Designing For A Low Resistance Earth Interface (Grounding)

Roy B. Carpenter, Jr.
Joseph A. Lanzoni

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Lightning Eliminators & Consultants, Inc.
6687 Arapahoe Road, Boulder CO, 80303-1453, USA
(303) 447-2828 • FAX (303) 447-8122
www.LECglobal.com
HITACHI INDUSTRIES CO. LTD. BUSINESS PARTNER

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Introduction

Grounding (or earthing) is the art of making an electrical connection to the earth. The process is a combination of science and "art" as opposed to pure science, because it is necessary to "test the options," as opposed to using predetermined methods and calculations. The options for each site must be determined through visualization and evaluation, individually, using a related analytical process.

The earth must be treated as a semiconductor, while the grounding electrode itself is a pure conductor. These factors make the design of an earthing system complex, not derived from a simple calculation or the random driving of a few rods into the soil. Knowledge of the local soil conditions is mandatory and is the first step in the design process. This includes its moisture content, temperature, and resistivity under a given set of conditions.

Evaluating the Soil Conditions

Accurate design of a grounding system requires an accurate assessment of the site's soil conditions. However, even a small site will often have widely varying soil resistivity from one spot to another. Using a four-point soil resistivity tester, many measurements must be made, and samples of the soil must be taken from several test locations and analyzed for both moisture and temperature. The actual measurement technique using the four-point tester is illustrated in Figure 1. Note that at least ten measurements are recommended to properly assess the site soil resistivity. Large areas require more measurements, but ten should be the minimum. Only soil to a depth of 10 feet (3 meters) needs to be tested in most situations. In very unusual situations, more specifically in very dry areas or under extreme conditions, refer to the test meter instructions for the procedure required to assess resistivity as a function of depth. Table 1 lists some common soils and their resistivity.

When the measurements are completed, the soil resistivity should be calculated, its temperature measured and the moisture content assessed. Moisture content is assessed by taking a representative soil sample at a depth of about 1 foot (⅓ meter) and putting it in a plastic bag immediately. The weigh the sample, dry it out completely and weigh it again. Express the difference as a percentage, with the result being the soil's percent moisture by weight.

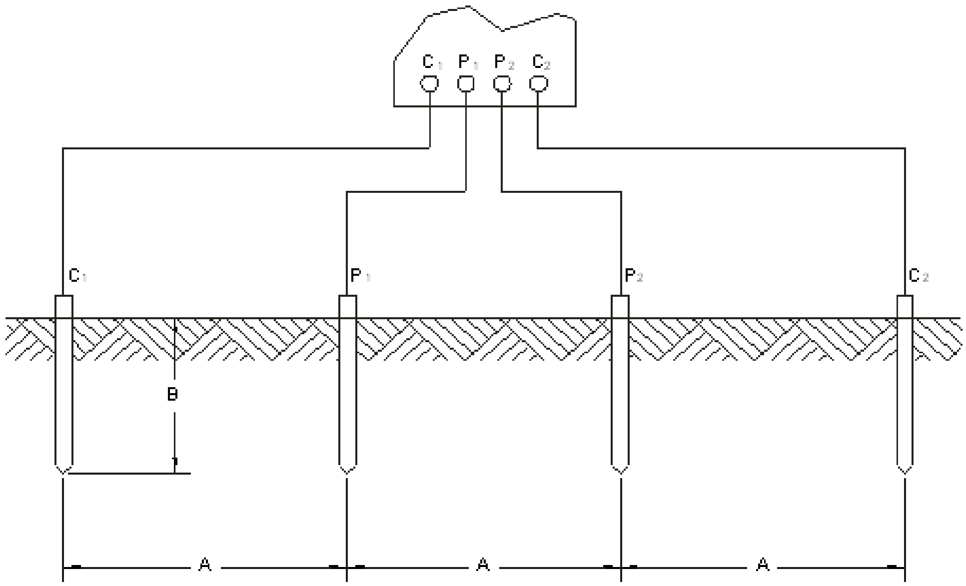

Figure 1: Soil Resistivity Testing Using Four Point Method

Figure 1 Notes
1. Distance between probes (A) should equal twenty times depth of probes (B).
2. Soil resistivity in ohm-meters is equal to 19.15 times the instrument reading when A equals 10 feet and B equals 6 inches.

Table 1: Soil Resistivities (approximate ohm-meters)

Soil Description	Median	Minimum	Maximum
Topsoil, loam	26	1	50
Inorganic clays of high plasticity	33	10	55
Fills – ashes, cinders, brine wastes	38	6	70
Gravelly clays, sandy clays, silty clays, lean clays	43	25	60
Slates, shales	55	10	100
Silty or clayey fine sands with slight plasticity	55	30	80
Clayey sands, poorly graded sand-clay mixtures	125	50	200
Fine sandy or silty clays, lean clays	190	80	300
Decomposed gneisses	275	50	500
Silty sands, poorly graded sand-silt mixtures	300	100	500
Clayey gravel, poorly graded gravel, sand-clay mixture	300	200	400
Well graded gravel, gravel-sand mixtures	800	600	1,000
Granites, basalts, etc.	1,000	---	---
Sandstone	1,010	20	2,000
Poorly graded gravel, gravel-sand mixtures	1,750	1,000	2,500
Gravel, sand, stones, little clay or loam	2,585	590	4,580
Surface limestone	5,050	100	10,000

Table 1 Notes
1. Low-resistivity soils are highly influenced by the presence of moisture.

2. Low-resistivity soils are more corrosive than high-resistivity soils.

The percent of moisture and the temperature measurement should be compared with Figures 2 and 3, respectively, to determine the actual soil resistivity under optimum and worst-case conditions. This will permit a calculation of the range in grounding resistance achievable in that soil with the final system design. The required design data has now been defined, and the design process can start from a solid foundation, i.e., the required parameters. The initial calculations should be based on the **measured resistivity**, and the final **system** design must take into account the extreme moisture and temperature variations. Variations of about 250 percent are normal for conventional systems.

