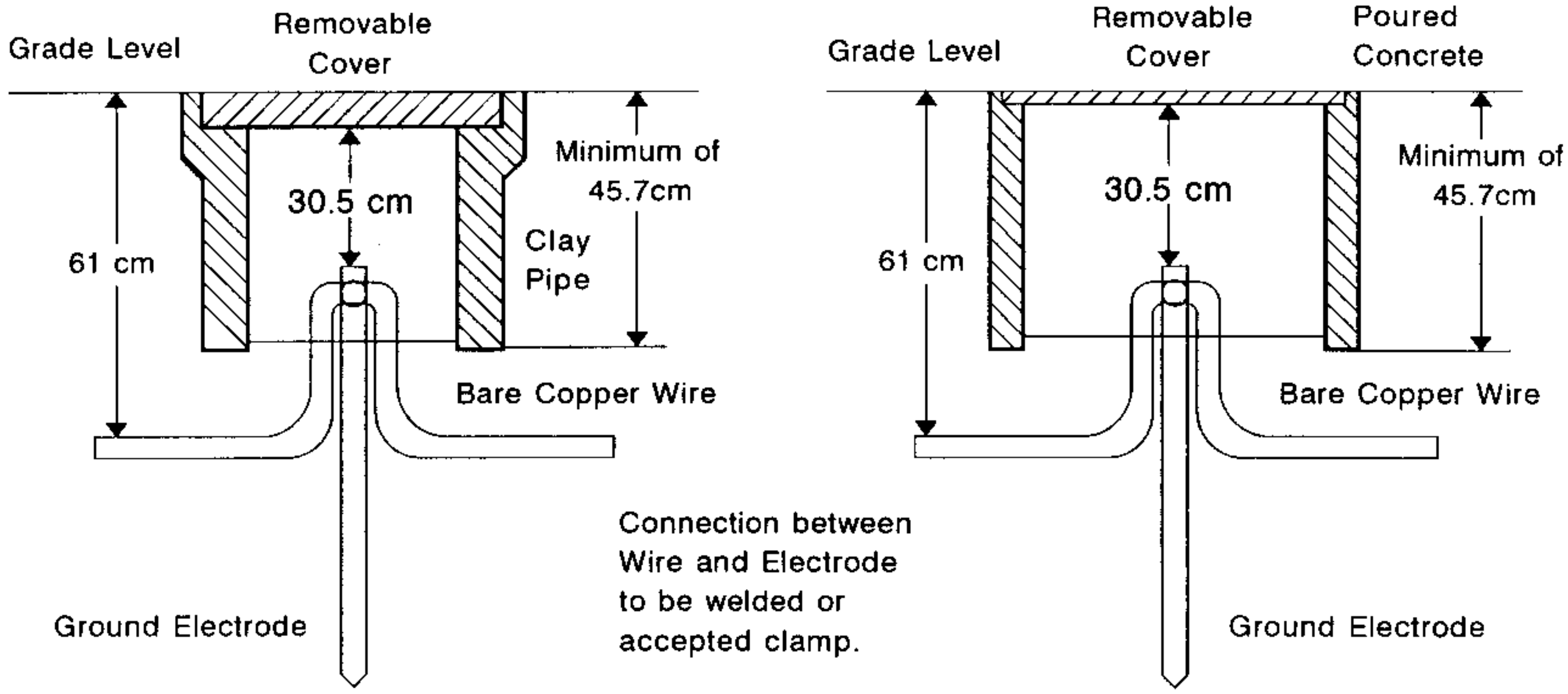


Figure C1: "Four-Terminal" Method of Measuring Soil Resistivity

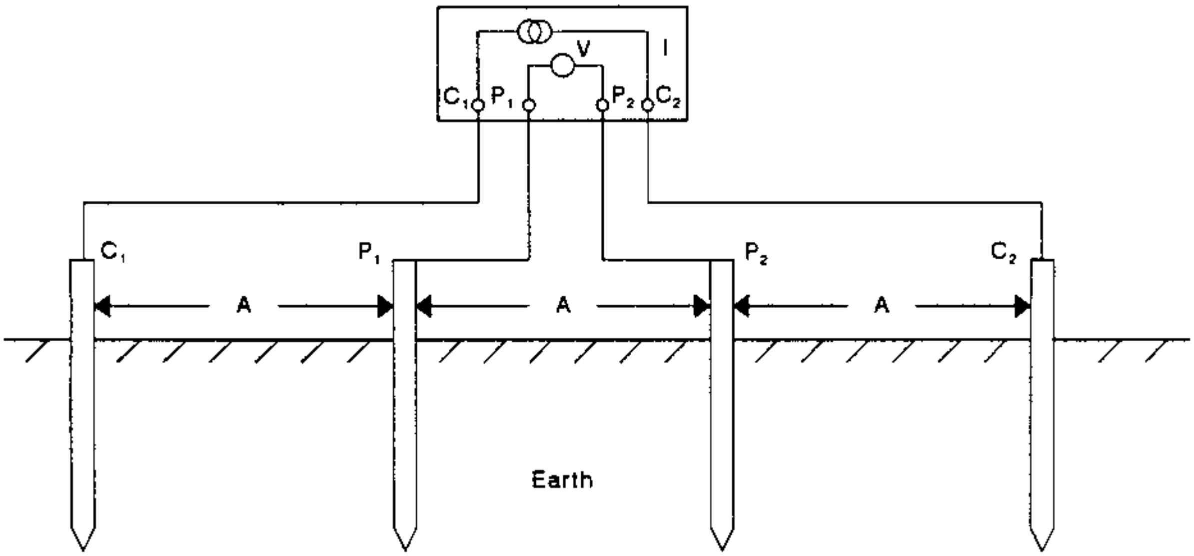
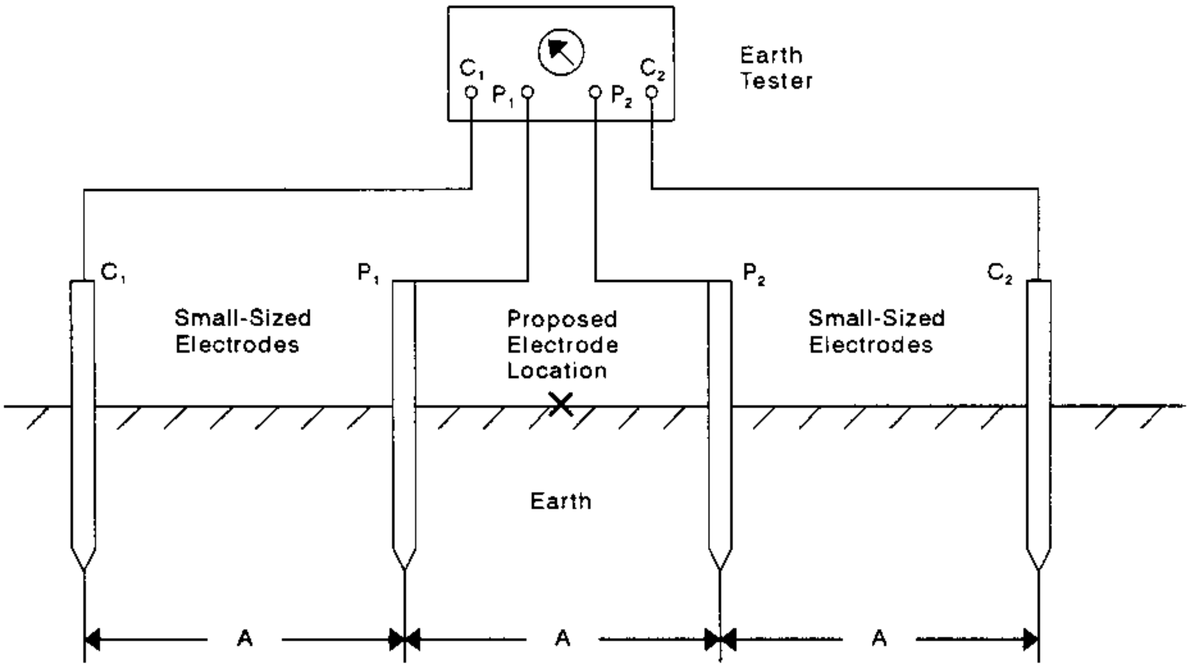


