A CONTAINER FOR ELECTRICAL NOISE: ULTRAGUARD THEORY AND PRACTICE

Karl Anderson
Valid Measurements
3761 W. Avenue J-14
Lancaster, CA 93536-6304
Phone: (661) 722-8255
karl@vm-usa.com

Abstract - A theory for active containment of electrical noise within a region is presented. A technique called the ultraguard, based on this theory, is presented and experimentally verified. The ultraguard is demonstrated to prohibit undesired charge flow in a signal-carrying conductor from arising due to noise signals that develop between a region's conductive boundary and a signal-carrying conductor passing through the region. The technique is experimentally demonstrated to operate despite distributed and randomly varying impedance between the signal conductor and the conductive region boundary. The region can be volumetric (i.e. within the shield of a signal cable or within an enclosure surrounding a system or subsystem) semi-volumetric (i.e. within a partially-open container) or planar (i.e. within a conductive boundary such as a guard ring or channel on a printed circuit board surface). The contained noise can arise from various causes, such as the triboelectric effect, radiation- and thermally-induced charge separation in practical insulation, ion migration between the signal conductor and shield, etc. Impedance variations can arise from insulation degradation between the signal conductor and its surroundings, mechanical variation of the capacitance between a conductor and its shield, etc.

INTRODUCTION

Guarding is a well-known technique for reducing the effects of electrical current leakage through imperfect insulation and through shunt capacitance in low-level and highly precise measurements as well as to reduce common-mode interference. These effects result from the finite impedances to ground and to nearby conductors that accumulate throughout a system.[1]

Guarding has been traditionally applied to protect regions containing a *single* electrical potential. Driven guards typically take the form of an electrostatic shield and are often referred to as "guard shields." A new approach is able to extend the benefits of guarding to regions containing *gradients* in potential, both desired and parasitic.

Any electrical circuit will necessarily develop voltage gradients when it is placed in operation. A non-self-generating voltage gradient example is a current-carrying conductor developing a potential gradient along its length. Some self-generating voltage gradient examples include parasitic potentials that develop *within* a guarded region via tribo- and radiation-electric effects as well as the changing potential on mechanically variable cable capacitance holding an essentially constant charge. By using the technique presented here, almost any circuit or conductor can now experience essentially zero leakage in operation—even when poor insulation exists between the circuit and its environment.

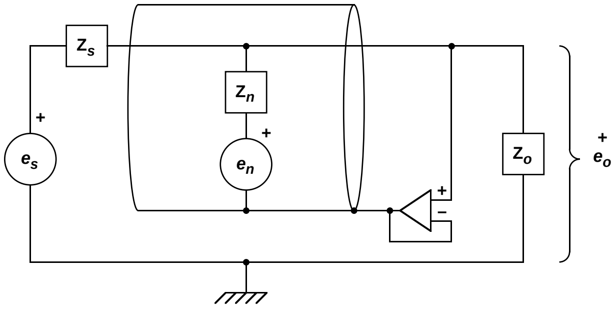
The technique is called the "ultraguard." It was invented with Linear Measurements, San Diego, CA (patent pending), while designing Anderson loop signal conditioning[2] to obtain accurate measurements from platinum resistance temperature detectors (RTDs) in a high-temperature application. Temperatures were so high that available insulation compounds developed enough leakage to unacceptably raise measurement uncertainty. The technique was later found to prevent essentially all charge transfer from within a guarded region, even from parasitic potentials between a guard and conductors within the guard.

GUARD THEORY

This section recalls the theory of conventional (single-potential) guards and ultraguards. The conventional driven guard is shown to be a special case of the more general ultraguard concept.[3]

Single-Potential Guards

The classical guarding technique cancels leakage effects by requiring conductors to be at the *same* potential (the single-potential case). Under these conditions there will be no current between the conductors regardless of the impedance between them. Figure 1 illustrates the single-potential driven guard concept applied to a conductor sensing a signal, e_s, from a high-impedance source, Z_s. The effect of a noise source within the guard is modeled by e_n in series with Z_n. The observing instrument load is modeled by Z_o.



$$e_o = \frac{(e_s / Z_s) + (e_n / Z_n)}{(1 / Z_o) + (1 / Z_n)}$$

Figure 1, A single-potential guard with internal noise

In Fig. 1, the operational amplifier is connected as a unity-gain buffer which causes the guard shield to assume the same potential, e, as the signal conductor. When there is no potential difference between the signal conductor and the guard shield ($e_n = 0$), no current will flow through Z_1 regardless of e_s. Current that might have leaked from the cable to ground is supplied instead by the output of the operational amplifier through Z_2, thereby preserving all of the signal available from e.

