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AFFECTING NEUTRAL-TO-EARTH VOLTAGE LEVELS
THROUGH MODIFICATIONS OF THE FARM
ELECTRICAL GROUNDING SYSTEM

presented by

Jonathan Ronald Althouse

has been accepted towards fulfillment
of the requirements for

M. S. degree in Agricultural Technology and Systems Management

Truman C Surbrook

Major professor

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AFFECTING NEUTRAL-TO-EARTH VOLTAGE LEVELS THROUGH MODIFICATIONS OF THE FARM ELECTRICAL GROUNDING SYSTEM

By

Jonathan Ronald Althouse

A THESIS

Submitted to
Michigan State University
in partial fulfillment of
the requirements for

MASTER OF SCIENCE

in

Agricultural Technology and Systems Management

Department of Agricultural Engineering

1990

ABSTRACT

AFFECTING NEUTRAL-TO-EARTH VOLTAGE LEVELS THROUGH MODIFICATIONS TO THE FARM ELECTRICAL GROUNDING SYSTEM

By

Jonathan Ronald Althouse

By modifying the on-farm electrical grounding system, neutral-to-earth voltage levels can be altered. Possible methods of modifying the on-farm electrical grounding system include the installation of an equipotential plane and isolation of the grounding system. Both are widely used means for reducing the level of neutral-to-earth voltage in cow contact areas.

Extensive research has been done on the design of equipotential planes. However, little work has been done on the transition areas on and off the equipotential plane. In these transition areas, a dairy cow can experience a step potential at a possible behavior altering level.

Power suppliers sometimes isolate the primary electrical system from the secondary electrical system. This is done by installing any one of several different isolating devices between the primary neutral and the secondary neutral, and connecting the neutral conductors to their own respective grounding electrodes. The earth is used as the isolating medium between the two grounding systems. Isolating an electrical system from its source will reduce the level of neutral-to-earth voltage entering the isolated grounding system from the source system.

This thesis examines the step potential circuit for a dairy cow as well as the voltage gradient in the areas adjacent to equipotential planes. It evaluates the gradient alterations caused by different modifications to the equipotential plane. A design was proposed for reducing the step potential to 1 volt when neutral-to-earth voltages were as high as 5 volts, measured from equipotential plane to reference ground.

Circuitry is analyzed and the affect of source system neutral-to-earth voltage levels and distance between ground rods has upon the isolated system are studied. The equivalent circuit for two isolated systems can be approximated by a linear resistive circuit. A procedure is given for determining current flow through an animal when it contacts a neutral and "true earth" on an isolated system.

Approved:

Truman C Surbrook
Major Professor

Larry J Segerlind
Department Chairperson

Copyright by

Jonathan Ronald Althouse

1990

DEDICATION

I would like to dedicate this thesis to my grandparents, Howard and Francis Althouse, who touched many hearts and passed on to me and to all those who knew them a great love for the outdoors, friends and family in a way that can not be expressed in words.

ACKNOWLEDGMENTS

I would like to express my deepest gratitude to Dr. Truman C. Surbrook, advisor and friend, for his encouragement as well as the moral and technical support he has shared with me since I became an Electrical Technology student in 1980.

I would like to thank Dr. Roger Mellenberger, Dr. John Gerrish and Mr. Norman Reese for serving on my guidance committee and the Wisconsin Electric Utilities Research Foundation for funding this project. Also, I would like to thank the faculty and staff of the Department of Agricultural Engineering and the Institute of Agricultural Technology for their assistance and cooperation.

A special thanks goes to my parents Ronald and Judith Althouse and all of my friends and family whose advice, understanding and moral support made this a success and for being there during the bad as well as the good times.

A very special thanks goes to Lori whose encouragement, love and understanding made the countless hours of work go by a little easier and made this dream a reality. Even with her patience stretched to the limit, she still found it within herself to care.

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LIST OF SYMBOLS

E_I Measured voltage on the isolated system, volt

E_{IC} Calculated voltage on the isolated system, volt

E_S Measured voltage on the source system, volt

E_{SC} Calculated voltage on the source system, volt

E_{S-I} Voltage between the source and isolated systems, volt

I_A Current that flows through the simulated animal, ampere

I_I Current measured that flows through the isolated grounding system, ampere

I_T Current measured that flows through the source grounding system, ampere

R_A Total resistance of the simulated animal, R_{AA} + R_{A1}, ohms

R_{AA} Variable resistance of the simulated animal circuit, ohms

R_{A1} Resistance of the isolated ground rod, ohms

R_D Resistance of the source farm grounding system, ohms

R_F Total resistance of the grounding electrode system for the isolated farm system circuit, R_{FF} + R_{F1}, ohms

R_{FF} Variable resistance of the grounding electrode system for the isolated farm system circuit, ohms

R_{F1} Resistance of the grounding electrode system for the isolated farm electrical system, ohms

R_I Portion of isolated ground rod resistance in the circuit, ohms

R_S Total resistance of the source ground rod, ohms

R_T Thevenin equivalent resistance of an animal on an isolated farm, ohms

I. INTRODUCTION

Electrical voltages are frequently measured on farms in locations where animals can potentially be exposed to the voltages. This voltage, frequently called neutral-to-earth voltage, may have a magnitude of a fraction of a volt or several volts. Other common terms used to describe neutral-to-earth voltage include stray voltage, neutral-to-ground voltage, transient voltage or tingle voltage. All of these terms describe a condition where the grounded electrical conductor is at a different potential than the adjacent earth. The primary causes of neutral-to-earth voltage are voltage drop on the grounded electrical conductor and ground faults that occur on the primary electrical system and/or on-farm wiring. This difference of potential is of concern to livestock farmers, electric power suppliers, agricultural equipment manufacturers, and service personnel because the voltage may be present in a location where animals may become a part of the circuit.

Though researchers commonly speak about levels of voltages, it is actually the electrical current flowing through the body of an animal that causes an electrical sensation or an effect. Voltage is what causes the electrical current to flow through the resistance of the circuit. Different paths through an animal have different levels of resistance. Consequently, a given voltage at one set of contact points may affect an animal, while the same level of voltage through a different path will not affect the animal. Even at a given voltage level for a particular path, there will be variability in the effect between different animals. Questions have also been raised regarding the effects that frequency and duration of exposure to the neutral-to-earth voltage has on an animal's behavior.

Depending on the source, there are a number of mitigating techniques to limit the level of neutral-to-earth voltage contacting an animal. One technique frequently employed on many dairy farms is to limit the level of voltage across the contact points of a cow in a dairy barn or milking parlor by installing an equipotential plane.

A grounding electrode or any metal element making contact with the earth creates a voltage gradient in the adjacent earth. Neutral-to-earth voltage can be measured from the neutral grounding bus to a distant reference point on the earth. A voltage gradient exists between the equipotential plane and the reference point on the earth where the voltage was measured. Depending on the magnitude and slope of this voltage gradient which radiates out from an equipotential plane, a high difference of potential may be present between front and rear hooves of a cow.

In most dairy operations, cows are not on an equipotential plane at all times. Cows entering or leaving a milking parlor or stanchion barn where an equipotential plane is installed may experience is a voltage gradient from "true-earth" to the equipotential plane. Researchers have suggested that a transition area or voltage ramp is necessary for cows to traverse when entering or leaving the equipotential plane. The transition plane should be designed so that a dairy cow will not be exposed to a behavioral modifying voltage.

Another possible method of reducing the level of neutral-to-earth voltage is to isolate the electrical grounding system. The most common form of isolation is to separate the on-farm electrical grounding system from the primary distribution electrical grounding system. While it is not possible to eliminate all sources of neutral-to-earth voltage, the purpose of isolation is to reduce the level of neutral-to-earth voltage present on one electrical system which can get to another electrical system.

There are a number of different methods and devices used to isolate one electrical system from another. However, all methods of isolation rely on the earth as an isolating medium for the two electrical grounding systems since the two systems are grounded to their own grounding electrodes. Questions have been raised concerning the effectiveness of the earth as an isolating medium between grounding electrodes to two electrical systems.

The major focus of this thesis was affecting neutral-to-earth voltage levels through modifications to the electrical grounding system. Specifically, this thesis studies altering the voltage gradients immediately surrounding an equipotential plane as well as studying the effectiveness of the earth as an isolating medium when two electrical grounding systems are isolated.

To test the effectiveness of the different modifications made to the equipotential planes, it was necessary to examine the step potential circuit for a dairy cow and establish a step potential voltage level at which a cow's behavior may be affected. To examine techniques of isolating two grounded electrical systems from each other, it was necessary to develop a series of tests to determine the level of voltage and current which appears on the isolated electrical system due to a neutral-to-earth voltage level on the source system.

II. LITERATURE REVIEW

Neutral-to-earth voltages have frequently been measured on U. S. farms in locations where animals can become part of the electrical circuit. According to Craine (1980), neutral-to-earth voltage problems have been reported internationally since the 1960's. Neutral-to-earth voltage is an inherent phenomenon of the grounded primary and secondary electrical systems. According to Woolford (1972), there may be a situation where the neutral-to-earth voltage may be present in a location at such a level that it may cause a behavioral change in dairy cows. Cloud et al. (1987) reported that this behavioral change may be in the form of a cow's nervousness, kicking, and reduced feed and water intake. These factors have been alleged to have an adverse effect on milk production [Lefcourt & Akers (1982), Norell et al. (1983), and Drenkard et al. (1983)].

Gorewit et al. (1989) studied water intake and milk yield before, during and after 21 days of exposure to a continuous voltage from a water bowl to a metal floor mat. Thirty cows under analysis were divided equally among treatments of 0, 0.5, 1, 2 and 4 volts. They concluded that there was no significant change in milk yield or water intake when the voltage from water bowl to metal floor mat was at or below 2 volts, though the initial application of voltage did cause delays in drinking. Two of the animals receiving 4.0 volts did not drink for 36 hours at which time the researchers disconnected the voltage source.

There has been a great deal of research on the sources, measuring and mitigation of neutral-to-earth voltage. This research focuses primarily on mitigation techniques, specifically modifications to the on-farm electrical grounding system. The design criteria was to modify the on-farm electrical grounding system so that most dairy cows would not experience a shock which could affect her behavior most of the time. In order to establish this design criteria, it was necessary to examine the step potential circuit for a dairy cow.

A. Neutral-to-Earth Voltage Sources

Their are two major sources of neutral-to-earth voltage: voltage on the neutral conductor and ground faults. These two sources are broken down into two categories, on-farm and off-farm. Both sources can appear simultaneously, which makes their identification difficult [Appleman & Cloud (1981) and Surbrook et al. (1987)].

1. Voltage Drop

Neutral-to-earth voltage is an inherent characteristic of both the on- and off-farm grounded electrical distribution systems. In most rural sections of the United States and in several other countries, the power suppliers utilize a grounded electrical system on the primary as required by the National Electrical Safety Code.

The National Electrical Code requires the grounding for most on site or customer owned electrical systems. The purpose for this grounding is discussed in the National Electrical Code Section 250-1 (FPN No. 1). The customer-owned electrical system is grounded to limit voltages resulting from lightning line surges or unintentional contact with higher voltages. It is also grounded to stabilize the voltage-to-ground during normal operation and to facilitate the operation of overcurrent devices for ground faults. Though grounding the primary and secondary electrical systems, neutral-to-earth voltage will be produced at some level due to voltage drop on the neutral conductor. This is the most frequent source of on- and off-farm neutral-to-earth voltage [Reese and Surbrook, (1984)].

All electrical conductors have a finite amount of resistance to the flow of electrical current. When current flows through a grounded neutral conductor, a naturally occurring voltage drop is produced on that neutral [Reese & Surbrook (1984) and Appleman & Gustafson (1985)]. High resistance in the neutral conductor can be caused by loose or oxidized connections and inadequately sized feeder conductors. Improper load balancing can increase the voltage drop on the secondary neutral conductor [Seeling (1980)] and likewise for the primary neutral conductor [Surbrook et al. (1988)]. Gustafson (1983) illustrated how voltage drop on the primary and/or secondary neutral can produce neutral-to-earth voltage in areas where dairy cows can be affected.

2. Ground Faults

The other major source of neutral-to-earth voltage is ground faults [Surbrook & Reese (1981) and Appleman & Gustafson (1985)]. Like voltage drop, both on- and off-farm ground faults can lead to neutral-to-earth voltage. A ground fault is a condition where electrical current flows directly from an ungrounded circuit conductor to an equipment grounding conductor and/or into the earth. The fault current is attempting to complete the circuit back to its source. If adequate grounding is not provided, the fault current must take a high resistance path through the earth which can cause dangerous step and touch potentials in the area of the fault [Gustafson & Cloud, (1981)]. Typical causes of on-farm ground faults are insulation breakdown and improper connections. Usually, a ground fault causes only a local problem and the seriousness of the situation depends on the circuit parameters involved. Surbrook et al. (1988) discussed the effects that ground faults on the primary distribution system can have on neutral-to-earth voltage levels and the on-farm effects are discussed by Gustafson (1983).

B. Measuring Neutral-to-Earth Voltage

There are two methods of measuring neutral-to-earth voltages. One method involves taking measurements between animal contact points such as between the stanchions and the floor or water bowl and floor. The other method involves taking measurements from a reference ground to an object where a voltage may be present [Cloud et al. (1987)]. When making a thorough neutral-to-earth voltage investigation it is often necessary to use both methods [Surbrook et al. (1988), and Luddington et al. (1987)].

Surbrook and Reese (1984) and Soderholm (1982) discussed the materials needed to make neutral-to-earth voltage measurements to a reference ground. They include a voltmeter and a reference ground.

1. Voltmeter

The voltmeter can be either an analog or digital. If an analog meter is used it should have a scale with a range not greater than 0.0 to 5.0 volts AC. Surbrook et al. (1988) reported that the meter must be able to discriminate between AC and DC.

The digital voltmeter usually samples input voltages over an increment of time and has a much higher internal impedance than analog meters. Gustafson (1983) stated that the meter used should have a relatively high internal impedance, at least 5,000 ohms per volt, AC, because low-impedance meters may read low as a result of the voltage drop in the external circuit.

2. Reference Ground

The reference ground, consisting of a ground rod, should be place away from any metal, grounds and equipment because such items could effect the voltage reading due to voltage gradients in the earth. Cloud et al. (1987) suggest that the reference ground should be placed at least 25 feet (7.6 m) from such objects. According to Surbrook and Reese (1984) a reference ground 14 to 18 inches (36 to 46 cm) in length is satisfactory for making voltage measurements, Gustafson (1983) reported that the reference ground must be placed in the earth at least 48 inches (1.2 m).

C. Animal Step Potential Circuit

Animals are not affected by the voltage but by the electrical current produced by these voltages [Norell et al (1983)]. It is electrical current flowing through the body of an animal that causes an electrical sensation or an affect, but it is voltage which causes electrical current to flow through the resistance of the circuit.

Different paths through a cow have different levels of resistance [Norell et al. (1983)]. Consequently, a given voltage at one set of contact points of the cow may affect the animal, while the same level of voltage across a different path may not affect an animal. Even at a given voltage level for a particular path through an animal, there will be variability in the effect upon different animals. This is demonstrated for dairy cows by Gustafson et al. (1985) and Norell et al. (1983).

1. Circuit Parameters

The relationship between voltage, current and resistance is known as Ohm's Law. Ohm's Law can be written, $E = I \times R$, where E is the voltage (volts), I is the current flow (amperes), and R is the resistance (ohms) [Surbrook & Mullin (1985)].

The step potential circuit of a dairy cow consists of the front hooves' resistance-to-earth, the rear hooves' resistance-to-earth and the resistance through the cow's body from front to rear hooves [Reese et al. (1988)]. In the <u>Agricultural Engineers Year Book of Standards</u>, it is reported that from front to rear hooves an average mature dairy cow has a step length of 4 feet (1.2 m). Norell et al. (1983) determined a range of values of front to rear hoof body resistance of 28 dairy cows. The resistances reported ranged from 496 ohms to 1,152 ohms with a mean of 734 ohms. Based on this data, statistical analysis revealed a probability that only ten percent of dairy cows based upon this data would have a resistance less than 496 ohms [Norell et al. (1983)].

The lowest resistance path through a dairy cow is from mouth to all four hooves [Norell et al. (1983)]. For this path the resistance ranged from 244 to 525 ohms with a mean of 475 ohms. Based on this data, statistical analysis revealed a probability that only ten percent of dairy cows would have a resistance less than 244 ohms. Craine (1975) determined that the lowest mouth to all hooves resistance of 70 cows that were tested was 324 ohms, with a mean of 350 ohms. Cloud et al. (1987) and Soderholm (1982) suggest a 300 ohm resister can be used to represent the mouth to all hooves resistance of a cow.

Behavioral studies of dairy cows by Gustafson et al. (1985) revealed that the animals exposed to a step potential from front to rear hooves were less sensitive to electrical current flow than through some other body paths. Gustafson et al. (1985) concluded from the behavioral study that some cows in the test exhibited no significant change in behavioral response when the electrical current flow was below two milliamperes. However, at five milliamperes, 84 percent of the cows exhibited what the researchers described as an escape response. Scott et al. (1984) concluded that dairy cows exhibited a behavioral response between 2 and 5 milliamperes. Lefcourt et al. (1986) concluded that behavioral changes started at 2.5 milliamperes.

Researchers attempting to measure the cows' resistance-to-earth have discovered that the results are highly variable depending on whether the cow is standing on dry concrete or walking in mud. Reese et al. (1988) reported that a metal plate can be inserted between the hoof of a dairy cow and a concrete or earth surface without a significant difference in resistance-to-earth. This would imply that a metal plate the same size and shape of the cow's hoof could be substituted for the actual hoof. This research, however, did not account for the variability of the hoof-to-earth resistance and the different sizes and shapes of the dairy cow's hooves. Surbrook and Reese (1981) reported that a metal plate measuring four inches (10.16 cm) in diameter can be used to approximate the surface area for two hooves of a cow in neutral-to-earth voltage measurements.

D. Mitigation Techniques

Depending upon the source of neutral-to-earth voltage, there are a wide variety of mitigating techniques. Gustafson (1985) broke the mitigating techniques down into three categories: voltage reduction, isolation, and gradient control. All of these categories have their own particular advantages and disadvantages.

1. Voltage Reduction

Voltage reduction by means of eliminating or reducing the neutral-to-earth voltage source(s) is the most important mitigation technique. By eliminating the neutral-to-earth voltage sources, a dairy cow will not experience the troublesome differences of potential. The advantages, disadvantages and methods of eliminating the sources of neutral-to-earth voltage were pointed out by Surbrook & Reese (1984) and Appleman & Gustafson (1985). They indicated that maintaining zero current flow on the neutral conductor, to eliminate voltage drop on the neutral, is not always possible because of changing demand loads.

2. Gradient Control

Gradient control is used by power suppliers to minimize the risk of hazardous step and touch potentials in and around substations. In a livestock facility, an equipotential plane can be used as a gradient control by reducing the voltage potential difference in the areas where a cow may come in contact with a metal object and the floor [Soderholm (1982)]. A voltage gradient is produced when current flows to earth via a grounding electrode [IEEE (1982)].

Grounding electrodes are metal elements that make contact with the earth. According to the National Electrical Code Sections 250-81 and 250-83 metal underground water pipes, the metal frame of a building, ground rings and ground rods are possible grounding electrodes. The National Electrical Code, requires that a single ground rod which does not have a resistance-to-ground of 25 ohms or less shall be augmented by one additional grounding electrode.

Soil resistivity varies widely with soil type, moisture content and temperature [Soares (1980)]. It is important to realize that the resistance-to-earth of the grounding electrodes are not the source of neutral-to-earth voltage. Changing the grounding electrode resistance will merely change the level of neutral-to-earth voltage at the various buildings [Surbrook & Reese (1984) and Soderholm (1982)].

When current flows to earth via a grounding electrode, a voltage gradient is produced around the electrode. For example, a ground rod that is connected to a voltage source will produce symmetrical dish-shaped voltage contours extending outward away from the ground rod as long as the soil is homogeneous [IEEE (1982)]. This is due to the earth being made up of equal-thickness, concentric shells of resistive earth. See Figure 1. The earth shell nearest to the electrode offers the greatest resistance. With increased distance from an electrode, the earth shells are of greater surface area and, therefore, of lower resistance [IEEE (1982)]. For a ground rod that has the resistance-to-earth of 25 ohms, one half of that resistance would likely be contained within the first 1 foot (0.3 m) diameter cylinder [IEEE (1982)]. For the same reason, the majority of the voltage drop resulting from current flowing in the ground would appear across the first foot (0.3 m) of the earth's surface. The typical voltage gradient surrounding a ground rod is shown in Figure 2.

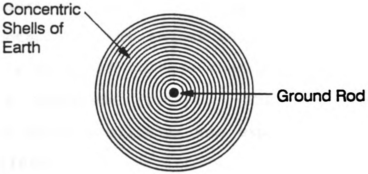

Figure 1. Equal-thickness concentric shells of resistive earth surrounding a ground rod.

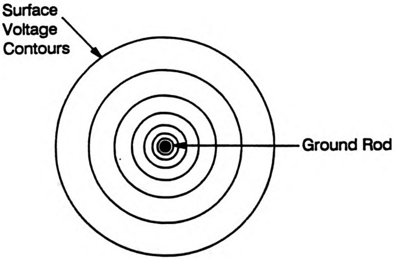

Figure 2. Symmetrical voltage gradients that would surround a ground rod in a homogeneous soil.

a. Equipotential Plane

The installation of an equipotential can reduce the possibility of animals coming in contact with neutral-to-earth voltage by keeping all cow contact surfaces at the same voltage potential [Soderholm (1982)]. By bringing all conductive surfaces that an animal may come in contact with to the same potential, the animal will be less likely to be exposed to a level of voltage that may alter its behavior [Appleman & Gustafson (1985)]. The equipotential plane concept for dairy facilities was explored by Phillips and Parkinson (1963).

The National Electrical Code Section 547-8 (b) describes an equipotential plane as an area where conductive elements are embedded in concrete and are bonded to all adjacent conductive equipment. An equipotential plane does not reduce the level of neutral-to-earth voltage. It does, however, bring all metal objects that are bonded to the equipotential plane and the equipotential plane itself to the same potential [Surbrook & Reese, (1984) and Gustafson (1985)].

