Information Circular 8767

Guide for the Construction of Driven-Rod Ground Beds

By R. L. King, H. W. Hill, Jr., R. R. Bafana, and W. L. Cooley

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GUIDE FOR THE CONSTRUCTION OF DRIVEN-ROD GROUND BEDS

by

R. L. King,[1] H. W. Hill, Jr.,[2] R. R. Bofana,[2] and W. L. Cooley[3]

ABSTRACT

This report describes a method for designing and constructing ground beds that has been developed under the sponsorship of the Bureau of Mines. The procedures for designing and constructing a driven-rod ground bed with a resistance of 5 ohms or less are given. Some of the theory of soil resistivity and fall-of-potential resistance measurements is included. Results of a bed constructed at the Bureau of Mines mine car roadway are presented.

INTRODUCTION

Electrical equipment used in underground and surface mines is required by law to be grounded. The purpose of requiring a good ground connection is to prevent the development of dangerous potentials on the exposed frames of equipment in the event of an electrical insulation failure. Since the equipment frequently changes location, it is necessary that a fixed contact with earth be made remote from the equipment and connected to the equipment as specified in Parts 75 and 77, Subpart H--Grounding, Title 30, Code of Federal Regulations.[4] If this earth contact is a driven-rod ground bed, it will probably be located near the electrical substation which supplies power to the mine.

A low-resistance safety ground bed is essential to the safe operation of the mine power system. This is important because the ground bed will conduct current during conditions such as those illustrated in figures 1 and 2. This

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[4]Code of Federal Regulations. Title 30, Mineral Resources, Revised July 1, 1976. Part 75--Mandatory Safety Standards--Underground Coal Mines, Subpart H--Grounding, pp. 387-391; Part 77--Mandatory Safety Standards, Surface Coal Mines and Surface Work Areas of Underground Coal Mines, Subpart H--Grounding, pp. 460-463.

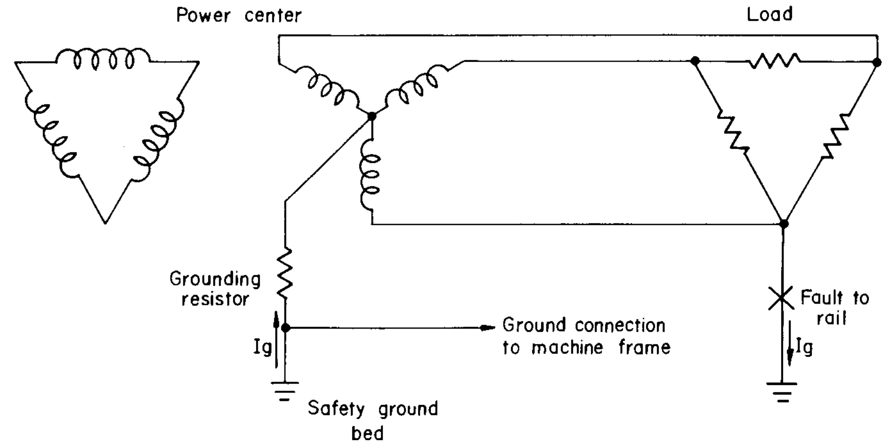

FIGURE 1. - Ground bed conducting fault current during a phase-to-rail fault.

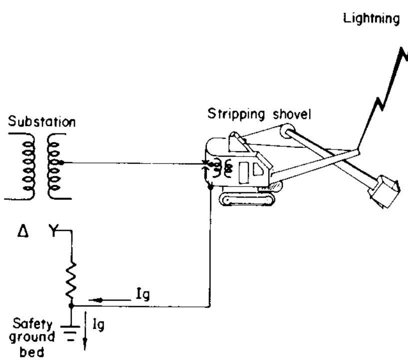

FIGURE 2. - Ground bed conducting lightning stroke to earth.

current flow through the safety ground bed will elevate the frames of all equipment connected to the bed to a voltage determined by

$$V_f = I_g \ (R_g + R_{ext}), \tag{1}$$

where V_f = voltage that machine frame is elevated to,

I_g = current flowing through safety ground bed,

R_g = resistance of safety ground bed,

and R_{ext} = resistance of fault, connections, etc.

Although the present Federal law does not specify an acceptable ground bed resistance, 2 to 5 ohms is usually recommended.

The work reported herein was done at West Virginia University under sponsorship of a Bureau of Mines grant,[6] as part of the Bureau's program of improving safety in mines.

SOIL RESISTIVITY MEASUREMENTS

The resistance of a single driven ground rod is

$$R = \frac{\rho}{2\pi L}\left[\ell n \frac{2L}{r}\right], \qquad (2)$$

where R = resistance of ground rod, ohms,

ρ = resistivity of soil, ohm-feet,

L = length of rod, feet,

and r = radius of rod, feet.

As can be seen from equation 2, the resistance of a ground rod, and therefore of a complete grounding system, is directly proportional to the resistivity of the soil in which the bed is constructed.

The soil resistivity is measured with a four-point electrode arrangement known as the Wenner array (fig. 3), which consists of four electrodes placed in a straight line at equal distances apart, a. The Wenner array measures the

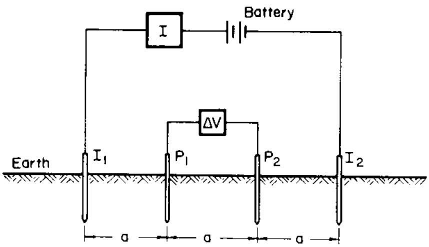

FIGURE 3. - Electrode arrangement for measuring earth resistivity.

[6] Cooley, W. L. Evaluation of In-Mine Grounding System and Codification of Ground Bed Construction and Measurement Techniques. (USBM Grant G0144138, Annual Report.) BuMines Open-File Rept. 20-77, Aug. 1, 1975, 169 pp.; available for consultation at Bureau of Mines facilities in Denver, Colo., Twin Cities, Minn., Bruceton and Pittsburgh, Pa., and Spokane, Wash.; at the Department of Energy Library in Morgantown, W. Va.; and at the National Library of Natural Resources, U.S. Department of the Interior, Washington, D.C.; and from the National Technical Information Service, Springfield, Va., PB 263 119/AS.

potential difference between two points to determine the resistivity of the soil it is in. Referring to figure 3, I_1 and I_2 are the current electrodes and P_1 and P_2 are the potential electrodes.

The general formula for calculating resistivity using the Wenner array is

$$\rho = 2\pi aR, \tag{3}$$

where ρ = resistivity, ohm-feet,

a = spacing of electrodes, feet,

and R = measured resistance, ohms.

This assumes that the depth the electrodes are driven to is much less than their spacing.

A rule of thumb is that the electrode spacing, a, is equal to the average resistivity of the soil at a depth "a" in the vicinity of the electrodes.

GROUND BED RESISTANCE MEASUREMENTS

The objectives of ground bed resistance measurements are to--

1. Verify the adequacy of a new ground system.

2. Detect changes in an existing grounding system.

3. Determine the hazardous step and touch voltages.

4. Design protection for personnel.

To accomplish these objectives, a technique of ground bed measurement must be selected. Four techniques have been considered during the research program: (1) Two-point method, (2) triangulation method, (3) ratio method, and (4) fall-of-potential method.