This approach is widely known as the driven-guard technique for dealing with electrical current leakage through the insulation impedance (Z_1) of the cable.

However, the situation changes when noise exists within the guard shield in Fig. 1 ($e_n > 0$). In this case the voltage output differs from the voltage source as indicated by the equation within Fig. 1. The classic driven shield circuit topology is unable to prevent errors from arising due to the presence of a noise source within the guarded region.

Multi-Potential Guards

The multi-potential (ultraguard) guarding technique cancels leakage and certain internal voltage effects with two guard shields as illustrated in Fig. 2. Desired electrical potentials e_1 and e_2 as well as noise potential, e_n, exist within the inner guard. Without an effective guard, these potentials would cause current to flow to ground through any distributed impedance, especially leakage through imperfect insulation. To explain how ultraguards work, the general case of circuit impedances and leakage paths is represented in lumped form by various impedances within the inner guard Z_A through Z_E. Z_1 exists between the inner and outer guard and Z_2 exists from the outer guard to the environment.

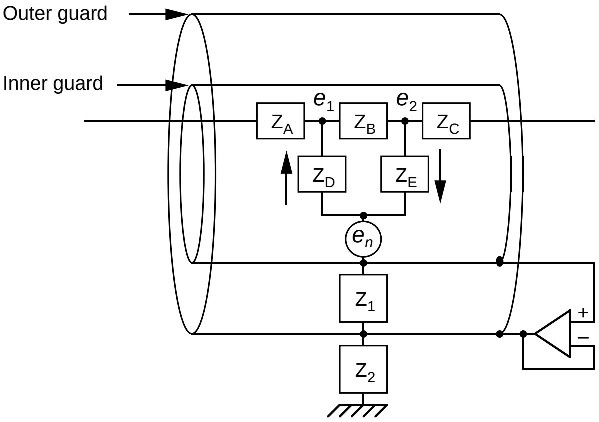


Figure 2, A multi-potential "ultra guard"

Suppose the inner guard is caused to assume a "balance" potential such that all leakage currents flowing from the more positive potentials within the circuitry to the inner guard is matched by other currents from the inner guard back to the more negative potentials in the circuitry. Stated another way, suppose the potential of the inner guard is such that the net current flow *to* the inner guard from *within* the guard is zero. (The balance potential will be somewhere between the extremes of potential within the guard.) Then arrange for the outer guard to assume the same potential as the inner guard.

This situation is similar to the concept of the conventional driven guard. Consider “expanding” the signal conductor of Fig. 1 to become the shell that contains the volume enclosed by the inner guard of Fig. 2. Now conventional guard theory applies to the circuit node consisting of the single-potential shell of this inner guard—because there is no potential difference between the inner and outer guard shields, no current will flow through Z_1, thereby preserving whatever signal potential exists on the inner guard. (The conventional guard technique is simply a “single-potential” or “no-gradient” application of the more general ultraguard technique to guard a region containing a potential gradient.)

If the above conditions are met, then there will be no *net* current flow from the potentials within the inner guard to the inner guard and *no* current between the inner and outer guards regardless of the potentials within the inner guard. Therefore, no current will flow from the potentials within the inner guard to the outer guard, other conductors or ground regardless of the finite insulation impedances distributed within the inner guard, as well as Z_1 and Z_2.

But, what is the appropriate “balance” potential for the inner guard? When the outer guard is driven to the potential of the inner guard then no current can flow between the two guards. The inner guard can be analyzed as a circuit node into which the sum of the currents must be zero. So, if no current can leave the inner guard through Z_1, then the inner guard circuit node *must* assume a potential such that the currents entering this node from the various potentials within the inner guard sum to zero. So driving the outer guard from the potential of the inner guard causes the inner guard to simply assume the “balance” potential *automatically*.

The inner and outer guard shield arrangement to guard a region containing a potential gradient is similar to the “box-within-a-box” construction used in sensitive instruments. An operational amplifier to drive the outer box with the potential assumed by the inner box of the instrument is all that has been added. Extremely good insulation is ordinarily used between these conductive boxes. But with the ultraguard technique, even poor insulation between the inner box and outer box can appear to have essentially infinite impedance.