Various equipotential planes have been proposed since the concept was first introduced. Phillips and Parkinson (1963) introduced some preliminary recommendations on creating equipotential planes. Phillips and Parkinson (1963) suggested that a metal mesh be welded to the stallwork. Kammel et al. (1986) recommended design criteria for newly installed equipotential planes. For the newly installed equipotential plane, they recommended using 6 inch by 6 inch (15.2 cm by 15.2 cm), 10 gauge wire mesh embedded in concrete. All metal objects adjacent to the plane are then bonded to the wire mesh by means of approved connectors or exothermic welding and the plane is in turn bonded back to the grounding bus of the electrical panel serving the area. The requirements for bonding are found in Article 250 of the National Electrical Code.

Kammel and Jones (1987) indicated that a properly installed equipotential plane can reduce voltages at cow contact points. Their research showed that after installation of an equipotential plane, cow contact voltages in one barn dropped from 0.4 volts to less than 0.1 volts. It has been suggested that equipotential planes be installed in all areas where an animal may come in contact with neutral-to-earth voltage [Surbrook et al. (1983), and Appleman & Gustafson (1985)]. These locations include all areas where electrical equipment and livestock are located, such as stanchion barns, milking parlors, feeders and waterers. The Wisconsin State Electrical Code requires the installation of an equipotential plane in all newly installed and remodeled livestock facilities.

b. Transition Planes

In most dairy operations, cows are not on an equipotential plane at all times. Cows entering from a feed lot or pasture to a milking parlor or stanchion barn that has an equipotential plane installed will experience a voltage gradient in the earth [Appleman & Gustafson (1985)]. Cows may experience neutral-to-earth voltage in the form of a step potential when leaving or entering an equipotential plane. Woolford (1969) pointed out the need to control the voltage gradients occurring where the equipotential plane ends. The need for voltage gradient control was also recognized by Fairbank and Craine (1978), Cloud et al. (1987), and McCurdy et al. (1982).

Woolford, (1969), Gustafson (1983) and Surbrook and Reese (1984) have suggested that a transition or a voltage ramp may be needed for the animals to traverse when coming upon or leaving an equipotential plane. The concept behind the transition plane is to install grounding elements in the earth at the approach paths to the equipotential plane. Installing these grounding elements will raise the surface voltage by decreasing the slope of voltage gradients surrounding the equipotential plane [Gustafson & Folen (1984)]. The transition plane or voltage ramp needs to provide a way for the animals to approach an equipotential plane without being exposed to a bothersome step potential [Surbrook et al. (1986) and Appleman & Gustafson (1985)].

Various transition planes to limit the step potential for a dairy cow have been proposed. However, limited testing has been done on their effectiveness at different voltage levels. Gustafson & Folen (1984) concluded that the transition plane should have a horizontal length at least equal to the step length of the animal. They also state that, for a given horizontal span, the step potential on the earth's surface decreases as the end of the transition is placed deeper into the earth.

To limit voltage gradients at the edge of an equipotential plane, Woolford (1969) suggested sloping the reinforcing mesh down, beneath the concrete of the floor at the entry and exits of the equipotential plane. Another gradient control method recommended by Woolford consisted of interconnecting a series of horizonal rods, embedded in concrete, over a distance of 8 feet (2.4 m) and bonding these rods to the equipotential plane. Woolford and Phillips (1981) recommended installing ground rods 30 cm apart and 2 to 3 meters in length into the earth at an angle of 20 to 30 degrees, sloping down away from the mesh and bonded to the mesh of the equipotential plane, to decrease the voltage gradients at the edge of the plane.

Another transition design suggested by Folen and Gustafson (1984) consists of ground rods driven into the earth at a 45 degree angle away from the equipotential plane. This transition design seems to be the one most widely accepted. Kammel et al. (1986), Farm Buildings Wiring Handbook (1986); and Cloud et al. (1987) suggest the use of this type of transition plane.

3. Isolation

Isolation of part of the grounding system can reduce neutral-to-earth voltage levels that an animal can contact on the isolated system. The National Electrical Safety Code allows separation of the primary and secondary neutral conductors at the farm service transformer.

Isolation is essentially separating the neutral conductor, which is the source of the neutral-to-earth voltage, from the neutral conductor that serves the area where animals reside. Isolation does not address the cause of the neutral-to-earth voltage, it simply changes the circuit parameters. Field studies undertaken by Prothero et al. (1988) indicated that isolation should be viewed as a temporary solution to a neutral-to-earth voltage problem. Cloud et al. (1987) state that isolation will not prevent neutral-to-earth voltages from being produced on the isolated system.

a. Isolation Techniques

When the whole farm is isolated, often the primary neutral conductor is separated from the secondary neutral conductor by a high impedance device. Such devices include a saturable core reactor, thyristor switch, or a spark gap [Surbrook & Reese (1984)]. Gustafson (1985) noted that careful consideration is required in choosing which device is to be installed, because each has its own operating characteristics. These operating characteristics include saturation or breakdown voltage levels, where the device will reconnect the neutral conductors by reducing its impedance when the voltage on the neutral is above this level.

When two electrical systems are isolated by using a high impedance device, each neutral conductor is connected to its own respective grounding electrode. The National Electrical Safety Code requires that these grounding electrodes be placed at least 6 feet (1.8 m) from each other. Soderholm (1982) stated that if this separation is not maintained, it will lead to continuing neutral-to-earth voltage problems on the isolated system. This spacing is required because the earth is used as the isolating medium between the neutral conductors. As an isolating medium, the earth must reduce the level of current flowing from the primary neutral conductor to the secondary neutral conductor, to a level were an animal's behavior is not altered when the animal comes in contact with the neutral on the isolated system.

To insure proper separation, it is necessary to remove all conductive interconnections between the neutrals which could bypass the isolation [Surbrook & Reese (1984), Cloud et al. (1987) and Appleman & Gustafson (1985)]. Common neutral interconnections include telephone grounding conductors and metal water lines. Any conductive interconnection will reduce the effectiveness of the isolation.

III. OBJECTIVES

Often it is not possible to eliminate or reduce all sources of neutral-to-earth voltage to acceptable levels. Therefore, electrical grounding systems are often altered to reduce the possibility that a dairy cow might come in contact with a difference of potential at such a level that would affect the animal's behavior.

The primary objective of this research was to analyze how modifications of the on-farm electrical grounding system would affect neutral-to-earth voltage levels. The secondary objective was to propose modifications to the electrical grounding system which are best suited for use on dairy farms.

A. Equipotential Planes

Meeting this objective required an examination of the voltage gradients surrounding equipotential planes. Several modifications were made to an equipotential plane to determine whether any had particular advantages or disadvantages in reducing the voltage gradients surrounding an equipotential plane. The objectives here are as follows:

1. Determine the maximum acceptable neutral-to-earth voltage measured from an equipotential plane to reference ground that will not expose a dairy cow to a step potential which exceeds the lower step potential threshold limit.
2. Determine the maximum neutral-to-earth voltage level, measured from an equipotential plane to a reference ground, that will not expose a dairy cow to a step potential which exceeds the lower step potential threshold limit, when a dairy cow steps onto the equipotential plane at a transition area consisting of diagonal eight foot (2.4 m) ground rods driven into the earth at a 45 degree angle.
3. Determine a design of a transition area which, if installed at an equipotential plane, will not expose a dairy cow to a step potential above the lower threshold limit with a minimum of 5.0 volts, neutral-to-earth, on the plane.

B. Neutral Isolation

Along with studying voltage surrounding equipotential planes, a series of tests were devised to determine the effectiveness of earth as an isolating medium for two earth grounded electrical systems, where one of the electrical systems is a source of neutral-to-earth voltage and the other is an isolated system. The objectives here are as follows:

1. Determine the equivalent circuit for a neutral-to-earth voltage source electrical system and an isolated farm electrical system, where the earth is utilized as the isolation medium between two ground rods.
2. Develop and verify a mathematical equation to determine the neutral-to-earth voltage of an isolated electrical system when there is a neutral-to-earth voltage on a source electrical system, and the earth is used as an isolation medium between a ground rod of each system.
3. Determine why the neutral-to-earth voltage on an electrical system isolated from the neutral-to-earth voltage source system, utilizing the earth as an isolation medium between a ground rods of the two systems, is less than the gradient voltage at the point where the isolated ground rod is installed.
4. Determine if a six foot (1.8 m) separation between the ground rods of a isolated and source electrical system is adequate to prevent an electrical current flow, in an animal circuit consisting of a resistance of 274 ohms, from exceeding 2.0 milliamperes.
5. Determine the maximum neutral-to-earth voltage level on a source electrical system which will cause an electrical current, not exceeding 2.0 milliamperes, to flow through a 274 ohm animal circuit, from an isolated electrical system's neutral to earth when the source and isolated ground rods are separated by a distance of six inches (15.2 m).

IV. METHODOLOGY

The test site was an actual farm consisting of a residence, shop and barn. The primary electrical system supplying the test site was an ungrounded 4.8 kV primary distribution system which insured that no off-farm sources would affect the measurements that were taken.

From the grounded secondary of the transformer, an American Wire Gauge (AWG) number 1/0, aluminum triplex supplied the residence which was grounded to the well casing. An AWG number 2 aluminum triplex feeder supplied the shop and the barn from the house. The shop and the barn were both grounded using a ground rod at each site.

The neutral-to-earth voltage source was connected onto the feeder wires that ran between the house and the shop. The equipotential plane and subsequent transitions were at the barn. All voltage measurements for the equipotential plane modifications were taken to reference ground.

A. Equipotential Plane

Before any analysis and subsequent modification of voltage gradients could be made, possible behavior affecting step potentials for dairy cows were analyzed and an equipotential plane had to be constructed. The equipotential plane that was constructed closely resembled the designs that have been suggested by many researchers.

An equipotential plane 10 feet long by 6 feet wide (3.05 m by 1.8 m) was installed at an entrance to the barn. This entrance was in an area where animals would frequently be and frequently traverse. The equipotential plane was installed in an area of sandy loam soil. The plane consisted of 6 inch (15.2 cm) square, 10 gauge welded wire mesh. The wire mesh covered the entire area of the plane except for a 3 inch (7.6 cm) border around the outer edge. Before the concrete slab was poured, the wire mesh was supported so it would be approximately 1 1/2 inches (3.8 cm) below the surface of the concrete. Also, before the concrete was poured, four 8 foot (2.4 m), 5/8 inch (1.6 cm) diameter, copper ground rods were driven into the earth at a 45 degree angle extending out away from the equipotential plane. The ground rods were spaced 12 inches (30.48 cm) apart and were bonded to each other and the wire mesh using AWG number 3, bare copper conductor. Figure 3 shows the equipotential plane that was installed.

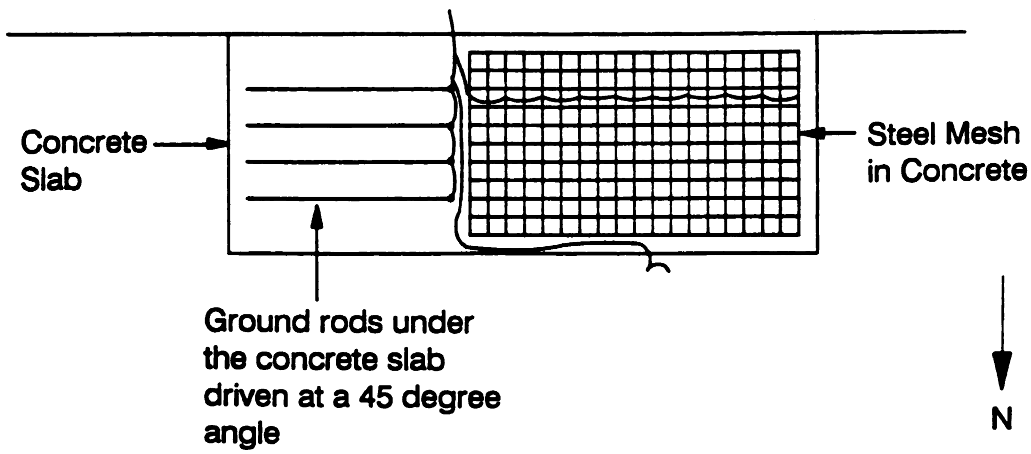

Figure 3. Diagram of the equipotential plane installed for analysis of the voltage gradients that surrounded it.

The connections to the ground rods were made with approved grounding connectors and to the connections to the wire mesh were accomplished by brazing. To insure good contact, the bare copper conductor was bonded to the wire mesh in several different locations. From one ground rod, the AWG number 3 bare copper conductor continued around the mesh to the adjacent side of the plane, and extended 6 inches (15.2 cm) out from the bottom edge of the concrete slab, so it could be accessed later for the different modifications that were to be made. From one ground rod, an AWG number 3 bare copper conductor was installed so that it could be connected to the voltage source. At the point where this wire exited the concrete slab it was installed in PVC conduit.

After all the connections were reexamined to insure proper contact, the concrete slab was poured. The slab was cured for three days before any animals were allowed in the area and approximately two months passed before any data was recorded.

B. Neutral-to-Earth Voltage Source

The source of the neutral-to-earth voltage for the experiment was produced by voltage drop on the neutral serving the barn. Voltage drop was chosen as the neutral-to-earth voltage source over ground faults because it was safer and easier to control.

At a pole along the overhead feeder to the barn, the neutral and phase wires were connected to a disconnect before proceeding to the barn. At the disconnect, the neutral passed through a resister and then was grounded at the neutral bus. The wire leaving the equipotential plane was connected to the neutral bus. One of the phase wires and the neutral were connected to a load box where loads could be turned on and off, thus increasing the current flow on the neutral. Increasing the current flow on the neutral would increase the voltage drop on the neutral, producing neutral-to-earth voltage.

The load box consisted of four 240 volt, 1,200 watt water heating elements connected in parallel. Each water heating element was connected for 120 volts and was controlled by a switch so each could be operated independently. To keep the resistance of the heating elements from changing over a period of time, the heating elements were placed in a pail of water which was constantly recirculated to maintain a constant temperature.

The neutral resistor consisted of an AWG number 12 solid copper wire, which was wound around a 4 inch (10.2 cm) piece of nonmetallic ridged conduit, and had three taps available. This allowed the resistance of the neutral conductor to be altered. The resistance of the neutral could be set at four values: 0.2, 0.3, 0.4 and 0.5 ohms. The nonmetallic rigid conduit was mounted vertically on the pole to allow circulation of air for cooling. A schematic diagram for the neutral-to-earth voltage source is shown in Figure 4.

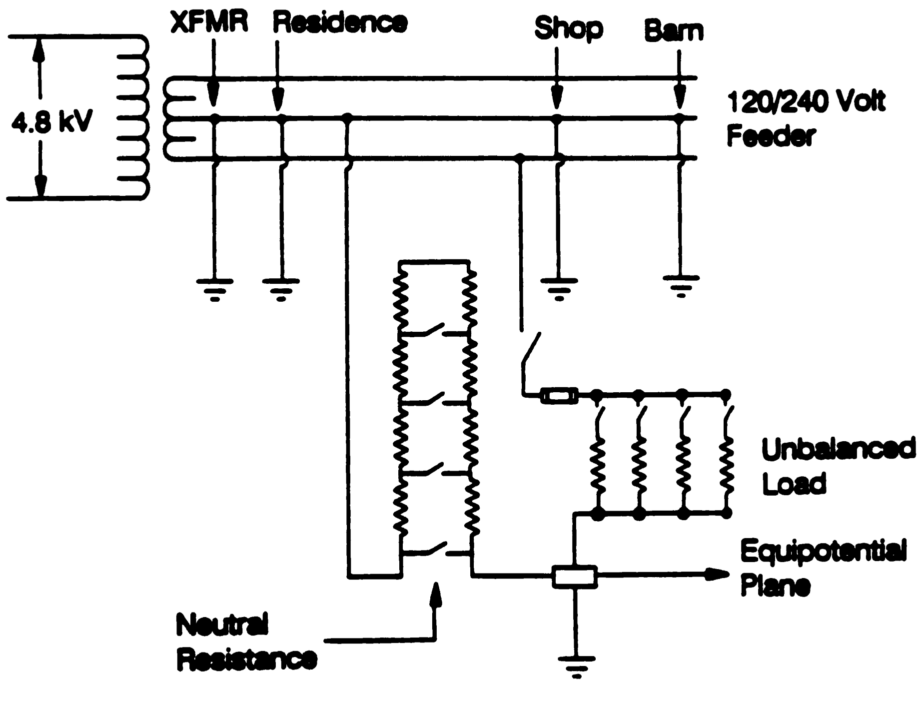

Figure 4. A schematic diagram for the neutral-to-earth voltage source.

By controlling the neutral's resistance and the loads on the neutral, it was possible to achieve the desired levels of neutral-to-earth voltage on the equipotential plane for the experiments. Neutral-to-earth voltages at or near 1, 2, 3 and 5 volts were used for evaluating the equipotential plane modifications.

C. Cow Step Potential Evaluation

The current flow from the earth through the front hooves of a cow and out the rear hooves back into the earth and vice versa is determined by the voltage difference divided by the resistance of the path. Assuming that the lower threshold of current flow that will cause a behavioral response in some cows is two milliamperes [Gustafson et al. (1984)], and that the lower values of a cow's body resistance from front to rear hooves is 496 ohms as determined by Norell (1983), a threshold step potential can be calculated by using Ohm's Law (Equation 1). A diagram of the step potential circuit is shown in Figure 5.

$$E = I \times R \qquad \text{Eq. 1}$$

where: E is the voltage potential (Volts)
I is the current flow (Amperes)
R is the resistance of the circuit (Ohms).

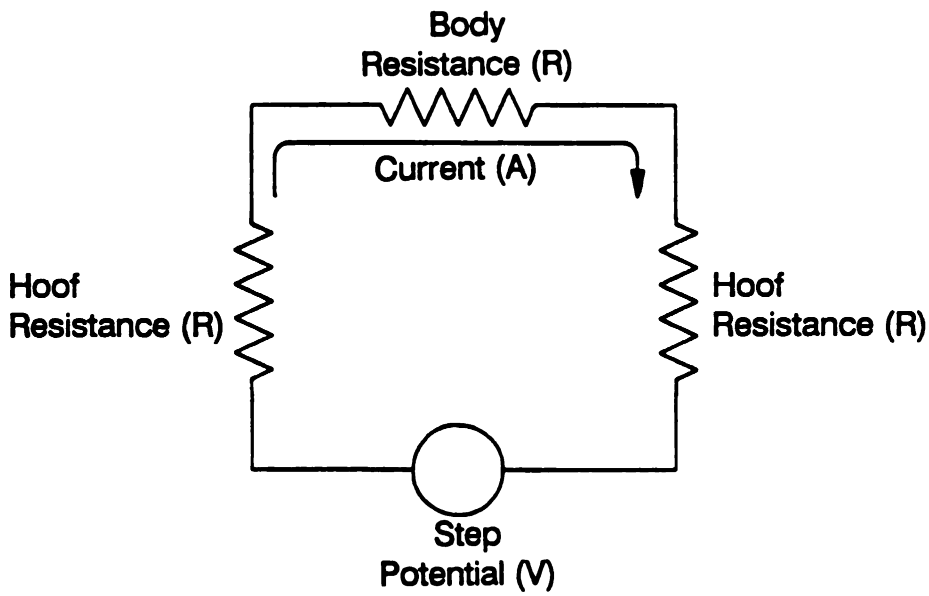

Figure 5. A schematic diagram of the step potential circuit for a dairy cow.

Assuming that there is no contact resistance between hooves and concrete or earth, the calculated step potential will be at a level at which current flow will not elicit a behavioral response in most cows most of the time. Using Equation 1, this lower threshold step potential is:

$$E = .002 \text{ amperes} \times 496 \text{ ohms}$$

$$E = 1 \text{ volt}$$

Since a dairy cow has a step from front to rear hooves of four feet (1.2 m), any voltage level measured over this distance above the threshold step potential level of 1 volt could alter the behavior of some cows some of the time. Therefore, the 1 volt step potential over a four foot (1.2 m) distance will be used to determine the effectiveness of modifications to the equipotential plane.

D. Analysis of Voltage Gradients

Several tests where proposed to analyze the voltage gradients surrounding an equipotential plane and the effects that modifications made to the plane would have on those gradients. Comparisons of the same approach path were desired, no analyses of the voltage gradients over the ground rods covered by concrete are presented.

1. Test No. 1 (Control)

Test number 1 was the control test, no modifications were made to the equipotential plane. Voltage measurements were taken on the equipotential plane and in the area of bare earth to reference ground, extending outward adjacent to the equipotential plane. This experiment resembles an equipotential plane that does not have a transition plane for the animals to traverse when entering or leaving the equipotential plane. See Figure 3.

2. Test No. 2

In test 2, four 8 foot (2.4 m) ground rods, spaced one foot (30.5 cm) apart, were driven at a 45 degree angle out away from the equipotential plane. This is shown in Figure 6. The 5/8 inch (1.6 cm) diameter ground rods were covered by 4 inches (10.2 cm) of earth and were bonded together by an AWG number 2 copper conductor. The ground rods were then bonded to the equipotential plane by connecting them to the bare copper wire that extended from the plane.