The fall-of-potential method (fig. 4) was selected for the guide because it is already widely accepted and is accurate enough for most practical

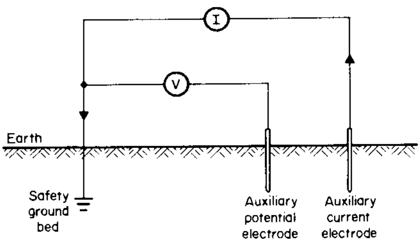

FIGURE 4. - Electrode placement for fall-of-potential measurement.

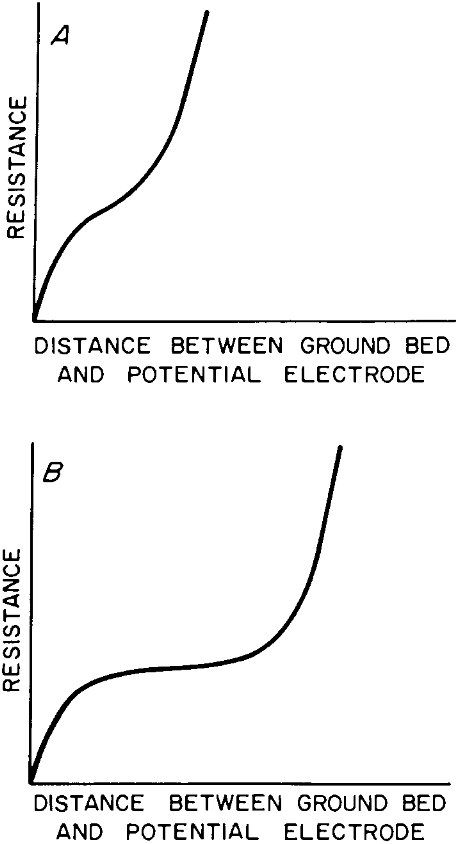

FIGURE 5. - Effect of current electrode placement.

purposes. A known current, I, is passed between the auxiliary current electrode and the safety ground bed, and the potential difference, V, is measured between the auxiliary potential electrode and the safety ground bed. Then the ratio V/I will give a resistance which, with proper electrode spacings, results in the required resistance of the ground bed.

If a series of measurements is made with the auxiliary potential probe at various distances from the ground bed, a curve as shown in figure 5 can be plotted in which the ratio V/I is plotted against the distance of the potential electrode from the ground bed.

The nature of the earth resistance curve greatly depends upon the distance of the auxiliary current electrode from the ground bed. If the current electrode is too close, a curve of the nature of A is obtained and error will be introduced. Conversely, if the current electrode is placed sufficiently away from the ground bed under test, then curve B is obtained, which will enable the mine engineer to obtain a satisfactory measurement.

It follows from the preceding discussion that the accuracy of measurements greatly depends upon the distance between the ground bed and the auxiliary current electrode. The larger this distance, the less the error introduced.

At this point, a practical difficulty arises as to where in the ground bed the measurements of the distances of potential and current electrodes should be made. In a single-driven-rod ground bed, it is easy to see that the rod is the starting point; but when the ground bed covers a large area and comprises multiple driven rods and/or plates or buried wires, where is the starting point? Theoretically, the measurements should be made from the center of an equivalent hemisphere. It is assumed that the grounding system can be replaced by an equivalent hemisphere with a radius, r, having the same resistance as the bed. For a single driven rod, the radius of the equivalent hemisphere is found using equation 4:

$$r = \frac{L}{\ell n \left[\frac{96L}{d} \right] - 1}, \tag{4}$$

where r = radius of equivalent hemisphere, feet,

L = length of rod, feet,

and d = diameter of rod, inches.

Tagg[6] provides tables that show the radius of the equivalent hemisphere for some of the commonly used ground bed configurations. Examination of these tables yields a rule of thumb which states that the radius of the equivalent hemisphere is 50 percent of the maximum dimension of the bed.

An important result can be derived based on the ideal hemispherical electrode. The true earth resistance is obtained at a potential electrode distance from the center of the equivalent hemisphere of 61.8 percent of the distance (0.618 D) to the current electrode (fig. 6). Of course, this assumes that the hemisphere is small compared to the current electrode spacing. A safe measure would be to place the current electrode at a distance equivalent to 10 times the radius of the equivalent hemisphere.

This result is widely used in practice since it eliminates plotting an earth resistance curve. However, there are three difficulties in the application of this result to ground beds:

1. The theory is based on homogeneous soil. However, since most soils are nonhomogeneous, as the distance between the current electrode and the ground bed is increased, the degree of penetration of the test current in the ground will change and the true earth resistance point will deviate from 61.8 percent.

2. The theory is also based on a starting point from the center of the equivalent hemisphere of the ground bed. Since the true center of the hemisphere is quite difficult to locate, errors will be introduced again.

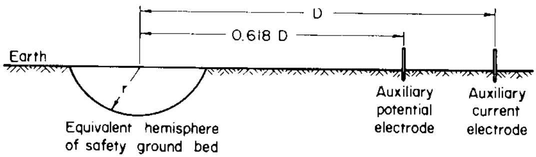

FIGURE 6. - Measurement of ground bed resistance using fall-of-potential technique.

3. The current distribution of the equivalent hemisphere is altered by the presence of the auxiliary current probe.

[6] Tagg, G. F. Earth Resistances. Pitman Publishing Corp., New York, 1964, pp. 186-192.

GUIDE FOR DESIGN AND CONSTRUCTION

A guide for the design and construction of safety ground beds has been included as an appendix to this report. This guide has used the most practical techniques for measurements and the most common construction materials and electrode arrays.

The guide shows how to build a ground bed that takes the greatest advantage of the nonuniformities of the soil within the proposed site. The guide specifies four resistivity measurements. This is the minimum number of economically feasible measurements that will obtain information about the surface variation in resistivity, as well as a crude idea of the degree of anisotropy and depth variation of resistance.

Rods were chosen as the grounding medium, as opposed to plates, bare wires, etc., because they do not have to be buried. This feature is important, of course, in construction costs, but even more important is the good contact with the earth obtained by driving the rods, as opposed to digging a hole and filling dirt in around them. The rods chosen for use in the guide are 4, 6, 8, and 10 feet long and 0.5 or 1 inch in diameter. Longer rods were not covered because 10 feet is approaching the limit for hand-driven rods in rocky soil. Rods shorter than 4 feet were left out because of problems associated with frost.

The requirements for resistance of the ground bed are set at 5 ohms or less; therefore, a small array of rods will generally yield the required resistance. The range of soil resistivity was limited to safety ground beds built in moderate resistivity earth, 20 to 3,000 ohm-feet.

CONSTRUCTION OF A PROTOTYPE GROUND BED

A ground bed was constructed at the Bureau of Mines mine car roadway facility using the criteria contained in this report. Since more detailed information was desired for the construction of this ground bed, soil resistivity measurements were made at 1-, 2-, 5-, 10-, and 15-foot spacings. The data for the base line and perpendicular surveys are given in table 1.

