Grounding Fundamentals

Grounding requires a knowledge of soil resistivity, the impact of rod electrodes and the effects of the environment on resistivity.

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INTRODUCTION

In the study, analysis, and design of lightning protection systems, earth grounding is perhaps one of the most difficult portions of the protection design. This is true because earth grounding systems must be designed individually based on specific site and soil conditions, which vary widely. That information and an understanding of grounding fundamentals is often not readily available to engineers, contractors, and project managers. The focus of this article is to provide the reader with the basic information and knowledge to understand and design a safe, effective, and reliable earth grounding system.

For the purposes of this article, grounding can be described as the science of obtaining a low-resistance path for the dissipation of current into the earth. There are different methods to obtain a ground, but first a discussion of grounding fundamentals is crucial to understanding and designing a grounding system.

Grounding is the physical bonding or connection of equipment by a conductor to the earth. The earth is composed of many materials that are variously good and poor conductors of electricity, but the earth as a whole is considered a good conductor. For this reason and as a reference point, the earth's potential is assumed to be zero. When an object is grounded, it is thereby forced to assume the same zero potential as the earth. If the potential of the grounded object is higher or lower, current will pass through the grounding connection until the potential of the object and earth are the same. The earth electrode is that connection path from equipment to the earth. The resistance of the electrode, measured in ohms, determines how quickly, and at what potential, energy is equalized. Hence, grounding is necessary to maintain an object's potential the same as that of the earth.

Grounding is critical for several reasons. The first is human safety. A low resistance ground will keep equipment at or near earth potential, reducing any voltage difference between equipment and "earth." This will prevent an accident or fatality during human contact.

Second, grounding is meant, along with transient voltage surge suppressors (TVSS), to protect equipment from voltage surges and transients. Damage to sensitive telecommunication equipment from surges caused by lightning, etc., can result in the loss of millions of dollars in damages and downtime.

The third reason is the cost of failures. Equipment failures caused by inadequate grounding hinder performance and productivity which increase costs of operations.

Finally, grounding offers peace of mind. When a low resistance ground is in place, equipment, personal and financial investments are protected.

A grounding system design has two main objectives. First, it is meant to provide personal safety and equipment protection by providing a low-resistance path to safely dissipate any unwanted charges or potentials. Second, it is meant to provide a "reference point" approximately equal to the potential of the earth for sensitive equipment. To be effective, a grounding system must be stable and reliable in all adverse environmental conditions, be maintenance-free, and have a long life expectancy with no recurring costs.

LIGHTNING PROTECTION

Air terminals, catenaries or down-conductors, bonding connections, surge suppression devices, and grounding are the primary components of a lightning protection system. The NFPA Lightning Protection Code 780 explains the design and application of most of these components using mathematical models. The same depth and detail is not specified for grounding, and as such, is not addressed as thoroughly by lightning protection design professionals.

The grounding system is the most important 'end point' of the lightning protection system. Without the ground or 'end point' the lightning protection system cannot function or protect as designed. The earth grounding is essentially buried under the ground and is invisible to inspection and maintenance. Since it is the only part of the lightning protection system which cannot be regularly inspected, it is even more important to design the grounding system safely and properly.

The grounding system is responsible for dissipating or transferring the high energy event of a lightning strike from man-made metal structures into the 'natural' earth. The grounding system must be conductive, durable, heat-resistant, and resilient. It should be low enough in impedance to minimize the ground potential rise in the soil surrounding the grounding system and the voltage potentials on all interconnected components.

GROUND SYSTEM DESIGN FUNDAMENTALS

SOIL CHARACTERISTICS

Soil characteristics determine the design and physical construction of a grounding system necessary to achieve a desired ohmic resistance. This includes grounding electrodes, electrode spacing, and placement. The single most important characteristic that we are concerned about is the soil's conductivity or ability to conduct electricity, inversely called soil resistivity. Soil resistivity testing will determine how resistive to electric current flow the soil is, and ultimately the grounding system layout necessqary to achieve a specific earth-ground resistance. Factors that affect soil resistivity are its moisture content, its electrolyte and metal content, and environmental changes in temperature.