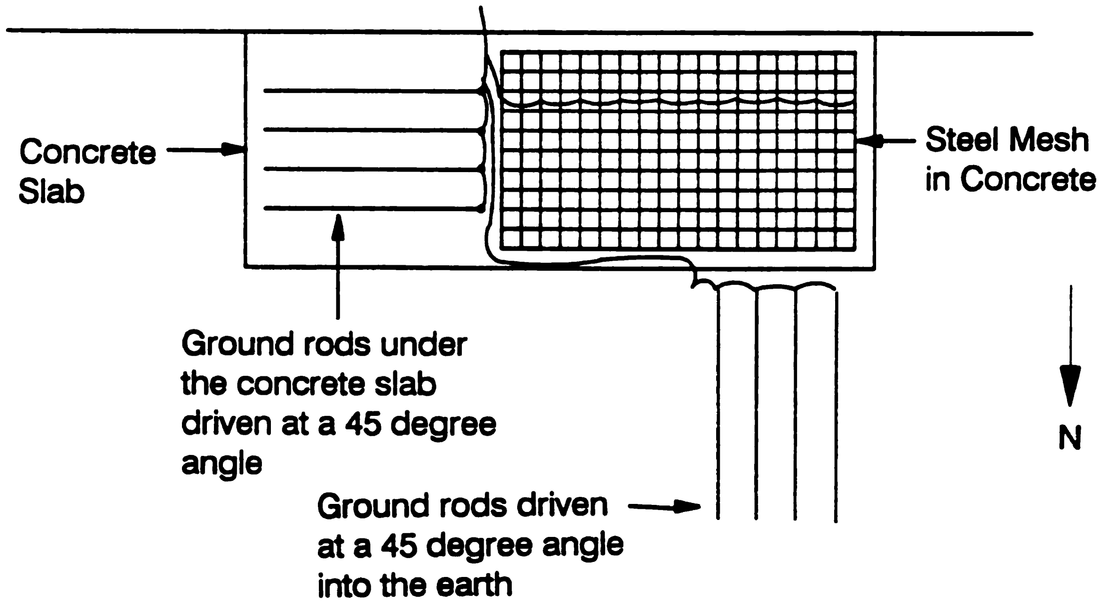

Figure 6. Diagram of the equipotential plane used for test number 2, where ground rods were driven into the earth at a 45 degree angle.

3. **Test No. 3**

For test 3, the ground rods from test number 2 were removed. A single run of bare copper wire, size AWG number 2, was installed into the earth starting at four inches (10.2 cm) below the surface of the earth at the edge of the equipotential plane. The wire that ran adjacent to the equipotential plane extended outward 20 feet (6.1 m). The wire was sloped so that the end of the wire was 2 feet (61 cm) below the surface of the earth, as illustrated in Figure 7.

The wire was bonded to the wire mesh in the equipotential plane by connecting it to the wire that extended from the plane.

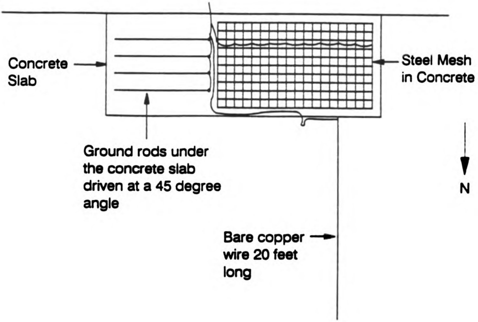

Figure 7. Diagram of the equipotential plane modifications that were used for test number 3, where a single copper wire was installed.

4. Test No. 4

The design for test 4 was based upon the analysis of results of the other tests. For test 4, two bare copper wires, size AWG number 2, were installed in the earth from the equipotential plane, radiating outward to a distance of 30 feet (9.1 m) rather than 20 feet (6.1 m) as used in test 3. One wire extended straight out while the second wire, located 2 feet (0.61 m) away, was parallel to the first wire a distance of 4 feet (1.2 m). At the four foot point, the second wire then angled away from the first wire so that at a distance of 30 feet (9.1 m) from the plane, the wires were 10 feet (3.1 m) apart. This is shown in Figure 8. The wires start at the equipotential plane 4 inches (10.2 cm) below the surface of the earth and were sloped until the wires were 3 feet (0.91 m) below the surface at a point 30 feet (9.1 m) away from the plane. There is also a 2 foot (0.61 m) piece of AWG number 2 wire in the earth in the center of the two longer wires. All three wires were bonded to the wire mesh in the equipotential plane by connecting them to the wire that extended from the plane.

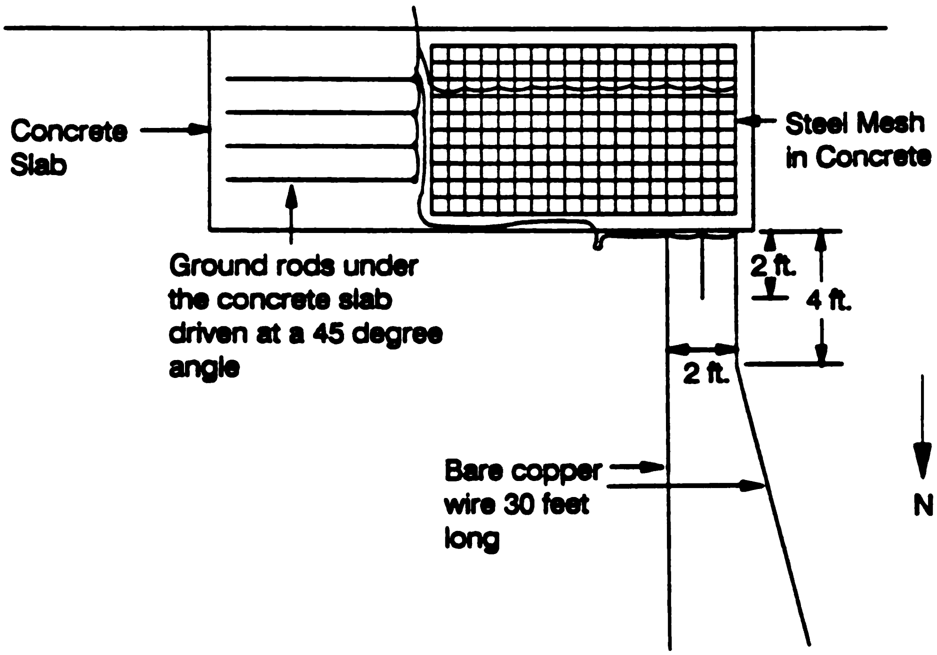

Figure 8. Modifications made to the equipotential plane for test number 4.

5. Measuring Techniques

A digital Fluke® 27, multimeter, with an internal impedance of 10 mega-ohms was used for all voltage measurements. It was verified that the meter did not read DC on the AC scale.

All measurements where taken to a reference ground that was located 140 feet (42.7 m) away from the equipotential plane. The reference ground consisted of a ground rod which was driven into the earth five feet (1.5 m). The reference ground was at least 190 feet (48.3 m) away from any other electrodes and measurements where taken by the means of a copper probe. The probe consisted of an AWG number 8 solid copper conductor fastened to a three foot (0.91 m) wooden handle. The conductor extended one inch below the bottom of the handle and the insulation was removed from that portion of the wire which was below the handle. The probe was firmly placed against the measuring surface, either concrete or earth, and the voltmeter was allowed to stabilize before any data was recorded.

6. Pre-measurement Procedure

Prior to taking measurements, oxide on the copper probe was removed with steel wool and the voltage drop on the neutral was adjusted so that the voltage from the equipotential plane to the reference ground was as close to a specified value as possible. The desired neutral-to-earth voltage levels, measured from the equipotential plane to the reference ground, were 1, 2, 3, and 5 volts. Measurements were taken after a three minute waiting period to allow the resistance of the water heating elements to stabilize. The voltage from the equipotential plane to the reference ground was then verified again.

Also, before any measurements where taken, a grid work of one square foot (30.5 cm) boxes where laid out. Measurements were then taken at intersecting points on this grid pattern. This grid work was taken from a series of reference points so the grid was consistent between tests. Using the same reference points to establish the grid made it possible to check the voltage gradient levels from a given point or points for different experiments. A data sheet with the grid work on it was used to record all measurements. The concrete and the earth were dampened at the measuring points to insure good contact between the copper probe and the measuring surface.

E. Neutral Isolation

An isolated electrical system was established at the farm. The neutral-to-earth voltage on the source system was produced and controlled by the same means as in previous tests. The neutral-to-earth voltage source, isolated and animal circuits are shown in Figure 9. The farm grounding system consisted of electrodes at the transformer, residence, shop and barn. The neutral-to-earth voltage source was produced at different levels and caused a current flow through the earth from the source ground rod, R_S, to the farm grounding system, R_D. Measurements were made to determine the level of current, I_I, and voltage, E_I, that would appear on the isolated system, and that could be contacted by an animal.

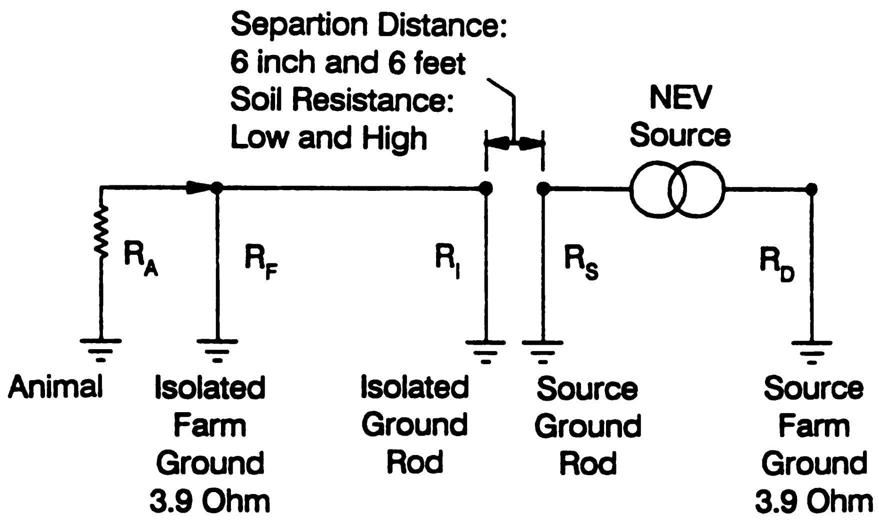

Figure 9. An illustration of the neutral-to-earth voltage source, isolated and animal circuits used in the isolation tests.

1. Simulated Electrical System

A simulated isolated farm electrical system was established by driving an isolated ground rod, R_I, six inches (15.2 cm) and six feet (1.8 m) from the source ground rod R_S as shown in Figure 9. The isolated ground rod at an actual farm would be connected by the farm neutral to the various grounding electrodes on the farm creating a circuit as shown in Figure 8. The isolated ground rod, R_I, was connected to a grounding electrode system, R_F, which was located 90 feet (27.4 m) from the nearest grounding electrode of the actual farm grounding system. The isolated farm "earth-neutral" electrical system would function the same as an actual farm electrical system, where a ground rod was located near a ground rod of a primary distribution system. If neutral-to-earth voltage of the source electrical system was to cause neutral-to-earth voltage in an isolated electrical system, this test would create the same conditions but in a manner where currents, voltages and resistances could be controlled and measured.

The source electrical system and the isolated electrical system in Figure 9 actually form one electrical circuit, because the two electrical systems are connected through the earth which has finite resistance. Figure 10 is a schematic diagram of the circuit created by the source and isolated electrical systems. Figure 10 also shows the locations of the instrumentation to measure voltages and currents during the testing. The source and isolated ground rods behave like variable resistors which are connected. The resistance-to-earth of the source ground rod, R_S, consists of two resistances, R_{S1} and R_{S2}, where the $R_S = R_{S1} + R_{S2}$. Resistance R_{S1} increases and approaches the value of R_S as the source ground rod and the isolated ground rod are located further apart. The resistance R_I is not the resistance-to-earth of the isolated ground rod, but is a value less than the resistance-to-earth. As the two ground rods are moved further apart, the resistance R_I increases and approaches the resistance-to-earth of the isolated ground rod.

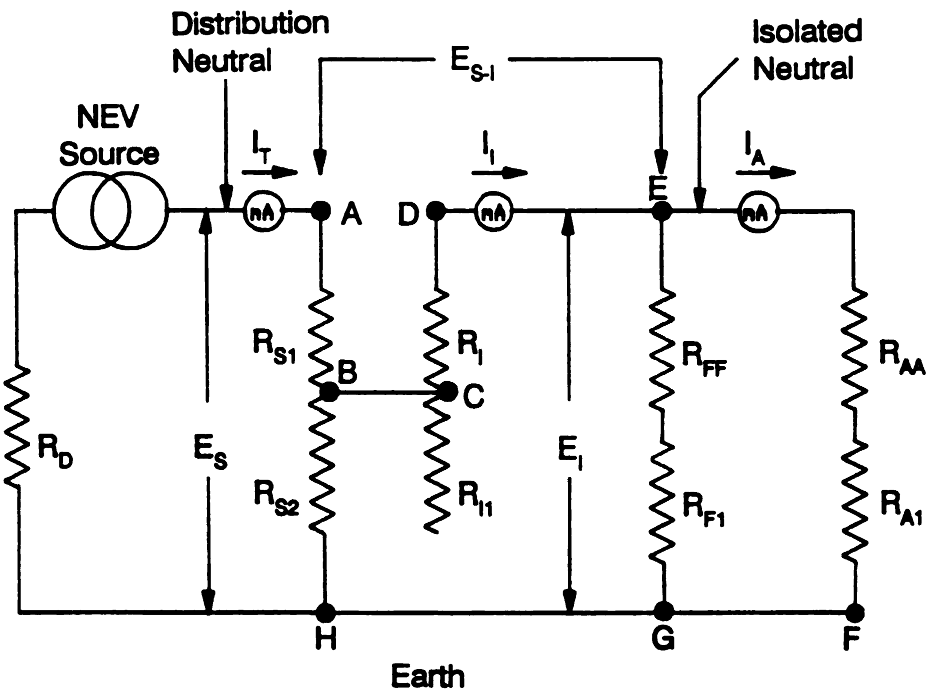

Figure 10. A schematic diagram of the circuit created by the source and isolated electrical systems and the locations of the instrumentation to measure voltages and currents during testing.

2. Data Collection

To determine the effects of grounding electrodes' resistance-to-earth on an isolated system, the ground rods of the two systems where placed in two different locations. Data was collected for the isolated electrical system tests with source and isolated ground rods located in soils where the resistance-to-earth of each ground rod was less than 25 ohms, and in locations where it was more than 100 ohms. Tests in both types of soils were conducted with the source and isolated ground rods located six inches (15.2 cm) apart. A frame was constructed to maintain parallel spacing of the ground rods which were located six inches (15.2 cm) apart. The ground rods were removed from the earth after the tests and examined to make certain they had not been deflected by a hard object in the earth.

The locations of the milliammeters and the voltmeters for the collection of data are shown in Figure 10. The total current, I_T, was measured by installing a milliammeter in series with the neutral conductor leading to the source ground rod. The current flowing in the isolated electrical system, I_I, was measured by installing a milliammeter in series with the neutral leading from the isolated ground rod. The current flowing in the isolated circuit was due to the voltage gradient surrounding the source electrical system ground rod. Animal current was measured by installing a milliammeter in series with a resistor simulating the animal resistance. Voltage was measured from the source ground rod, E_S, to a reference ground rod, and from the isolated ground rod, E_I, to the same reference ground rod with a high impedance digital voltmeter. The voltage was also measured from the source ground rod to the isolated ground rod, E_{S-I}.

A null balance three-point fall of potential meter was used to measure the resistance of ground rods and grounding electrode systems. The farm grounding electrode system, R_D, and the isolated farm grounding electrode system, R_{F1}, were both measured at 3.9 ohms. Ground rod resistances measured for each test were the reference ground used for voltage measurements, the animal circuit ground R_{A1}, the source ground rod R_{S1} + R_{S2}, and the isolated ground rod resistance R_I + R_{I2}. Resistors were place in series with the isolated farm grounding electrode system, R_{FF}, and to act as simulated animal body resistance R_{AA}. Using an ohmmeter the values of these resisters were determined to be 2990, 868, 500, 249, 95.8 and 52.1 ohms. These values were verified for each test.

An animal making contact with the isolated electrical system neutral was created by establishing an animal resistance circuit, R_A, that was equal to R_{AA} + R_{A1}. The animal resistance was in parallel with the isolated farm grounding system R_F. Values of resistance, R_{AA}, were placed in a circuit from the isolated system neutral to an isolated ground rod, R_{A1}. Using the three-point fall of potential method, R_{A1} was measured at 24.8 ohms.

V. RESULTS AND DISCUSSION

The primary objectives of this research were to analyze how modifications of the electrical grounding system would affect the levels of neutral-to-earth voltage. The secondary objective of this research was to propose modifications to the electrical grounding system best suited for use on dairy farms.

In this chapter the results are presented and analyzed in the following order: (1) evaluation of a dairy cow's step potential, (2) voltage gradients and step potentials for an equipotential plane with no transition plane, (3) step potentials and voltage gradients for the various modifications made to the equipotential plane, and (4) the effects that earth has upon isolation of two electrical systems.

A. Evaluation of a Dairy Cow's Step Potential Circuit

The one volt step potential was determined as the design criteria using equation 1 and published research. Published research results included current flow effects on a cow as well as the front to rear hoof resistance of a cow's body. The step potential was of a level that may cause a behavioral change of some of the cows some of the time.

Gustafson et al. (1985) and Lefcourt et al. (1986) suggested that current flow through a cow's body at or above the 2 milliampere level may elicit a behavioral response in some cows some of the time. Current levels below 2 milliamperes flowing through a cow's body have not been found to have a significant effects on their behavior [Lefcourt et al. (1986), Norell et al. (1983) and Woolford (1972)].

In analyzing the resistance of the front to rear hoof pathway of a dairy cow, Norell et al. (1983) determined the lowest resistance through this pathway of the cows tested was 496 ohms. They found the mean value of front to rear hoof resistance for the cows tested was 734 ohms. For dairy cows, no front to rear hoof resistance has been reported below 496 ohms. In Norell et al. (1983) determination of the of the front to rear hooves' pathway, the cows tested were standing on a metal electrode. This metal electrode would not duplicate the hoof to surface resistance of a cow standing on earth or concrete. The hoof to surface contact resistance could vary depending on the surface type and conditions and could have a significant impact on the front to rear hooves' resistance pathway, because it is in series with the body resistance of a cow. Not including the hooves to surface contact resistance should resemble the worst case scenario where a cow was standing on a muddy surface with no hoof to surface contact resistance. Not accounting for the hoof to surface contact resistance, Norell et al. (1983) concluded that 90% of the cows would respond 20% of the time when exposed to a step potential voltage of 1 volt. Woolford (1972) suggested that any voltage gradients in excess of 2 volts over a distance of 4 feet (1.2 m) may be sufficient to cause a behavioral change.

B. Modifications Made to the Equipotential Plane

Five volts was chosen as the high limit of neutral-to-earth voltage measured on an equipotential plane to reference ground. In conducting research and neutral-to-earth voltage investigations, my other colleges and I believe that this level of voltage should encompass most neutral-to-earth voltage levels found on dairy farms in the U.S. I feel that any neutral-to-earth voltage levels above this level require significant voltage reduction measures, which must be undertaken by the local power supplier and/or a licensed electrician.

Step potentials shown in the graphs in this section are calculated by taking the voltage measured at one point to reference ground and subtracting the voltage to reference ground of a point four feet (1.2 m) away. Tests were conducted to evaluate the difference between this technique of determining step potential and actually measuring the step potential between of two points four feet (1.2 m) away from each other. No differences were found when the two techniques were compared.

When examining the line graphs presented in this section, a brief statement is needed to clarify the "X" (Distance from Equipotential Plane) axis. Unless otherwise noted, the point zero feet away from the plane is a point of reference. This point is just off the edge of the plane in the earth. Negative numbers signify the distance from this point back onto the equipotential plane, positive numbers indicate the distance from this point out to a place on the earth. Also for all modification tests, the same approach path was used for analysis. Data for the tests presented within this section are found in the Appendix.

1. Test No. 1 (Control)

This was the case of an equipotential plane with no modifications. The voltage level from the plane to the reference ground was 5.38 volts. Voltage measurements were taken from the equipotential plane and bare earth to the reference ground. Figure 11 shows a voltage gradient near and on the equipotential plane for one approach path to the equipotential plane. Once a cow places a hoof off of the equipotential plane, the animal experiences a difference in potential. Comparing the voltages measured off the equipotential plane to reference ground to the 5.38 volts measured from the plane to reference ground, the voltage on the earth's surface along the approach path drops by 39.6% at one foot (0.3 m) 55.4% at four feet (1.2 m), 69.0% at ten feet (3 m) and 74.9% at fifteen feet (4.6 m) away from the equipotential plane. The level of the voltage gradients decrease further away from the equipotential plane.

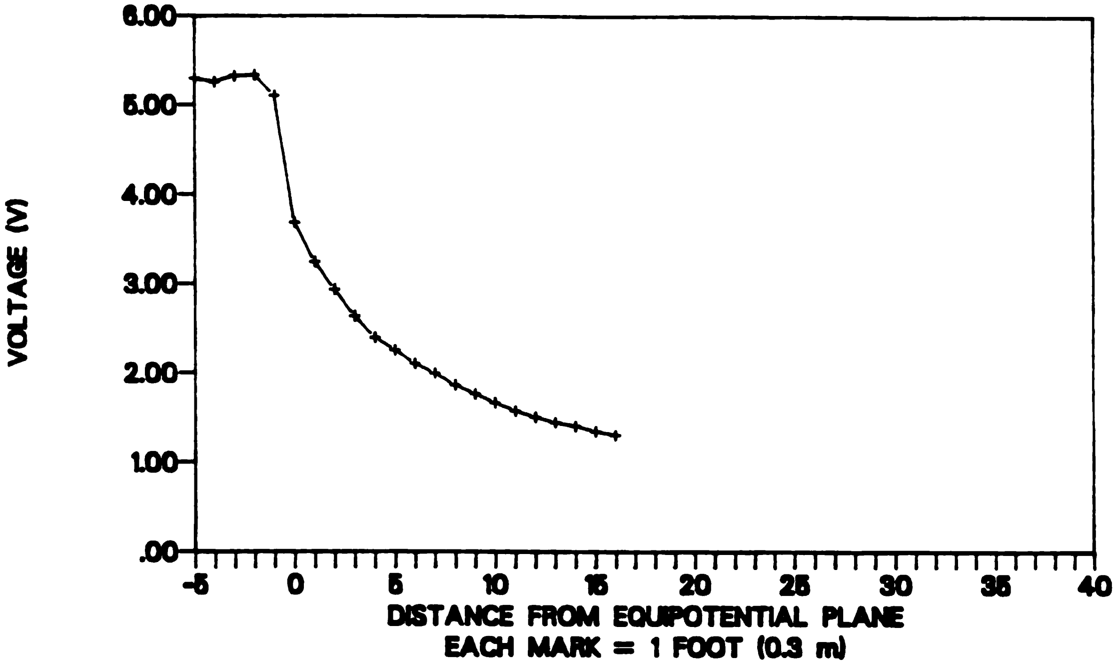

Figure 11. Voltage gradient of one approach path, measured from the point shown to a reference ground for test number 1.