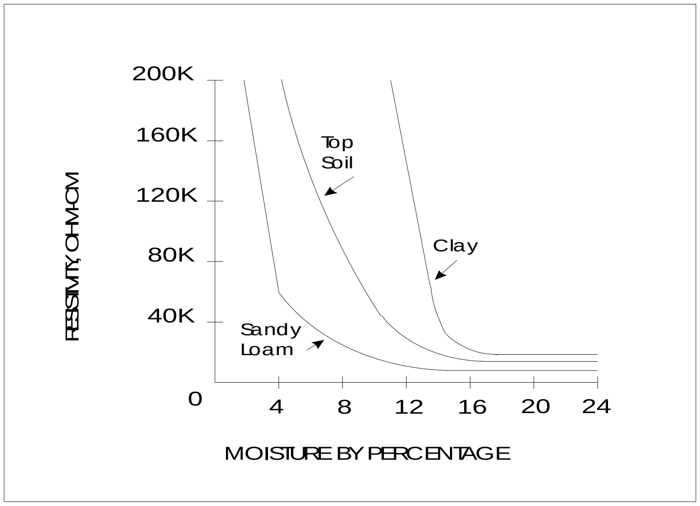

Figure 2: The Influence of Moisture Content

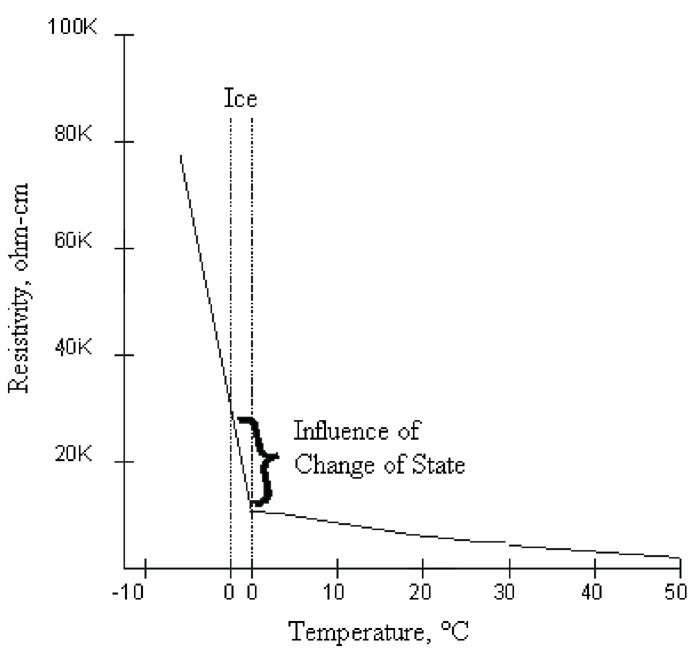

Figure 3: The Influence of Temperature

Design Step 1: Calculating the Requirements with Conventional Ground Rods

From the IEEE and other references, we know that the resistance of any vertical grounding electrode R_1 may be calculated from the following equations:

English Units — Metric Units (1)

$$R_1 = \frac{\rho}{1.915L}\left[\ln\frac{96L}{d} - 1\right] \qquad R_1 = \frac{\rho}{6.283L}\left[\ln\frac{8L}{d} - 1\right]$$

Where: ρ = Soil resistivity in ohm-meters
L = Electrode length in feet (English units) or in meters (metric units)
d = Electrode diameter in inches (English units) or in meters (metric units)

For example, if the soil resistivity averaged 100 ohm-meters, then the resistance of one three quarter inch by 10 foot long electrode to true earth would be found to be 0.321ρ or 32.1 ohms. Obviously, that is high and most likely not acceptable. The next step is to determine how many of these rods R_N are required to achieve a given target resistance goal.

Design Step 2: Calculating the Required Number of Ground Rods

$$R_N = \frac{R_1 K}{N}$$

Where: R_1 = Resistance of one vertical ground rod (2)
K = Combining factor ≈ 0.377527 ln (N) + 0.89057
N = Number of rods required (**when** they are properly deployed)

Since making an electrical connection to earth involves a connection between a conductor and a semiconductor, it is not point-to-point contact but conductor-to-area contact. That is, making an electrical contact with earth requires a significant volume of that earth around the conductor to complete the connection. This can best be illustrated by considering the implications of the data presented by Figure 4, which illustrates the result of measuring the change in resistance of equal segments of earth along any radial from a driven rod. Notice that the **change** in measured resistance **decreases** exponentially with distance from the rod, as illustrated by Figure 4.

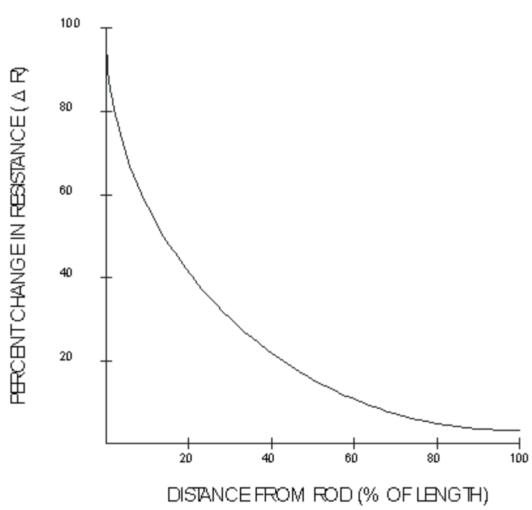

Figure 4: Measured Resistance Change as a Function of Distance from the Ground Rod

It is important to note that at about 1.1 times the length of the rod **in earth**, the change in resistance becomes negligible. This indicates that its connection to earth is nearly complete. Actually, at this length about 94% of the connection has been completed.