ULTRAGUARD APPLICATIONS

There are two general classes of applications for ultraguards, 1) gradient guards and 2) charge channels. Both application classes can function as active noise containers. Gradient guards prevent current from flowing between the environment and guarded circuitry. Charge channels cause the current injected into a guarded region to be “channeled” such that *all* of the injected current exits the region at only the desired point(s).

Gradient Guard

The gradient guard active noise container application of the ultraguard concept is illustrated in Fig. 2. As long as noise source e_n does not alter the desired potential gradients within the inner guard, the effects of noise will be eliminated and no charge will be exchanged due to a noise potential, e_n, between the inner-guard region and its external environment. This feature can reduce noise experienced within signal-carrying cables when various noise-generating effects cause the insulation to accumulate a charge.

The gradient guard applies to the one-dimension line, the two-dimensional surface and to the three-dimensional volume topology guarding cases. So the surface of a printed circuit board or integrated circuit can benefit from a gradient guard as well as circuitry contained within a guarded volume.

A gradient guard can be applied to equipment located in poorly-insulated and charge-developing environments. Examples are areas with high humidity and contamination or ionization as well as areas or volumes that include parasitic energy sources. There can even be a conductive liquid between the inner and outer guards and between the outer guard and the environment. The operational amplifier driving the outer guard supplies the necessary current to the environment around the outer guard as long as the conductivity of the liquid is significantly less than the conductivity of the guards.

Charge Channel

An ultraguard in a noise-containing charge-channel application is illustrated in Fig. 3. It also applies to the line, surface and volume guard topologies. Distributed wire and insulation resistances are represented in lumped-parameter form. Noise voltages (not shown) can also exist within the inner guard in series or parallel with any impedance. When no current can flow through Z_1 then (as previously discussed) the inner-guard circuit node must assume the potential that results in no net current flow from the current-carrying wire (the heavy line). Therefore i_1 must equal i_2. A perfectly insulated conducting region leaks no charge to its surrounding environment and will deliver all mobile charges that are injected at one point (and not stored on the conductor) to one or more other points where they will exit from the conductor. A real conductor in a charge channel appears to be imbedded in essentially perfect insulation, even if noise sources exist within the inner guard.

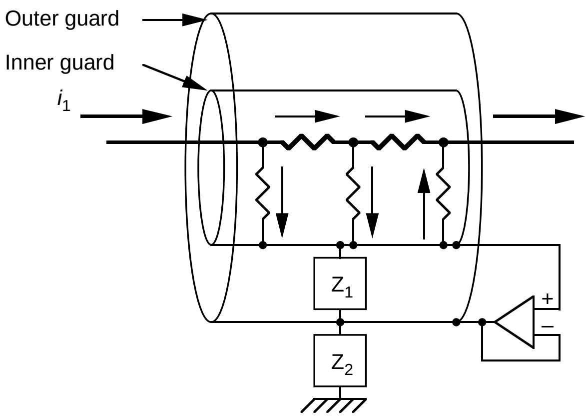


Figure 3, The charge channel

One application for a charge channel is excitation wiring through hostile environments to platinum resistance thermometers (PRTs). The charge channel technique can prevent insulation leakage from allowing current to shunt around the sensing element and thereby cause its apparent resistance (and indicated temperature) to be lower than its actual resistance. In fact, it is necessary to employ a charge-channel guard around only one conductor carrying current in an Anderson loop signal conditioner. The details of this approach are beyond the scope of this paper.

Guard Groups

Segmenting an ultraguard physically into smaller driven regions may be useful when guard dimensions become long or transit time effects become significant. A set of ultraguard regions in an application is called a guard group. Each guard region has its own double guard shield and operational amplifier. Guard effectiveness may be enhanced when the guard conductors overlap somewhat to minimize end effects at the edges of conductors in otherwise uniform electrical fields.

The design of guard groups is directed at achieving an acceptable apparent insulation impedance with a minimum of gradient guard and/or charge channel regions. The details of guard-group design is beyond the scope of this paper.

Ultraguard Limitations

Four significant limitations of the ultraguard have been identified. First, while the ultraguard will theoretically eliminate charge transfer from the inner guard to the environment, it cannot guarantee that intended or desired potential gradients within the inner guard are unaffected by all internal impedance variations or noise sources.