The step potentials for Figure 11 are shown in Figure 12. With 5.38 volts measured on the equipotential plane to reference ground, a cow with a step length of 4 feet (1.2 m) from one set of hooves to the other would experience a difference of potential of 2.47 volts. This value is 1.47

volts above the 1 volt design criteria which was determined to be the threshold level of step potential that may alter the behavior of some cows some of the time. The maximum step potential voltage will occur when a cow has one set of hooves on the edge of the equipotential plane and the other set of hooves in contact with the earth four feet (1.2 m) away.

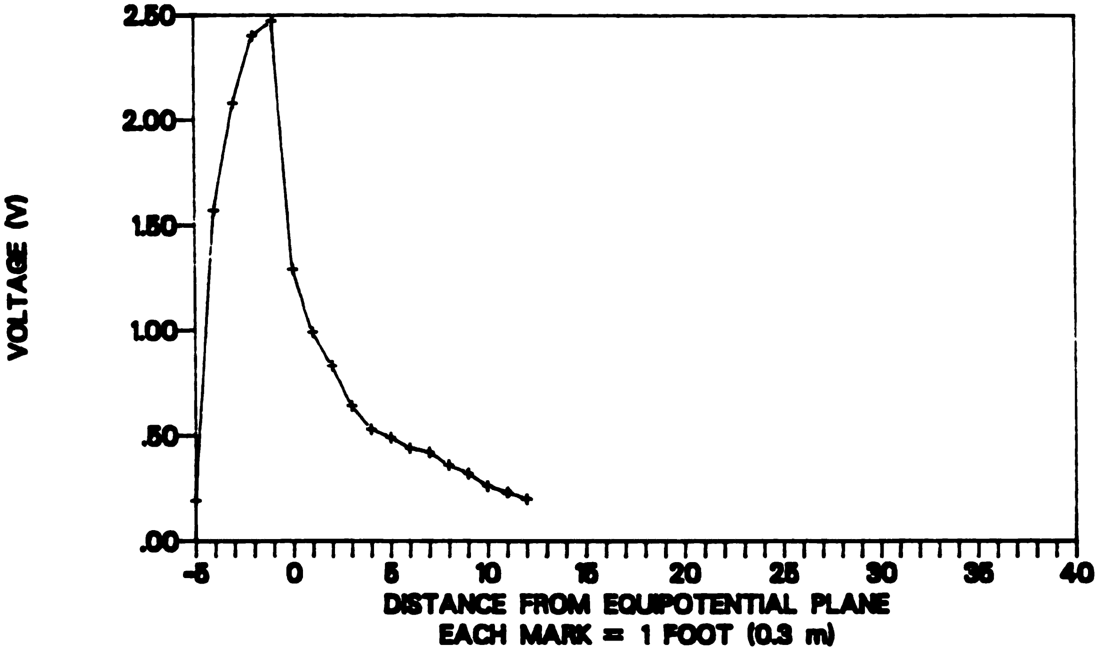

Figure 12. Step potential that a cow will experience from one set of hooves to the other for the voltage gradient of Figure 11.

While Figure 11 only shows the voltage to reference ground measurements for one path, Figure 13 shows the voltage gradients, represented by isometric lines, around a section of the equipotential plane. This figure was generated by using a topographical program where voltages were used rather than elevations. By modifying the equipotential plane, it was desired to increase the space between the isometric lines. Greater the distance between the lines should result in lower step potentials, because the slope of the voltage gradient would not be as great.

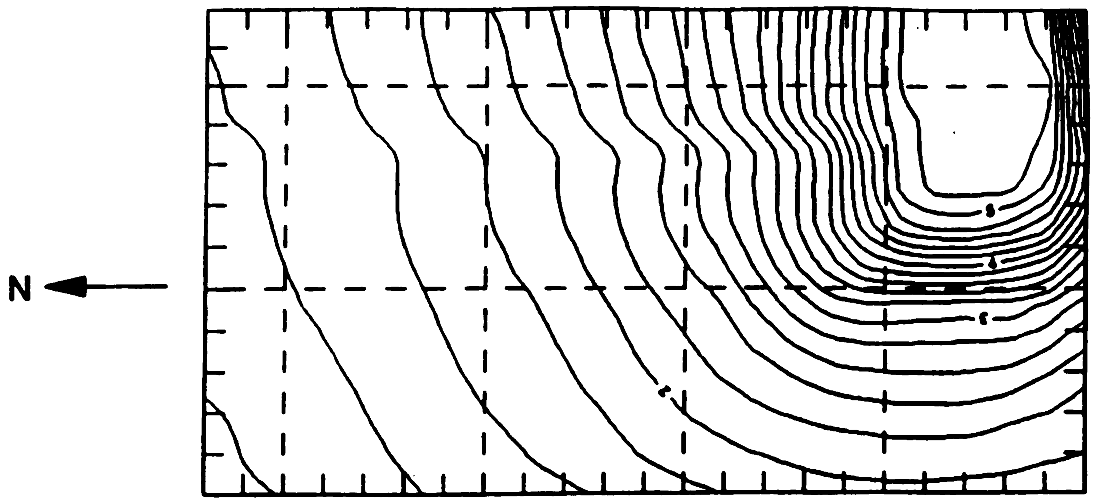

Figure 13. Voltage gradients surrounding the plane in test number 1, with 5.38 volts measured from the equipotential plane to reference ground, represented by isometric lines.

Achieving a step potential under 1 volt was possible around the equipotential plane with no modifications installed. This was accomplished by lowering the voltage level on the plane. Figure 14 represents the step potential voltages for an equipotential plane without any modifications made to it. With 1.80 volts on the plane measured from the plane to the reference ground, the step potentials did not exceed 1 volt.

After examining the data from this test, it became apparent that it was necessary to modify the equipotential plane transition area when more than approximately 2 volts were measured from plane to reference ground. With the maximum step potentials occurring when a cow has one set of hooves at the edge of the equipotential plane, and the other set of hooves four feet (1.2 m) away, any alterations to the equipotential plane had to reduce the step potentials in this area.

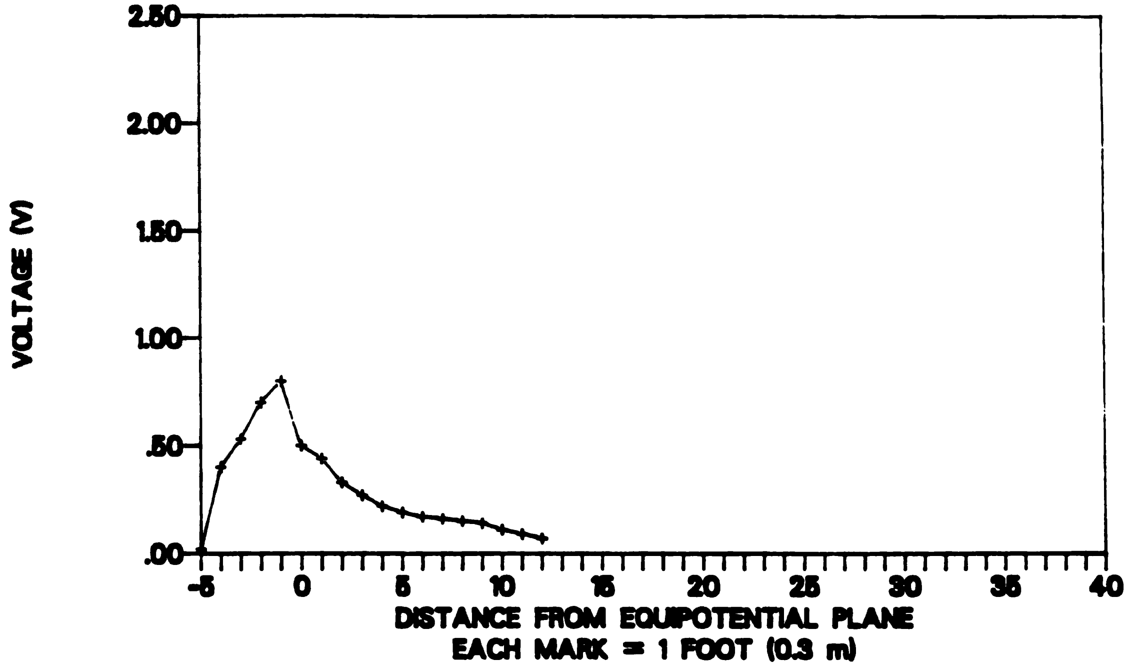

Figure 14. Step potential that a cow will experience from front to rear hooves for one approach path to the equipotential plane used in test number 1, with 1.80 volts measured from the plane to a reference ground.

2. Test No. 2

In this test, ground rods were driven into the earth at a 45 degree angle, extending away from the equipotential plane in the areas where dairy cows would approach the plane.

When 5.29 volts were measured from the equipotential plane to reference ground, the installation of the ground rods altered the voltage gradients around the equipotential plane. Figure 15 shows the voltage gradient for one path on and off of the equipotential plane. Comparing the measured voltage off the equipotential plane to reference ground to the voltage measured from the plane to reference ground, the earth to reference ground voltage along the approach path drops by 8.3% at one foot (0.3 m), 25.3% at four feet (1.2 m), 57.3% at ten feet (3 m) and 66.0% at fifteen feet (4.6 m) away from the equipotential plane. The voltage gradients decreased slower than in the previous case where no modifications were made.

The step potentials for Figure 15 are shown in Figure 16. With 5.29 volts measured from the equipotential plane to reference ground, a cow with a step of 4 feet (1.2 m) from front to rear hooves would experience a step potential of 1.21 volts. This value is above the 1 volt design criteria and 0.21 volts above the level of step potential that may alter an animal's behavior. Maximum step potential voltage occurs when a cow has one set of hooves in contact with the earth one foot (0.3 m) away from the equipotential plane and the other set of hooves five feet (1.5 m) away from the equipotential plane.

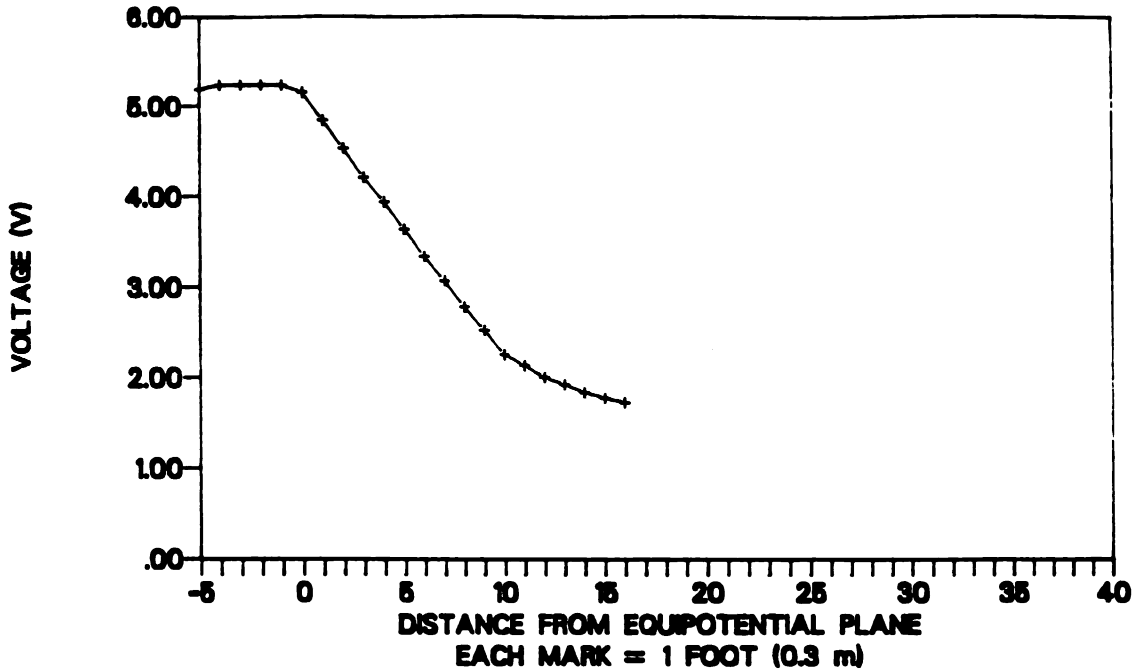

Figure 15. Voltage gradient of one approach path, measured from the point shown to a reference ground for test number 2.

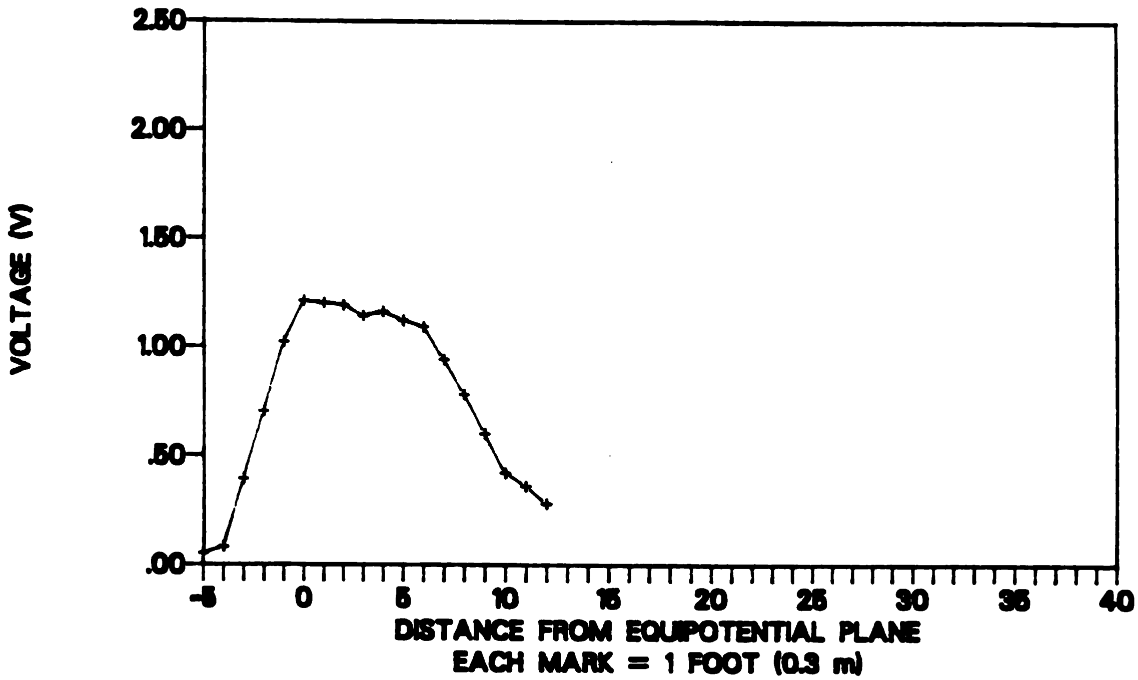

Figure 16. Step potential that a cow will experience from one set of hooves to the other for the voltage gradient of Figure 15.

With approximately 5.0 volts measured from the equipotential plane to reference ground, it was not possible to achieve a step potential voltage at or below 1.0 volt with this treatment. Figure 17 shows the step potentials for an equipotential plane with 3.58 volts measured from plane to reference ground. The maximum step potential that a cow would experience with this installation and voltage would be 0.84 volts, which is below the level of voltage that may alter an animal's behavior.

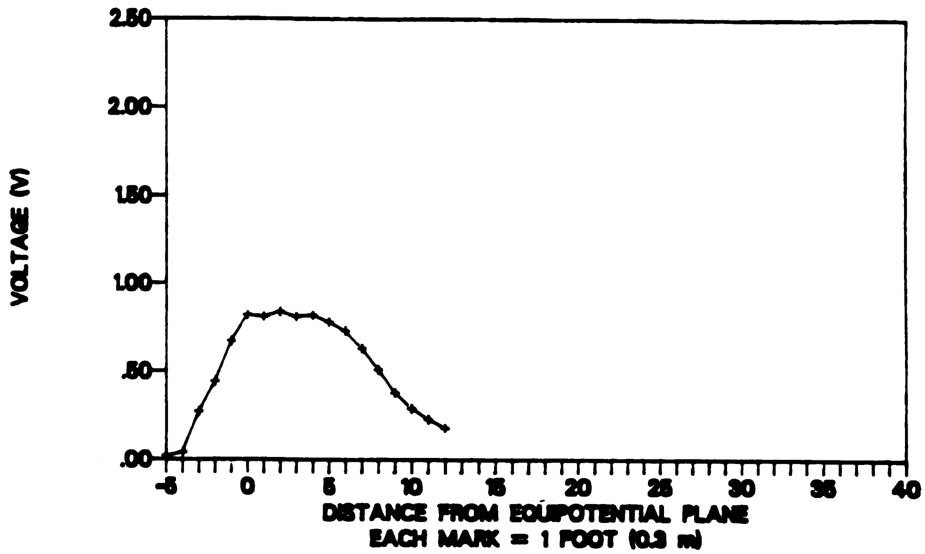

Figure 17. Step potential that a cow will experience from one set of hooves to the other for one approach path to the equipotential plane used in test number 1, with 3.58 volts measured from the plane to a reference ground.

3. Test No. 3

This test consisted of burying a bare copper wire in the earth. The wire extended from the equipotential plane 20 feet

(6.1 m) and was buried four inches (10 cm) deep at the edge of the equipotential plane and two feet (61 cm) deep at the 20 foot (6.1 m) distance.

With 5.75 volts measured from reference ground to equipotential plane, Figure 18 shows the voltage gradient along one path of approach to the equipotential plane. This path is directly over the wire that was buried in the earth. Along the approach path, the earth to reference ground voltage dropped by 17.0% at one foot (0.3 m), 30.0% at four feet (1.2 m), 42.6% at ten feet (3 m), 48.9% at 15 feet (4.6 m), 60.5% at 20 feet (6.1 m), and 74.0% at 25 feet (7.6 m) away from the equipotential plane.

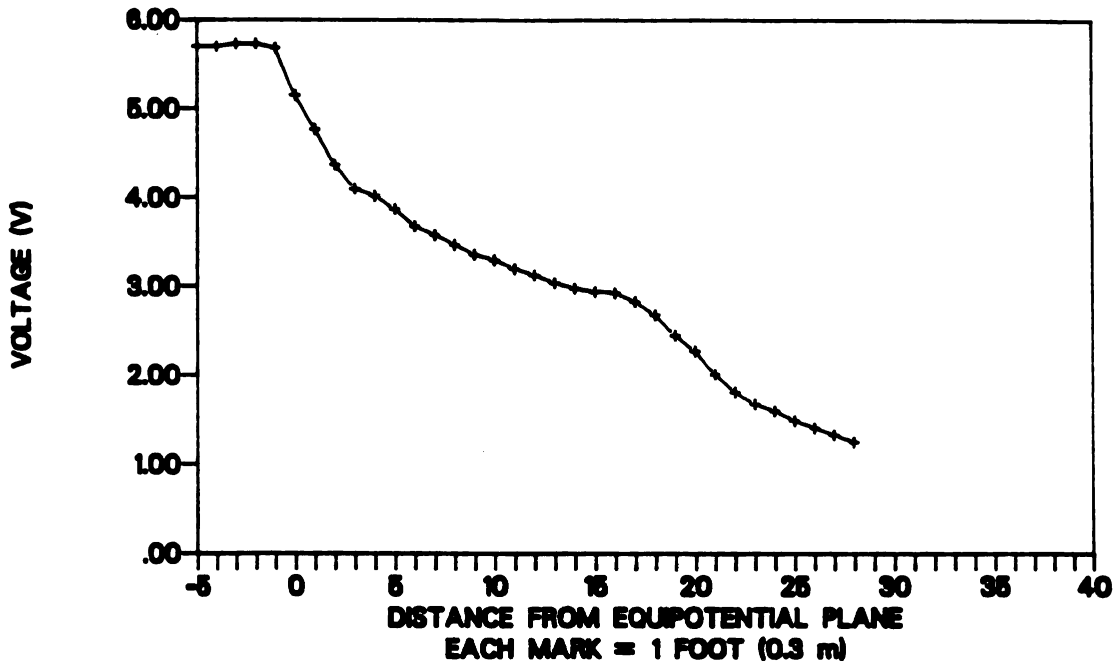

Figure 18. Voltage gradient of one approach path, measured from the point shown to a reference ground for test number 3.

Step potentials for Figure 18 are shown in Figure 19. The maximum step potential that a dairy cow will encounter will be at the point where one set of hooves are in contact with the concrete and the other set of hooves are in contact with bare earth. This maximum step potential voltage is 1.57 volts. To keep the step potentials below the point were a cow's behavior may be altered, the voltage on the plane had to be reduced to at least 3.0 volts. The step potential voltages for an equipotential plane with 2.96 volts measured from the plane to a reference ground are shown in Figure 20.