From these data, we know that for every rod driven into earth, an interfacing hemisphere of that earth is required to complete the electrical connection. The diameter of that hemisphere is approximately 2.2 times the length of the rod (L) in earth, as illustrated by Figure 5. When more than one rod is required, they should be spaced no closer than 2.2 times the length of that rod in any direction. If multiple rods are driven too close together, those connections are considered incomplete because all rods do not have a complete interfacing hemisphere, and the effectiveness of those additional rods is reduced proportionately and, in reality, wasted.

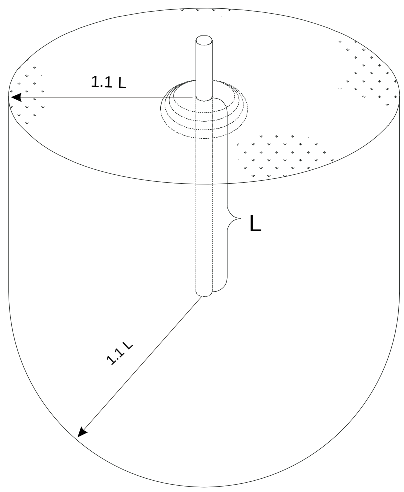

Figure 5: The Interfacing Hemisphere

To illustrate, consider Figure 6. Using those data, if we assume that one 10-foot rod provides a resistance to earth of 100 ohms, then 10 rods at 5-foot intervals reduces the resistance to about 28 ohms. At 10-foot intervals, it is about 18 ohms and at 22-foot intervals (2.2 times their length), it is down to only about 8 ohms. There are the same number of rods, but properly spaced.

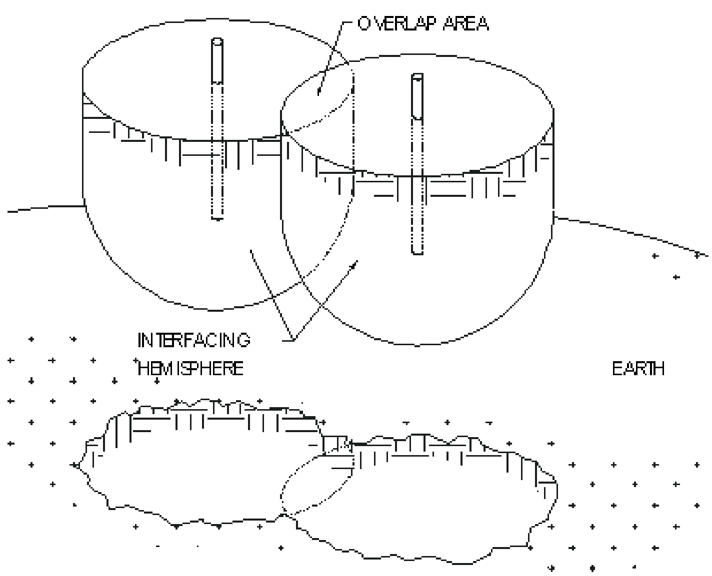

Figure 6: Overlapping Interfacing Hemispheres from Ground Rods Spaced Too Closely

One other factor of concern is **length** of the grounding electrode. It is common practice to keep extending the length of the electrode into the earth to lower its resistance. This practice is not recommended for most situations, as will become apparent from an evaluation of the data offered by Figure 7. An analysis of these data shows that as the electrode is extended into the earth, the percent reduction in resistance to earth per unit length of rod becomes exponentially less with each increment of length. For example, to reduce the resistance of a 10-foot rod in a given soil to half the 10-foot value, it requires extending that rod to 100 feet **in that same soil**. Further, it is unusual for the soil to remain constant as a function of depth. Most often, resistivity increases with depth, further compounding the problem. A reasonable conclusion from these data is this: Many short rods (six to ten feet in length) are usually more productive than a few long ones in achieving a given resistance to earth. In addition, longer rods have greater interfacing hemisphere diameters, which increase the risk of hemispheres overlapping.

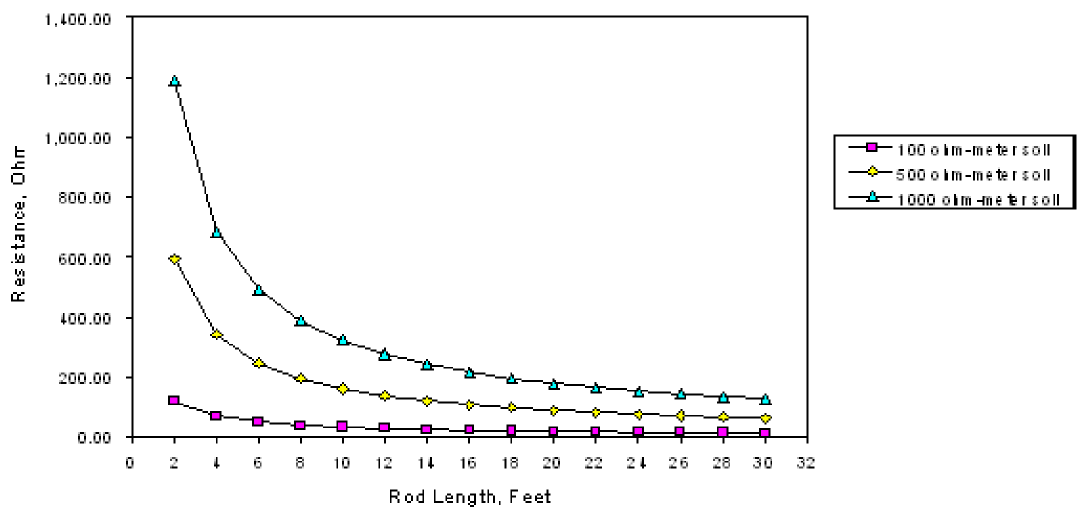

Figure 7: Ground Rod Resistance versus Length (for ¾ inch Diameter Ground Rod)

Figure 7 Notes

1. Often one or a few very long rods are tried and, because of measurement errors, the user **thinks** he has achieved a low resistance when, in fact, he probably has not.
2. More often than not, grounding systems are subjected to lightning impulses and other transient phenomena where the di/dt can exceed 100 kA/microsecond. In these situations, the surge impedance is the most important factor, not the DC resistance. Using more short, large-diameter rods is far more effective in reducing the surge impedance than using fewer long rods.