Second, for best performance, each conductor in a signal pair or an excitation pair may require its own ultraguard. To the extent that two conductors are at essentially the same potential and they are balanced within the inner guard with respect to leakage and noise voltages, they may be simultaneously protected within the same ultraguard. This should be regarded as a special case which may not apply in a given application. The conventional driven guard also shares this limitation.

Third, the ultraguard is a guard, not a shield in the sense that a coax cable carrying video signals has a shield within which electromagnetic fields propagate and by which outside signals are attenuated. An additional shield, “grounded” at each end is required around an ultraguard to provide this shield function. The conventional driven guard also shares this limitation.

Fourth, the practical capabilities of the guard-drive operational amplifier can limit ultraguard effectiveness. Real amplifiers lack infinite gain and bandwidth and have input offset voltages and currents which influence overall guard quality. The conventional driven guard also shares this limitation.

Other Considerations

There is no theoretical limit to the dimensions of an ultraguarded region or to the number of guard groups in a system. An ultraguard can enclose a surface area or a volume and apply to a portion of an integrated circuit, a current-carrying or potential-sensing conductor, a test probe assembly in a wafer test system, an electronic instrument, even to a building or a signal transmission cable.

The most significant consideration to be observed in applying ultraguards is the need for the inner guard to act as a single-potential node. So, wavelength and propagation delay effects must be considered when higher frequencies are involved. Also, the guards should be a few orders of magnitude more conductive than the finite impedance of the insulation in the system.

Another practical consideration is the need for the inner-guard to receive no net charge from the region between the inner and outer guard. But any outer guard can itself be treated as an inner guard by the application of an additional driven guard shield to prevent inter-guard charge transfer in unusual situations. The details of this approach, called a nested ultraguard, are beyond the scope of this paper.

Practical operational amplifiers require a path for input bias currents to flow. A sufficient bias current path may exist through poor insulation for operational amplifiers serving in ultraguard applications. But the designer is cautioned to assure that an appropriate bias current path exists where insulation for direct currents is “good,” for example, when the guard’s purpose is to minimize capacitive leakage or to deal with self-generating parasitic voltages between a driven guard shield and the conductors it guards.

EXPERIMENTAL VERIFICATION

Two lumped-parameter models were constructed to demonstrate experimentally the effectiveness of the active noise containment feature of the ultraguard technique. In the charge channel model, several “leakage” components were included to permit significant variations in the current distribution and to permit electrical current injection among the “inner-guard” components. In the gradient guard model, a source of potential difference is observed in the presence of varying impedance and electrical current injection between a conductor and its guard.

In each experiment the circuit model was varied by attaching passive and active test shunts to elements of the network. Both “legal” and “illegal” conditions were simulated by the active test shunt. The automatic change of the inner guard node potential to result in essentially no current through Z1 and the constant voltage observed across the load demonstrate the technique’s effectiveness in both models for “legal” conditions.

Charge Channel Experiment Design

The first experiment was designed using lumped-parameter impedances to demonstrate the charge channel application of the ultraguard active noise containment technique. The test circuit schematic diagram, including component values, is presented in Fig. 4. The circuit simulates a high-resistance (2 KΩ) conductor in extremely poor insulation (100 KΩ components). The conductor and insulation impedances can be drastically lowered by paralleling them with a passive test shunt resistance (1 KΩ). Active noise is injected as a current from an alkaline cell (nominally 1.5 V) in series with a 100 KΩ resistor. A constant current is applied to develop a voltage gradient as it passes through the conductor. Without activating the guard system, only part of the input current flows through the conductor to a load resistor. The remainder of the current flows to ground through resistors simulating poor insulation. When the guard system is activated, the same current level provided by the source should also flow through the load resistance. The guard drive amplifier should operate to make R_1, the simulated impedance between the inner and outer guards, appear to be an open circuit.

Metal-film components with 1% tolerance and 100 ppm/°C stability were used to construct and vary the circuit. Components with greater stability and accuracy were not deemed necessary because of the large changes to be made in the circuit and particularly because the goodness of the technique is indicated by the magnitude of any changes that occur in the voltage drop, V_{out}, across R_L.