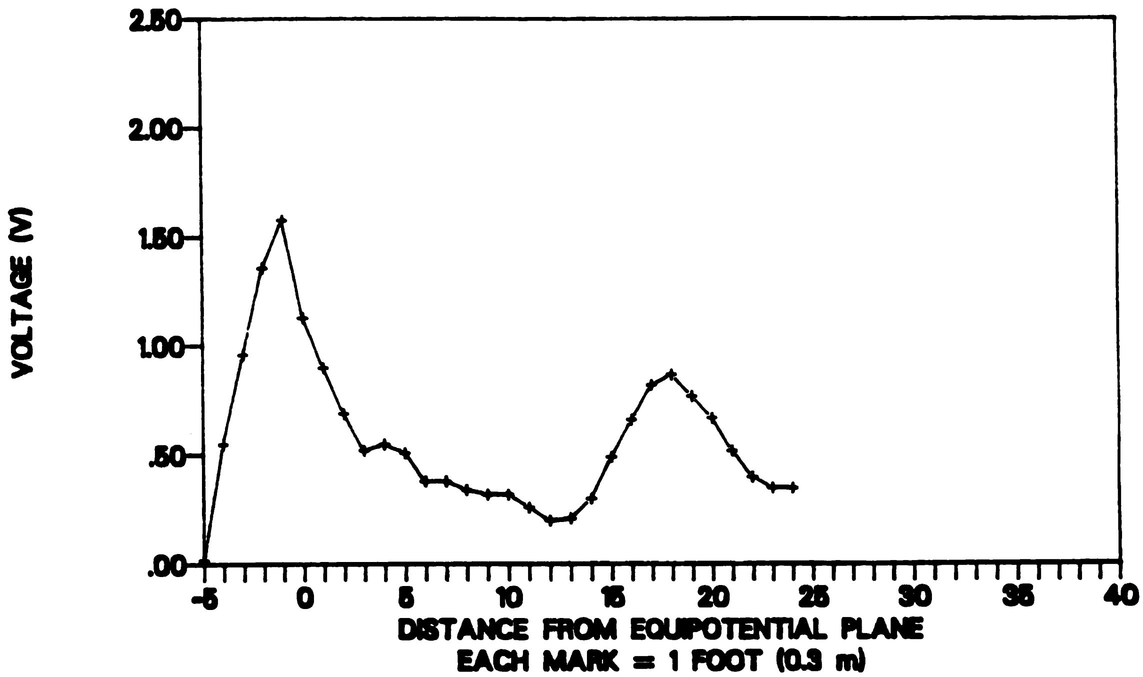

Figure 19. Step potential that a cow will experience from front to rear hooves for the voltage gradient of Figure 18.

The isometric lines of Figure 21 clearly indicate the location of the wire. The voltage on the earth's surface is increased directly over the buried wire because it is bonded to the equipotential plane. Just as with a ground rod, the resistance of the shells of earth are affecting the surface voltage levels. As the depth of the wire increases, the overall resistance of the shells of earth decreases, which results in a decreased surface voltage. Consequently, near the equipotential plane the surface voltage is highest, because there are only a few shells of earth above the wire.

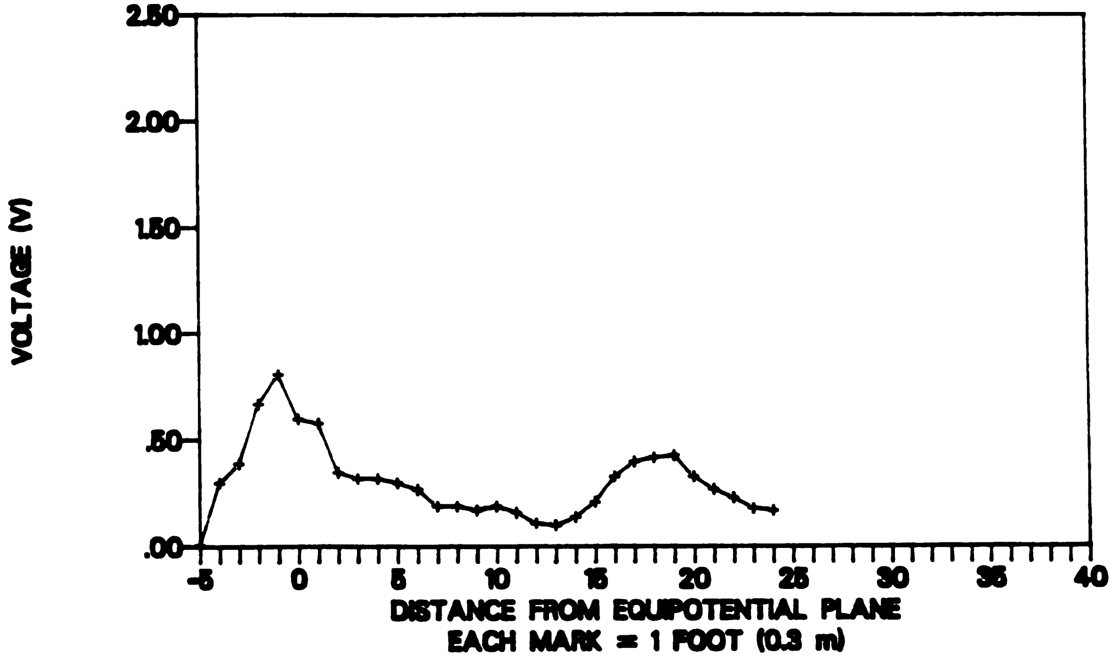

Figure 20. Step potential that a cow will experience from one set of hooves to the other for one approach path to the equipotential plane used in test number 3, with 2.96 volts measured from the plane to a reference ground.

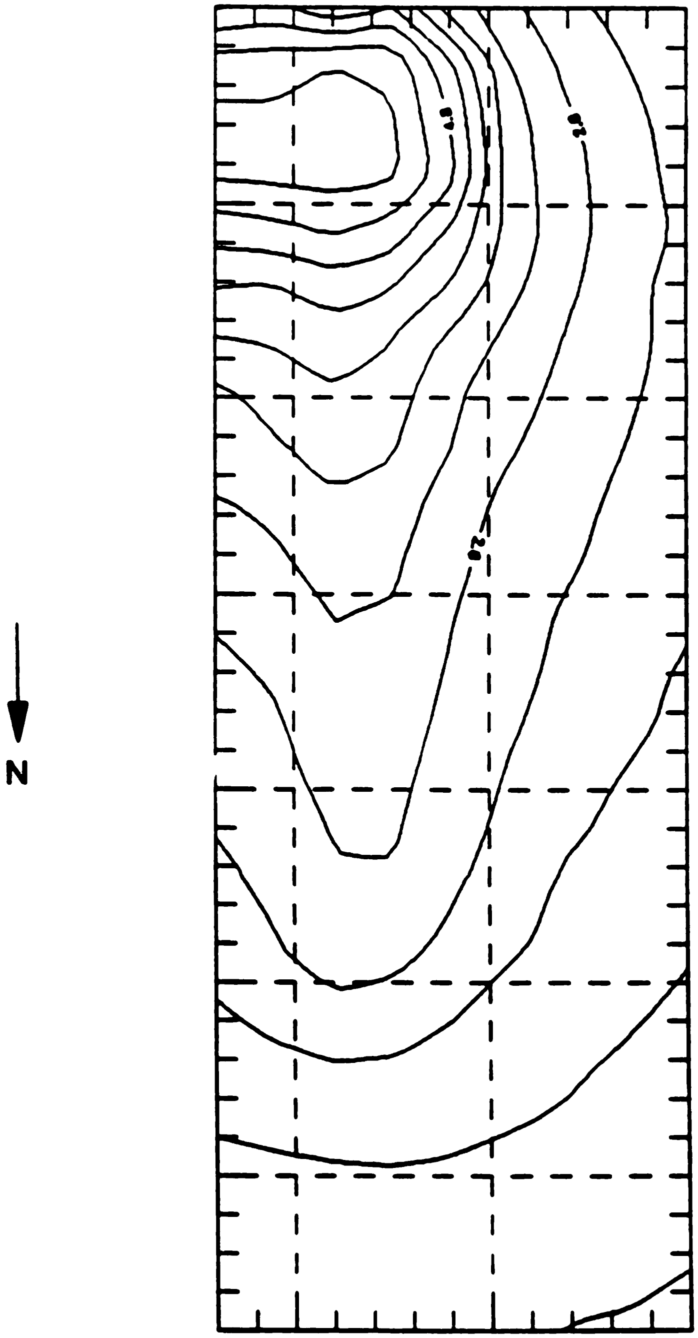

Figure 21. Voltage gradients surrounding the equipotential plane in test number 3, with 5.75 volts measured from the plane to a reference ground, represented by isometric lines.

To illustrate this further, refer to Figure 22. This figure represents a cross-section of surface voltages across several different locations, leading up to an equipotential plane which has 5.75 volts measured from reference ground to plane. The lines 0 to 20 feet (0 to 6.1 m) represent the distance from the equipotential plane. The cross-section voltages represented by the 20 foot (6.1 m) line are the voltages at the end of the wire. The line representing 0 feet represents the voltages measured on the equipotential plane. Column "S" shows the voltage where the wire is buried. Compared to the other columns, the voltage on the surface of the earth is slightly higher than in any other column, until the equipotential plane is reached. This would be expected, because the greater the distance from the wire to the earth's surface, the higher the number of shells of earth. This results in a decreasing resistance and decreasing surface voltage.

A cow may take an alternate path to approach the equipotential plane, and come in contact with a lower step potential voltage than when approaching the plane directly over the wire. Figure 23 shows the step potentials for three possible paths that a cow may take when approaching the plane. Each path is represented by a column, "R", "S", and "T" are all one foot (0.3 m) away from each other. A cow using column "S" or "R" for her approach will encounter slightly lower step potentials than for column "T".

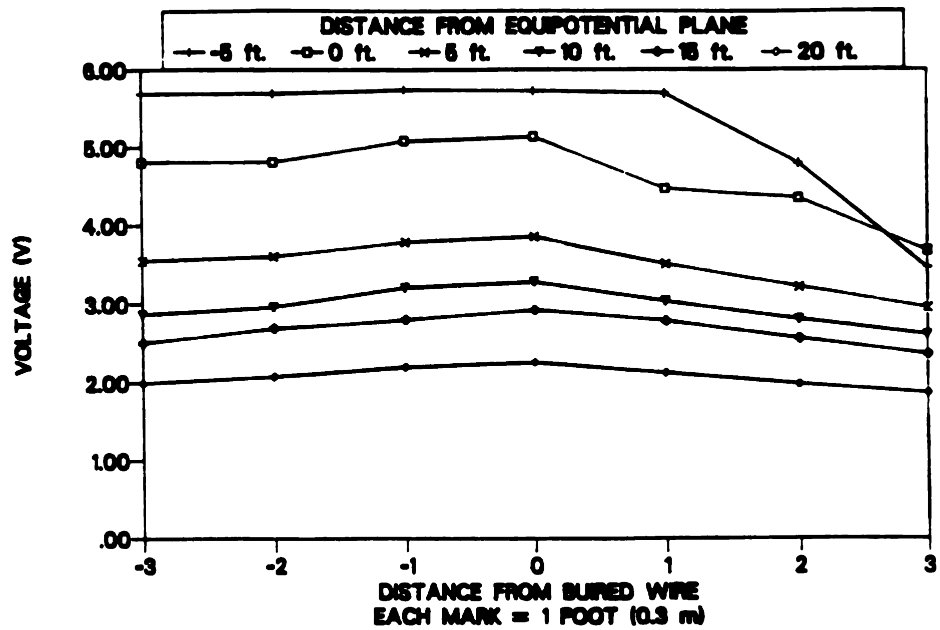

Figure 22. A cross section of the voltage gradients leading up to the equipotential plane used in test number 3, with 5.75 volts measured from the equipotential plane to a reference ground.

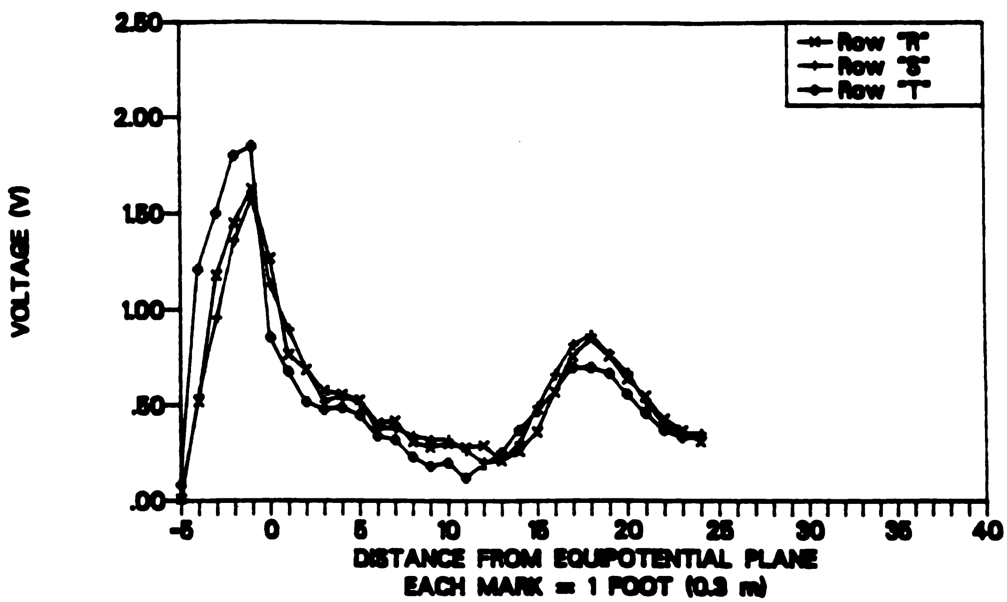

Figure 23. Step potentials for three different approach paths to the equipotential plane in test 3 with 5.75 volts measured from the plane to a reference ground.

4. Test No. 4

The installation of a single copper wire in the earth did not lower step potentials below 1.0 volt. Therefore, in test 4, the wire was extended ten feet (3 m) making its horizontal length 30 feet (9.1 m). Two additional wires were also installed in the earth. One of the wires was two feet (0.61 m) away from the first wire and ran parallel out into the earth a distance of four feet (1.2 m). The wire then angled away from the first wire so that the ends of the wires where 10 feet (3 m) apart. In addition, a short two foot (0.61 m) piece of wire was added between the two longer wires. Both of the wires continued at the same slope as the first wire.

The results of test 3 indicated that a second wire could be installed to obtain a transition area of greater width. The second wire was installed so that their would be a minimal drop in voltage along the surface of the earth between the wires. Table 15 in the appendix shows that the voltage between the wires was nearly the same as the voltage of the earth over the wires.

A lower step potential was obtained at the edge of the equipotential plane when four ground rods spaced one foot (0.3 m) apart were installed at the edge of the plane than when one bare wire was connected to the plane. This can be seen by comparing Figure 16 for the ground rods with Figure 19 for the single copper wire. In order to decrease the step potential at the edge of the plane, wires were spaced one foot (0.3 m) center-to-center. This effectively reduced the step potential near the equipotential plane to less than 1 volt, as seen in Figure 25.

Voltage gradients extending from the plane when 5.04 volts measured from the equipotential plane to reference ground are shown in Figure 24. The voltage gradients are reduced by 5.9% at one foot (0.3 m), 17.5% at four feet (1.2), 28.2% at 10 feet (3 m), 29.2% at 15 feet (4.6 m), 30.6% at 20 feet (6 m) 33.7% at 25 feet (7.6 m), 44.1% at 30 feet (9.1 m), 59.5% at 35 feet (10.6 m) and 69.3% at 40 feet (12.2 m) away from the equipotential plane. In this experiment, the percent of change in voltage was not as sufficient as in previous experiments. Therefore, the step potential voltages would be lower than those of previous treatments because the voltage gradients are being extended further from the equipotential plane in the approach path than in any other treatment. The step potentials for Figure 24 are shown in Figure 25.

When 5.04 volts was measured from the plane to reference ground, the maximum step potential encountered is 0.85 volts. This step potential voltage is below the design criteria of 1 volt and occurs when a cow has one set of hooves on the edge of the concrete and the other set four feet away on the earth. Under these conditions, the step potential voltage would not alter the behavior of dairy cows.

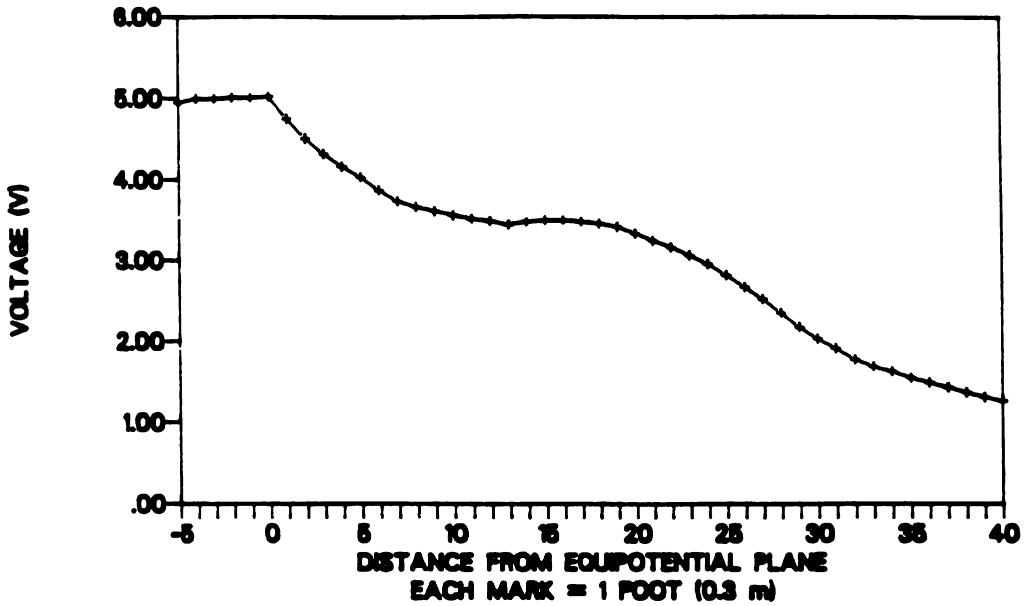

Figure 24. Voltage gradient of one approach path, measured from the point shown to a reference ground for test number 4.

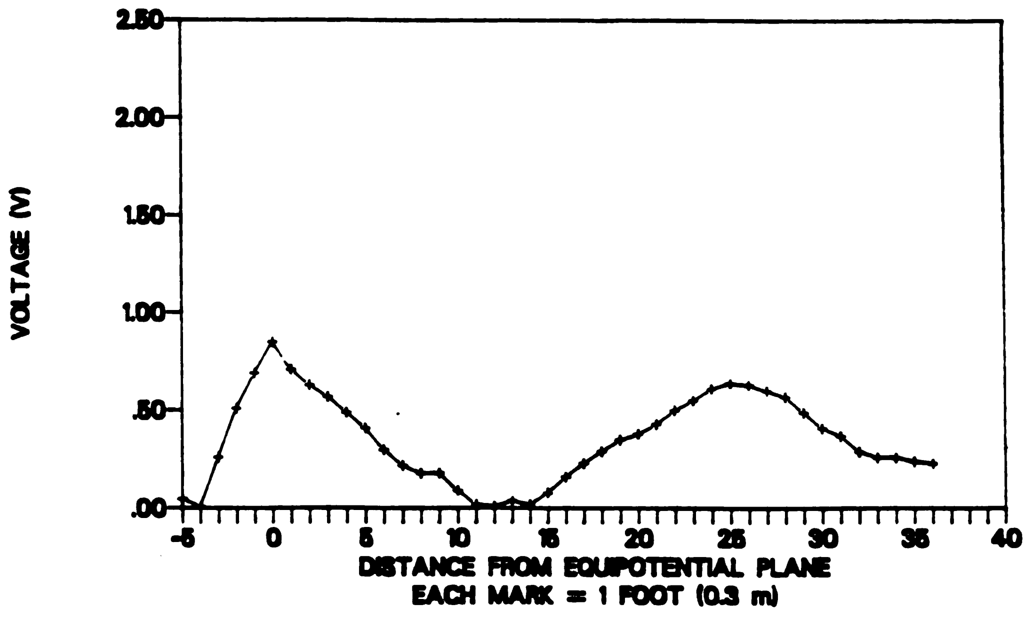

Figure 25. Step potential that a cow will experience from one set of hooves the other set for the voltage gradient of Figure 24.

C. Comparing Transition Techniques

Care must be taken when comparing the data from all the transition techniques. It was not possible to obtain the same voltage levels on the equipotential plane for all tests, because moisture content of soil could not be held constant from test to test. Table 1 compares the voltage measured on the equipotential plane and the maximum step potential obtained along the approach path for each test where 5 volts was desired on the equipotential plane. Table 1 also indicates the voltage on the equipotential plane and the maximum step potentials when the design criteria of 1 volt was not exceeded.

Table 1. Comparison of the test voltage and step potentials for the approach path when 5 volts measured from the equipotential plane to reference ground was desired as well as when step potentials did not exceed design criteria.

	Approximately 5 Volts Measured on the Equipotential Plane to Reference Ground		Maximum Values for Tests Not Exceeding the 1 Volt Design Criteria	
Test No.	Voltage	Max. Step Potential	Voltage	Max. Step Potential
1	5.38	2.46	1.80	0.80
2	5.29	1.20	3.58	0.84
3	5.75	1.57	2.95	0.52
4	5.04	0.85	5.04	0.85

The proposed transition design that could be installed at any approach path to an equipotential plane is shown in Figure 26 and should prevent most cows from receiving a step potential greater then 1 volt. In this figure, two additional wires have been added to the transition area on the opposite side of those in test number 4. Assuming that the transition area is in homogeneous soil, voltage contours on both sides of the wire that extend straight outward from the plane should be identical.

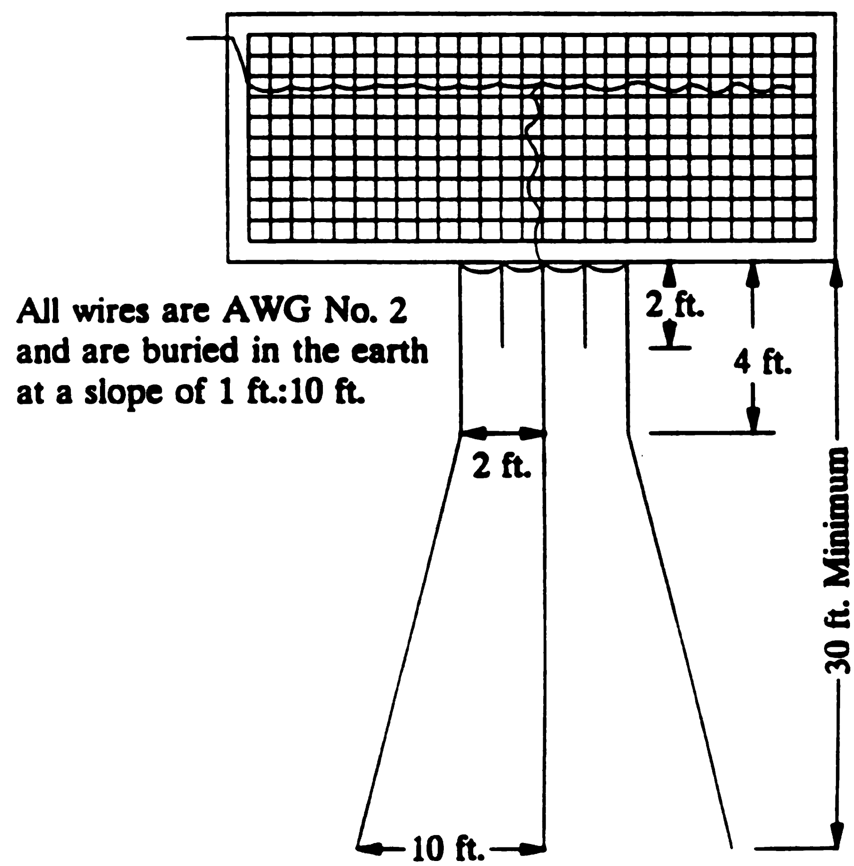

Figure 26. Proposed transition design that could be installed at every approach path to an equipotential plane.