Given the foregoing guidelines, the design process can start with the proper spacing criteria, using the expression given to calculate the resistance of one rod plus that for N rods (R_N) as described above. When there is limited space, as there usually is, that must be taken into account. To optimize the calculations, a personal computer may be programmed to:

1. Vary electrode length and the size of the interfacing hemisphere in concert.
2. Vary the location of these interfacing hemispheres to gain maximum use of available land area.

3. Conduct a trade-off analysis between the number, length, and location of the electrode-hemisphere combination.

When the lowest resistance combination has been found and yet is too high to satisfy the requirements, other factors must be considered. Limits have been reached which are established by the area of land available and the soil resistivity. Doubling the rods in that area will reduce the resistance by no more than about 10%. To reduce the grounding resistance, either more land is required or the resistivity of the available land soil must be lowered. Soil resistivity **can** be lowered, and the related cost is usually much less than the cost of more land.

Dealing With High Soil Resistivity (Soil Conditioning)

Soil resistivity is a function of several factors. These include the type of soil, moisture content, temperature, mineral content, granularity and compactness. Usually, moisture and mineral content are the only factors that can be influenced by any practical control concept. Figures 2, 3, and 8 illustrate the influences of moisture, temperature, and mineral content, respectively. Controlling temperature is usually not practical, but reducing sensitivity to temperature is practical. Moisture can be controlled where required, but the mineral content has the most dramatic influence, as illustrated by Figure 8. The higher mineral content also reduces soil **sensitivity** to moisture content. It is, therefore, obvious that increasing the mineral content is the first step to be considered in soil conditioning.

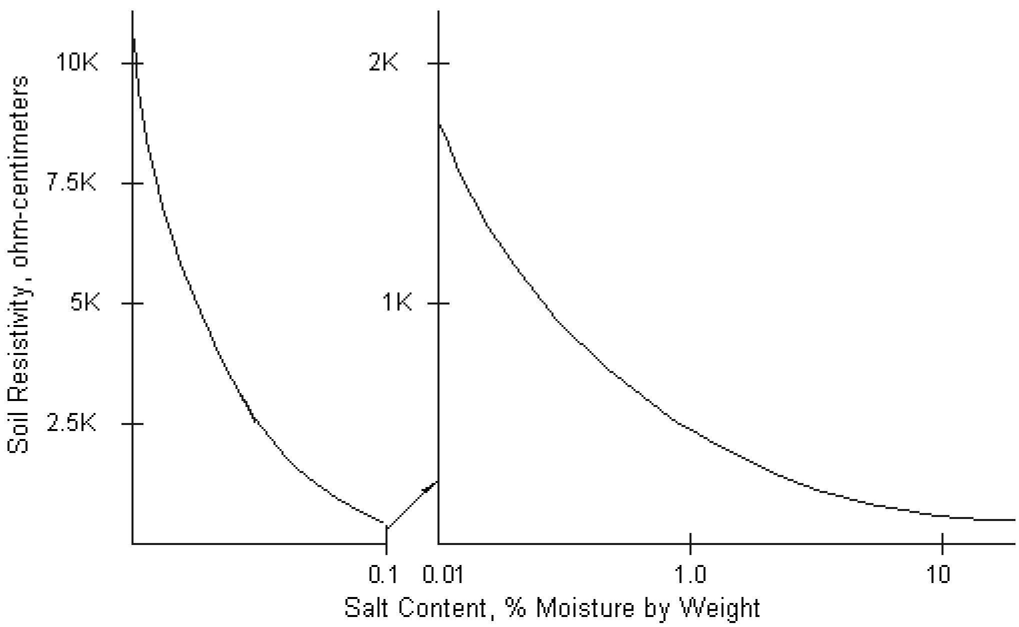

Figure 8: The Influence of Salt on Soil Resistance

Soil conditioning is the process of adding the right amount of metallic salt into the soil—**uniformly**—to achieve the required conductivity. Various methods have been attempted to accomplish this objective. In Table 2, the results of three different methods are compared to a conventional ¾ inch by 10 foot conventional rod in five different soils. The first sample is the conventional rod alone; the second and third samples involve a conventional rod in soil that was mixed with salt (NaCl) and measured after one and three years. The fourth sample is a two-inch diameter copper tube filled with salt, provided with air breathing holes at the top and leaching holes at the base. It extracts moisture from the air (if it has any) and forms a saturated solution of the metallic salts which are leached out as the solution is formed. In dry areas where conditioning is needed the most, it is about as effective as the equivalent length of **empty** two-inch pipe.

Table 2: Resistances and Variations of Grounding Electrodes

Sample No.	Grounding Electrode	Measured Soil Resistivity (ohm-meters)	Electrode Resistance (ohms)	Variation Over One Year
1	Copper Clad	9	7.2	
	Ground Rod	62	22	
	(¾ inch diameter x	270	65	
	10 feet long)	3.7K	430	
		30K	10K	2.5
2	Rod in Manually	9	2.3	
	Salted Soil	62	18	
	– First Year	270	44	
		3.7K	350	
		30K	1.5K	2.0
3	Rod in Manually	9	5.0	
	Salted Soil	62	30	
	– Third Year	270	80	
		3.7K	400	
		30K	3K	2.0
4	Air-Breathing Rod	9	0.5	
	(10 feet long)	62	9	
		270	22	
		3.7K	240	
		30K	2K	2.0
5	Chem-Rod®	9	0.2	
	(10 feet long)	62	2	
		270	10	
		3.7K	90	
		30K	1K	0.4

In 1984, LEC introduced the Chem-Rod® to the marketplace. The Chem-Rod® is a chemically activated grounding electrode that conditions the surrounding soil. Its design results in a more uniform distribution of the metallic salts throughout the electrode's interfacing hemisphere. It absorbs moisture from the soil and air and leaches the metallic salts out at all levels, conditioning most of the interfacing hemisphere while using the available soil moisture. The metallic salts are selected on the basis of application and location.