TABLE 1. - Resistivity surveys for Bureau of Mines ground bed

Spacings, ft	Base line, ohm-ft	Perpendicular, ohm-ft
1.....................	73	63.7
2.....................	88.2	89.6
5.....................	111.5	109
10.....................	87	87
15.....................	84	84.3

The resistivity surveys for 5- and 15-foot spacings were selected for determining the construction of the ground bed. It is obvious that the 5-foot spacings are close (within 20 percent) and that the 15-foot spacings are also close, but different from the 5-foot spacings. Therefore, as the guidelines instruct, the average resistivity was computed to be 97.2 ohm-feet. Rounding this up to 100 ohm-feet and selecting a 1/2-inch, 8-foot ground rod for the bed construction, the design tables were entered to find the appropriate spacings. A hollow square configuration with 16-foot, 4-inch spacings was then selected. Although the present design tables do not list this specific ground bed design, the version of the tables that existed when this bed was constructed did list the hollow square configuration. The present design tables indicate that a triangular ground bed with 13-foot, 3-inch spacings would also be appropriate.

The four rods were then driven into the ground and interconnected with #2 bare copper wire. The interconnections were made approximately 18 inches under the surface to avoid fluctuations in bed resistance caused by frost penetration.

A fall-of-potential measurement was then made, and the bed resistance was found to be 2.67 ohms. Figure 7 is a plot of the fall-of-potential measurement made on the ground bed.

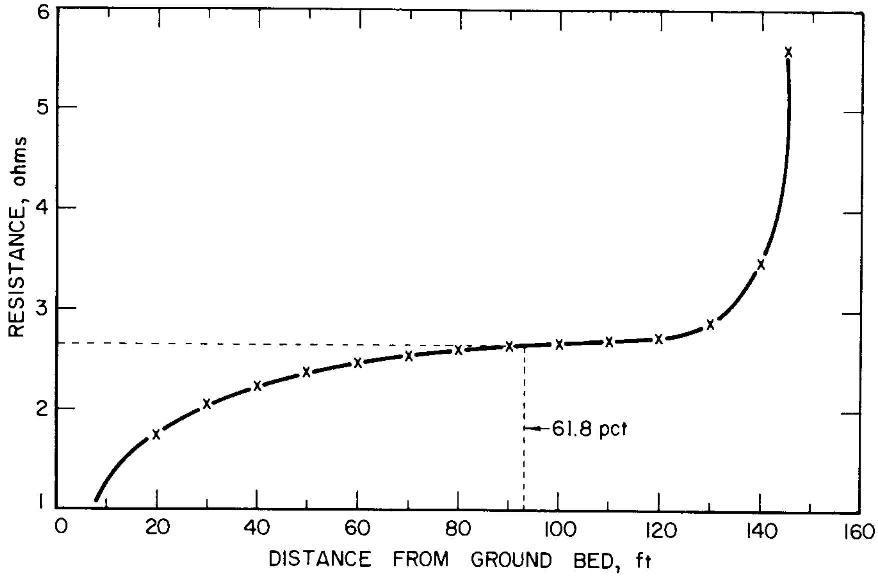

FIGURE 7. - Fall-of-potential measurement conducted on Bureau of Mines ground bed.

CONCLUSIONS

A reliable method for designing and constructing ground beds with a resistance less than 5 ohms has been developed. Actual usage of the guidelines resulted in a ground bed measuring 2.67 ohms. The application of ground beds with a low resistance will result in safer mine power systems.

APPENDIX.--GUIDE FOR CONSTRUCTION OF GROUND BEDS

This guide is intended as an aid in the construction of safety ground beds. It is not a textbook on the theory of earth grounding arrangements, nor is it a review of current grounding practices. In fact, many of the techniques listed in this paper depart from current practices considerably.

While the lack of explanation for the given techniques is regrettable, it was felt that the audience for this paper would consist of two types of readers: Those with a general interest in the subject of grounding, and those with a ground bed to build. The latter will find this booklet to be a concise procedure for construction of a truly "safe" safety ground bed.

This guide is intended to fill a void in the available material on grounding, in that it allows considerable flexibility in the actual materials and land area devoted to the ground bed. Relative areas and rod weights are given with each design so that the designer may choose, from several electrically equivalent designs, the one that is economically optimum.

The ground bed designs given in this booklet are "electrically equivalent" in the sense that all configurations will produce a ground bed that has resistance of 5 ohms (or less). This is the maximum value that will guarantee that grounded equipment be safe to touch during system faults or other transient conditions.

All the ground bed construction techniques covered in this guide involve the use of driven rods. There are three reasons for this:

1. Driven rods avoid the expense of earth removal to bury plates, wire, etc.

2. Driven rods avoid the problem of packing the earth around buried electrodes to insure good contact with the earth.

3. Any desired resistance that could be obtained using other forms of electrodes can, in general, be obtained using rods.

Ground bed construction consists of four steps: Measuring the resistivity of the ground bed site, choosing a design based on the measurements, building the ground bed, and finally, checking the resistance of the completed ground bed.

Resistivity Measurements

The method used to determine the earth resistivity of the ground bed site is the Wenner array. The details of the procedure depend on the equipment used. Basically four electrodes are placed in a straight line with equal spacing between adjacent electrodes. A known current is passed between the outer two electrodes, and the voltage is measured between the two inner electrodes (fig. A-1). Then the earth resistivity is computed from the formula

$$\text{Res.} = 2\pi \times \frac{V}{I} \times a,$$

where a is the spacing (in feet) between any two adjacent electrodes.

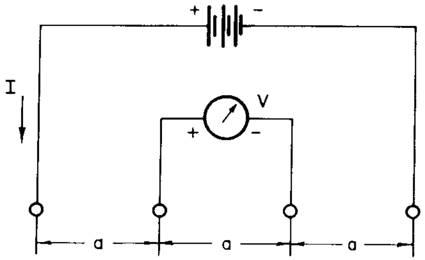

FIGURE A-1. - Electrode arrangement for measuring earth resistivity.

It is recommended that a commercial resistivity meter be used to make the measurement of voltage and to apply the current, instead of a simple voltmeter and battery. Polarization effects due to dc voltages and stray currents in the earth make accurate measurement of resistivity difficult without special equipment.

It is possible that the manufacturer of the resistivity meter will give formulas for computation of the earth resistivity that differ from the one given above. In such a case, follow the manufacturer's instructions, but be sure that the procedure involves the Wenner array as shown in figure A-1 and that the spacing between the electrodes is varied as dictated in the following paragraph.

The earth resistivity is measured with the interelectrode spacing (a in fig. A-1) equal to 6 feet. Then the electrode spacing is increased to 18 feet, and the measurement is repeated. (An easy way of doing the second measurement is to remove the two inner electrodes and move each one to 18 feet beyond the outer electrodes; see fig. A-2.) Next, two more measurements are taken along a line at right angles to the first line, the first with 6-foot spacing and the second with 18-foot spacing. To summarize:

Measurement A: Electrodes at 6-foot spacing along base line.

Measurement B: Electrodes at 18-foot spacing along base line.

Measurement C: Electrodes at 6-foot spacing perpendicular to base line.

Measurement D: Electrodes at 18-foot spacing perpendicular to base line.

The measurements are also shown in figures A-3 and A-4.

Choice of Ground Bed Site

The earth's resistivity varies enormously with locality. This is a mixed blessing: On one hand, more complicated methods are called for to determine what that resistivity is than would be necessary if it were constant everywhere; on the other hand, a low-resistivity region (that is, a lower resistivity than the average) can sometimes reduce the cost of ground bed construction.