Figure C2: "Four-Terminal" Method of Measuring Soil Resistivity



A = 20 B (Approximately)

Figure D1: Triangulation Method for Measuring the Resistance of a Ground Electrode

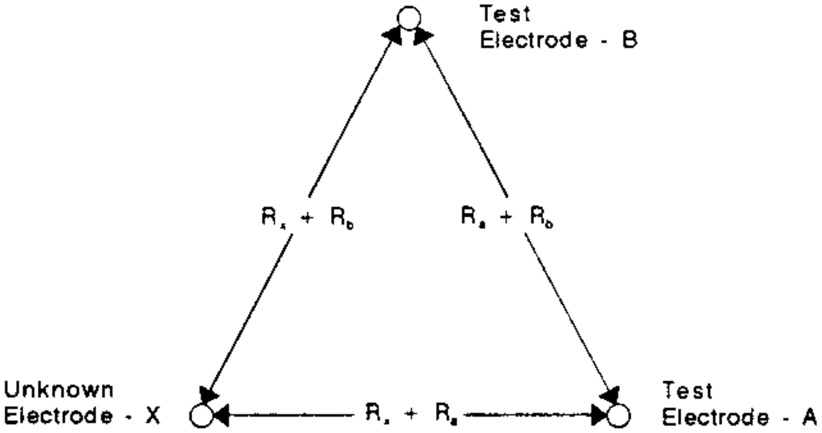


Figure D2: Direct Method for Measuring the Resistance of a Ground Electrode