From the Table 2 data, two factors are evident:

1. The Chem-Rod® provides a much lower resistance to earth than any other option available.
2. That resistance is much more **stable**; it varied by only 40%, while the other options varied from 200 to 250%.

It is important to note that the Chem-Rod® resistance is dependent on the conditioning process. When the metallic salts migrate slowly through the soil, it may take up to six months for the process to stabilize at the lower resistance. The higher the soil's resistivity, the longer the conditioning process takes.

Design Step 3: Calculating the Required Number of Chem-Rod®s

The next step in the design process is to calculate resistances R_1 and R_N using the same equations (equation #1 and equation #2) as before but with the Chem-Rod® parameters. The resistance of one Chem-Rod® in English units **after conditioning is completed** can be estimated from:

$$R_{CR} = \frac{c\rho}{1.915L}\left[\ln\frac{96L}{d} - 1\right] = \frac{0.2\rho}{1.915L}\left[\ln\frac{96L}{2.625} - 1\right] \tag{4}$$

Where: ρ = Soil resistivity in ohm-meters
L = Chem-Rod® length in feet
d = Chem-Rod® outer diameter in inches = 2.625 inches
c = Conditioning Coefficient = 0.2

Note that the Conditioning Coefficient c can vary between 0.5 and 0.05 but normally does not exceed 0.2 after six months. The higher the initial soil resistance, the greater the percentage of reduction. High-density soil will take much longer to stabilize.

If this still does not meet the objective, or if time is a critical constraint, then more extensive steps are in order. Still, we must deal with the soil within the interfacing hemisphere (IH).

Replacing Soil in the Interfacing Hemisphere (IH)

Since about 94% of the grounding resistance of a given electrode is determined by the character of the soil within the IH, it is obvious that replacing that soil with a more conductive soil could achieve the desired objective. However, that action may prove impractical. A more practical action may be to replace only that part of the soil that exercises the greatest influence on the ultimate grounding resistance and to use the lowest resistivity "soil" available. Figure 9 is a graph demonstrating the influence of the surrounding soil as a function of the radius of what is called the "critical cylinder" (that is, the soil immediately around the grounding electrode). Notice that 52% of the connection to earth is completed by a 12-inch-diameter critical cylinder, and 68% of that connection is completed by a 24-inch diameter critical cylinder. The most productive option is, therefore, expected to be between these two diameters.

The next step is to select the proper backfill or soil to replace that within the critical cylinder. The options include top soil (which has a resistivity of about 10 ohm-meters), bentonite (which has a resistivity of about 2.5 ohm-meters) or various forms of special mixes. LEC has chosen to use a special mix to overcome the negative effects of various conductive clays such as bentonite and provide a very conductive backfill. Bentonite has various shortcomings, including the fact that its volume varies by 300% between wet and dry, and that it does not absorb or transmit metallic salts easily. The LEC backfill is called Grounding Augmentation Fill (GAF). The resistivity of GAF is 0.5 ohm-meters and is hydroscopic (meaning that it absorbs moisture), thus assuring the required moisture supply. Refer to Table 3 for a list of backfill options and their parameters.

Table 3: Soil Enhancement Options

1. Conductive Concrete
   Resistivity of 30 to 90 ohm-meters
   Subject to ice and corrosive effects
2. Clay-Based Backfill Materials, e.g. Bentonite
   Resistivity of approximately 2.5 ohm-meters
   Highly variable with respect to moisture (300%)
3. Carbon-Based Backfill Materials
   Resistivity of 0.1 to 0.5 ohm-meters
   Water-retention capability inferior to clays
4. Blended Clay-Carbon Backfill Materials, e.g. GAF
   Resistivity of 0.5 ohm-meters
   High water-retention capability

Design Step 4: Calculating the Required Number of Chem-Rod®s in GAF

The next step is to determine the impact of using GAF backfill within the previously defined critical cylinder. To replace the soil within the critical cylinder with a conductive backfill, first auger the appropriately sized hole in the interfacing hemisphere, insert the Chem-Rod® or other type of grounding electrode, then backfill the hole with 100% GAF, wetting it as it is installed.