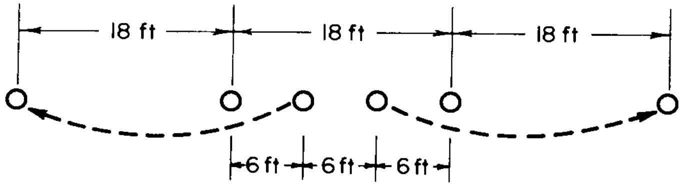

FIGURE A-2. - Electrode locations for variation-with-depth measurement.

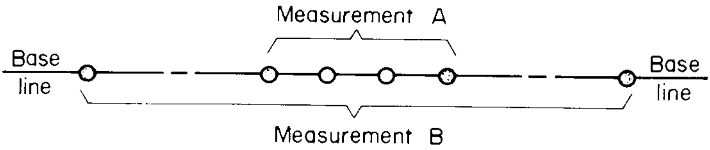

FIGURE A-3. - Measurements A and B.

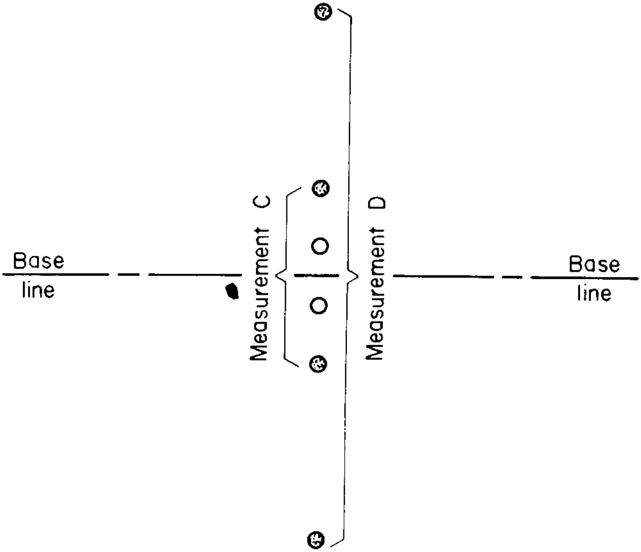

FIGURE A-4. - Measurements C and D.

A low-resistance ground bed can be built in almost any soil, but capital investment increases considerably as earth resistivity increases. For example, to build a satisfactory ground bed in soil with an average resistivity of 30 ohm-feet requires only one 6-foot rod of 1/2-inch diameter. To build a comparable bed in soil with resistivity of 300 ohm-feet, using the same type of rod, requires 24 rods over an area of 743 square feet.

It is difficult to predict exactly where, in a given plot of land, the resistivity will be minimum. However, in general, the region of least altitude is preferred because it is likely to contain the most ground water (an extremely important factor for low resistivity) and because it is least likely to freeze in the winter. An exception to this rule is that a small depression within a gently sloping plot may yield a lower resistivity than a site chosen at the lowest part of the plot. If there is more than one possible site, the measurements described in the next section should be done over each potential site, and the one that yields the lowest resistivity should be chosen.

If only one site is measured and that site gives a high value of resistivity (greater than about 1,600 ohm-feet), it would probably be better to look for another site of lower resistivity than to build the ground bed in the original site.

Once the site(s) has been selected, a "base line" for the measurement is chosen over the site as follows: Choice of the direction of the "base line"--that is, the line along which the measurements A and B are made--depends on the terrain of the ground bed site. Preferably, this line follows some natural geological feature of the site. For example, if a stream flows through the site, the line would be parallel to the stream. If the site is hilly, the base line should follow some natural depression in the land; for example, a small valley.

Interpretation of Results

The design of the ground bed depends on the relative values of resistivity obtained in the four measurements. There are four possibilities considered here:

1. All four measurements are close; that is, within 20 percent of each other.

2. Measurements A and C are close (within 20 percent), and measurements B and D are also close but differ from A and C.

3. Measurements A and B are close, and measurements C and D are also close but differ from A and B.

4. At the most, two of the measurements are close.

If all four measurements are close, the tables given in the back of this guide can be used directly with no restrictions. Simply look up the table that corresponds to the average value of resistivity measured and pick out a ground bed design that corresponds to the available land and materials.

If the measurements at 6-foot spacings (A and C) are close but less than the 18-foot measurements (B and D), use any of the designs that require 4- or 6-foot rods. The value of resistivity to be used for choosing the design is the average of the four measurements.

If the measurements taken along the base line (A and B) are close and the measurements perpendicular to the base line (C and D) are close but differ from the first two, then the following procedure must be followed:

1. The average resistivity (average of the four measurements) is computed and used as the basis for all procedures that follow; that is, begin with a ground bed design corresponding to this resistivity, modifying the design as specified in the steps that follow.

2. If there is a one-rod solution corresponding to the average resistivity, it can be used with no modifications.

3. If there is a two-rod solution corresponding to the average resistivity, the rods must be placed along whichever line the lower resistivity was measured on.

4. If any other design is used, the dimensions of the ground bed must be increased along whichever line the higher resistivity was measured on. The increase in length should be the same as the percentage difference in measured resistivity. For example, suppose that the resistivity measured along the base line was 65 ohm-feet and the resistivity perpendicular to the base line was 130 ohm-feet. Then, using the tables for 100 ohm-feet, one possible solution is eight 4-foot-long, 0.5-inch-diameter rods arranged in a hollow square with a spacing of 3 feet, 10 inches between rods. Therefore, this would be the spacing for rods along the base line, but the spacing perpendicular to the base line would be increased to 7 feet, 8 inches (fig. A-5).

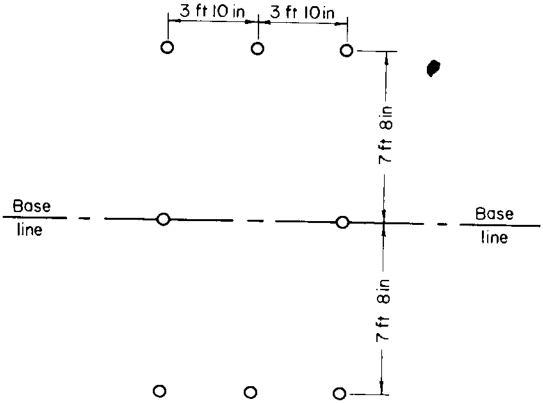

FIGURE A-5. - Alteration of "hollow square" configuration for a case of anisotropic soil.

If no more than two of the resistivity measurements are close (less than 20 percent apart), then the base line should be moved 45° clockwise or counterclockwise and all four measurements repeated. If these numbers are still all different, then only those designs given in the table that call for 10 or more rods should be used, and the value of resistivity used to look up the design should be the highest of the four measured values, NOT the average.

Interconnection of Rods

Once the rods are driven with the required spacing (note that the spacings given in the tables are minimum spacings and may be increased if desired) they must be solidly interconnected with flexible, and preferably bare, copper wire. There should be adequate slack in the connecting wire to allow for settling and thermal expansion. It is probably best to bury the connecting wire and the joints to the rods below the surface for their mechanical protection.