D. Neutral Isolation

The key to the analysis of the isolated electrical system was the determination of the resistances for the source ground rod, R_{S1} and R_{S2}, and of the isolated ground rod R_I. Figure 27 is the equivalent circuit for the isolated and source electrical systems with the animal circuit removed, thus I_A is equal to zero. The top of the source ground rod is point "A" and the top of the isolated ground rod is point "D". Figure 27 shows that the voltage E_I is actually the voltage measured across the isolated farm grounding electrode system and is the voltage which would be experienced by a cow touching the neutral of the isolated system and earth. Table 2 contains the data for an isolated electrical system with the animal portion of the circuit removed, as indicated by infinite resistance for R_A and no current flowing through the simulated animal, I_A. Data for Table 2 was collected when the source ground rod resistance R_S was 19.6 ohms, the isolated ground rod resistance-to-earth was 21.4 ohms, and they were placed at a distance of six inches (15.2 cm) center-to-center. R_F is the sum of R_{FF} and R_{F1} as shown in Figure 10.

In the source portion of the circuit, the total current, I_T, flowing in the source circuit only flows through the source ground rod resistance, R_{S1}. The isolated neutral current, I_I, passes through the isolated farm grounding electrode system resistance, R_F, across which the voltage E_I was measured. Using equation number 1, the voltage E_I can be calculated, E_{IC}, by multiplying R_F by I_I. The earth does not behave exactly as pure resistance in a circuit and exact measurements are difficult to make in a "real-earth" circuit. Therefore, some variability will occur between the calculated value, E_{IC}, and the measured value of E_I. Using the data from Table 2, Table 3 indicates the calculated values for E_I and E_{IC}.

Table 2. Data for a ground rod of an isolated system spaced 6 inches (15.2 cm) from a ground rod of the source system with the animal circuit removed. The ground rod resistances was 19.6 ohms for R_S and 21.4 ohms for R_I.

I_T (mA)	I_I (mA)	I_A (mA)	E_S (Volts)	E_I (Volts)	E_{S-I} (Volts)	R_F (Ohms)	R_A (Ohms)
409	0.0	0.0	7.73	4.15	3.62	∞	∞
413	1.3	0.0	7.80	4.15	3.66	2994	∞
415	4.6	0.0	7.81	4.10	3.72	872	∞
418	7.9	0.0	7.82	4.05	3.78	504	∞
421	15.3	0.0	7.82	3.92	3.90	253	∞
430	35.3	0.0	7.79	3.57	4.22	99.8	∞
441	56.0	0.0	7.75	3.20	4.55	55.9	∞
500	192.7	0.0	7.46	0.73	6.65	3.9	∞
220	0.0	0.0	4.15	2.22	1.94	∞	∞
106.1	0.0	0.0	2.00	1.07	0.93	∞	∞
49.9	0.0	0.0	0.95	0.51	0.46	∞	∞

It would seem logical that to determine the combined resistance of R_{S1} and R_I, R_{S-I} would be equal to the voltage across the two ground rods E_{S-I} divided by the current flowing on the isolated neutral I_I. The calculated values of R_{S-I} are shown in Table 3. This value should remain constant because Surbrook et al. (1986) as well as Gustafson and Cloud (1982) have been able to model the electrical systems as linear resistive circuits.

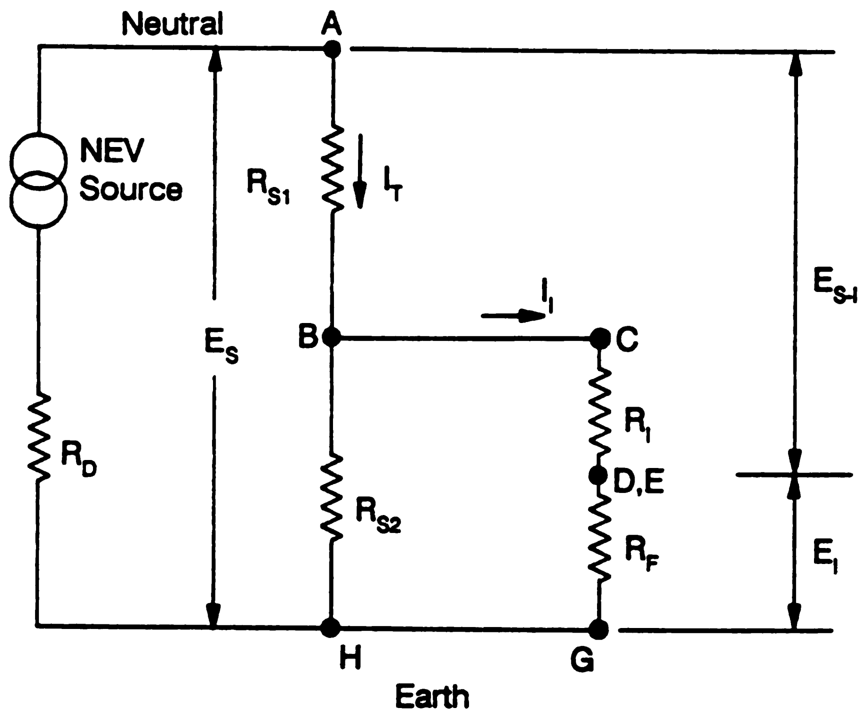

Figure 27. The equivalent circuit for the isolated and source electrical systems with the animal circuit removed.

An examination of the calculated values of R_{S-I} indicates that they rapidly decrease as more current flows on the isolated system, making the circuit seem non-linear. This contradicts what Surbrook et al. (1986) and Gustafson and Cloud (1982) found. Furthermore, the calculated value of R_{S-I} can not be greater than the sum of the measured values of R_S

and R_I, 41 ohms, because current flowing on the isolated system, I_I, flows through R_{S1} not R_{S2}. Therefore, R_{S1} had to be determined when the isolated neutral was open.

The values of source ground rod resistance R_{S1} and R_{S2} was determined from the measured resistance of the ground rod to earth if the isolated electrical system current I_I is zero. Thus, I_T passes through both R_{S1} and R_{S2}. If the isolated electrical system neutral is opened to prevent current flow, such as at points "D" or "E", the voltage E_I is now the voltage across R_{S2}, and E_{S-I} is the voltage across R_{S1}. The voltage from the source electrical system to earth, E_S, can be calculated from the data by adding E_{S-I} and E_I. The calculated value of voltage from the source neutral to reference ground, E_{SC}, is compared with the measured value of E_S in Table 3.

The values for source ground rod resistances R_{S1} and R_{S2} are determined from the measured value of source ground rod resistance, R_S, E_{S-I} and E_I. Open neutral on an isolated system is represented in Table 2 by infinite values of resistance for R_F. Equations 2 and 3 can be used to determine values of R_{S1} and R_{S2} respectively. The calculated values of R_{S1} and R_{S2} for the data of Table 2 are shown in Table 3.

$$R_{S1} = R_S \times \frac{E_{S-I}}{E_S} \qquad \text{Eq. 2}$$

$$R_{S2} = R_S \times \frac{E_I}{E_S} \qquad \text{Eq. 3}$$

An equation can be derived from Figure 27 to determine the value of isolated ground rod resistance, R_I, for all cases including the case of the isolated system open neutral. Equation 4 is derived from Figure 27 for determining the source system to earth voltage.

$$E_S = (I_T \times R_{S1}) + (I_I \times R_I) + E_I \qquad \text{Eq. 4}$$

Solving the equation for the isolated ground rod resistance provides a method for calculating the resistance of the isolated ground rod in the equivalent circuit. The value calculated must be less than the measured resistance-to-earth of the isolated ground rod. Equation 5 is used to determine the isolated ground rod resistance in the equivalent circuit.

$$R_I = \frac{E_S - E_I - (I_T \times R_{S1})}{I_I} \qquad \text{Eq. 5}$$

Table 3 shows the calculated values of R_{S1}, R_{S2}, E_{IC} and E_{SC} for the data in Table 2, where the isolated neutral was opened and R_{S-I}, R_{IC} and E_{SC} are shown for the data in Table 2, when the isolated neutral was closed. Measured values of voltages in Table 3 were not significantly different from the calculated voltages, and R_{S1} and R_{S2} remained consistent, indicating that the circuit was being properly analyzed.

Table 3. Values of E_{IC}, E_{SC}, R_{S1}, R_{S2} and R_{S-I} are calculated from the data in Table 2 and are shown with the measured values of E_I and E_S.

E_{IC} (Volts)	E_I (Volts)	E_{SC} (Volts)	E_S (Volts)	R_{S1} (Ohms)	R_{S2} (Ohms)	R_{S-I} (Ohms)
4.09	4.15	7.77	7.73	8.85	10.15	--
3.89	4.15	7.81	7.80	--	--	2815
4.01	4.10	7.82	7.81	--	--	808.7
3.98	4.05	7.83	7.82	--	--	478.5
3.87	3.92	7.82	7.82	--	--	254.9
3.52	3.57	7.79	7.79	--	--	119.5
3.13	3.20	7.75	7.75	--	--	81.3
0.73	.073	7.38	7.46	--	--	34.5
2.19	2.22	4.16	4.15	8.84	10.11	--
1.06	1.07	2.00	2.00	8.79	10.11	--
0.51	0.51	0.97	0.95	9.15	10.15	--

Data collected when the animal circuit was installed in the isolated system circuit is shown in Table 4. The equivalent circuit of an animal making contact with the neutral of the isolated system is shown in Figure 28. This is the same circuit as Figure 27 with the addition of the animal path from point "D", "E" to point "F" through the simulated cow resistance R_A. The resistance R_A consists of a resistor, R_{AA}, in series with a ground rod. The current flowing through the simulated cow is I_A. The values of resistance used to simulate the resistance of a cow are not intended to imply actual animal resistances. The purpose is to provide data for resistance values which will encompass a wide range of actual cow resistances.

For the purpose of this analysis and based upon research literature, it will be assumed that it is not likely that a typical animal circuit path would be found to be less than 274 ohms. Norell et al. (1983) found that the least resistance pathway for a dairy cow was from mouth to all hooves. The lowest resistance measured for this pathway was 244 ohms. However, the cow was standing on a metal grid which can not account for the hoof to surface contact resistance. Gustafson (1983) and Soderholm (1982) suggested a 300 ohm resistor be used to represent the mouth to all four hooves resistive pathway for a dairy cow. Therefore, the simulated cow resistance of 274 ohms is certainly les than a cow's body resistance, including hoof to surface contact resistance.

Examining current flowing through the simulated cow, I_A, in Table 4, only when the voltage on the source ground rod was 7.48 volts did the animal current exceed two milliamperes, which is the current level that has been found by Gustafson et al. (1986) that could alter the behavior of some dairy cows some of the time. With 3.92 volts on the source ground rod, the animal circuit current was only 1.43 milliamperes.

Table 4. Data for a ground rod of an isolated system spaced 6 inches (15.2 cm) from a ground rod of the source system. The ground rod resistances were 19.6 ohms for R_S and 21.4 ohms for R_I.

I_T (mA)	I_I (mA)	I_A (mA)	E_S (Volts)	E_I (Volts)	E_{S-I} (Volts)	R_F (Ohms)	R_A (Ohms)
500	193.2	0.25	7.46	0.73	6.71	3.9	3015
501	193.7	0.86	7.47	0.73	6.72	3.9	893
499	193.6	1.45	7.45	0.73	6.70	3.9	525
502	195.0	2.77	7.48	0.73	6.74	3.9	274
503	195.6	6.00	7.47	0.71	6.74	3.9	120.7
502	196.3	9.06	7.47	0.70	6.76	3.9	74.8
263	102.6	0.13	3.94	0.38	3.54	3.9	3015
262	101.9	0.43	3.90	0.37	3.51	3.9	893
261	101.9	0.74	3.89	0.37	3.51	3.9	525
262	102.7	1.43	3.92	0.38	3.54	3.9	274
263	102.9	3.09	3.91	0.37	3.53	3.9	120.7
261	102.8	4.64	3.90	0.36	3.53	3.9	74.8
125.6	47.9	0.07	1.88	0.20	1.68	3.9	3015
125.0	48.0	0.22	1.88	0.20	1.68	3.9	893
125.0	47.6	0.39	1.88	0.20	1.67	3.9	525
124.6	47.4	0.76	1.88	0.21	1.67	3.9	274
124.7	47.6	1.66	1.88	0.20	1.67	3.9	120.7
124.7	47.8	2.44	1.87	0.19	1.67	3.9	74.8
62.0	23.9	0.03	0.93	0.09	0.83	3.9	3015
61.8	23.8	0.11	0.92	0.09	0.84	3.9	893
62.3	24.0	0.18	0.93	0.09	0.84	3.9	525
62.1	24.0	0.34	0.93	0.09	0.84	3.9	274
62.1	24.0	0.76	0.93	0.09	0.84	3.9	120.7
62.2	24.0	1.15	0.93	0.09	0.84	3.9	74.8

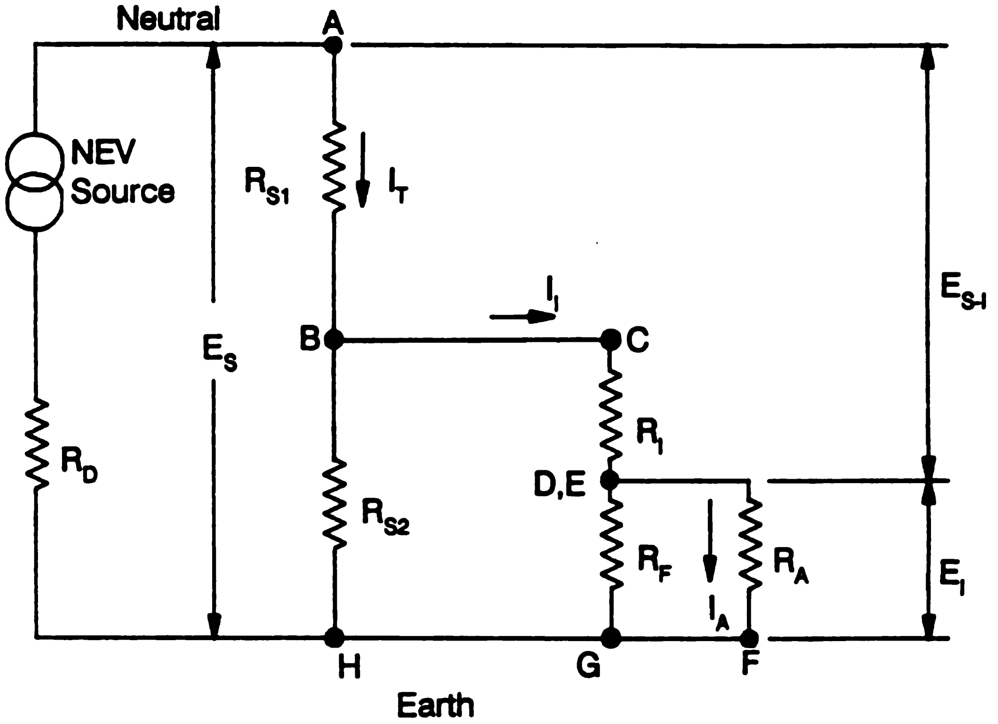

Figure 28. The equivalent circuit of an animal making contact with the neutral of the isolated system.

Using the data from Table 4 when the simulated animal was removed from the circuit, Table 5 indicates the calculated values of R_I, E_{IC} and E_{SC} are shown for the case where the simulated cow was added to the circuit as show in Figure 28. The values were calculated to determine if the circuit was being properly analyzed. The calculated values of E_{IC} and E_{SC} were not significantly different from the measured values. As would be expected in a linear circuit, current flow on the isolated system did not significantly alter the resistance of the isolated ground rod.

Table 5. Values of E_{IC}, E_{SC}, and R_I are calculated from the data in Table 4 and are shown with the measured values of E_I and E_S.

E_{IC} (Volts)	E_I (Volts)	E_{SC} (Volts)	E_S (Volts)	R_I (Ohms)
0.73	0.73	7.44	7.46	11.78
0.74	0.73	7.45	7.47	11.75
0.74	0.73	7.43	7.45	11.74
0.74	0.73	7.47	7.48	11.65
0.74	0.71	7.45	7.47	11.50
0.75	0.70	7.46	7.47	11.49
0.39	0.38	3.92	3.94	11.79
0.39	0.37	3.88	3.90	11.59
0.39	0.37	3.88	3.89	11.58
0.39	3.38	3.92	3.92	11.66
0.39	0.37	3.90	3.91	11.45
0.39	0.36	3.89	3.90	11.54
0.18	0.20	1.88	1.88	12.11
0.18	0.20	1.88	1.88	12.19
0.18	0.20	1.87	1.88	12.32
0.18	0.21	1.88	1.88	12.47
0.18	0.20	1.87	1.88	12.38
0.18	0.19	1.86	1.87	12.10
0.09	0.09	0.92	0.93	12.02
0.09	0.09	0.93	0.92	11.75
0.09	0.09	0.93	0.93	11.85
0.09	0.09	0.93	0.93	11.92
0.09	0.09	0.93	0.93	11.92
0.09	0.09	0.93	0.93	11.88

Some may feel that the simulated resistive values for a cow may not be representative of an actual cow. Any value of animal resistance can be used, if the isolated and source electrical system circuit can be represented by a Thevenin Equivalent circuit consisting of an open circuit voltage in series with a source resistance. Figure 29 is the equivalent circuit as observed from the location of the animal making contact with the isolated system neutral and standing on the earth or a floor. The Thevenin Equivalent circuit was shown in Figure 30. The open circuit voltage will be the actual neutral-to-earth voltage measured with a high impedance voltmeter such as a digital voltmeter. The equivalent circuit resistance, R_T, is determined from the known resistances of Figure 29 by shorting across the voltage source and determining the total circuit resistance as seen from the animal contact points. For the data of Table 4, the source resistance, R_T, is 3.2 ohms. The animal current can be determined from the circuit of Figure 30 for any desired animal resistance by using equation 6.

$$I_A = \frac{E_I}{R_T + R_A} \qquad \text{Eq. 6}$$

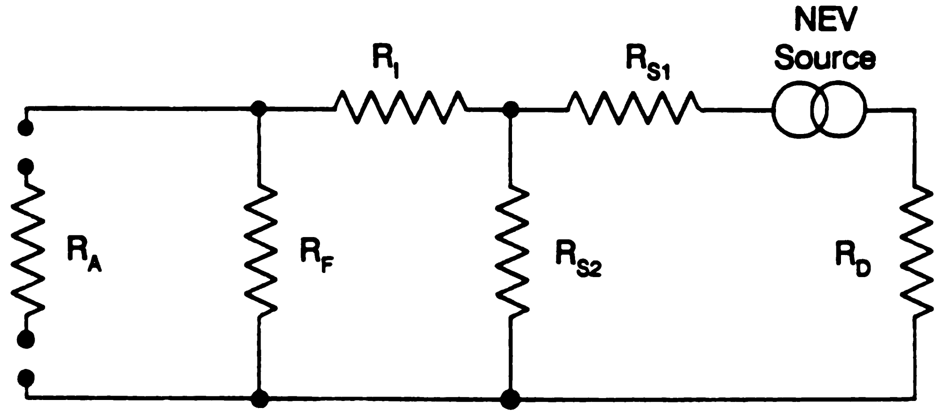

Figure 29. The equivalent circuit as observed from the location of the animal making contact with the isolated system neutral and standing on the earth or floor.

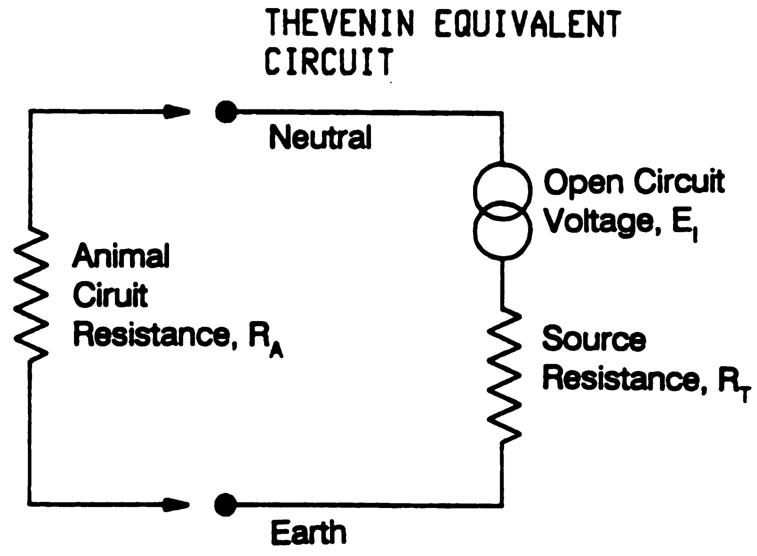

Figure 30. The Thevenin Equivalent circuit for Figure 29.

It is important to keep in mind that this value of Thevenin equivalent circuit source resistance, R_T, is only valid for the data of Table 2. The procedure described in this discussion can be used on a farm to determine the value of the Thevenin equivalent circuit source resistance.