**See advertisement on page 58*

SOIL RESISTIVITY

Soil or earth resistivity is the soil's electrical resistance to the flow of dc and ac current. The most common unit used is the ohm-meter, which refers to the resistance measurement between opposite faces of a cubic meter of soil. Theoretically, the earth-ground resistance of any ground system or electrode, R, can be calculated using the general resistance formula:

$$R = \rho(L/A)$$

where
ρ = Resistivity of the earth (ohm-meter)
L = Length of the conducting path (meters)
A = Cross-sectional area of the path (square meters)

This design process will be discussed later. Hence, soil resistivity is a proportional constant that relates the resistance of a ground system to the length of the conducting path and its cross-sectional area. It is important to measure soil resistivity since resistivity can vary widely in different soil mediums. For example, typical surface soils can vary in resistivity from a range of 100 to 5000 ohm-cm. Moreover, knowing what the resistivity is in surface soil is necessary for an effective grounding design.

MEASUREMENT

Typically, soil resistivity is measured according to the Wenner four-pin electrode method using a ground resistance meter. Four metal pins are placed in contact with the ground in a straight line equally spaced (Figure 1). A constant current is then injected through the ground via the tester and the outer two electrodes, labeled C1 and C2.

The potential drop is then measured across the inner two electrodes, labeled P1 and P2. The meter provides a direct ohm reading that is used in the following formula to determine soil resistivity:

$$\rho = 191.5 \cdot R \cdot A$$

Where
191.5 = Constant
ρ = Soil resistivity (ohm-cm)
R = Ground resistance meter readout (ohms)
A = Distance between electrodes (feet)

The resistivity calculated is the resistivity of the soil between the surface of the ground and a depth equal to the pin spacing.

EFFECTS OF MOISTURE, TEMPERATURE AND SALT ON RESISTIVITY

Most soils naturally contain varying amounts of electrolytes that conduct electricity. As a result, the addition of moisture will enhance conductive properties; the greater the moisture content in soil, the lower the resistivity. However, the addition of moisture to soils which include granite, sandstone, and surface limestone will have little or no effect in reducing the resistivity.

Temperature, like moisture, can have a significant impact on resistivity. The soil resistivity does not vary much with temperature until the temperatures reach freezing conditions; i.e., 32° F. At this temperature the moisture in the soil will "freeze-up" and the resistivity will increase.

The amount of salts in the ground also influence a soil's resistivity. In general, the more salts or electrolytes that a soil contains, the lower the resistivity.

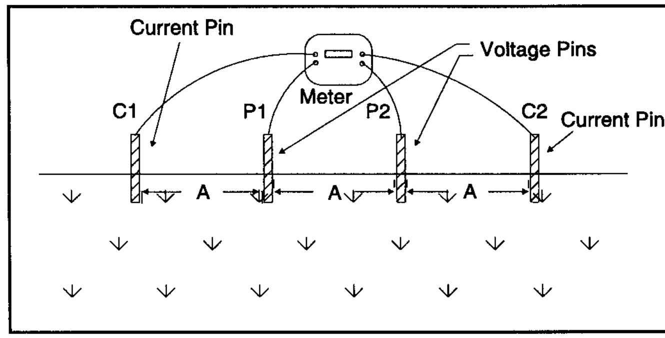

Figure 1. Wenner Four-pin Electrode Method.

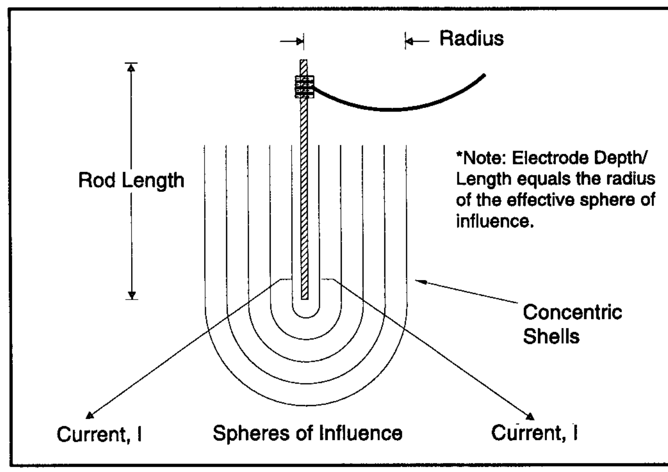

Figure 2. Spheres of Influence of the Electrode.