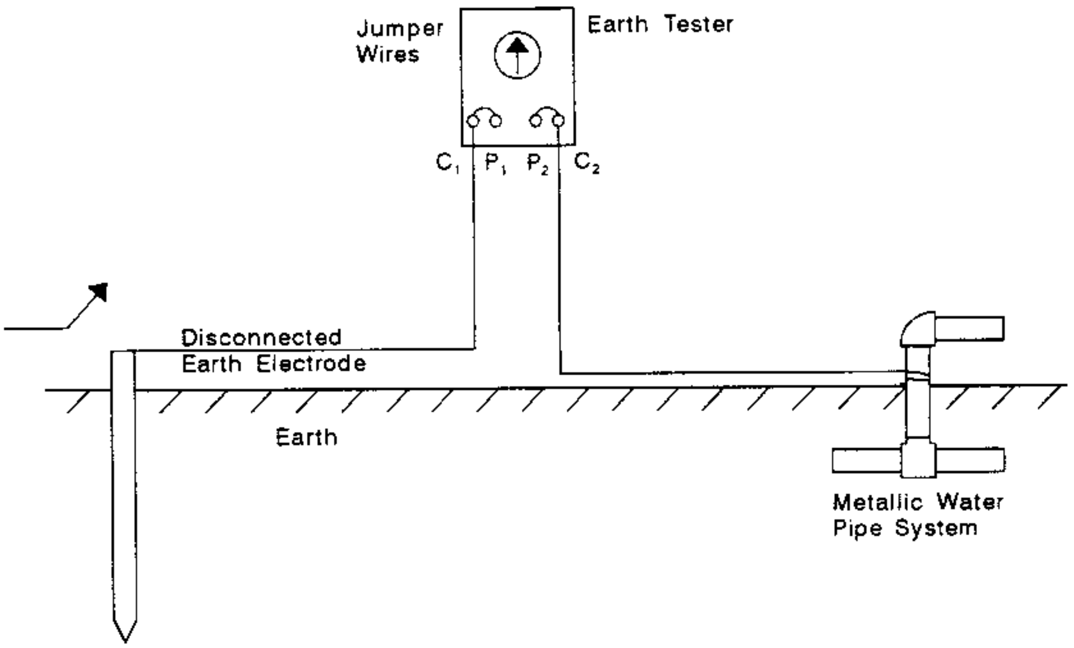


Figure D3: Fall of Potential Method

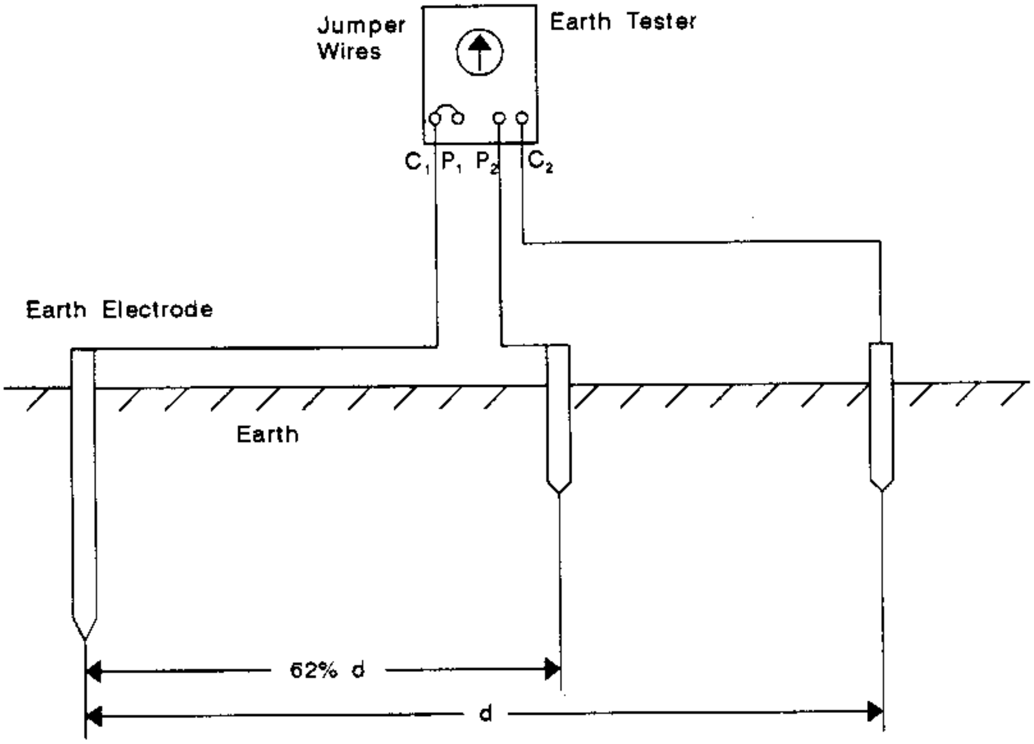


Figure D4: Example of Earth Resistivity Curve

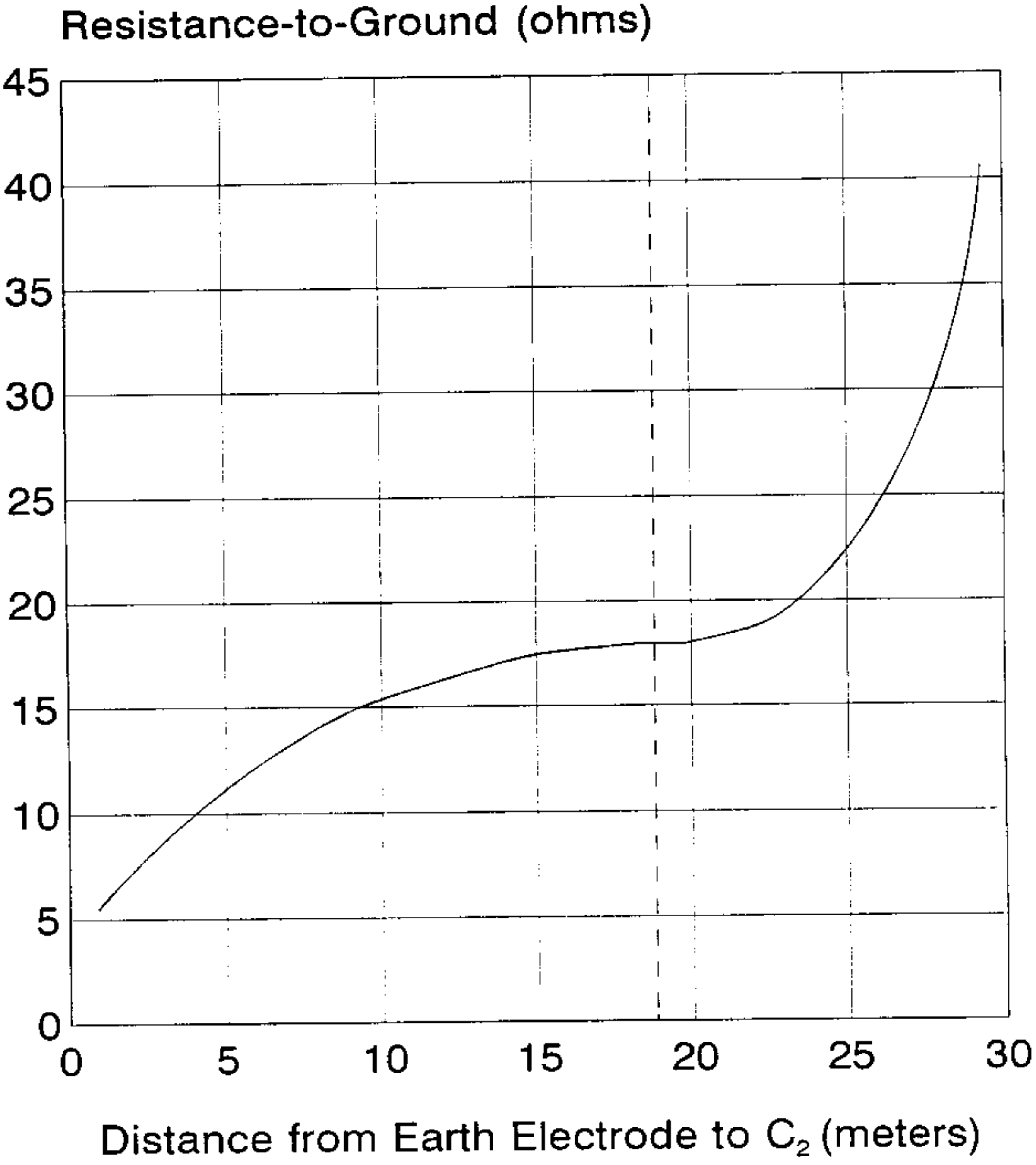


Figure D5: Effect with C_2 Located Far from Earth Electrode