The excitation current was adjusted without leakage to develop a 1.000 0 V drop across the 1 KΩ load resistor, R_L, using a digital voltmeter with an input resistance of 10 MΩ. Ideally, the voltage drop across R_L will remain at 1.000 0 V when the gradient-guard drive from the output of the operational amplifier is connected to the outer guard node and the various other resistances in the circuit are individually shunted with passive and active networks. The guard node, node E in Fig. 4, should experience wide variations in potential as the operational amplifier acts to maintain the charge channel.

When the operational amplifier output is disconnected from the outer-guard node, the voltage drop across R_L is expected to be less than 1 V and to experience significant variations as the several circuit elements are individually shunted with 1KΩ.

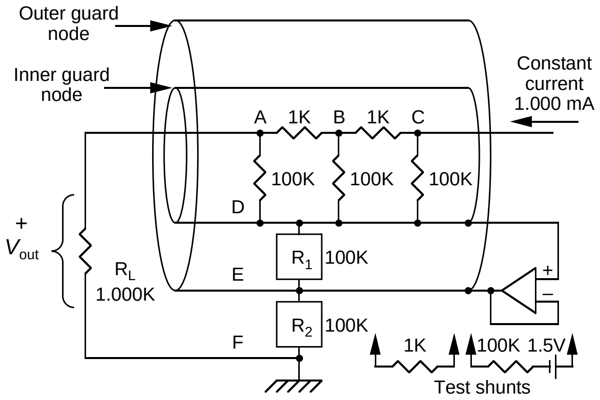


Figure 4, Charge channel test circuit

An active test shunt was also used with the circuit of Fig. 4, consisting of a 100 KΩ resistor in series with a single AA alkaline cell. Similar results were obtained, except for the case of shunting from D to E. This "illegal" test violates the condition that the inner guard receive no charge from outside the region it serves to guard.

Gradient Guard Experiment Design

The second experiment was designed using lumped impedances and a voltage source to demonstrate an ultraguard's rejection of conductor-to-guard impedance and voltage variations. The test circuit schematic diagram, including component values, is presented in Fig. 5. The electronic components, test equipment and procedure used were the same those employed in the first experiment.

The input voltage, V_{in}, is adjusted to result in an indication, V_{out}, of 1.000 0 volts with the guard system activated. Again, both passive and active shunts were used to provide circuit variations. V_{out} is expected to remain at 1.000 0 V when the gradient-guard drive from the output of the operational amplifier is connected to the outer guard node and various resistances in the circuit are "legally" shunted. The guard node, node E in Fig. 4, should experience wide variations in potential as the operational amplifier acts to maintain the charge channel.

DISCUSSION

The Tables present the data validity checks and the experimental results. The various test conditions during the experiment are listed along with the corresponding output voltage, V_{out}, and the voltage at the output of the guard-drive amplifier as applicable.

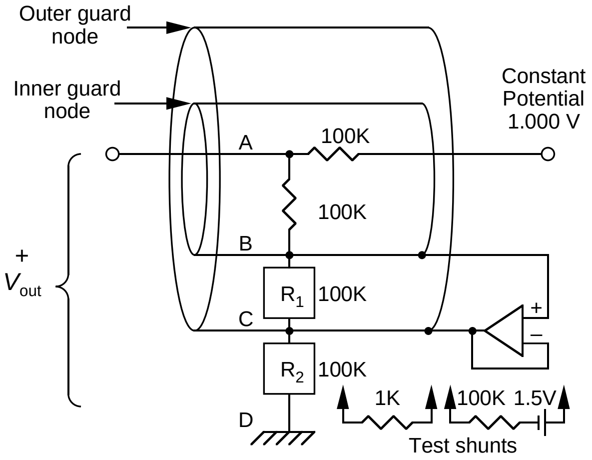


Figure 5, Guarded potential test circuit

The results from the first experiment presented in Table 1 demonstrate that a charge-channel guard does indeed cause significant variations in potential gradients and leakage impedances to have an insignificant impact on the voltage drop across R_L. The variations in the output voltage were below 100 ppm (the resolution of the voltmeter observing the output) while the guard node assumed potentials ranging from 1.0285 to 2.9220 V. The constant voltage across R_L in the first experiment in the presence of quite large variations in conductor and leakage demonstrates that a charge channel was, in effect, created for the excitation current. Connecting the active shunt between nodes D and E violates the requirement that no charge may be arrive at the inner guard from outside the guarded region. As expected, the output voltage varies from ideal in this situation.