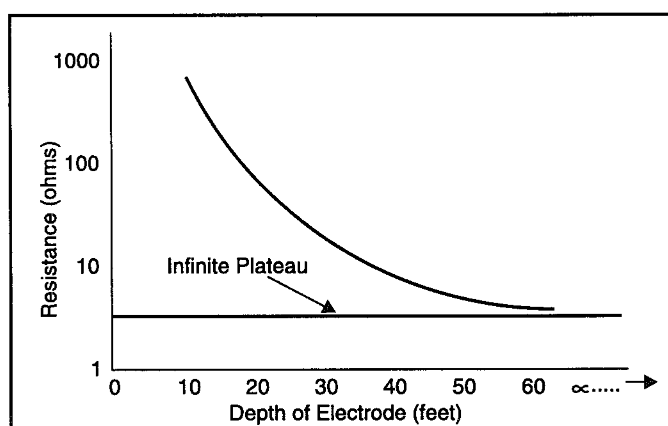

Figure 3. Resistance vs. Electrode Length.

GROUND ELECTRODES

A grounding rod driven into the earth of uniform soil resistivity will radiate current in all directions. This is the electrode's sphere of influence on the environment (Figure 2). The ability of the electrode to radiate current is directly dependent on the soil's resistivity. The higher the resistivity, the less effective the grounding electrode will be in dissipating the current. Hence, higher resistivities will result in high resistance earth-grounds, which are compensated for in a grounding system design strategy.

SPHERES OF INFLUENCE AND AVAILABLE SPACE

An electrode of length L will have a sphere of influence with a radius approximately equal to length L. In a grounding

DAMPED SINE WAVE
and
DOUBLE EXPONENTIAL WAVEFORMS

Model 9354-1 Universal Transient Generator for susceptibility tests per MIL-STD-461C/D, DO-160C and other specifications

APPLICATION

Model 9354-1 Universal Transient Generator performs a variety of pulse susceptibility tests in accordance with RTCA DO-160D, Section 22; Tri-Service Specification MIL-STD-461C, methods CS10 and CS11; MIL-STD-461D, method CS116.

Through the use of many Solar accessories, including various resistive and/or reactive networks and coupling devices, as well as other commercially available items, the generated output may be modified and applied to other specifications (i.e. MIL-STD-1399, IEC 801-5).

DESCRIPTION

Model 9354-1 Universal Transient Generator provides nine selectable waveforms, including six damped sinusoidal pulses (10 KHz, 100 KHz, 1 MHz, 10 MHz, 30 MHz, and 100 MHz) and three double exponential pulses (6.4 μS, 70 μS and 500 μS).

For the 6.4 μS and the 70 μS duration pulses, the repetition rate is internally adjusted from 0.5 to 2.0 pulses per second. A panel-mounted push button is used for manually triggering single pulses. The peak amplitude of the selected output pulse is adjustable as a percentage of the charge voltage. The open circuit discharge voltage is displayed on the panel-mounted digital voltmeter.

The six damped sinusoidal waveforms meet the requirements of MIL-STD-461D, CS116, when applied in accordance with the corresponding test method of MIL-STD-462D.

These same waveforms are applicable to the requirements of MIL-STD-461C, CS10 and CS11 when applied per test method MIL-STD-462, Notice 5.

Two of the six damped sinusoidal waveforms (1 MHz and 10 MHz) have their limits extended to an open circuit voltage of 3200 volts and a short circuit current of 128 amperes to meet the requirements of DO-160C, Section 22, Table 22-2, for waveform 3 to level 5.

The three double exponential pulses meet the requirements of DO-160C, Section 22. The 70 μS pulse (waveform 4) and the 500 μS pulse (waveform 5) meet the requirements of Table 22-2 to levels 5 and 4 respectively. The 70 μS pulse (waveform 1) and the 6.4 μS pulse (waveform 2) meet the requirements of Table 22-3 to level 3.

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system, if two electrodes are spaced too close to each other, the spheres of influence will overlap with each other, reducing or minimizing the electrode(s) ability to dissipate current. To take full advantage of the electrode's sphere of influence, the electrodes should be placed at a minimum distance of two times the length of the electrode.

ROD LENGTH VS. RESISTANCE

Rod length is one of the factors that determines earth-ground resistance in a grounding system. Longer rods, greater than ten feet, have a larger sphere of influence and as a result will dissipate more current than shorter rods. This will result in a lower-resistance earth-ground in a soil of uniform resistivity. However, as the rod length increases, the sphere of influence will reach an infinite plateau where the resistance of the earth-ground will not change anymore (Figure 3). Once the infinite plateau is reached at length L, extending the length of the rod past this length will have little effect in lowering the resistance of the grounding system.

