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DEVELOPMENT OF A HUMAN ELECTROSTATIC DISCHARGE MODEL IN RELATION TO ELECTRONIC SYSTEMS

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ABSTRACT

Electrostatic Discharge (ESD) in this paper pertains to understanding the processes of electrical charge buildup on a human being or other conductive shape, followed by a discharge into another conductor such as an electronic device. Several megawatts of peak power may be involved.

In order to design and test for ESD, it is necessary to establish the electrical characteristics of the electrostatic buildup and discharge circuit. Crude models of a human being/electronic equipment system for ESD are developed by the author in references (1)* and (2). This paper further develops the modeling process to include a large metallic ground plane, under the facility floor covering, connected to earth. Also, the effects of hand-held sharp radii metallic objects are examined. From the circuit parameters, approximate wave shapes of the discharge are computed for various cases.

Much work has been done in actual laboratory measurements of electrostatic discharge phenomena, in order to properly design test equipment to simulate an actual discharge as accurately as possible. However, it is believed by the author that mathematical modeling of the system is essential.

*Numbers in parentheses designate references at end of paper.

ELECTROSTATIC DISCHARGE (ESD) may be considered similar in cause and effects to lightning. The observed arc in the ESD process behaves like a lightning arc. ESD, in this paper, is limited to the buildup and flow, or redistribution, of charge between a human being, an electronic system, a ground plane and earth. Flow of the charges takes place slowly during the charging phase, and very rapidly during the charge redistribution phase. Charges are built up on the person usually as a result of triboelectric action between the shoe soles and the floor covering.

The sudden release of built-up electrostatic energy from high to low potentials in the system causes potentially devastating voltages, currents and electromagnetic fields to occur in vulnerable components in the electronic system. Upon ionization and air dielectric breakdown (arcing), the rapid redistribution currents easily propagate down interconnecting cables and other units before finally bleeding off through the higher RF impedance (inductance) of the ground connection. A person has a strong capability to retain the built-up charge due to his high degree of insulation from the floor covering and earth.

Microcircuits may be destroyed or altered by either low voltage, long duration pulses, as in the case of RF interference, or with high voltage, short duration pulses. Typically, in ESD, several thousand volts may be applied to a system housing, resulting in short duration pulses on the order of 100 volts applied to the microcircuits, reference [2]. End item users of these sensitive circuits can be damaged or destroyed, or electronic data may be altered by the unwanted interference. The effects upon a person with various inplanted biomedical devices is as yet unknown.

ELECTROSTATIC DISCHARGE MODEL

Figure 1 demonstrates a typical setup for the charge buildup on a person in a room with an electronic system. The person is insulated from the ground plane while the machine is connected to earth through a safety ground. In this model, the earth is relatively far from the person and the machine, while the ground plane is close to the system. Both the person and the machine, for equal shapes, in accordance with our model, have relatively small equal capacitances to earth, but significantly greater capacitance to the ground plane and to each other. The earth is taken as reference potential (0 volt).

For simplicity, the cylinder is used for both the model of the person and the machine. The person's arms are assumed, for capacitance simplification, to be at his sides.

The person is assumed to be fairly large, 113 kilograms (250 pounds), and 1.9 meters (6 ft, 3 in.) in height. Considering that the mass for unit volume of a person is roughly that of water, the resulting volume is 0.1 cubic meters (4 cubic feet). A cylinder of equal size is chosen for the electronic machine. The radius, therefore, of each cylinder is approximately 13.8 centimeters (5.4 in.). The two cylinders are upright and parallel to each other.

In Figure 1, the person on the left is several feet away from the machine. At this distance, the person/machine capacitance is relatively small. The amount of charge that can be accumulated on the body surface is determined by the geometry of the person as related to corona effects, and primarily by the person/ground plane capacitance. The earth is relatively far removed. The model for the case without a ground plane is shown in reference [2].

For examination of the theoretical and actually measured values of voltage that can be sustained on the person's body, see reference [2], and Appendix A of this paper.

The dotted body on the right of Figure 1 is the new position of the person who has approached as near to the machine as possible before arcing occurs and before touching the machine. The person is also capacitively coupled to the grounded machine in a configuration equivalent to a person brushing by the machine with his body. At this point, the person/machine insulation fails by the air dielectric breakdown and arcing occurs, setting up rapid redistribution transient currents in the person and the machine, followed by slower current drain back to earth through the safety ground wire.

The electrostatic portion of the problem to be solved involves determining the total amount of energy that can be built up in the system before discharge. In a system of conductors in space, a matrix (determinants) is used for the number of conductors in the system. The charge on the conductor is proportional to the voltage on the conductor. The proportionality factors are called coefficients of capacitance if the indices are alike, for example, $C_{1,1}$, or coefficients of induction if unlike, such as $C_{1,2}$.