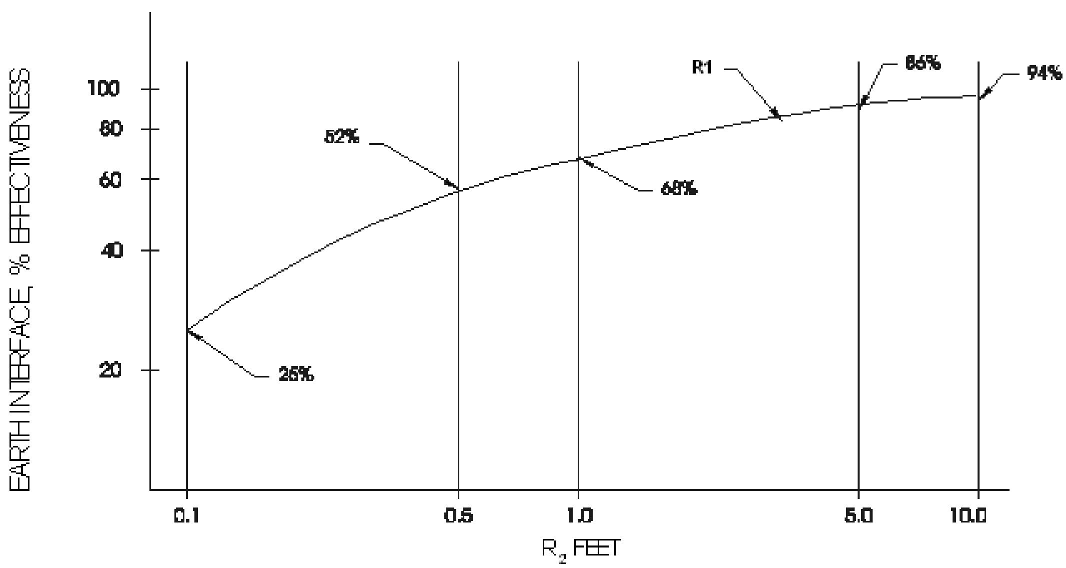

Figure 9: The Influence of Soil within the Critical Cylinder

The formula for the resistance of a single vertical ground rod in a conductive backfill is:

$$R_b = \frac{1}{2\pi L}\left(\rho(\ln\frac{8L}{D_b} - 1) + \rho_b(\ln\frac{8L}{d} - 1) - \rho_b(\ln\frac{8L}{D_b} - 1)\right) \qquad (5)$$

Where R_b = resistance of vertical ground in conductive backfill, ohms
ρ_b = conductive backfill resistivity, ohm-meters
D_b = backfilled hole diameter, meters

L = Electrode length, meters
d = Electrode diameter, meters

However, as you can see from Equation 5, if resistivity ρ_b of the chosen backfill is much less than the resistivity ρ of the native soil, (as would typically be the case) and the backfill's resistivity is less than one ohm-meter ($\rho_b < 1$), then the last two factors of Equation 5 are almost negligible and the most influential factor is the first one. Therefore, the resulting immediate resistance decrease (before conditioning) is attributed to the diameter of the critical cylinder hole becoming equal to the "effective" diameter of the grounding electrode, when the critical cylinder is filled with GAF. After conditioning provided by the mineral salts within the Chem-Rod®, the resulting long-term resistance will approach R_b times the Conditioning Coefficient c for the average site, as follows:

$$R_{Chem-Rod+GAF} = \frac{c}{2\pi L}\left(\rho(\ln\frac{8L}{D_b}-1)+\rho_b(\ln\frac{8L}{d}-1)-\rho_b(\ln\frac{8L}{D_b}-1)\right) \quad (6)$$

As an example, consider a 10 foot (3 meter) long Chem-Rod® in a 24 inch (0.6 meter) diameter hole backfilled with GAF, where the local soil has a resistivity of 100 ohm-meters. The resistance in ohms of the Chem-Rod® **before conditioning** is:

$$R_{Chem-Rod+GAF} = \frac{1}{6\pi}\left(100(\ln\frac{24}{0.6}-1)+0.5(\ln\frac{24}{2.625}-1)-0.5(\ln\frac{24}{0.6}-1)\right)=14.2 \quad (7)$$

Note that this resistance is the value **before** the Chem-Rod® has conditioned the local soil. After about three to six weeks of conditioning, the value will approach 2.8 ohms. (Some dense soils require a longer period of time.) If one Chem-Rod® does not achieve the desired goal, multiple Chem-Rod®s must be considered. By comparison, in 100 ohm-meter soil a conventional 10 foot (3 meter) long, ¾ inch (0.019 meter) diameter ground rod will achieve a resistance of only 32 ohms, over twice that of the Chem-Rod® before conditioning and over **eleven** times that of the Chem-Rod® after conditioning.

Permafrost and Temperature Problems

Frost levels and freezing temperatures have always been a problem situation for grounding systems. It is true that controlling temperature may not be practical; however, it is possible to minimize the effects. Using permafrost as the “worst-case” situation, consider the following situation: Figure 3 illustrates the impact of low temperatures on resistivity, based on conventional soils.

Tests performed by the U.S. Corps of Engineers in Alaska have proven that the resistance of a simple conventional electrode can be lowered to as little as 5% of its original resistance value simply by treating the soil around the electrode, by making the soil in the nearby critical cylinder and the greater interfacing hemisphere more conductive. The results of these tests are illustrated in Figure 10. Notice that the resistance of a single untreated rod reached about 20,000 ohms, while the treated rod reached only about 1,000 ohms, one-twentieth of the conventional rod.

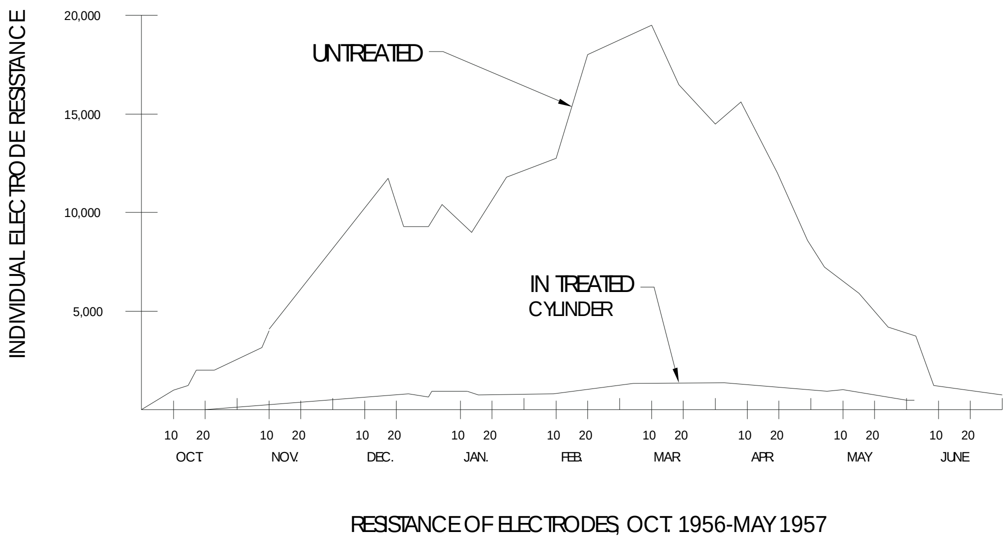

Figure 10: Ground Rods in Permafrost, Army Corps of Engineers, Point Barrow, Alaska

Surge Impedance Considerations

As established earlier, using more short, large-diameter rods is far more effective in reducing the surge impedance than using fewer long rods. Refer to Figure 11, where the surge impedance of one 1000 foot long wire was compared to the surge impedance of two 500 foot long wires, three 333⅓ foot long wires, etc. As you can see, the greater number of wires produced an overall surge impedance lower than that of fewer yet longer wires, even though the total amount of wire remained unchanged.