Measurement of Ground Bed Resistance

The completed ground bed should be measured using a "fall-of-potential method" to insure that its resistance is indeed correct. If the ground bed is built according to the given designs, there should be no problem. However, if the completed bed measures more than 5 ohms, the following procedure must be implemented.

First, check to see that all rods are solidly connected together and that a good connection was made to the ground bed when the resistance measurement was done. Repeat the measurement if any of the interconnections appear loose. If all connections are good, or if the second measurement of the ground bed resistance also measures more than 5 ohms, the design must be corrected.

Calculate a new value of earth resistivity from the formula:

$$\text{Resistivity (new)} = \text{resistivity (old)} \times \frac{\text{ground bed resistance}}{5} .$$

This new value is the value of earth resistivity that should have been measured in the first tests. Next, look through the tables for a ground bed corresponding to this new value of resistivity, which uses the same type of rods (or shorter). The spacing between rods in this design should be equal to or greater than the spacing in the bed already built. Then, using the existing ground bed as a beginning, build the new design. If no comparable design exists in the tables for the new value of resistivity, check the designs corresponding to the next highest value of resistivity for a solution. If no design can be found that can utilize the rods already driven, the ground bed will have to be redone completely.

Once the ground bed is reconstructed, its resistance must be checked as detailed above to insure a value less than 5 ohms.

Guide for Using the Ground Bed Design Tables

As explained in the text, any ground bed design can be chosen from the ones listed here that correspond to the earth resistivity measured in the proposed site. Note that the tables all are headed "Resistivity less than... ohm-feet"; that is, there is no lower limit on the measured resistivity for a given design, only an upper limit. Therefore, if a particular table is headed "Resistivity less than 100 ohm-feet" and the measured resistivity is only 53 ohm-feet, any of the designs from this table can be used, although there is another table headed "Resistivity less than 70 ohm-feet." However, it is generally advantageous to use the table that corresponds to a resistivity as close to the measured value as possible, because the required number of rods will be fewer and the spacing will be less. Note that the table for "Resistivity less than 50 ohm-feet" cannot be used in this case.

In addition to the restrictions listed in the text, there is an additional constraint on ground beds constructed at high elevations. If the altitude of the site exceeds 500 feet, and the latitude exceeds 37°, 4-foot rods cannot be used. If the altitude exceeds 2,000 feet, with latitude of 37°, neither 4- nor 6-foot rods can be used.

Finally, "length of rod" in these tables refers to the depth to which the rod is driven into the ground. If an 8-foot rod is driven only half way, it is a 4-foot rod as far as the design tables are concerned.

TABLE A-1. - Explanation of rod types

Rod type	Rod length, ft	Rod diameter, in
A....................	4	0.5
B....................	6	.5
C....................	6	1.0
D....................	8	.5
E....................	8	1.0
F....................	10	1.0

NOTES.--1. Rods of greater diameter and/or greater length can be substituted for given types.

2. Rod arrangements are shown in figure A-6.

3. Spacing is always the distance between adjacent rods.

4. Weight (rel.) in the following tables is the weight of a single 4-foot rod of 0.5-inch diameter; for example, 150 indicates that the total weight is 150 times the weight of such a rod.

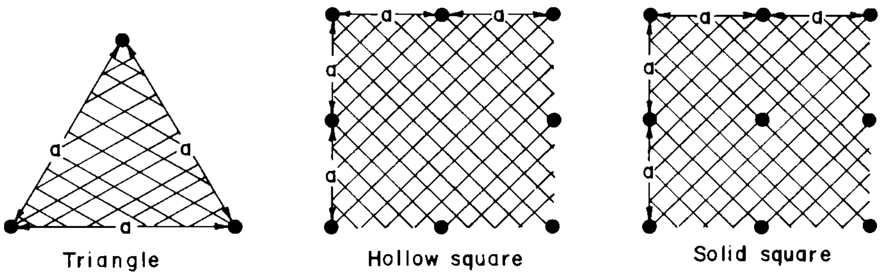

FIGURE A-6. - Rod arrangements for resistivity tables.

TABLE A-2. - Resistivity less than 20 ohm-feet

Arrangement	Rod type	Total rods	Spacing		Area,	Weight
			Ft	In	sq ft	(rel.)
Single rod............	A	1	0	0	0	1.0
Do..................	B	1	0	0	0	1.5
Do..................	D	1	0	0	0	2.0
Do..................	C	1	0	0	0	6.0
Do..................	E	1	0	0	0	8.0
Do..................	F	1	0	0	0	10.0

TABLE A-3. - Resistivity less than 30 ohm-feet

Arrangement	Rod type	Total rods	Spacing		Area,	Weight
			Ft	In	sq ft	(rel.)
Single rod............	B	1	0	0	0	1.5
Double rod............	A	2	1	5	0	2.0
Single rod............	D	1	0	0	0	2.0
Do..................	C	1	0	0	0	6.0
Do..................	E	1	0	0	0	8.0
Do..................	F	1	0	0	0	10.0

TABLE A-4. - Resistivity less than 50 ohm-feet

Arrangement	Rod type	Total rods	Spacing		Area,	Weight
			Ft	In	sq ft	(rel.)
Triangle..............	A	3	4	2	15	3.0
Double rod............	B	2	4	0	0	3.0
Do..................	D	2	2	1	0	4.0
Single rod............	F	1	0	0	0	10.0
Double rod............	C	2	2	8	0	12.0
Do..................	E	2	1	9	0	16.0

TABLE A-5. - Resistivity less than 70 ohm-feet

Arrangement	Rod type	Total rods	Spacing		Area,	Weight
			Ft	In	sq ft	(rel.)
Hollow square.........	A	4	7	0	50	4.0
Solid square..........	A	4	7	0	50	4.0
Double rod............	D	2	9	5	0	4.0
Triangle..............	B	3	5	10	30	4.5
Hollow square.........	A	8	1	11	15	8.0
Solid square..........	A	9	2	2	20	9.0
Hollow square.........	A	12	1	4	17	12.0
Double rod............	C	2	203	5	0	12.0
Solid square..........	A	16	1	5	20	16.0
Double rod............	E	2	5	2	0	16.0
Do..................	F	2	3	2	0	20.0
Solid square..........	A	25	1	1	22	25.0

TABLE A-6. - Resistivity less than 100 ohm-feet

Arrangement	Rod type	Total rods	Spacing Ft	Spacing In	Area, sq ft	Weight (rel.)
Hollow square.........	B	4	10	10	119	6.0
Solid square..........	B	4	10	10	119	6.0
Triangle..............	D	3	13	3	153	6.0
Hollow square.........	A	8	3	10	60	8.0
Solid square..........	A	9	4	1	69	9.0
Hollow square.........	A	12	2	3	47	12.0
Do..................	B	8	2	9	32	12.0
Solid square..........	B	9	3	2	42	13.5
Hollow square.........	A	16	1	7	44	16.0
Solid square..........	A	16	2	4	50	16.0
Hollow square.........	B	12	1	11	34	18.0
Triangle..............	C	3	40	1	1,397	18.0
Hollow square.........	A	20	1	3	44	20.0
Double rod............	F	2	24	0	0	20.0
Solid square..........	B	16	2	1	41	24.0
Triangle..............	E	3	8	5	62	24.0
Solid square..........	A	25	1	9	50	25.0
Do..................	A	36	1	5	50	36.0
Do..................	B	25	1	8	45	37.5
Do..................	A	49	1	2	53	49.0