RESISTANCE VS. NUMBER OF ELECTRODES

The earth-ground resistance of a ground system is dependent on the number of electrodes placed in the soil. The addition of electrodes will reduce the resistance of the ground system until, it too reaches an infinite plateau. The plateau is the result of overlapping spheres of influence of the electrodes in the ground system area. The ground system area can be also called counterpoise or ground grid. The addition of electrodes when the plateau point is reached will not make any significant changes in lowering the earth-ground resistance. In order to further minimize the earth-ground resistance in severe areas, it is necessary to increase the ground system area.

TYPES OF GROUNDING

There are several types of grounding systems used in industry today. Some of the most common include driven rods, water pipes, chemical wells, ufer grounds and electrolytic rods. Each is briefly described.

DRIVEN RODS & WATER PIPES

Driven rods are usually copper-clad steel rods that are pounded into the ground. They are inexpensive and are typically 10 feet long with a 5/8" diameter. Driven rods are used as part of grid systems or as isolated equipment grounds. Some of the drawbacks of using driven rods include the following:

- They are easily affected by the environment, aging, temperature, and moisture.
- Their resistance increases steadily with age.
- They are easily damaged during installation. Scratches expose the steel metal to the environment, which will make it susceptible to corrosion attack.

Driven rods are inexpensive and are adequate for a short time in good soil conditions; however they will eventually fail in service.

Water pipes or water mains are used as earth electrodes. There are some drawbacks to using a water pipe ground:

- They are difficult to test and impossible to maintain.
- Plastic inserts or o-rings destroy the circuit integrity.
- Cold water pipes produce condensation which encourages corrosion.

Water pipes should never be used as a single ground source. They are an unreliable grounding source which can be destroyed by a simple plumbing upgrade. Instead, water pipes should be used in conjunction with driven rods or a ground grid system in compliance with NEC 250.

CHEMICAL WELLS AND UFER GROUNDS

Chemical wells are ground wells that are filled with highly conductive chemicals and connected to grounding systems with copper rods. Many old-fashioned chemicals, such as copper sulfate and magnesium sulfate, are usually hazardous to the environment and are restricted by the EPA.

Ufer grounds consist of copper wire grids that are incorporated into the building foundation concrete during construction. Ufer grounds are impossible to test and maintain since the conductor, typically 4/0 stranded cable, disappears into the foundation. As a result, time and gradual removal of moisture can cause changes in foundation integrity and ground resistance.

ELECTROLYTIC RODS

Electrolytic rods are 100% copper tubes filled with natural earth salts. To be effective, "active" electrolytic rods must have holes drilled near the top and bottom of the rod. The holes near the top are referred to as "breather" holes and are an inlet for the air to enter. The hygroscopic salts in the tube absorb the moisture in the air and form an electrolytic solution. This solution is then deposited into the backfilled soil environment by "weeping" out through the bottom holes, creating electrolytic roots. The electrolytic roots produced further lower the resistance of the ground by ionizing the surrounding soil. For example, sodium chloride (NaCl), changes physically from a solid to a aqueous state producing the following ions:

$$NaCl(s) =====> Na^+ + Cl^-(aq.)$$

In general, the reaction that changes the physical state of any salt can be described as:

$$MX(s) =====> M^+ + X^- (aq.)$$

Where

M^+ = Metal cation

X^- = Nonmetal anion

This solution creates electrolytic roots that dissipate electrical current.

The active electrolytic rod does not have to be recharged or filled with salts as with most chemical systems. This allows it to be maintenance-free. Another advantage is the ability of the ionizing salts to lower the freezing temperature of the moisture, allowing the system to be effective in "freezing" conditions.

When these types of systems are installed, a hole is augered into the ground. The rod is then placed into the hole which is backfilled with bentonite — a natural, neutral pH clay. This makes electrolytic rods reliable since they are protected from the corrosive soil environment and are not as prone to corrosion attack which is a problem with driven rods and other systems.