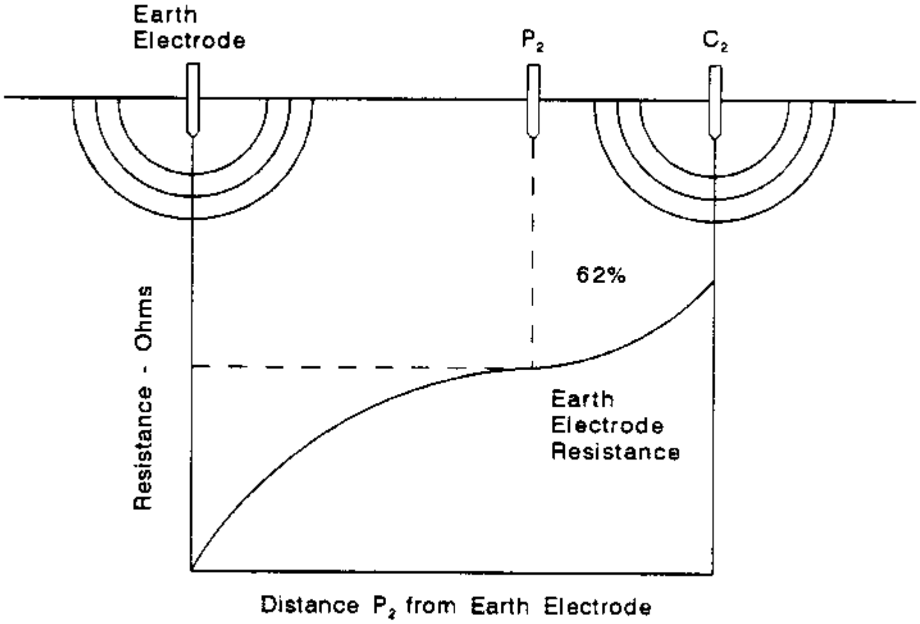


Figure D6: Effect with C_2 Located Close to Earth Electrode

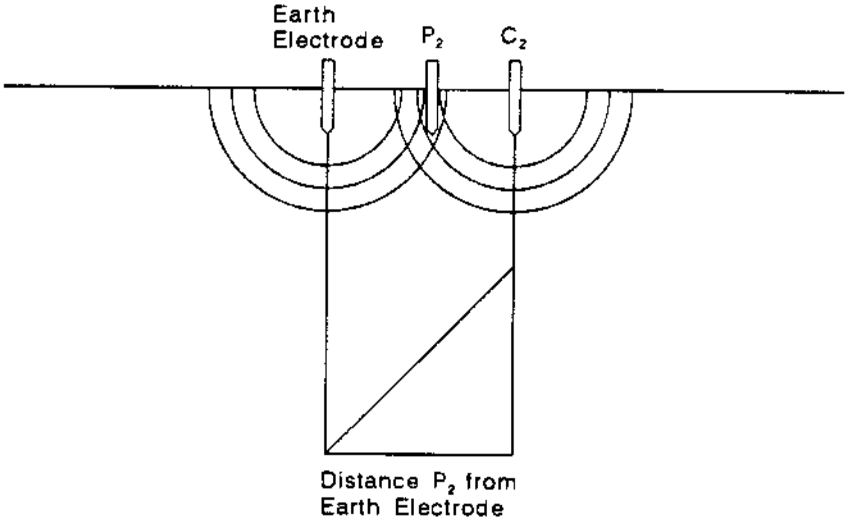


Figure D7: Earth Resistance Curve for Large Area Example

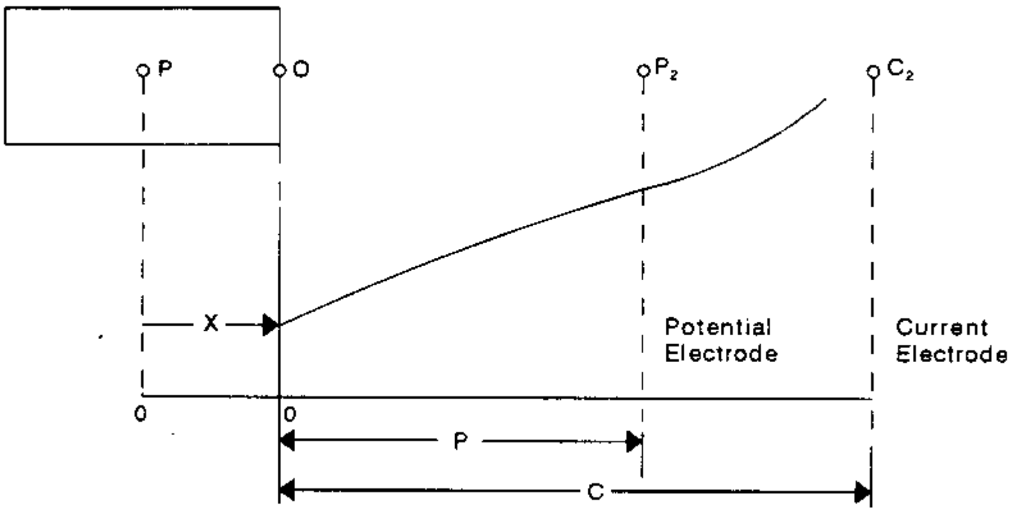
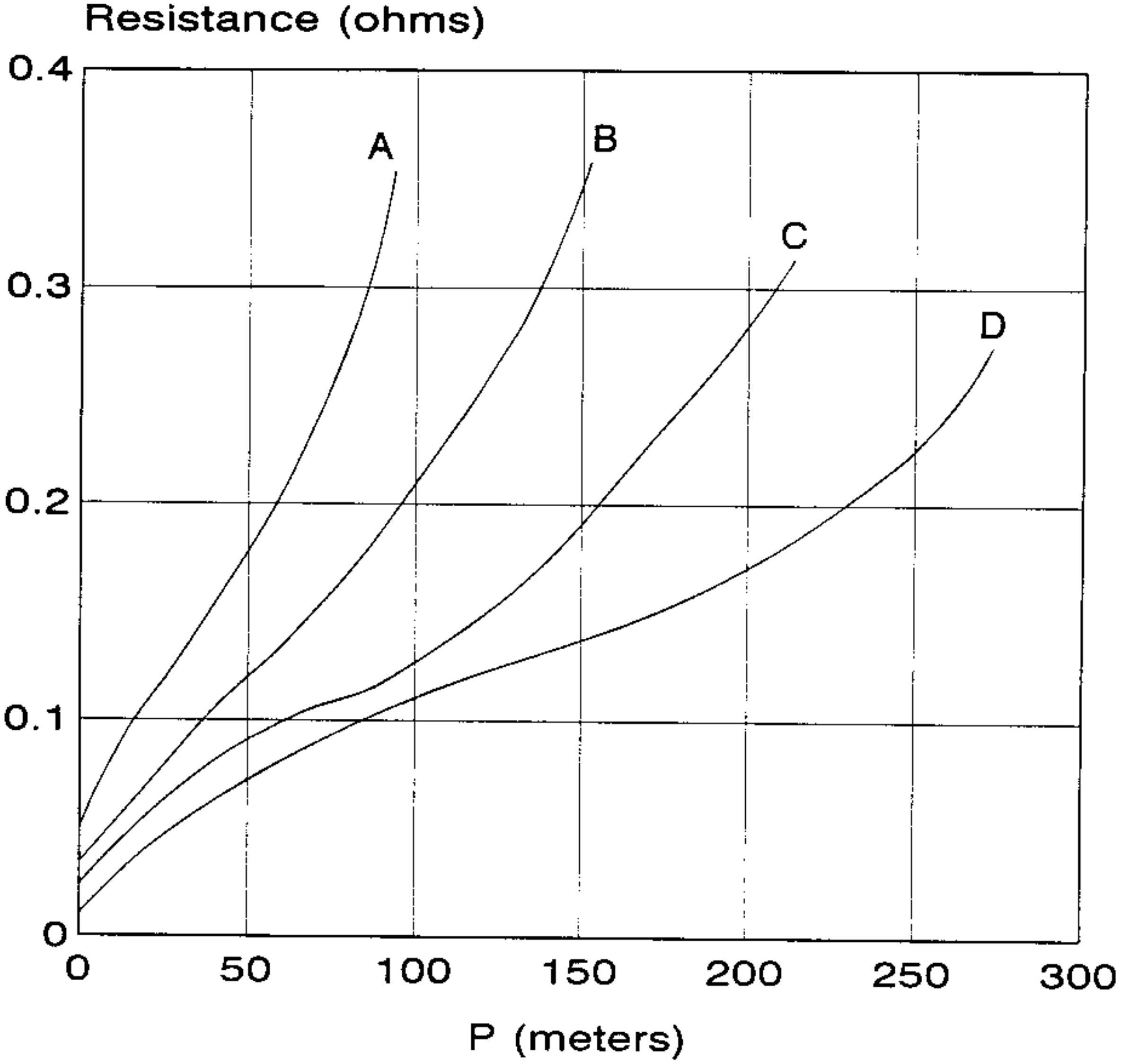