When there is neutral-to-earth voltage at a ground rod, a voltage gradient will radiate out from the ground rod in all directions. Figure 31 shows the voltage gradient data for a ground rod with a resistance-to-earth less than 25 ohms and for a ground rod with a resistance-to-earth greater than 100 ohms. If an isolated ground rod is placed into the earth near a ground rod with such a gradient, the isolated ground rod will have the same voltage as the point on the gradient where it is placed provided the isolated circuit current does not flow through the isolated ground rod. When the voltage E_I is measured with an open neutral as shown in Figure 27 with the values in Table 2, E_I is actually the voltage at the point on the gradient. When solving equation number 4 for the source of neutral-to-earth voltage, E_S represents the open isolated circuit case where the isolated neutral current is zero. After solving for E_I in equation 4, it is possible to determine the isolated ground rod to earth voltage for the open isolated neutral case using equation 7.

$$E_I = E_S - (I_T \times R_{S1}) \qquad \text{Eq. 7}$$

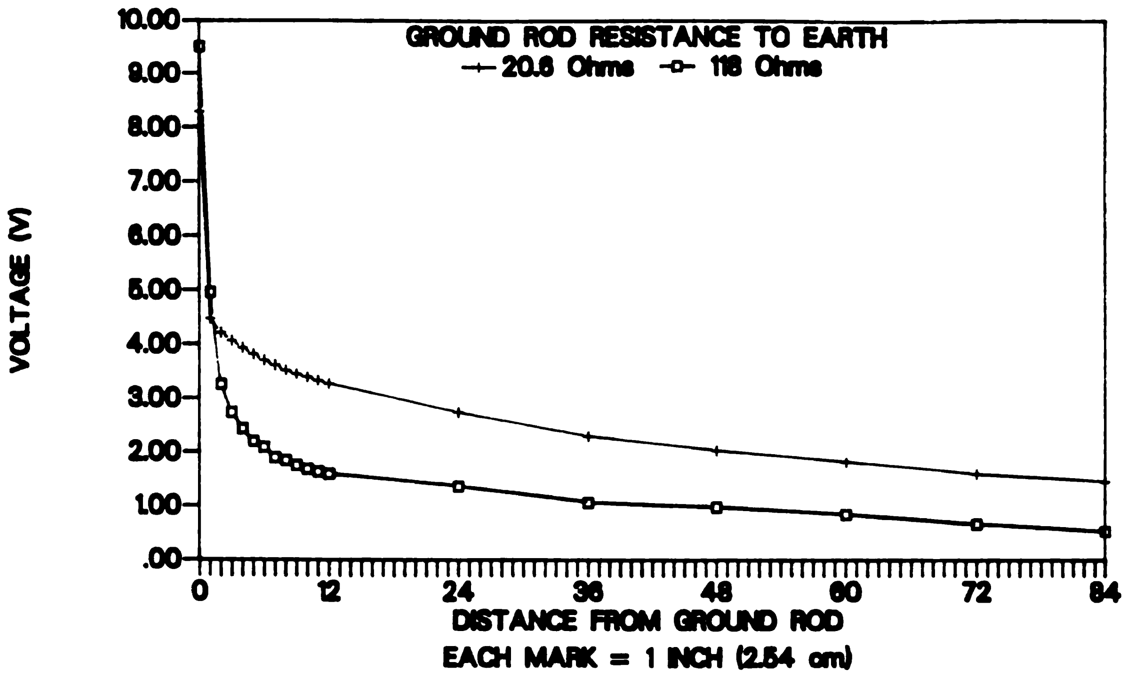

Figure 31. The voltage gradient data for a ground rod with a resistance-to-earth less than 25 ohms and for a ground rod with a resistance-to-earth greater than 100 ohms.

When there is current flow on the isolated neutral, the neutral-to-earth voltage of the farm neutral is represented by the previous equation for E_S rearranged to solve for E_I.

$$E_I = E_S - (I_T \times R_{S1}) - (I_I \times R_I) \qquad \text{Eq. 8}$$

Compare the previous two equations for isolated neutral to earth voltage E_I. Note that when there is neutral current flow in the isolated system, a voltage is created which subtracts from the gradient voltage. This can be observed in the data from each of the tests. The open circuit condition for the data in Table 4 is shown in Table 2. Compare the values of E_I when there is current flow on the isolated system neutral to when there is no current flow on the isolated neutral. For all cases, the voltage E_I is lower when there is current flow on the isolated system neutral than when there is no current flow on the isolated neutral.

As seen in equation 8, current flow on the isolated system neutral caused by the voltage gradient decreases the neutral-to-earth voltage on the isolated system neutral. The reduction of neutral-to-earth voltage becomes greater when the isolated ground rod resistance is high compared with the isolated farm grounding system resistance. This effect is observed by the data in Table 6. This data reflects the case where the source and isolated ground rods were only six inches (15.2 cm) apart but the resistance-to-earth of the source ground rod was 118 ohms and the isolated ground rod was 136 ohms. For this test, a cow with a resistance of 274 ohms contacting the neutral on the isolated system would only have 0.43 milliamperes flowing through her body with 9.33 volts neutral-to-earth voltage on the source system. The higher the resistance of the isolated ground rod, R_I, in comparison to the rest of the isolated farm grounding electrode system, R_F, the greater the reduction of current flowing through the animal.

Data shown in Table 7 is similar to the test data in Table 4. The ground rods were spaced six inches (15.2 cm) apart, the resistance-to-earth of the source ground rod was 20.6 ohms and the isolated ground rod was 14.7 ohms. Even when the ground rod resistance was lower than for the data shown in Table 4, the current levels through an animal are similar.

Table 6. Data collected from an isolated system where the source and isolated ground rods were only six inches (15.2 cm) apart. The resistance-to-earth of the source ground rod was 118 ohms and the isolated ground rod was 136 ohms.

I_T (mA)	I_I (mA)	I_A (mA)	E_S (Volts)	E_I (Volts)	E_{S-I} (Volts)	R_F (Ohms)	R_A (Ohms)
83.6	22.7	0.22	9.27	0.14		3.9	525
84.4	22.9	0.43	9.33	0.14		3.9	274
84.8	23.1	0.95	9.39	0.13		3.9	120.7
84.8	23.1	1.43	9.39	0.13		3.9	74.8
45.2	12.3	0.12	5.01	0.07		3.9	525
45.2	12.3	0.22	5.01	0.07		3.9	274
45.0	12.3	0.50	4.99	0.07		3.9	120.7
44.9	12.3	0.76	4.99	0.07		3.9	74.8
22.4	6.10	0.07	2.48	0.04		3.9	525
22.3	6.10	0.14	2.48	0.04		3.9	274
22.3	6.10	0.30	2.48	0.04		3.9	120.7
22.3	6.10	0.45	2.48	0.04		3.9	74.8
11.3	2.90	0.03	1.21	0.02		3.9	525
10.9	2.90	0.06	1.20	0.02		3.9	274
10.8	2.90	0.13	1.20	0.02		3.9	120.7
11.2	3.00	0.23	1.25	0.02		3.9	74.8

Table 7. Data collected from an isolated system where the source and isolated ground rods were only six inches (15.2 cm) apart. The resistance-to-earth of the source ground rod was 20.6 ohms and the isolated ground rod was 14.7 ohms.

I_T (mA)	I_I (mA)	I_A (mA)	E_S (Volts)	E_I (Volts)	E_{S-I} (Volts)	R_F (Ohms)	R_A (Ohms)
488	217	1.59	7.72	0.87		3.9	525
492	219	3.02	7.79	0.88		3.9	274
494	220	6.65	7.80	0.87		3.9	120.7
496	222	10.07	7.83	0.87		3.9	74.8
262	111.1	0.80	4.16	0.55		3.9	525
258	111.0	1.53	4.14	0.55		3.9	274
257	110.6	3.29	4.12	0.54		3.9	120.7
256	110.7	4.95	4.12	0.54		3.9	74.8
125.7	53.4	0.38	2.01	0.27		3.9	525
125.5	53.5	0.73	2.01	0.27		3.9	274
125.5	53.5	1.61	2.01	0.27		3.9	120.7
125.5	53.7	2.43	2.00	0.26		3.9	74.8
64.0	27.0	0.20	1.03	0.14		3.9	525
64.0	27.0	0.38	1.02	0.14		3.9	274
63.9	27.1	0.84	1.03	0.14		3.9	120.7
61.6	26.3	1.20	0.99	0.13		3.9	74.8

The test data shown in Table 8 is for the case where the ground rods were spaced six feet (1.8 m) apart, the resistance-to-earth of the source ground rod was 20.6 ohms and the isolated ground rod was 23.9 ohms. In this case with 8.36 volts measured on the source system, a 274 ohm cow circuit would only have 0.91 milliamperes flowing through her body when she would come in contact with the neutral or something bonded to the neutral and "true earth". Comparing the current flowing through the simulated cow for this test to tests where the ground rods were spaced only 6 inches (15.2 cm) apart, it becomes apparent that the requirement of source to isolated ground rod spacing of 6 feet (1.8 m) by the National Electrical Safety Code is a conservative requirement. This research shows that adequate isolation can be maintained under most cases when the 6 foot (1.2 m) spacing is not achieved. Soderholm (1982) stated that proper spacing must be maintained to accomplish isolation. Data presented in Tables 4, 6, and 7, ground rods were only spaced 6 inches (15.2 cm) apart, contradicts Soderholm's (1982) statement. Given the grounding electrodes' resistance-to-earth, Tables 4, 6 and 7 show that a 274 ohm cow circuit can come in contact with the neutral of an isolated neutral and "true earth" would not have more than 2 milliamperes flowing through her body when the neutral-to-earth voltage on the source system was at or below 3.92, 9.33, and 4.14 volts respectively.

Table 8. Data collected from an isolated system where the source and isolated ground rods were six feet (1.8 m) apart. The resistance-to-earth of the source ground rod was 20.6 ohms and the isolated ground rod was 23.9 ohms.

I_T (mA)	I_I (mA)	I_A (mA)	E_S (Volts)	E_I (Volts)	E_{S-I} (Volts)	R_F (Ohms)	R_A (Ohms)
418	55.6	0.47	8.36	0.30		3.9	525
418	55.6	0.91	8.36	0.30		3.9	274
418	55.8	2.01	8.35	0.29		3.9	120.7
417	56.0	3.00	8.33	0.29		3.9	74.8
221	29.4	0.25	4.42	0.16		3.9	525
220	29.2	0.47	4.40	0.16		3.9	274
220	29.3	1.06	4.40	0.15		3.9	120.7
220	29.3	1.60	4.39	0.15		3.9	74.8
107.7	14.2	0.12	2.15	0.08		3.9	525
107.4	14.1	0.23	2.14	0.08		3.9	274
105.0	14.0	0.48	2.10	0.07		3.9	120.7
104.6	14.0	0.74	2.09	0.07		3.9	74.8
53.3	5.20	0.05	1.06	0.08		3.9	525
52.8	5.17	0.11	1.06	0.08		3.9	274
52.8	5.19	0.23	1.06	0.08		3.9	120.7
52.6	5.18	0.36	1.06	0.08		3.9	74.8

VI. CONCLUSIONS

Neutral-to-earth voltage is a difference of potential between a grounded piece of equipment and true earth. The presence of this neutral-to-earth voltage in animal contact areas in dairy facilities has been implicated as causing changes in behavior of dairy cows. Though there are many different sources of neutral-to-earth voltage, there are mitigating techniques that can be used to reduce the effects on animals.

The conclusions which can be drawn from this study of modifications to a grounding system are as follows:

1. Exceeding 2.0 volts, neutral-to-earth, on an equipotential plane without some form of transition area modification will expose a dairy cow to a step potential which may alter behavior of some cows some of the time.
2. Exceeding 3.5 volts, neutral-to-earth, will permit a dairy cow to experience a step potential which exceeds the lower step potential threshold limit when a transition area consists of eight foot (2.4 m) ground rods driven at a 45 degree angle extending out away from the equipotential plane.

3. Dairy cows will not experience a step potential above the lower threshold limit with up to 5.0 volts on an equipotential plane when a transition area consists of AWG number 2 copper wire placed in the earth at increasing in depths at a slope of one unit of depth to ten units of distance away from the equipotential plane up to a distance of 30 feet installed as specified in Figure 26.

4. The equivalent circuit for a neutral-to-earth source electrical system and an isolated farm electrical system utilizing the earth as an isolation medium between a ground rod of each system can be approximated by a the linear resistive circuit of Figure 28.

5. Neutral-to-earth voltage of an isolated electrical system isolated from a neutral-to-earth source electrical system by a ground rod of each system separated by earth can be determined by using equation 8.

6. Current flow through the isolated electrical system's ground rod and neutral creates a voltage which is subtractive from the gradient voltage created by a neutral-to-earth source voltage electrical system at the point where the isolated ground rod is installed, and this subtractive voltage is of the magnitude of R_I times I_I of equation 8.

7. Separation of six feet (1.8 m) between grounding electrodes of an isolated system from a neutral-to-earth voltage source system will provide adequate separation to prevent a dairy cow making contact with the isolated system neutral from experiencing a current flow that could elicit a behavioral response.

8. An animal circuit of 274 ohms from isolated electrical system neutral to earth will not have a current flow greater than 2.0 milliamperes with up to 5.0 volts neutral-to-earth on a source electrical system where a ground rod of the isolated and source electrical system are separated by a distance of six inches (15.2 cm).

VII. SUGGESTIONS FOR FUTURE STUDY

This work is a fundamental study which explains some of the effects that grounding has on the level of neutral-to-earth voltages in cow contact areas. It can be used as a starting point for more in depth theoretical and practical research in this area.

It is suggested that future studies on this topic include determining the resistance between a cow's hooves and the surface she is standing on. Also it is suggest that future studies include evaluating equipotential designs and isolated grounding systems effectiveness with different soil types and soil parameters, such as moisture content and temperature.

APPENDIX

APPENDIX

Voltage Gradient Data

For the analysis of voltage gradients surrounding equipotential planes, the data was collected in blocks. While these blocks were of different sizes from test to test, they were consistent in the sense that the blocks were established from reference points that remained constant for all tests. Data was recorded in rows and columns, see Figure 32. The columns ran North to South, and the rows East to West. The approach path for the equipotential plane was Column "S".

The tests of equipotential plane transitions were as follows:

Test 1: No transition modifications (Figure 3).

Test 2: Ground rods driven at a 45 degree angle extending out away from the plane (Figure 6).

Test 3: Single wire extending from the equipotential plane (Figure 7).

Test 4: Multiple wires extending from the equipotential plane (Figure 8).

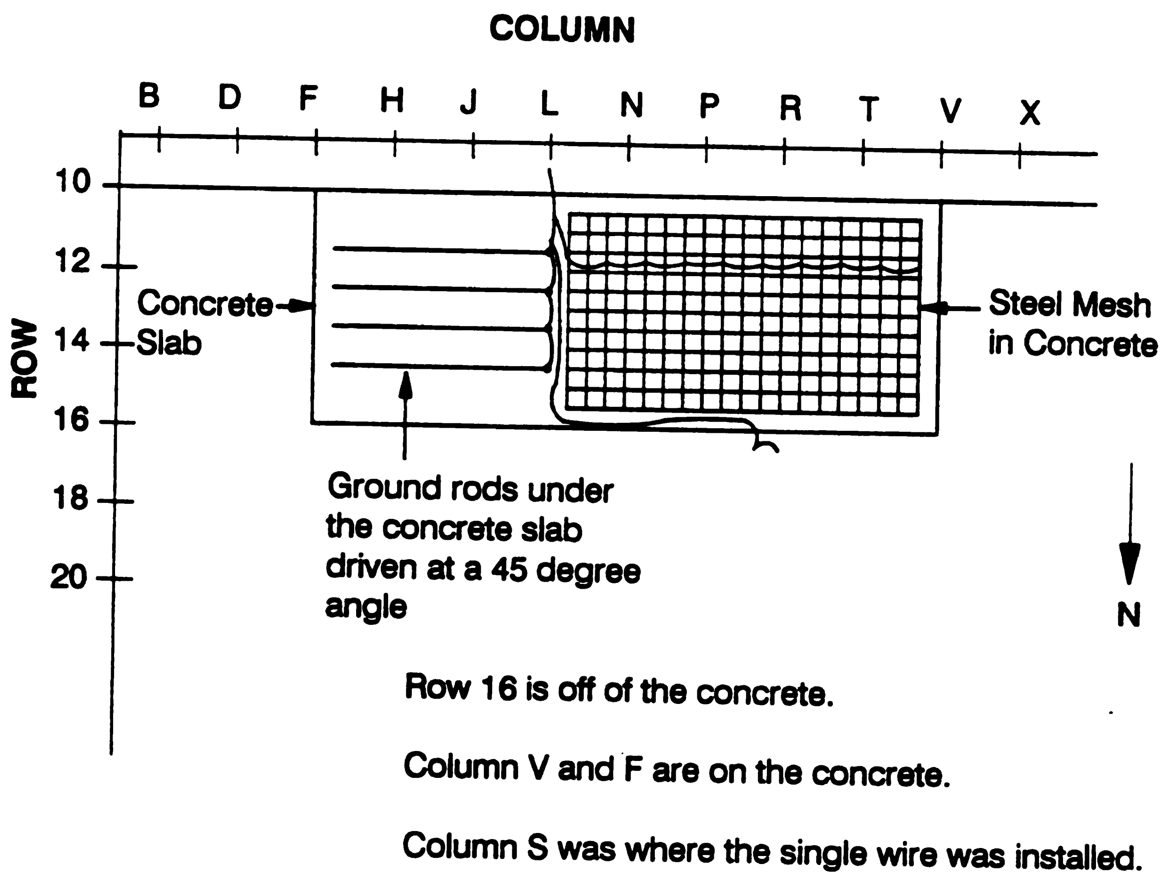

Figure 32. Illustration of the voltage gradient test area.

Table 9. Surface to reference ground voltage measurements for test 1 when 5.38 volts was measured from the equipotential plane to a reference ground.

	COLUMN												
ROW	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA
10	3.40	3.67	3.86	3.71	3.97	3.83	3.00	2.70	2.43	2.21	2.09	1.99	1.91
11	5.04	5.14	5.30	5.33	5.30	5.12	4.41	3.01	2.71	2.36	2.18	2.02	1.90
12	5.30	5.33	5.36	5.40	5.26	5.32	4.35	3.13	2.85	2.52	2.22	2.08	1.90
13	5.34	5.32	5.33	5.38	5.33	5.31	4.76	3.12	2.85	2.56	2.31	2.08	1.91
14	5.25	5.32	5.32	5.12	5.34	5.33	4.65	3.09	2.86	2.61	2.33	2.10	1.91
15	5.25	5.33	5.30	5.14	5.11	5.22	4.66	3.13	2.88	2.58	2.33	2.11	1.91
16	4.35	4.38	4.41	4.53	3.69	3.94	3.90	3.36	2.87	2.54	2.29	2.08	1.90
17	3.78	3.81	3.85	3.89	3.25	3.53	3.40	3.09	2.74	2.44	2.22	2.05	1.88
18	3.40	3.40	3.35	3.35	2.94	3.14	2.97	2.76	2.50	2.31	2.15	2.00	1.85
19	3.16	3.12	3.06	3.01	2.64	2.82	2.70	2.35	2.34	2.21	2.07	1.93	1.79
20	2.86	2.82	2.79	2.73	2.40	2.56	2.46	2.30	2.18	2.09	1.98	1.88	1.74
21	2.67	2.64	2.55	2.50	2.26	2.37	2.28	2.17	2.08	1.98	1.89	1.81	1.69
22	2.44	2.41	2.36	2.33	2.11	2.20	2.11	2.01	1.92	1.87	1.80	1.73	1.63
23	2.28	2.24	2.20	2.16	2.00	2.06	1.97	1.91	1.83	1.79	1.73	1.67	1.56
24	2.14	2.11	2.06	2.02	1.87	1.94	1.88	1.79	1.75	1.72	1.66	1.61	1.52
25	2.00	1.94	1.93	1.90	1.77	1.83	1.77	1.73	1.68	1.64	1.60	1.53	1.46
26	1.89	1.86	1.83	1.80	1.67	1.73	1.68	1.64	1.60	1.57	1.53	1.48	1.41
27	1.75	1.75	1.74	1.70	1.58	1.63	1.60	1.56	1.53	1.51	1.46	1.42	1.36
28	1.66	1.65	1.62	1.60	1.51	1.55	1.51	1.48	1.45	1.42	1.38	1.35	1.30
29	1.59	1.57	1.55	1.53	1.45	1.48	1.46	1.44	1.40	1.37	1.33	1.30	1.24
30	1.53	1.51	1.49	1.48	1.41	1.44	1.41	1.39	1.35	1.31	1.27	1.24	1.20
31	1.47	1.46	1.43	1.42	1.35	1.38	1.35	1.33	1.29	1.25	1.21	1.20	1.17
32	1.41	1.40	1.38	1.37	1.31	1.32	1.30	1.27	1.24	1.21	1.18	1.16	1.13

Table 10. Surface to reference ground voltage measurements for test 1 when 1.80 volts was measured from the equipotential plane to a reference ground.