DESIGN PROCESS

The design process for a grounding system begins with a site survey of the installation area. A site survey must include soil resistivity analysis at several depths, relevant site plans, a topography analysis and a boring core sample if available. The site survey will determine if any physical barriers such as rock, high-resistivity soil or power lines will affect the earth-ground

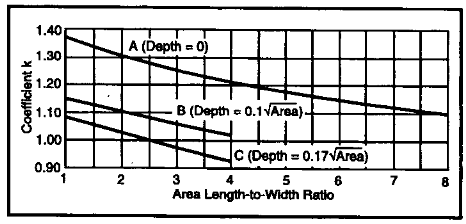

Figure 4. Coefficient "K" (courtesy of Gilbert Sharick).

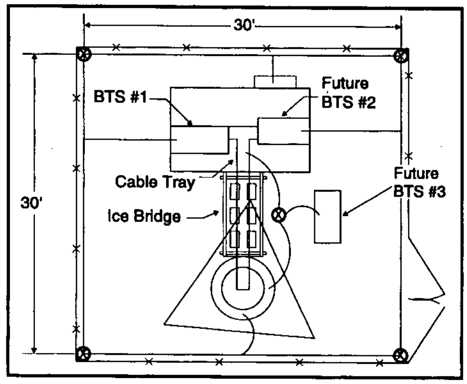

Figure 5. Grounding Design for Telecommunications Site.

resistance in the installation area. Once the information is obtained, a design can be initiated. Our discussion will begin with the most simple scenarios and equations.

SINGLE VERTICAL ROD DESIGN

The earth-ground resistance for a single electrode, such as a driven rod or electrolytic rod, can be calculated from the following formula:

$$R = \rho/2\ \pi(l(2l/r)(1 + 2K))$$

Where

R = Resistance (ohms)

ρ = Mean soil resistivity (ohm-cm)

l = Length of rod (cm)

r = Radius of rod (cm)

K = Coefficient from Figure 4.

Nomographs are available in various IEEE publications and provide basic information for simple designs.

In a grounding design there are many geometric configurations to consider when calculating resistance, i.e., 90° bends and conductor length. Formulas for different grounding configurations can be found in the IEEE Standard 142 Green book. Hand-calculating the formulas may result in errors; it is recommended that computer software be used to design the grounding system. By using a computer, the designer is able to investigate different configurations of the ground system in order to obtain a target resistance. This will save time since the computer will perform the computations of a grounding configuration in fractions of manual time.

30 NANOSECOND PULSE GENERATOR

For MIL-STD-461C/D, CS115

APPLICATION

Solar Model 9355-1 Pulse Generator is designed to provide impulse excitation by means of an injection probe placed around interconnecting cables or power wires. The unit uses a charged transmission line (50 ohms) to generate a pulse with less than 2 nS rise and fall time, and duration at least 30 nS, calibrated in a 50 ohm fixture to deliver up to 5 amperes at a rate of 30 p.p.s. for one minute as required by MIL-STD-461D, test method CS115.

DESCRIPTION

The charged line potential of the **Model 9355-1** is adjustable from less than 2 volts to greater than 2000 volts. The repetition rate is variable from less than 0.6 p.p.s. to greater than 150 p.p.s., or single pulses manually triggered by a panel mounted push button. Digital displays monitor the charging voltage and pulse repetition rate.

SPECIFICATIONS

OUTPUT PULSE

Charging voltage: Adj. from 2 to 2000 volts
Rise/Fall Time: <2 nanoseconds
Duration Time: 35 nanoseconds
Pulse Repetition Rate: 0.6 p.p.s. to 150 p.p.s.
Polarity: ±selectable
Output Load: 50 ±j 0 ohms

IMPEDANCE MATCHING INJECTION PROBE

Universal Coupling Device

APPLICATION

Various EMI specifications require the injection of high level voltage or current pulses and the reception of low level voltage or current emissions using a toroidal transformer or coupling device around the interconnecting conductors of the subsystems/equipment being tested.

The **Type 9335-1 Universal Coupling Device** is a split toroid, designed as a versatile impedance matching transformer used in conjunction with a generator as an injection probe for conducted susceptibility tests such as methods CS10 and CS11 of MIL-STD-462, Notice 5; CS116 of MIL-STD-462D; DO-160C, Section 22, Figure 22-12; and other specifications.

INJECTION – High power transient generators with source impedances from 0.25 Ω to 50 Ω can use this probe to deliver high peak voltage or high current pulses into the wires or cables passing through the window.

DESCRIPTION

The unique winding arrangement of this impedance matching probe provides step-up or step-down ratios with respect to either: 1) the source impedance of the connected generator, when used for injection, or 2) the load impedance of the connected receiver, when used for reception. This results in maximum power transfer into or out of the transformer winding formed by the cable bundle passing through the window.