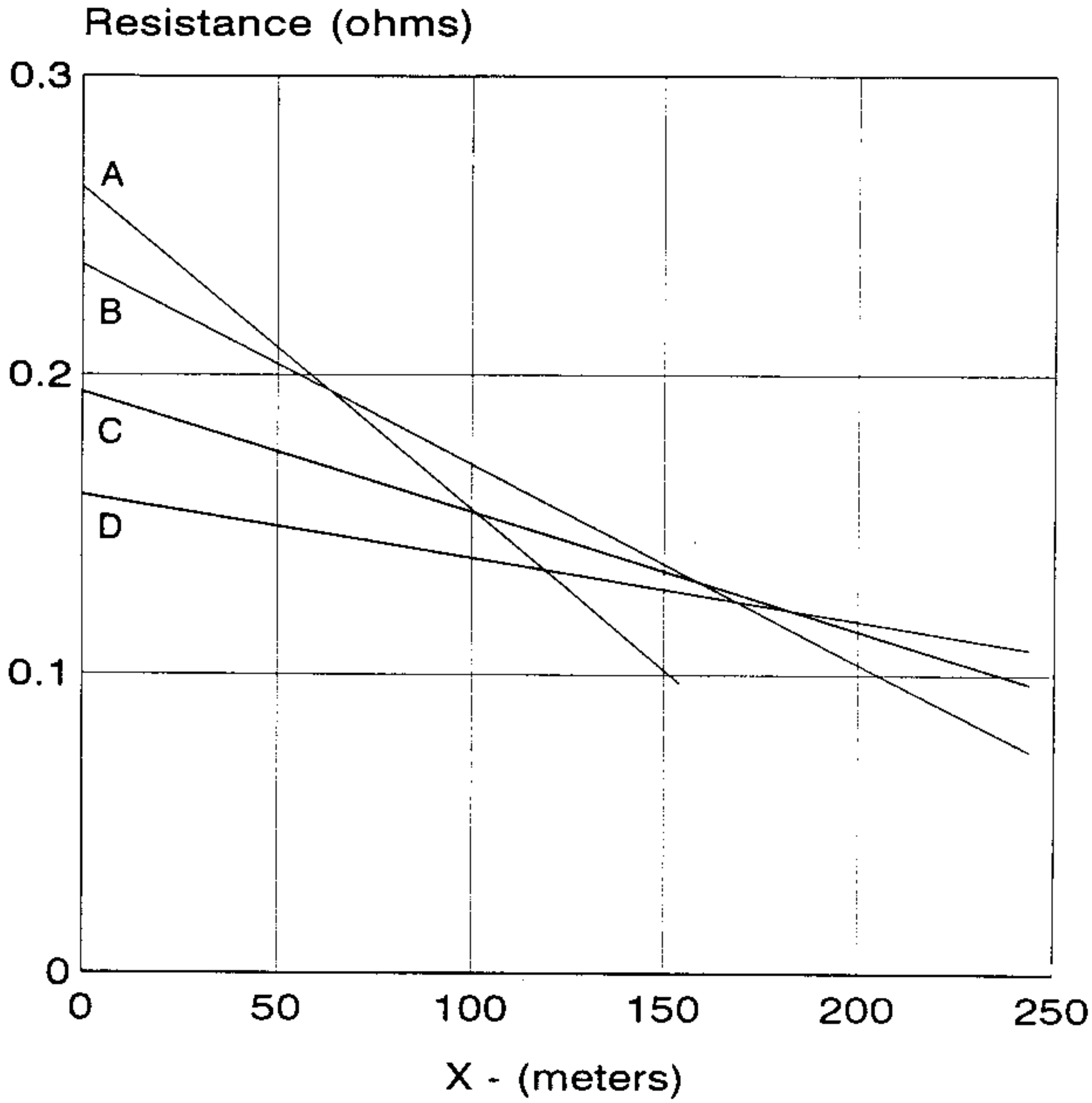
Figure D8: Example Resistance Curve for Large Area Example



Values of C

A - 400 Feet (122 meters)
B - 600 Feet (183 meters)
C - 800 Feet (244 meters)
D -1000 Feet (305 meters)

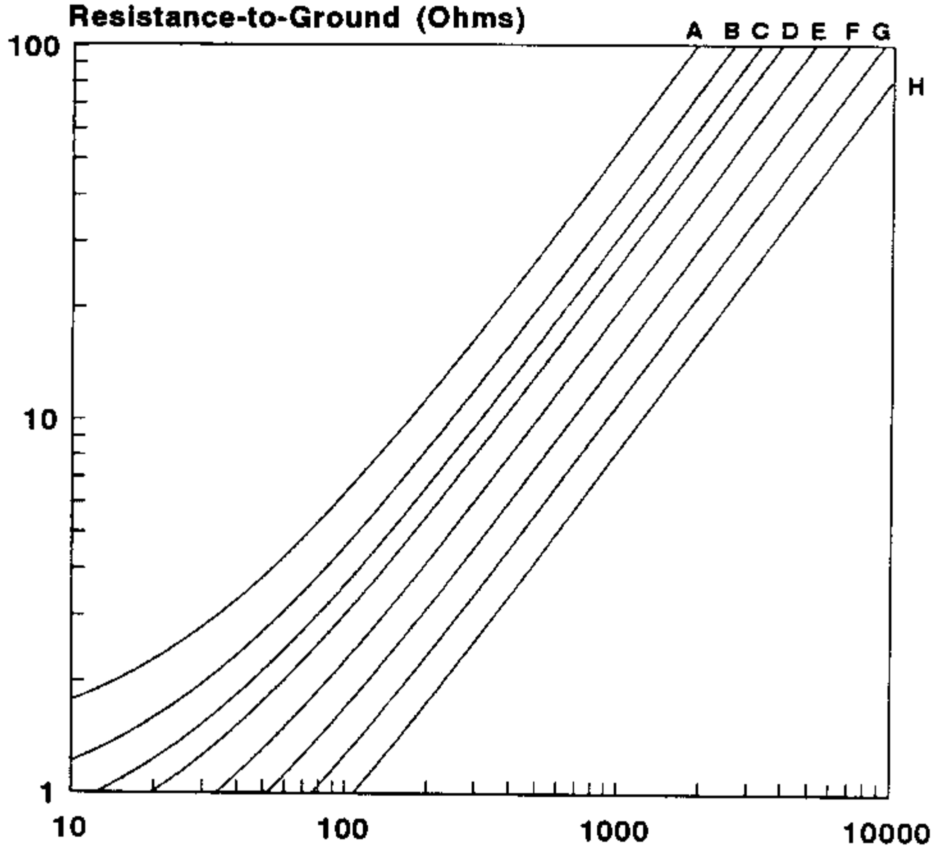
Figure D9: Intersection Curves for Figure D8