	COLUMN												
ROW	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA
10	1.36	1.36	1.36	1.35	1.42	1.23	1.07	1.03	0.84	0.77	0.73	0.69	0.66
11	1.69	1.72	1.77	1.78	1.77	1.75	1.48	0.94	0.93	0.82	0.75	0.71	0.66
12	1.79	1.79	1.80	1.80	1.79	1.79	1.61	1.07	0.98	0.85	0.77	0.73	0.66
13	1.80	1.78	1.79	1.79	1.80	1.80	1.59	1.07	1.00	0.87	0.80	0.72	0.65
14	1.79	1.78	1.79	1.79	1.80	1.80	1.52	1.06	1.00	0.89	0.81	0.74	0.66
15	1.79	1.79	1.78	1.78	1.79	1.78	1.55	1.06	0.99	0.90	0.81	0.73	0.65
16	1.46	1.45	1.49	1.53	1.39	1.34	1.34	1.06	1.01	0.87	0.80	0.72	0.66
17	1.28	1.30	1.30	1.31	1.27	1.20	1.15	1.17	0.92	0.84	0.77	0.71	0.63
18	1.17	1.16	1.15	1.13	1.10	1.06	1.01	1.06	0.86	0.80	0.74	0.69	0.63
19	1.07	1.05	1.05	1.02	0.99	0.96	0.92	0.93	0.80	0.76	0.72	0.66	0.61
20	0.97	0.95	0.94	0.92	0.89	0.87	0.83	0.85	0.75	0.72	0.68	0.65	0.60
21	0.90	0.88	0.87	0.84	0.83	0.81	0.77	0.79	0.70	0.68	0.65	0.65	0.58
22	0.83	0.81	0.80	0.78	0.77	0.75	0.72	0.73	0.66	0.64	0.61	0.60	0.54
23	0.78	0.76	0.75	0.74	0.72	0.71	0.68	0.69	0.60	0.62	0.60	0.57	0.54
24	0.73	0.72	0.68	0.68	0.67	0.65	0.62	0.65	0.57	0.59	0.58	0.55	0.52
25	0.68	0.67	0.66	0.65	0.64	0.63	0.61	0.62	0.55	0.56	0.55	0.53	0.50
26	0.65	0.64	0.63	0.61	0.60	0.59	0.57	0.59	0.52	0.54	0.53	0.51	0.48
27	0.59	0.59	0.58	0.57	0.56	0.54	0.54	0.56	0.50	0.50	0.50	0.48	0.46
28	0.56	0.55	0.54	0.53	0.52	0.51	0.51	0.53	0.48	0.49	0.48	0.46	0.44
29	0.54	0.53	0.52	0.51	0.50	0.50	0.49	0.51	0.46	0.47	0.46	0.44	0.42
30	0.51	0.50	0.50	0.49	0.49	0.48	0.47	0.49	0.44	0.45	0.44	0.42	0.41
31	0.49	0.49	0.47	0.47	0.47	0.46	0.45	0.45	0.42	0.43	0.42	0.41	0.40
32	0.48	0.47	0.47	0.46	0.45	0.41	0.40	0.43	0.42	0.41	0.41	0.40	0.38

Table 11. Surface to reference ground voltage measurements for test 2 when 5.29 volts was measured from the equipotential plane to a reference ground.

	COLUMN												
ROW	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA
10		3.87	3.53	3.74	3.61	3.39	2.86	2.60	2.43	2.31	2.23	2.15	2.09
11		5.12	5.17	5.20	5.19	5.02	4.15	3.00	2.73	2.55	2.38	2.21	2.12
12		5.14	5.24	5.27	5.24	5.18	4.56	3.23	2.93	2.69	2.48	2.32	2.16
13		5.25	5.26	5.28	5.24	5.20	4.47	3.43	3.05	2.76	2.55	2.35	2.20
14		5.26	5.26	5.29	5.24	5.23	4.43	3.51	3.17	2.85	2.60	2.43	2.24
15		5.24	5.24	5.29	5.24	5.16	4.58	3.66	3.35	2.97	2.69	2.48	2.28
16		4.71	4.86	5.15	5.16	5.14	5.05	3.96	3.47	3.06	2.79	2.54	2.35
17		4.48	4.66	4.82	4.85	4.85	4.55	3.96	3.43	3.06	2.83	2.54	2.37
18		4.25	4.32	4.51	4.54	4.50	4.31	3.81	3.38	3.02	2.77	2.55	2.39
19		4.00	4.04	4.16	4.22	4.16	3.99	3.61	3.26	2.99	2.79	2.53	2.37
20		3.75	3.79	3.95	3.95	3.82	3.68	3.42	3.10	2.83	2.66	2.47	2.31
21		3.54	3.56	3.59	3.65	3.58	3.39	3.19	2.97	2.74	2.60	2.40	2.27
22		3.26	3.04	3.37	3.35	3.24	3.15	2.95	2.76	2.61	2.48	2.32	2.18
23		2.98	2.78	3.10	3.08	2.96	2.85	2.75	2.60	2.48	2.38	2.23	2.11
24		2.75	2.50	2.82	2.79	2.70	2.63	2.55	2.46	2.35	2.26	2.11	2.05
25		2.54	2.32	2.46	2.53	2.47	2.44	2.39	2.30	2.23	2.13	2.04	1.96
26		2.33	2.16	2.30	2.26	2.27	2.24	2.21	2.18	2.10	2.02	1.93	1.87
27		2.19	2.04	2.12	2.14	2.13	2.15	2.10	2.06	1.99	1.92	1.85	1.81
28		2.06	1.94	2.01	2.01	2.00	2.00	1.97	1.93	1.87	1.80	1.75	1.71
29		1.96	1.87	1.93	1.93	1.91	1.90	1.88	1.85	1.79	1.74	1.67	1.64
30		1.87	1.80	1.85	1.84	1.82	1.80	1.78	1.74	1.68	1.64	1.60	1.56
31		1.80	1.75	1.80	1.78	1.75	1.72	1.74	1.60	1.61	1.58	1.53	1.50
32		1.73	1.74	1.74	1.73	1.70	1.67	1.63	1.60	1.54	1.51	1.48	1.44

Table 12. Surface to reference ground voltage measurements for test 2 when 3.58 volts was measured from the equipotential plane to a reference ground.

	COLUMN												
ROW	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA
10		2.60	2.50	2.45	2.32	2.34	1.89	1.77	1.66	1.59	1.53	1.48	1.44
11		3.46	3.51	3.53	3.53	3.41	2.77	2.02	1.86	1.74	1.65	1.52	1.46
12		3.50	3.56	3.58	3.55	3.51	3.19	2.19	1.99	1.82	1.70	1.59	1.48
13		3.55	3.56	3.58	3.55	3.54	3.14	3.32	2.09	1.88	1.72	1.61	1.52
14		3.55	3.56	3.58	3.55	3.55	3.18	2.39	2.16	1.95	1.76	1.67	1.55
15		3.56	3.55	3.57	3.55	3.50	3.10	2.47	2.27	2.05	1.85	1.71	1.56
16		3.21	3.29	3.50	3.51	3.51	3.35	2.66	2.36	2.12	1.90	1.73	1.61
17		3.04	3.18	3.29	3.28	3.27	3.09	2.69	2.34	2.09	1.90	1.75	1.63
18		2.90	2.96	3.04	3.11	3.06	2.91	2.60	2.30	2.09	1.90	1.73	1.64
19		2.69	2.77	2.83	2.88	2.82	2.71	2.47	2.19	2.06	1.88	1.73	1.62
20		2.55	2.59	2.65	2.69	2.60	2.51	2.32	2.10	1.96	1.81	1.69	1.59
21		2.38	2.43	2.43	2.47	2.41	2.31	2.19	1.99	1.89	1.78	1.65	1.56
22		2.21	2.26	2.28	2.27	2.22	2.14	2.00	1.88	1.79	1.69	1.57	1.49
23		2.04	2.07	2.12	2.07	2.02	1.94	1.86	1.77	1.70	1.63	1.52	1.44
24		1.87	1.89	1.91	1.87	1.86	1.80	1.72	1.68	1.62	1.54	1.45	1.40
25		1.72	1.70	1.71	1.69	1.68	1.64	1.63	1.58	1.53	1.45	1.40	1.35
26		1.58	1.57	1.56	1.54	1.55	1.52	1.50	1.48	1.44	1.37	1.33	1.29
27		1.48	1.47	1.45	1.44	1.46	1.45	1.42	1.40	1.35	1.30	1.26	1.23
28		1.40	1.39	1.37	1.36	1.37	1.36	1.33	1.31	1.27	1.23	1.19	1.17
29		1.34	1.31	1.31	1.31	1.30	1.29	1.28	1.25	1.22	1.19	1.15	1.13
30		1.27	1.26	1.26	1.25	1.24	1.22	1.20	1.18	1.15	1.12	1.09	1.07
31		1.21	1.22	1.22	1.21	1.20	1.18	1.15	1.13	1.10	1.07	1.05	1.03
32		1.17	1.18	1.18	1.18	1.16	1.14	1.11	1.09	1.05	1.03	1.01	0.99

Table 13. Surface to reference ground voltage measurements for test 3 when 5.75 volts was measured from the equipotential plane to a reference ground.

	COLUMN												
ROW	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA
10	4.37	4.24	4.19	4.12	4.28	3.96	3.45	2.95	2.65	2.46	2.35	2.24	2.14
11	5.28	5.22	5.65	5.71	5.70	5.65	4.45	3.26	2.95	2.62	2.46	2.28	2.15
12	5.66	5.61	5.70	5.73	5.70	5.69	4.75	3.43	3.13	2.77	2.56	2.36	2.19
13	5.72	5.69	5.70	5.75	5.73	5.70	4.80	3.48	3.19	2.86	2.62	2.40	2.21
14	5.70	5.72	5.73	5.77	5.73	5.71	5.05	3.46	3.19	2.94	2.65	2.44	2.25
15	5.71	5.72	5.68	5.72	5.68	5.57	4.77	3.52	3.24	2.94	2.68	2.46	2.28
16	4.75	4.81	4.82	5.21	5.15	4.48	4.35	3.69	3.27	2.92	2.74	2.48	2.27
17	4.43	4.42	4.38	4.57	4.77	4.20	3.98	3.50	3.18	2.87	2.67	2.44	2.20
18	4.09	4.14	4.18	4.32	4.37	3.91	3.64	3.33	3.05	2.80	2.62	2.43	2.29
19	3.83	3.89	3.94	4.09	4.10	3.72	3.44	3.17	2.93	2.75	2.48	2.39	2.25
20	3.52	3.67	3.77	3.94	4.02	3.62	3.28	3.07	2.86	2.67	2.54	2.39	2.22
21	3.48	3.55	3.61	3.80	3.87	3.52	3.22	2.96	2.75	2.60	2.48	2.30	2.21
22	3.28	3.36	3.45	3.63	3.68	3.39	3.14	2.81	2.66	2.54	2.43	2.28	2.15
23	3.12	3.21	3.32	3.51	3.58	3.24	3.01	2.74	2.58	2.49	2.39	2.24	2.14
24	3.00	3.09	3.18	3.38	3.47	3.13	2.92	2.70	2.56	2.44	2.35	2.21	2.09
25	2.86	2.96	3.08	3.27	3.36	3.07	2.85	2.63	2.48	2.37	2.29	2.16	2.03
26	2.79	2.87	2.97	3.22	3.30	3.05	2.81	2.62	2.45	2.34	2.24	2.11	2.00
27	2.72	2.77	2.87	3.09	3.20	2.92	2.77	2.60	2.43	2.31	2.18	2.07	1.96
28	2.51	2.67	2.84	3.07	3.13	2.90	2.72	2.55	2.36	2.25	2.13	2.02	1.91
29	2.50	2.66	2.78	2.99	3.04	2.89	2.63	2.49	2.31	2.18	2.06	1.97	1.86
30	2.48	2.57	2.75	2.92	2.98	2.85	2.62	2.46	2.25	2.11	2.02	1.91	1.83
31	2.39	2.51	2.70	2.81	2.94	2.80	2.57	2.37	2.21	2.04	1.93	1.89	1.78
32	2.34	2.45	2.61	2.78	2.93	2.71	2.53	2.31	2.11	1.91	1.91	1.85	1.75
33	2.21	2.38	2.57	2.78	2.83	2.64	2.43	2.23	2.05	1.91	1.87	1.83	1.69
34	2.11	2.31	2.47	2.66	2.68	2.48	2.30	2.12	1.99	1.88	1.82	1.76	1.63
35	2.01	2.18	2.31	2.45	2.45	2.33	2.13	2.03	1.88	1.81	1.75	1.65	1.55
36	1.92	2.00	2.09	2.21	2.27	2.14	1.99	1.88	1.79	1.71	1.67	1.59	1.50
37	1.80	1.91	1.98	2.02	2.01	1.94	1.89	1.78	1.71	1.65	1.60	1.52	1.44
38	1.67	1.73	1.77	1.81	1.81	1.78	1.74	1.69	1.62	1.59	1.55	1.47	1.38
39	1.57	1.60	1.63	1.69	1.68	1.66	1.65	1.60	1.56	1.52	1.47	1.40	1.33
40	1.52	1.53	1.55	1.57	1.60	1.58	1.56	1.53	1.49	1.45	1.40	1.36	1.30
41	1.44	1.45	1.46	1.47	1.49	1.48	1.47	1.45	1.42	1.39	1.35	1.30	1.25
42	1.38	1.39	1.39	1.38	1.41	1.41	1.41	1.38	1.34	1.31	1.28	1.25	1.21
43	1.32	1.32	1.31	1.32	1.33	1.33	1.33	1.31	1.28	1.25	1.22	1.20	1.17
44	1.26	1.26	1.26	1.26	1.25	1.25	1.24	1.23	1.21	1.19	1.18	1.15	1.14

Table 14. Surface to reference ground voltage measurements for test 3 when 2.95 volts was measured from the equipotential plane to a reference ground.

	COLUMN												
ROW	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA
10	2.42	2.29	2.39	2.39	2.09	1.97	1.84	1.55	1.41	1.33	1.24	1.18	1.13
11	2.77	2.94	2.96	2.95	2.95	2.95	2.50	1.71	1.53	1.37	1.30	1.19	1.13
12	2.96	2.97	2.98	3.00	2.98	2.98	2.64	1.79	1.59	1.45	1.31	1.24	1.15
13	2.96	2.97	2.98	2.97	2.97	2.98	2.63	1.81	1.66	1.50	1.36	1.26	1.14
14	2.97	2.95	2.95	2.97	2.97	2.96	2.50	1.80	1.65	1.52	1.39	1.26	1.18
15	2.96	2.96	2.94	2.96	2.96	2.88	2.69	1.83	1.65	1.50	1.39	1.27	1.18
16	2.47	2.47	2.50	2.70	2.68	2.33	2.26	1.96	1.69	1.53	1.40	1.30	1.19
17	2.30	2.30	2.37	2.53	2.58	2.08	1.81	1.63	1.49	1.39	1.29	1.29	1.19
18	2.13	2.15	2.15	2.25	2.30	2.05	1.91	1.74	1.59	1.45	1.37	1.27	1.19
19	2.02	2.03	2.07	2.13	2.15	1.97	1.80	1.65	1.52	1.45	1.33	1.25	1.17
20	1.88	1.93	1.96	2.04	2.08	1.84	1.72	1.59	1.47	1.38	1.32	1.24	1.18
21	1.81	1.81	1.85	1.97	2.00	1.82	1.65	1.53	1.43	1.35	1.30	1.19	1.13
22	1.71	1.74	1.78	1.88	1.95	1.75	1.60	1.45	1.37	1.30	1.18	1.17	1.11
23	1.62	1.62	1.71	1.79	1.83	1.68	1.52	1.42	1.33	1.28	1.21	1.18	1.09
24	1.53	1.58	1.62	1.75	1.76	1.62	1.52	1.37	1.32	1.26	1.12	1.14	1.07
25	1.47	1.52	1.58	1.66	1.70	1.56	1.46	1.35	1.27	1.21	1.16	1.10	1.04
26	1.42	1.47	1.52	1.63	1.68	1.55	1.44	1.34	1.26	1.19	1.14	1.07	1.02
27	1.37	1.42	1.47	1.60	1.64	1.49	1.40	1.30	1.22	1.17	1.10	1.06	0.99
28	1.29	1.36	1.45	1.53	1.57	1.46	1.37	1.28	1.22	1.15	1.08	1.02	0.97
29	1.27	1.34	1.41	1.50	1.53	1.45	1.34	1.26	1.18	1.11	1.06	0.98	0.94
30	1.24	1.29	1.39	1.47	1.49	1.43	1.34	1.25	1.14	1.07	1.01	0.96	0.91
31	1.20	1.27	1.35	1.45	1.48	1.39	1.31	1.21	1.09	1.01	0.97	0.96	0.90
32	1.15	1.24	1.29	1.42	1.46	1.37	1.27	1.17	1.08	0.98	0.96	0.94	0.89
33	1.12	1.20	1.28	1.39	1.43	1.33	1.21	1.14	1.03	0.97	0.94	0.93	0.86
34	1.06	1.14	1.22	1.34	1.35	1.26	1.16	1.07	1.00	0.96	0.93	0.87	0.83
35	1.00	1.09	1.16	1.25	1.27	1.17	1.09	1.02	0.96	0.91	0.89	0.84	0.80
36	0.96	1.01	1.08	1.13	1.13	1.08	1.01	0.96	0.91	0.87	0.85	0.81	0.76
37	0.91	0.97	1.02	1.03	1.03	0.98	0.95	0.90	0.87	0.84	0.79	0.77	0.73
38	0.84	0.87	0.91	0.93	0.93	0.92	0.90	0.85	0.83	0.81	0.78	0.75	0.71
39	0.80	0.82	0.83	0.84	0.84	0.84	0.83	0.81	0.78	0.76	0.74	0.70	0.67
40	0.76	0.77	0.79	0.79	0.80	0.78	0.79	0.77	0.75	0.72	0.71	0.66	0.65
41	0.72	0.73	0.74	0.75	0.76	0.75	0.74	0.71	0.71	0.69	0.68	0.66	0.63
42	0.69	0.70	0.69	0.70	0.70	0.70	0.70	0.69	0.68	0.66	0.64	0.63	0.61
43	0.67	0.66	0.66	0.66	0.66	0.67	0.67	0.66	0.64	0.63	0.62	0.61	0.59
44	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.62	0.61	0.60	0.59	0.58	0.58

Table 15. Surface to reference ground voltage measurements for test 5 when 5.04 volts was measured from the equipotential plane to a reference ground.

	COLUMN												
ROW	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA
10			3.33	3.33	3.09	2.91	2.86	2.61	2.49	2.34	2.26	2.22	2.17
11			4.95	4.96	4.95	4.81	4.04	2.94	2.72	2.56	2.42	2.30	2.20
12			5.02	5.02	5.00	4.95	4.20	3.10	2.88	2.68	2.50	2.38	2.25
13			5.03	5.03	5.00	4.90	4.29	3.18	2.95	2.77	2.58	2.44	2.30
14			5.02	5.04	5.01	5.00	4.22	3.28	3.06	2.90	2.66	2.52	2.35
15			5.02	5.03	5.00	4.96	4.39	3.40	3.14	2.90	2.74	2.57	2.38
16			4.52	4.83	5.01	4.96	4.71	3.80	3.26	3.00	2.80	2.63	2.46
17			4.24	4.50	4.74	4.69	4.53	3.85	3.31	3.06	2.86	2.68	2.50
18			4.09	4.31	4.50	4.52	4.39	3.84	3.31	3.06	2.88	2.73	2.53
19			3.95	4.16	4.31	4.29	4.31	3.81	3.34	3.09	2.94	2.74	2.56
20			3.80	4.02	4.16	4.19	4.23	3.82	3.37	3.14	2.95	2.78	2.60
21			3.70	3.88	4.03	4.09	4.17	3.79	3.38	3.15	2.97	2.79	2.63
22			3.55	3.73	3.87	3.90	4.00	3.81	3.42	3.19	3.01	2.80	2.63
23			3.46	3.63	3.74	3.75	3.79	3.74	3.40	3.15	3.01	2.80	2.63
24			3.36	3.57	3.67	3.67	3.67	3.63	3.37	3.14	2.97	2.79	2.63
25			3.33	3.52	3.62	3.59	3.56	3.55	3.41	3.19	2.97	2.78	2.63
26			3.26	3.42	3.57	3.53	3.48	3.50	3.40	3.17	2.97	2.77	2.63
27			3.21	3.43	3.52	3.46	3.42	3.42	3.38	3.20	3.00	2.81	2.64
28			3.39	3.22	3.49	3.44	3.37	3.36	3.35	3.21	3.01	2.85	2.69
29			3.21	3.31	3.44	3.40	3.34	3.31	3.28	3.21	3.02	2.87	2.70
30			3.22	3.39	3.48	3.41	3.33	3.28	3.24	3.17	3.01	2.89	2.72
31			3.22	3.38	3.50	3.44	3.34	3.26	3.20	3.14	3.04	2.92	2.75
32			3.20	3.36	3.50	3.44	3.33	3.25	3.20	3.15	3.07	2.95	2.78
33			3.23	3.36	3.48	3.44	3.33	3.24	3.20	3.18	3.12	2.99	2.83
34			3.22	3.36	3.46	3.41	3.28	3.22	3.21	3.21	3.16	3.04	2.86
35			3.21	3.34	3.42	3.34	3.24	3.19	3.17	3.19	3.18	3.05	2.86
36			3.12	3.29	3.34	3.27	3.20	3.15	3.13	3.15	3.16	3.07	2.86
37			3.06	3.23	3.25	3.21	3.14	3.10	3.09	3.10	3.12	3.05	2.83
38			2.95	3.13	3.17	3.12	3.07	3.04	3.02	3.05	3.07	3.05	2.82
39			2.89	3.00	3.07	3.04	3.01	2.97	2.98	3.00	3.05	3.03	2.84
40			2.81	2.91	2.96	2.95	2.90	2.89	2.89	2.92	2.97	3.00	2.84
41			2.65	2.77	2.82	2.82	2.82	2.79	2.79	2.83	2.87	2.90	2.82
42			2.54	2.64	2.67	2.70	2.70	2.65	2.68	2.71	2.75	2.80	2.70
43			2.40	2.47	2.52	2.53	2.55	2.54	2.57	2.58	2.63	2.63	2.61
44			2.27	2.32	2.35	2.35	2.35	2.36	2.39	2.42	2.45	2.45	2.43
45			2.13	2.16	2.18	2.18	2.21	2.22	2.24	2.26	2.29	2.28	2.24
46			2.00	2.02	2.04	2.04	2.04	2.05	2.08	2.11	2.13	2.13	2.12
47			1.89	1.91	1.92	1.93	1.93	1.95	1.96	1.97	1.99	1.99	1.95
48			1.77	1.78	1.78	1.78	1.78	1.78	1.78	1.79	1.82	1.84	1.81
49			1.67	1.68	1.69	1.70	1.69	1.68	1.68	1.68	1.68	1.71	1.72
50			1.60	1.61	1.63	1.63	1.63	1.61	1.60	1.60	1.60	1.59	1.58
51					1.55								
52					1.49								
53					1.43								
54					1.37								
55					1.31								
56					1.26								

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