TABLE A-7. - Resistivity less than 200 ohm-feet

Arrangement	Rod type	Total rods	Spacing Ft	Spacing In	Area, sq ft	Weight (rel.)
Solid square..........	A	9	2,125	6	18,071,088	9.0
Hollow square.........	A	12	11	4	1,165	12.0
Do..................	B	8	17	1	1,175	12.0
Solid square..........	B	9	14	6	844	13.5
Hollow square.........	A	16	5	5	475	16.0
Solid square..........	A	16	7	9	542	16.0
Hollow square.........	D	8	9	2	336	16.0
Do..................	B	12	6	1	341	18.0
Solid square..........	D	9	9	5	359	18.0
Hollow square.........	A	20	3	8	349	20.0
Do..................	A	24	2	10	302	24.0
Do..................	B	16	4	0	255	24.0
Solid square..........	B	16	5	8	291	24.0
Hollow square.........	D	12	4	11	219	24.0
Solid square..........	A	25	4	6	331	25.0
Hollow square.........	A	28	2	4	281	28.0
Do..................	B	20	3	0	229	30.0
Do..................	A	32	2	0	270	32.0
Do..................	D	16	3	5	195	32.0
Solid square..........	D	16	5	0	222	32.0
Hollow square.........	A	36	1	9	264	36.0
Solid square..........	A	36	3	3	275	36.0

TABLE A-7. - Resistivity less than 200 ohm-feet--Continued

Arrangement	Rod type	Total rods	Spacing		Area, sq ft	Weight (rel.)
			Ft	In		
Hollow square.........	B	24	2	5	221	36.0
Solid square..........	B	25	3	11	246	37.5
Hollow square.........	D	20	2	9	189	40.0
Do..................	F	4	65	0	4,229	40.0
Solid square..........	F	4	65	0	4,229	40.0
Hollow square.........	B	28	2	1	218	42.0
Do..................	B	32	1	10	218	48.0
Do..................	C	8	11	8	548	48.0
Do..................	D	24	2	3	190	48.0
Solid square..........	A	49	2	8	260	49.0
Do..................	D	25	3	7	213	50.0
Do..................	B	36	3	0	229	54.0
Do..................	C	9	11	3	511	54.0
Do..................	A	64	2	3	249	64.0
Hollow square.........	E	8	7	8	239	64.0
Do..................	C	12	5	5	266	72.0
Solid square..........	D	36	2	10	209	72.0
Do..................	E	9	8	3	277	72.0
Do..................	B	49	2	6	230	73.5
Hollow square.........	F	8	6	4	162	80.0
Solid square..........	A	81	2	0	249	81.0
Do..................	F	9	7	1	203	90.0
Do..................	B	64	2	1	228	96.0
Hollow square.........	C	16	3	8	220	96.0
Solid square..........	C	16	5	3	251	96.0
Hollow square.........	E	12	4	6	188	96.0
Solid square..........	D	49	2	5	215	98.0
Do..................	A	100	1	8	247	100.0
Hollow square.........	C	20	2	10	206	120.0
Do..................	F	12	4	1	155	120.0
Solid square..........	B	81	1	10	232	121.5
Hollow square.........	E	16	3	3	177	128.0
Solid square..........	E	16	4	8	202	128.0
Hollow square.........	C	24	2	4	203	144.0
Solid square..........	C	25	3	9	227	150.0
Hollow square.........	E	20	2	7	176	160.0
Do..................	F	16	3	1	156	160.0
Solid square..........	F	16	4	5	177	160.0
Hollow square.........	C	28	2	0	204	168.0
Solid square..........	E	25	3	6	202	200.0
Do..................	C	36	2	11	218	216.0
Do..................	F	25	3	5	188	250.0
Do..................	E	36	2	10	202	288.0
Do..................	C	49	2	5	222	294.0
Do..................	F	36	2	9	193	360.0
Do..................	C	64	2	1	222	384.0
Do..................	E	49	2	4	210	392.0

TABLE A-8. - Resistivity less than 300 ohm-feet

Arrangement	Rod type	Total rods	Spacing		Area, sq ft	Weight (rel.)
			Ft	In		
Hollow square.........	A	16	22	8	8,249	16.0
Solid square..........	A	16	32	4	9,409	16.0
Hollow square.........	D	8	93	3	34,817	16.0
Do..................	B	12	21	8	4,243	18.0
Solid square..........	D	9	39	2	6,141	18.0
Hollow square.........	A	20	9	5	2,236	20.0
Do..................	A	24	6	2	1,385	24.0
Do..................	B	16	9	0	1,297	24.0
Solid square..........	B	16	12	9	1,479	24.0
Hollow square.........	D	12	11	7	1,213	24.0
Solid square..........	A	25	9	5	1,436	25.0
Hollow square.........	A	28	4	8	1,082	28.0
Do..................	B	20	5	11	885	30.0
Do..................	A	32	3	9	936	32.0
Do..................	D	16	6	9	740	32.0
Solid square..........	D	16	9	8	844	32.0
Hollow square.........	A	36	3	2	853	36.0
Solid square..........	A	36	6	0	889	36.0
Hollow square.........	B	24	4	6	743	36.0
Solid square..........	B	25	7	1	808	37.5
Hollow square.........	D	20	5	0	616	40.0
Do..................	B	28	3	8	676	42.0
Do..................	B	32	3	2	642	48.0
Do..................	D	24	4	0	568	48.0
Solid square..........	A	49	4	6	742	49.0
Do..................	D	25	6	3	628	50.0
Hollow square.........	B	36	2	9	622	54.0
Solid square..........	B	36	5	1	648	54.0
Do..................	C	9	118	3	55,997	54.0
Hollow square.........	D	28	3	4	547	56.0
Solid square..........	A	64	3	8	666	64.0
Hollow square.........	D	32	2	10	538	64.0
Do..................	E	8	32	2	4,145	64.0
Do..................	C	12	14	9	1,977	72.0
Do..................	D	36	2	6	535	72.0
Solid square..........	D	36	4	8	558	72.0
Do..................	E	9	24	10	2,472	72.0
Do..................	B	49	4	1	604	73.5
Hollow square.........	F	8	17	0	1,151	80.0
Solid square..........	A	81	3	1	637	81.0
Do..................	F	9	16	6	1,097	90.0
Do..................	B	64	3	5	575	96.0
Hollow square.........	C	16	7	8	942	96.0
Solid square..........	C	16	10	11	1,075	96.0
Hollow square.........	E	12	9	9	862	96.0
Solid square..........	D	49	3	10	546	98.0
Do..................	A	100	2	9	615	100.0