Value of C

A - 400 Feet (122 meters)
B - 600 Feet (183 meters)
C - 800 Feet (244 meters)
D -1000 Feet (305 meters)

Figure E1: Concrete Encased Electrodes in a Square Ring Configuration



Earth Resistivity (ohm•meters)

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

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

Figure E2: Concrete Footing

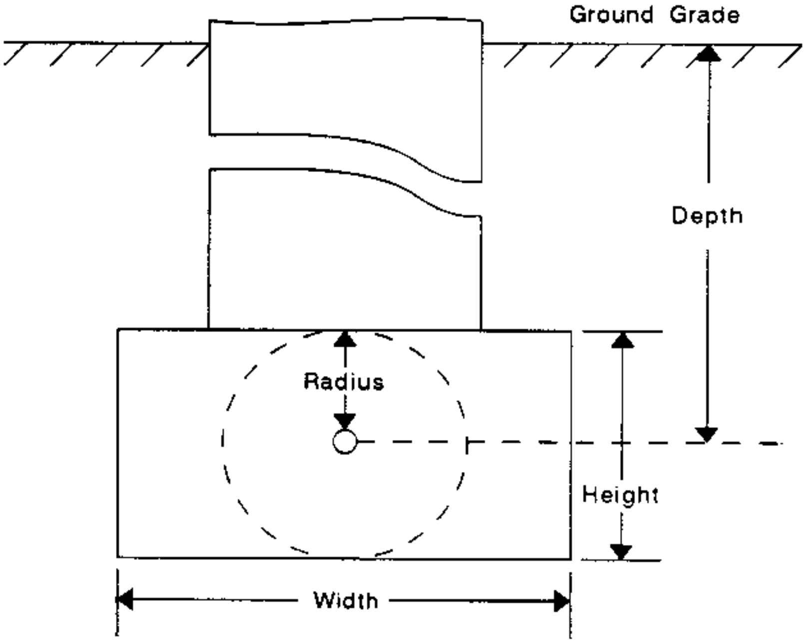


Figure E3: Basic Elements for Calculation

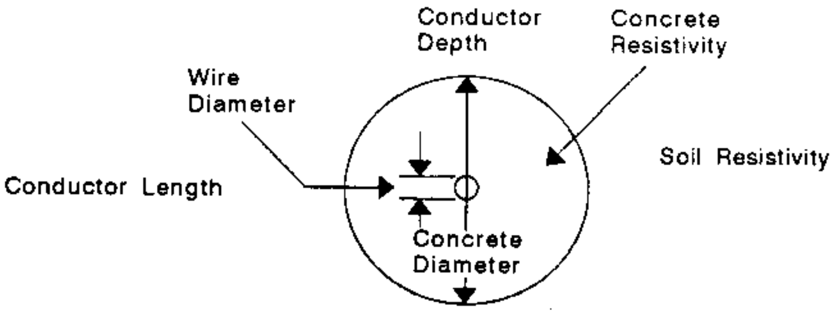
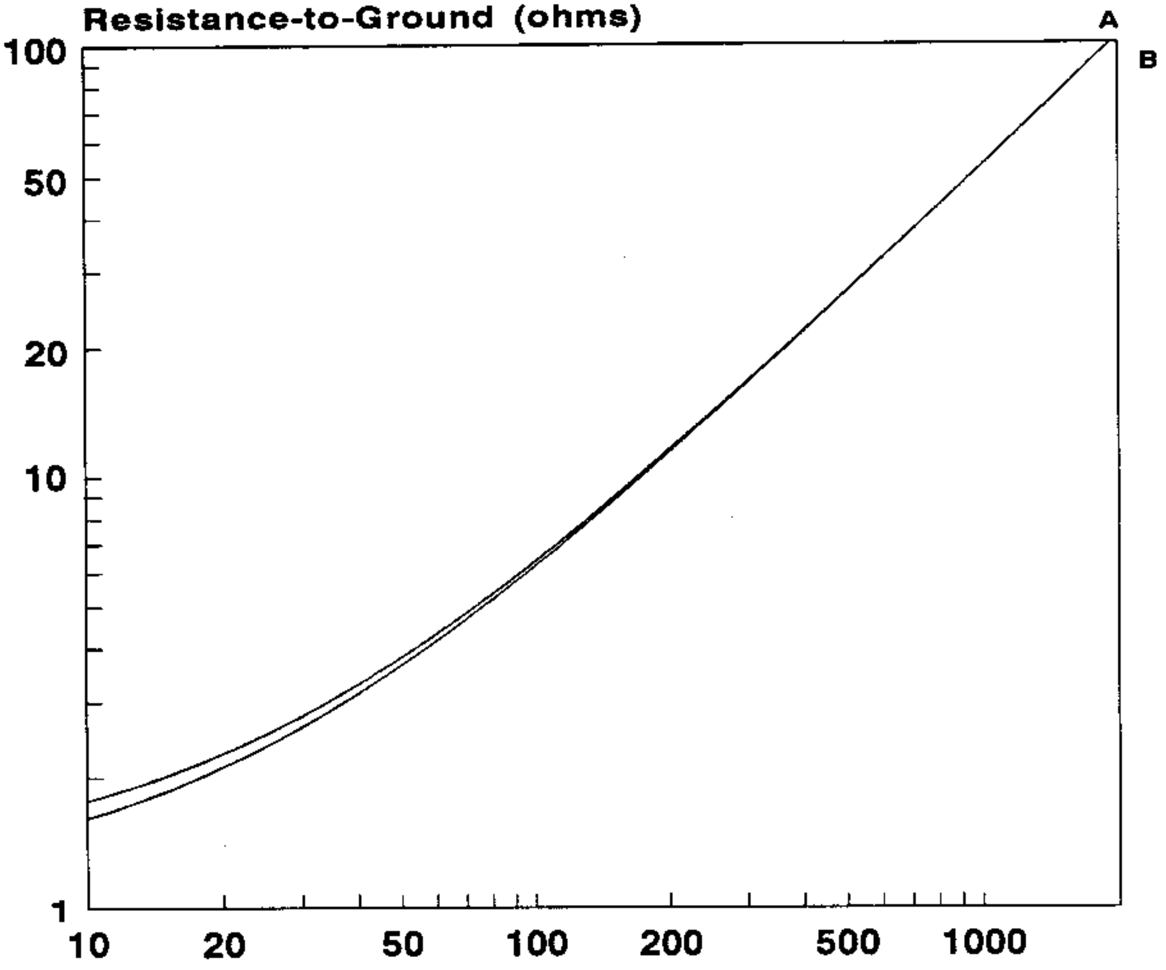