Through connector port selection, the open circuit voltage or short circuit current can be easily adjusted for maximum transfer of energy. This is especially useful as an accessory to the **Model 9354-1 Universal Transient Pulse Generator** with its differing source impedances, enabling it to meet various open circuit voltage, and short circuit current requirements.

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Some programs require only resistivity data and ground system dimensions. The program can develop a soil resistivity model from the raw field data which the designer then uses in the design. Using a three-dimensional coordinate system, the user can program a geometric arrangement from the site dimensions incorporating buried conductor; i.e., 4/0, grounding electrodes and mesh grids.

The program then uses a matrix to compute the earth-ground resistance. The designer can use several different arrangements until the a target resistance is reached.

SAMPLE APPLICATION (SPECIFIC TO PCS SITES)

Figure 5 shows a grounding design for a personal communication system (PCS) telecommunications site. Typically, these sites require earth-ground resistances of 10 ohms or less. Electrolytic rods are commonly used since they are more reliable and stable in harsh environments and because the earth-ground resistance is low and improves over time. Telecommunications providers understand that even short equipment failures can cost immensely in repairs and customer loyalty.

The design was modeled using a proprietary software. The design is a 30′ x 30′ grid counterpoise consisting of buried conductor buried 2.5′ deep or 6" below the frost line. Electrolytic rods are placed on each corner of the counterpoise and one between the plenum/base transceiver station (BTS) shelter and the base of the tower.

The BTS equipment and the legs of the tower base are connected to the rod that is located between the shelter and tower. The rod is intentionally placed there for lightning protection. The design in these soil conditions will provide a highly dependable earth-ground resistance (under 10 ohms is required), which is intended to last longer than the PCS unit itself.

Grounding for the PCS site requires knowledge of grounding fundamentals. For example, using 10′ electrolytic rods, the rods must be spaced at least 20′ apart (2L) in order to take full advantage of the sphere of influence of the rods. Ground conductors must be buried below the frost line and connected to the rods in a counterpoise arrangement — this insures system integrity. Finally, the PCS grounding system is an example of a grounding system that is stable, reliable, safe, maintenance-free and long lasting with no recurring costs (Figure 5). The use of electrolytic rods is recommended in any grounding system.

CONCLUSION

Grounding requires a knowledge of soil resistivity, the impact of rod electrodes and the effects of environment on resistivity. These characteristics ultimately determine the grounding layout to obtain a "target" earth-ground resistance. In general, increasing the moisture and salt content of soil will decrease its resistivity. However lowering the temperature of the environment, i.e., 32° F, will increase its resistivity.

There are several types of grounding methods, such as chemical wells, ufer grounds, driven rods and electrolytic rods, that will offer the earth-ground reference. Electrolytic rods have the advantage of producing their own electrolytes, since moisture is absorbed by the salts in the rod. The electrolytes then "weep" out the bottom, creating electrolytic roots that lower the resistance of the ground system.

The first step in any grounding design is to obtain accurate soil resistivity data. Second, it is necessary to determine which grounding configuration will give a specific resistance within the installation area. This can be determined by using formulas (IEEE Standard 142, Green Book) or nomographs for calculating the resistance of a single vertical rod. If the target earth-ground resistance is not achieved, it is necessary to use multiple rods, or another arrangement. The use of computer software to determine a grounding configuration is recommended.

Another recommendation is that all engineers, builders, and managers contact a firm specializing in grounding system design and with a proven and verifiable history of experience. Grounding is a scientific process and one on which equipment protection and human safety are critically reliant.

***OSWALDO MOLINA** received a BSChE from California State Polytechnic University. He is experienced in the design of earth grounding and lightning protection systems and frequently works in the field performing grounding system testing and supervising installation. (800) 962-2610.*

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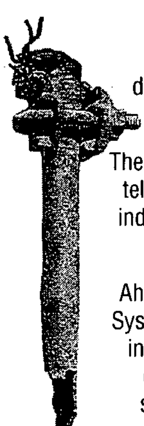
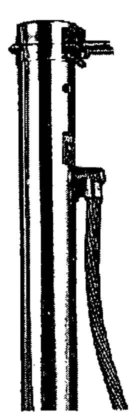
ancient ruins. **buried treasure.**





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