The results from the second experiment presented in Table 2 demonstrate that a gradient guard does indeed cause significant variations in potential gradients and leakage impedances to have an insignificant impact on the output voltage, V_{out}. The constant output voltage, V_{out}, in the second experiment in the presence of quite large variations in noise voltage and leakage impedance leakage demonstrates that a gradient guard was, in effect, created to transmit the input voltage. Again, connecting an active shunt between nodes B and C violates the requirement that no charge may be arrive at the inner guard from outside the guarded region. As expected, the output voltage varies from ideal in this situation.

Table 1

Charge channel test results

	No Guard	Passive Shunt = 1 KΩ		Active Shunt = 1.53V + 100 KΩ	
Test Condition	V_{out} (Volts)	Guard Node (Volts)	V_{out} (Volts)	Guard Node (Volts)	V_{out} (Volts)
Excitation-off zero (noise check)	0.000 0	0.000 0	0.000 0	—	—
Excitation on on, no leakage network:					
Constant I directly to RL (1 KΩ load)	1.000 0	—	—	—	—
Constant I source check (additional 2 KΩ load)	1.000 0	—	—	—	—
Excitation and guard drive on, indicated network nodes shunted					
No Shunt,	0.991 5	1. 991 5	1.000 0	1.991 5	1.000 0
A to B	0.994 3	1.662 7	1.000 0	1.991 6	1.000 0
B to C	0.992 2	1.991 5	1.000 0	1.957 5	1.000 0
A to D	0.994 9	1.028 5	1.000 0	1.353 3	1.000 0
B to D	0.990 2	1.990 7	1.000 0	1.610 4	1.000 0
C to D	0.985 6	2.922 0	1.000 0	1.857 7	1.000 0
D to E	0.985 3	1.988 1	1.000 0	2.525 5	0.961 7
E to F	0.981 3	1.991 5	1.000 0	1.991 5	1.000 0

Table 2

Gradient guard test results

	No Guard	Passive Shunt = 1 KΩ		Active Shunt = 1.53V + 100 KΩ	
Test Condition	V_{out} (Volts)	Guard Node (Volts)	V_{out} (Volts)	Guard Node (Volts)	V_{out} (Volts)
Excitation-off zero (guard amplifier removed)	0.000 0	0.000 0	0.000 0	—	—
Excitation on, no noise or leakage network:	1.000 0				
Voltage source directly to meter	1.005 5	—	—	—	—
Voltage source through 100 KΩ to meter	0.995 5	—	—	—	—
Excitation and guard drive on, indicated network nodes shunted					
No shunt	0.748 3	1.014 3	1.000 0	—	—
A to B	0.666 9	1.009 9	1.000 0	1.778 2	1.000 0
B to C	0.666 8	0.994 4	0.989 0	4.077 0	2.517 0
C to D	0.666 8	1.014 2	1.000 0	1.014 4	1.000 0

The second experiment also demonstrates how a real (non-ideal) operational amplifier can cause difficulties. The amplifier in use had an input offset voltage of about 100 microvolts. This appeared as a constant, non-zero potential difference between the inner and outer guard shields. With “fair” insulation between the inner and outer guards (100KΩ) the current injected into the inner guard node (100 microvolts divided by 100KΩ) was insignificant. However, with “really poor” insulation (1KΩ) the current becomes significant as indicated by the 11 mV (about one percent) change in V_{out}.

The experiments were designed to demonstrate the power of the active noise containment function of the ultraguard technique and some of its limitations, not to model particular applications. The experiments used values representing unusually large wire- and small insulation-impedance magnitudes along with a large noise voltage all undergoing huge variations. Even so, variations in the output voltage were typically unobservable. The ultraguard technique can be expected to perform well in practical applications.

SUMMARY

The classical driven guard technique applies only to electronic circuit regions that contain a single potential. A new ultraguard principle (patent pending) uses a driven outer guard to effectively guard regions within an inner guard that contains various potential gradients and noise sources. The gradient-guard configuration contains charges within an inner guard and the charge-channel configuration assures that the current entering a conductor at one end will all exit the conductor at its other end even when the conductor and its guards are imbedded in poor insulation resistance to ground. The ultraguard has been determined to significantly reduce the externally-observable effects of noise potentials within the guarded region which may arise from tribo-electric effects, radiation exposure, electro-mechanical inputs and other noise sources.

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