Figure E4: Variation
with Wire Size



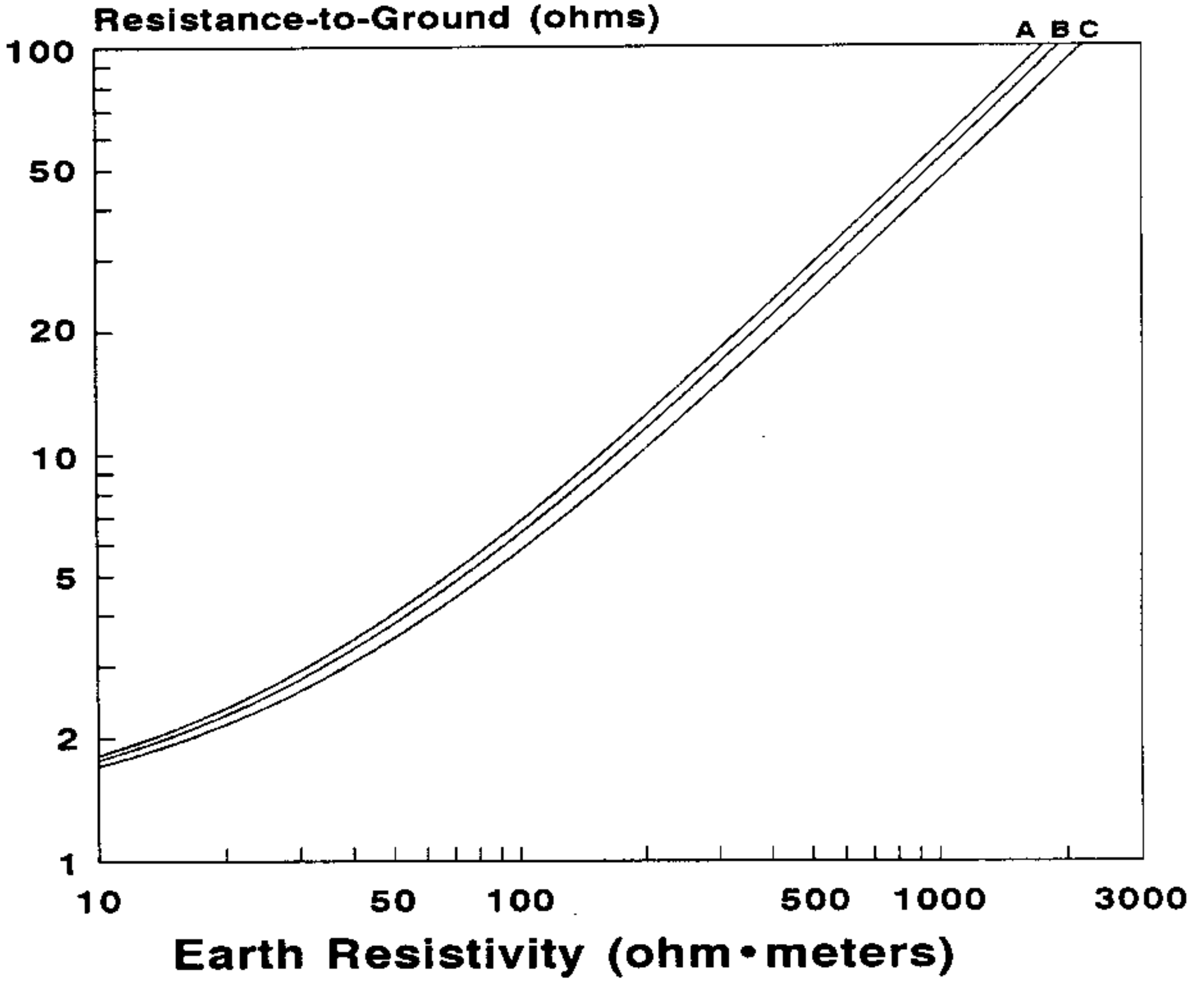
Earth Resistivity (ohm•meters)

Conductor Size & Diameter

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

Ring Size - 400 Sq. Ft. (37 Sq. m)
Concrete Resistivity - 50 ohm meters
Concrete Diameter - 1 foot (31 centimeters)
Conductor Depth - 4 feet (1.2 meters)