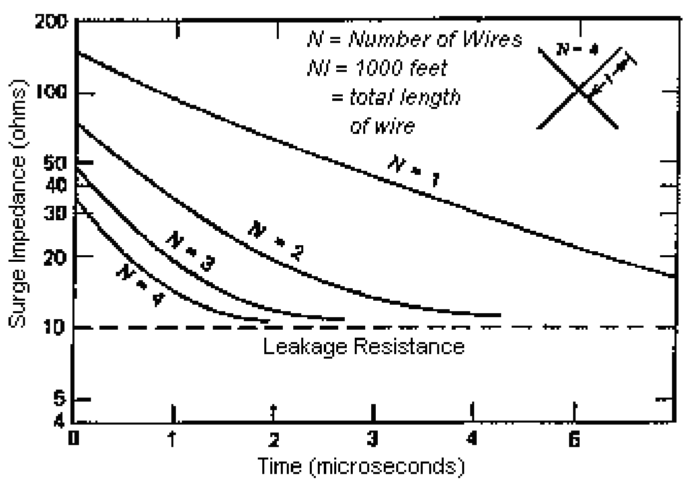

Figure 11: Surge Impedances of Various Wire Lengths

The surge impedance characteristics of a grounding system are very important under lightning, high frequency and other electrical transient situations. It is critical that a grounding system be able to respond rapidly under lightning and transient conditions, since one of the primary reasons for having a grounding system is personnel safety.

Because the surge impedance of a grounding system cannot be easily measured, impedance considerations must be addressed during the design phase. These considerations lead to the following recommendations:

1. Use grounding conductors and electrodes with large surface areas, since high frequency impulses tend to travel on the surface of conductors (called the "skin effect").
2. Use multiple short grounding electrodes instead of fewer long electrodes.
3. Keeping grounding conductors as straight and as short as possible.

Assessing the Results – Ground Resistance Testing

Finally, it is essential that the end results are measured correctly. The resistance of a grounding system must be measured with a ground resistance tester, which is a specialized instrument made specifically for ground resistance testing. All too often, it has been assumed that a single measurement may be made from one point of a grounding system, regardless of its size. In fact, that is seldom correct.

The most common method of testing the resistance of a grounding electrode or system is to use the three-point Fall-of-Potential (FOP) test. The FOP test requires the installation of two auxiliary test probes, called the voltage probe and the current probe. When performing the FOP test, it is essential that the current probe be installed outside of the interfacing hemisphere of the electrode(s) under test. When testing a single grounding electrode, the current probe is typically installed 100 feet (30 meters) away from the electrode under test, per Figure 12. When testing a grounding grid, the current probe should be installed at a distance greater than five times the length of the grid's largest diagonal measurement, per Figure 13. Increasing the distance to the current probe will result in more accurate resistance readings.

The proper way to perform the FOP test is to take multiple readings along a line from the electrode under test to the current probe. These readings are usually taken at incremental distances of ten percent. For example, if the current probe is installed 100 feet away, a reading should be taken with the voltage probe installed at 10 feet, 20 feet, etc. These readings should then be plotted on a graph similar to that shown in Figure 14. If the resulting plot takes the shape of an inverted-sideways "S", as shown in the figure, then the readings are assumed to be accurate. FOP tests should be conducted in multiple directions away from the electrode under test for an accurate assessment.

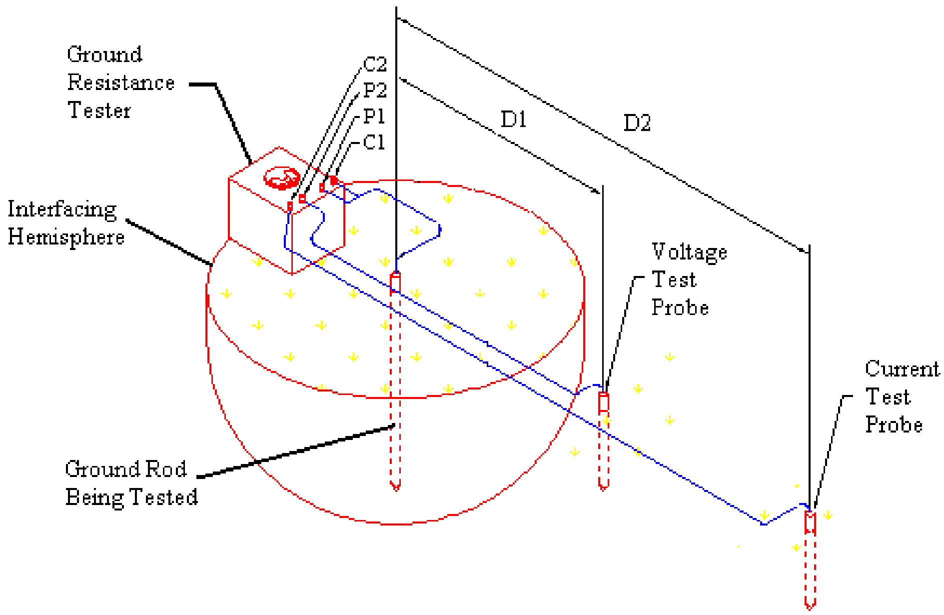

Figure 12: Ground Resistance Test for Single Ground Rod Using Fall-of-Potential Method

Figure 12 Notes
1. The Fall-of-Potential test method is also called the three-point test method.
2. The current test probe must be well outside of the interfacing hemisphere of the electrode being tested. For a single ground rod, distance D2 is typically 100 feet.
3. The electrode resistance is measured when D1 is at a distance of 62% of D2.