TABLE A-8. - Resistivity less than 300 ohm-feet--Continued

Arrangement	Rod type	Total rods	Spacing		Area, sq ft	Weight (rel.)
			Ft	In		
Hollow square.........	C	20	5	4	723	120.0
Do..................	F	12	8	0	583	120.0
Solid square..........	B	81	3	0	570	121.5
Do..................	D	64	3	3	533	128.0
Hollow square.........	E	16	6	2	614	128.0
Solid square..........	E	16	8	9	700	128.0
Hollow square.........	C	24	4	2	641	144.0
Solid square..........	B	100	2	7	563	150.0
Do..................	C	25	6	7	703	150.0
Hollow square.........	E	20	4	7	541	160.0
Do..................	F	16	5	6	487	160.0
Solid square..........	F	16	7	10	556	160.0
Do..................	D	81	2	10	538	162.0
Hollow square.........	C	28	3	6	602	168.0
Do..................	C	32	3	0	583	192.0
Do..................	E	24	3	9	515	192.0
Solid square..........	D	100	2	6	539	200.0
Do..................	E	25	6	0	572	200.0
Hollow square.........	F	20	4	3	459	200.0
Do..................	C	36	2	7	573	216.0
Solid square..........	C	36	4	10	597	216.0
Hollow square.........	E	28	3	2	505	224.0
Do..................	F	24	3	6	453	240.0
Solid square..........	F	25	5	7	507	250.0
Hollow square.........	E	32	2	9	503	256.0
Do..................	F	28	3	0	455	280.0
Solid square..........	E	36	4	7	527	288.0
Do..................	C	49	4	0	572	294.0
Do..................	F	36	4	5	488	360.0
Do..................	C	64	3	4	552	384.0
Do..................	E	49	3	9	524	392.0
Do..................	C	81	2	11	553	486.0
Do..................	F	49	3	8	497	490.0
Do..................	E	64	3	3	518	512.0
Do..................	C	100	2	7	550	600.0
Do..................	F	64	3	2	498	640.0
Do..................	E	81	2	10	527	648.0
Do..................	E	100	2	6	529	800.0

TABLE A-9. - Resistivity less than 500 ohm-feet

Arrangement	Rod type	Total rods	Spacing		Area, sq ft	Weight (rel.)
			Ft	In		
Hollow square.........	A	24	70	5	178,738	24.0
Solid square..........	A	25	71	6	81,906	25.0
Hollow square.........	A	28	20	6	20,631	28.0
Do..................	B	20	26	0	16,922	30.0
Do..................	A	32	12	4	9,797	32.0
Do..................	D	16	28	2	12,703	32.0
Solid square..........	D	16	40	1	14,490	32.0
Hollow square.........	A	36	9	0	6,554	36.0
Solid square..........	A	36	16	6	6,829	36.0
Hollow square.........	B	24	13	8	6,736	36.0
Solid square..........	B	25	20	3	6,613	37.5
Hollow square.........	D	20	13	10	4,840	40.0
Do..................	B	28	9	6	4,438	42.0
Do..................	B	32	7	4	3,506	48.0
Do..................	D	24	9	6	3,283	48.0
Solid square..........	A	49	10	1	3,693	49.0
Do..................	D	25	14	8	3,452	50.0
Hollow square.........	B	36	6	1	3,020	54.0
Solid square..........	B	36	11	2	3,146	54.0
Hollow square.........	D	28	7	4	2,676	56.0
Solid square..........	A	64	7	5	2,735	64.0
Hollow square.........	D	32	6	1	2,373	64.0
Do..................	D	36	5	2	2,197	72.0
Solid square..........	D	36	9	6	2,289	72.0
Do..................	B	49	8	1	2,396	73.5
Do..................	A	81	6	0	2,354	81.0
Do..................	B	64	6	5	2,052	96.0
Hollow square.........	C	16	53	4	45,518	96.0
Solid square..........	C	16	75	11	51,922	96.0
Hollow square.........	E	12	111	2	111,270	96.0
Solid square..........	D	49	7	4	1,965	98.0
Do..................	A	100	5	1	2,126	100.0
Hollow square.........	C	20	17	9	7,884	120.0
Do..................	F	12	32	2	9,356	120.0
Solid square..........	B	81	5	5	1,912	121.5
Do..................	D	64	6	0	1,787	128.0
Hollow square.........	E	16	20	0	6,422	128.0
Solid square..........	E	16	28	6	7,326	128.0
Hollow square.........	C	24	11	1	4,444	144.0
Solid square..........	B	100	4	8	1,813	150.0
Do..................	C	25	16	10	4,551	150.0
Hollow square.........	E	20	11	8	3,438	160.0
Do..................	F	16	14	4	3,295	160.0
Solid square..........	F	16	20	5	3,758	160.0
Do..................	D	81	5	2	1,725	162.0
Hollow square.........	C	28	8	2	3,334	168.0
Do..................	C	32	6	7	2,819	192.0
Do..................	E	24	8	6	2,613	192.0

TABLE A-9. - Resistivity less than 500 ohm-feet--Continued

Arrangement	Rod type	Total rods	Spacing		Area, sq ft	Weight (rel.)
			Ft	In		
Solid square..........	D	100	4	6	1,673	200.0
Do..................	E	25	13	2	2,795	200.0
Hollow square.........	F	20	9	7	2,327	200.0
Do..................	C	36	5	7	2,532	216.0
Solid square..........	C	36	10	3	2,638	216.0
Hollow square.........	E	28	6	9	2,254	224.0
Do..................	F	24	7	5	1,982	240.0
Solid square..........	F	25	11	7	2,161	250.0
Hollow square.........	E	32	5	8	2,068	256.0
Do..................	F	28	6	1	1,821	280.0
Do..................	E	36	4	11	1,959	288.0
Solid square..........	E	36	9	0	2,041	288.0
Do..................	C	49	7	8	2,150	294.0
Hollow square.........	F	32	5	2	1,738	320.0
Do..................	F	36	4	6	1,691	360.0
Solid square..........	F	36	8	4	1,762	360.0
Do..................	C	64	6	2	1,904	384.0
Do..................	E	49	7	1	1,824	392.0
Do..................	C	81	5	3	1,808	486.0
Do..................	F	49	6	9	1,654	490.0
Do..................	E	64	5	10	1,695	512.0
Do..................	C	100	4	7	1,736	600.0
Do..................	F	64	5	8	1,580	640.0
Do..................	E	81	5	1	1,657	648.0
Do..................	E	100	4	5	1,622	800.0
Do..................	F	81	4	11	1,571	810.0
Do..................	F	100	4	4	1,555	1,000.0

TABLE A-10. - Resistivity less than 700 ohm-feet

Arrangement	Rod type	Total rods	Spacing		Area, sq ft	Weight (rel.)
			Ft	In		
Hollow square.........	A	32	294	3	5,542,511	32.0
Do..................	A	36	37	4	113,244	36.0
Solid square..........	A	36	68	8	117,991	36.0
Hollow square.........	B	24	99	2	354,298	36.0
Solid square..........	B	25	100	6	161,635	37.5
Hollow square.........	D	20	61	3	93,860	40.0
Do..................	B	28	28	9	40,564	42.0
Do..................	B	32	17	4	19,237	48.0
Do..................	D	24	24	0	20,713	48.0
Solid square..........	A	49	21	5	16,538	49.0
Do..................	D	25	34	8	19,232	50.0
Hollow square.........	B	36	12	7	12,863	54.0
Solid square..........	B	36	23	1	13,402	54.0
Hollow square.........	D	28	15	4	11,602	56.0
Solid square..........	A	64	13	4	8,725	64.0
Hollow square.........	D	32	11	6	8,494	64.0
Do..................	D	36	9	3	6,998	72.0