Figure E5: Variation with Depth for Concrete Encased Electrodes

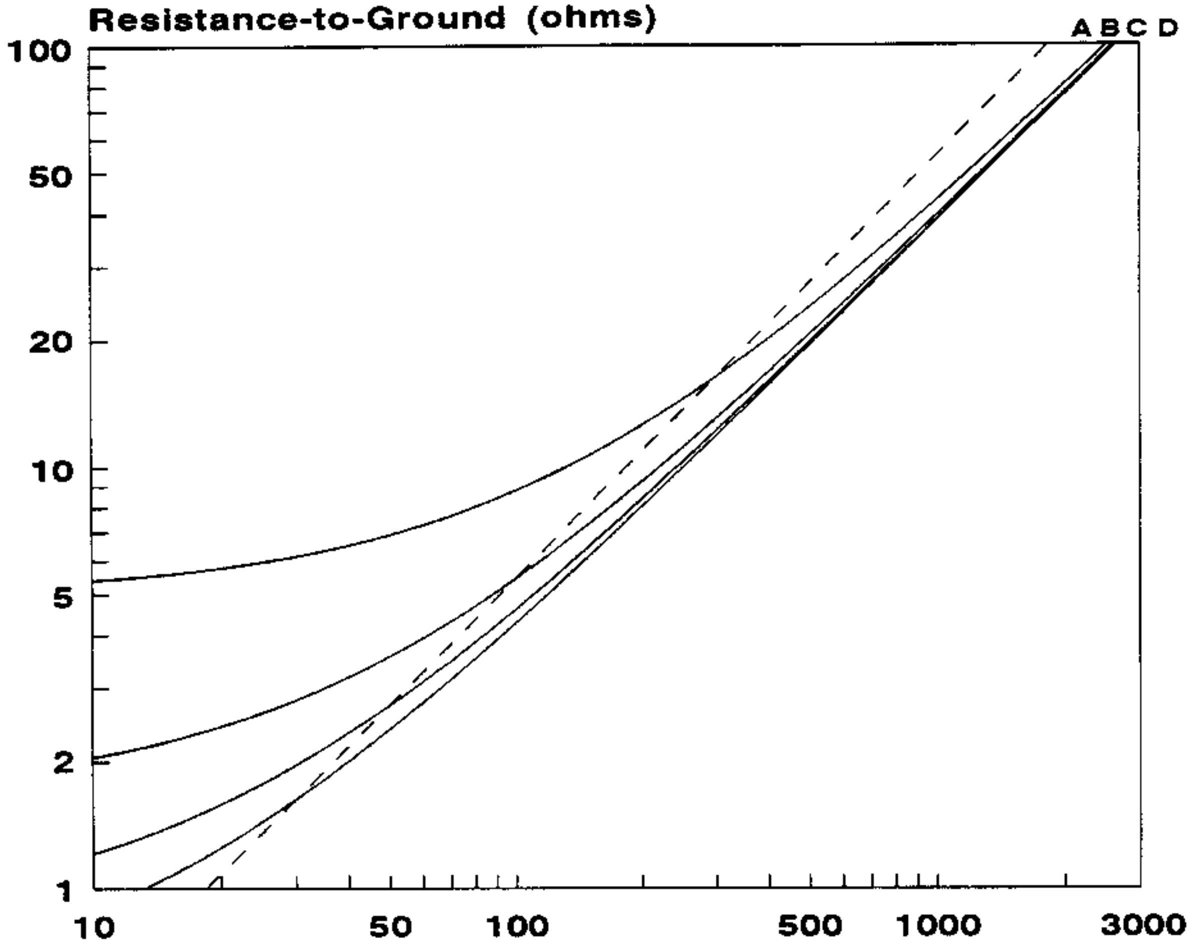


<u>Conductor Depth</u>

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

Ring Size - 400 Sq. Ft. (37 Sq. m)
Conductor Size - #2
Concrete Resistivity - 50 ohm-meters
Concrete Diameter - 1 feet (31 centimeters)

Figure E6: Comparison Between Encased and Direct Buried Electrode with Different Concrete Resistivities

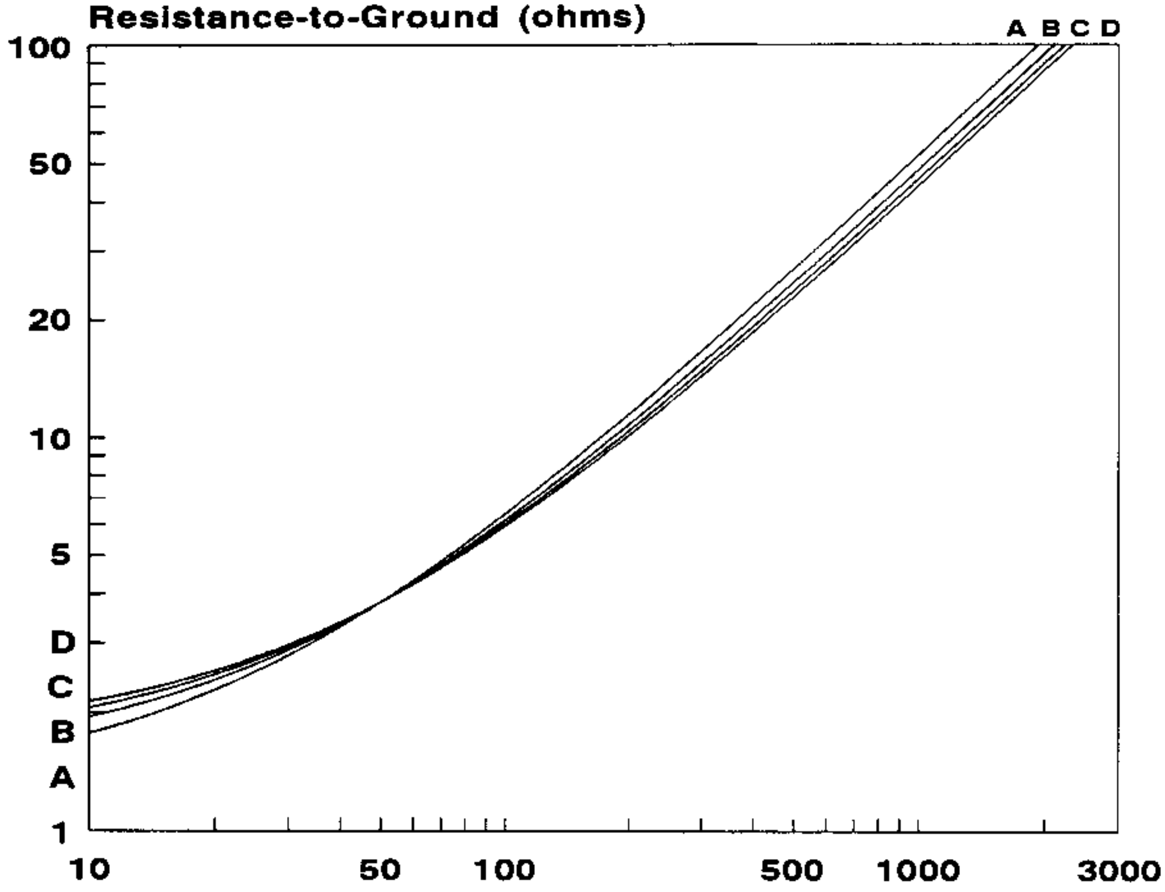


Earth Resistivity (ohm•meters)

Horizontal Electrode	Concrete Resistivity
——— Concrete Encased	A - 300 ohm•meters
----- Direct Buried	B - 100 ohm•meters
	C - 50 ohm•meters
	D - 30 ohm•meters

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

Figure E7: Variation with Concrete Diameter for Concrete Encased Electrodes



Earth Resistivity (ohm•meters)

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 sq. ft. (37 sq. m)
Conductor Size #2
Conductor Depth - 4 feet (1.2 meters)
Concrete Resistivity - 50 ohm•meters