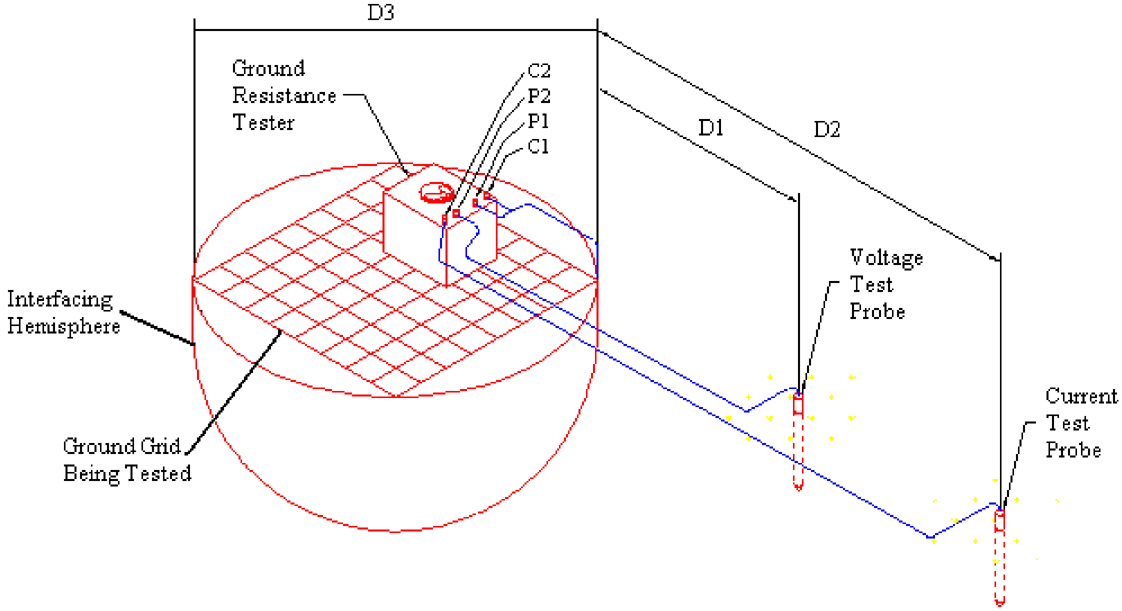

Figure 13: Ground Resistance Test for Ground Grid Using Fall-of-Potential Method

Figure 13 Notes
1. The current test probe must be outside of the interfacing hemisphere of the ground grid.
2. The distance D2 should be at least 5 times the diagonal distance D3 of the grid.
3. The electrode resistance is measured when D1 is at a distance of 62% of D2.

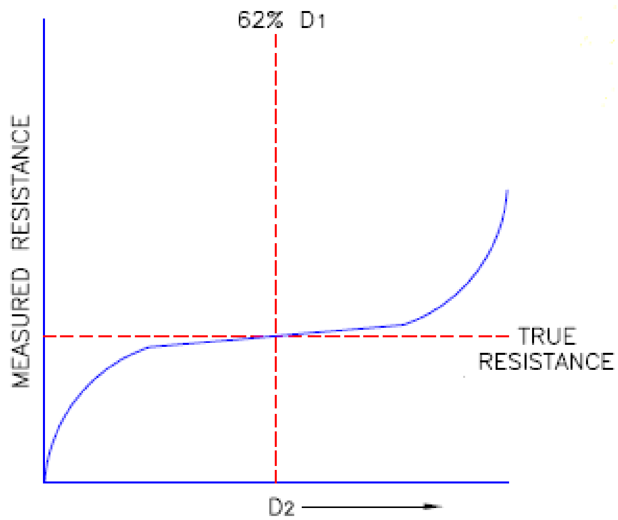

Figure 14: Plot of Readings from Fall-of-Potential Ground Resistance Test

An alternate method of FOP ground resistance testing is to use a handheld clamp-on ground resistance tester. This type of tester relies on the principle that the electrode under test in connected in parallel to a large number of other grounding electrodes outside of its interfacing hemisphere. Thus, the clamp-on ground resistance tester is useful for measuring the resistance of transmission and distribution line grounds, residential grounds, etc. It cannot be used to measure large and/or complex grounding grids, isolated grounding electrodes, etc.

Advanced Ground Resistance Testing

As mentioned above, the current probe used in the FOP test should be installed at a distance greater than five times the length of the grid's largest diagonal measurement. For a very large grid, such as those found at a power plant or petrochemical facility, this may not be practical. In addition, the wire leads between the test instrument and the test probes may receive unwanted radio frequency or electromagnetic interference, thus corrupting the test data. For these and other reasons, the Smart Ground Testing (SGT) method was developed.

SGT is a new grounding resistance testing method developed specifically for measuring large and/or complex ground grids, such as those found at refineries and generating stations. SGT provides numerous advantages over FOP testing, including

1. The distance to the voltage and current probes are not excessive.
2. SGT compensates for electrical background noise and interferences.
3. SGT quantifies the confidence levels of the test results.

Conclusion

This paper has presented a logical approach to the design of a required electrical grounding (earthing) system. Key grounding principles have been explained and various applicable grounding equations have been provided for the reader to design his or her grounding system in a logical, methodical way. For more information or assistance with grounding system design, testing or any related topic, please contact Lightning Eliminators & Consultants.