TABLE A-10. - Resistivity less than 700 ohm-feet--Continued

Arrangement	Rod type	Total rods	Spacing		Area, sq ft	Weight (rel.)
			Ft	In		
Solid square..........	D	36	17	0	7,292	72.0
Do.................	B	49	14	2	7,244	73.5
Do.................	A	81	10	0	6,437	81.0
Do.................	B	64	10	5	5,362	96.0
Do.................	D	49	12	0	5,190	98.0
Do.................	A	100	8	1	5,329	100.0
Hollow square.........	C	20	1,315	1	43,236,320	120.0
Solid square..........	B	81	8	5	4,614	121.5
Do.................	D	64	9	4	4,306	128.0
Hollow square.........	E	16	476	6	3,633,305	128.0
Solid square..........	E	16	678	7	4,144,473	128.0
Hollow square.........	C	24	37	0	49,461	144.0
Solid square..........	B	100	7	2	4,167	150.0
Do.................	C	25	49	10	39,800	150.0
Hollow square.........	E	20	33	7	28,293	160.0
Do.................	F	16	45	8	33,447	160.0
Solid square..........	F	16	65	1	38,153	160.0
Do.................	D	81	7	10	3,940	162.0
Hollow square.........	C	28	19	7	18,900	168.0
Do.................	C	32	13	7	11,928	192.0
Do.................	E	24	18	4	12,181	192.0
Solid square..........	D	100	6	9	3,694	200.0
Do.................	E	25	27	5	12,063	200.0
Hollow square.........	F	20	20	9	10,804	200.0
Do.................	C	36	10	7	9,081	216.0
Solidssquare..........	C	36	19	5	9,461	216.0
Hollow square.........	E	28	13	0	8,241	224.0
Do.................	F	24	13	11	6,995	240.0
Solid square..........	F	25	21	4	7,304	250.0
Hollow square.........	E	32	10	1	6,599	256.0
Do.................	F	28	10	8	5,578	280.0
Do.................	E	36	8	4	5,729	288.0
Solid square..........	E	36	15	5	5,970	288.0
Do.................	C	49	12	11	6,019	294.0
Hollow square.........	F	32	8	8	4,882	320.0
Do.................	F	36	7	5	4,483	360.0
Solid square..........	F	36	13	8	4,671	360.0
Do.................	C	64	9	10	4,755	384.0
Do.................	E	49	11	3	4,605	392.0
Do.................	C	81	8	1	4,234	486.0
Do.................	F	49	10	5	3,952	490.0
Do.................	E	64	9	0	3,968	512.0
Do.................	C	100	6	11	3,904	600.0
Do.................	F	64	8	6	3,567	640.0
Do.................	E	81	7	7	3,710	648.0
Do.................	E	100	6	7	3,527	800.0
Do.................	F	81	7	3	3,427	810.0
Do.................	F	100	6	4	3,315	1,000.0

TABLE A-11. - Resistivity less than 1,000 ohm-feet

Arrangement	Rod type	Total rods	Spacing		Area, sq ft	Weight (rel.)
			Ft	In		
Solid square..........	A	49	131	6	622,813	49.0
Hollow square.........	B	36	62	4	314,939	54.0
Solid square..........	B	36	114	6	328,139	54.0
Hollow square.........	D	28	81	7	326,762	56.0
Solid square..........	A	64	32	6	51,814	64.0
Hollow square.........	D	32	34	9	77,513	64.0
Do.................	D	36	22	7	41,338	72.0
Solid square..........	D	36	41	6	43,071	72.0
Do.................	B	49	31	9	36,413	73.5
Do.................	A	81	19	8	24,776	81.0
Do.................	B	64	19	5	18,543	96.0
Do.................	D	49	22	7	18,398	98.0
Do.................	A	100	14	5	16,846	100.0
Do.................	B	81	14	6	13,490	121.5
Do.................	D	64	16	0	12,549	128.0
Do.................	B	100	11	8	11,086	150.0
Do.................	D	81	12	8	10,368	162.0
Hollow square.........	C	32	65	10	277,745	192.0
Do.................	E	24	140	11	714,950	192.0
Solid square..........	D	100	10	7	9,141	200.0
Do.................	E	25	143	1	327,626	200.0
Hollow square.........	F	20	155	3	602,703	200.0
Do.................	C	36	32	1	83,593	216.0
Solid square..........	C	36	59	0	87,097	216.0
Hollow square.........	E	28	41	0	82,525	224.0
Do.................	F	24	40	10	60,117	240.0
Solid square..........	F	25	57	6	53,006	250.0
Hollow square.........	E	32	24	8	39,188	256.0
Do.................	F	28	24	4	29,171	280.0
Do.................	E	36	18	0	26,217	288.0
Solid square..........	E	36	33	0	27,316	288.0
Do.................	C	49	26	1	24,565	294.0
Hollow square.........	F	32	17	8	20,104	320.0
Do.................	F	36	14	0	16,023	360.0
Solid square..........	F	36	25	10	16,694	360.0
Do.................	C	64	17	5	14,909	384.0
Do.................	E	49	20	3	14,774	392.0
Do.................	C	81	13	6	11,669	486.0
Do.................	F	49	17	8	11,319	490.0
Do.................	E	64	14	11	10,938	512.0
Solid square..........	C	100	11	1	9,977	600.0
Do.................	F	64	13	8	9,190	640.0
Do.................	E	81	12	1	9,414	648.0
Do.................	E	100	10	2	8,502	800.0
Do.................	F	81	11	4	8,307	810.0
Do.................	F	100	9	9	7,730	1,000.0

TABLE A-12. - Resistivity less than 2,000 ohm-feet

Arrangement	Rod type	Total rods	Spacing		Area, sq ft	Weight (rel.)
			Ft	In		
Solid square..........	A	100	156	1	1,974,672	100.0
Do..................	B	81	84	5	456,452	121.5
Do..................	D	64	91	5	409,946	128.0
Do..................	B	100	44	4	159,420	150.0
Do..................	D	81	46	5	138,089	162.0
Do..................	D	100	32	0	83,216	200.0
Do..................	C	64	173	1	1,468,888	384.0
Do..................	E	49	263	0	2,491,244	392.0
Do..................	C	81	58	9	220,932	486.0
Do..................	F	49	92	3	306,785	490.0
Do..................	E	64	65	0	207,255	512.0
Do..................	C	100	36	9	109,729	600.0
Do..................	F	64	46	6	106,326	640.0
Do..................	E	81	39	4	99,103	648.0
Do..................	E	100	28	10	67,386	800.0
Do..................	F	81	32	6	67,740	810.0
Do..................	F	100	25	4	52,101	1,000.0

TABLE A-13. - Resistivity less than 3,000 ohm-feet

Arrangement	Rod type	Total rods	Spacing		Area, sq ft	Weight (rel.)
			Ft	In		
Solid square..........	B	100	640	1	33,191,232	150.0
Do..................	D	81	397	6	10,113,468	162.0
Do..................	D	100	97	10	775,469	200.0
Do..................	C	100	161	6	2,113,410	600.0
Do..................	F	64	233	5	2,671,479	640.0
Do..................	E	81	156	3	1,562,624	648.0
Do..................	E	100	73	0	432,086	800.0
Do..................	F	81	85	3	465,569	810.0
Do..................	F	100	54	2	237,933	1,000.0

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