The equations for the four bodies (person, machine, ground plane, and earth) are as follows:

$$\text{Person } q_1 = C_{1,1}V_1 + C_{1,2}V_2 + C_{1,3}V_3 + C_{1,4}V_4 \qquad (1)$$

$$\text{Machine } q_2 = C_{2,1}V_1 + C_{2,2}V_2 + C_{2,3}V_3 + C_{2,4}V_4 \qquad (2)$$

$$\text{Ground Plane } q_3 = C_{3,1}V_1 + C_{3,2}V_2 + C_{3,3}V_3 + C_{3,4}V_4 \qquad (3)$$

$$\text{Earth } q_4 = C_{4,1}V_1 + C_{4,2}V_2 + C_{4,3}V_3 + C_{4,4}V_4 \qquad (4)$$

For example, $C_{1,1}$ is a constant which relates the charge q_1 on body 1 (person) to the voltage V_1 on body 1. $C_{1,2}$ relates the charge q_1 on body 1 to the voltage V_2 on body 2 (machine), etc. The q's are solved by employing determinants. Since the machine, ground plane, and earth are all at zero potential before discharge, $V_2 = V_3 = V_4 = 0$. Therefore, the equations reduce to: $q_1 = C_{1,1}V_1$, $q_2 = C_{2,1}V_1$, $q_3 = C_{3,1}V_1$, $q_4 = C_{4,1}V_1$. The induced charge on the machine is q_2, q_3 is the induced charge on the ground plane, and q_4 is the induced charge on the earth resulting from the process of giving up charge to the person and to the machine. $C_{1,1}$ is the coefficient of capacitance of the person, V_1 is the potential of the person, $C_{2,1}$ is the coefficient of induction between the person and the machine, $C_{3,1}$ is the coefficient of induction between the person and the earth, and $C_{4,1}$ is the coefficient of induction between the person and the ground plane. Simply stated, the net charge on each of the bodies is proportional to the voltage of the person.

The potential on each body of an electrostatic system may be expressed in terms of the charge on each body. The proportionality constants $P_{1,1}$, $P_{1,2}$, $P_{1,3}$, $P_{1,4}$, etc., are called the coefficients of potential.

The equations are as follows:

$$V_1 = P_{1,1}q_1 + P_{1,2}q_2 + P_{1,3}q_3 + P_{1,4}q_4 \quad (5)$$

$$V_2 = P_{2,1}q_1 + P_{2,2}q_2 + P_{2,3}q_3 + P_{2,4}q_4 \quad (6)$$

$$V_3 = P_{3,1}q_1 + P_{3,2}q_2 + P_{3,3}q_3 + P_{3,4}q_4 \quad (7)$$

$$V_4 = P_{4,1}q_1 + P_{4,2}q_2 + P_{4,3}q_3 + P_{4,4}q_4 \quad (8)$$

Since $V_2 = V_3 = V_4 = 0$, $V_1 = P_{1,1}q_1 + P_{1,2}q_2 + P_{1,3}q_3 + P_{1,4}q_4$. This says that the potential on the person is related to induced charges on the entire system, as well as to his own charge; for example, $P_{1,2}$ is the coefficient of potential relating the voltage on body 1 (person) to charge on body 2 (machine), etc. Circuit parameters are developed in later paragraphs.

ESD PHASES

Three phases of the ESD process are examined: (1) initial charge buildup, (2) induction and (3) discharge.

PHASE 1, INITIAL CHARGE BUILDUP — By walking across a floor, a person can build up very high potentials before corona ionization causes leakage of charge to the atmosphere. For worst case analysis, the user has taken no steps to control factors which lessen the severity of ESD ionization. The carpet is a highly insulating material. Under these conditions, charges can accumulate on the human body to result in voltages in excess of 25,000 volts. The average value of voltage generated is typically 5,000 to 12,000 volts, reference [3]. The magnitude of the voltage depends primarily upon the material of the shoe soles, the type of carpet fiber, type of carpet backing, wear on the carpet, human walking characteristics, the sharpness of radii of various parts of the human body, and the temperature and humidity of the room.

At this remote position, as shown in Figure 1, the person shares the built-up charge with all conductors in contact with him, such as ionized atmospheric particles. Should he stop walking, the voltage drops off at a rate called the relaxation time.

Once a charge is built up on the human body and sustained, all of the free charge on the body resides on its surface. Since the charges are essentially at rest, the electric field for the static condition is perpendicular to the body surface, and for irregularly shaped surfaces, the surface charge density and the electric field intensity vary with the geometry of the surface. For a given electrostatic charge on a body, the charge density is greater for the sharper surfaces. Appendix A (taken from reference [2]) shows why this is true, and how the corona discharge voltage, approximately 3×10^6 volts per meter, limits the amount of voltage that can be sustained on a human body. The technique involves distorting a single charged conductive sphere to two spheres of unequal radii, connected together by a very thin wire. It is shown that corona discharge will occur from a sphere of 1 centimeter radius when the voltage reaches 30,000 volts The human thumb tip is approximately 1 cm in radius and is fairly well isolated from the rest of the hand so that the electric field is enhanced at the tip. Hence, it is reasonable to expect that levels as high as 30,000 volts may occur, and this level should be used in the worst case ESD modeling process.

Under these conditions, the electrostatic energy may be calculated by applying the relationship $E_s = 1/2\ CV^2$ where C is the capacitance of the cylindrical man in relation to the nearby ground plane at his feet.

Reference [4] shows the capacitance of an upright cylinder above a horizontal ground plane to be:

$$\text{For } \frac{L}{r} \gg 1,\ C = \frac{2\pi\epsilon_0 \ell}{\ln\left[\left(\frac{\ell}{r}\right)\left(\frac{4h+\ell}{4h+3\ell}\right)^{1/2}\right]} \quad (9)$$

C = the capacitance in farads,

r = the radius of the cylinder in meters,

L = the height of the cylinder in meters,

h = the distance from the bottom of the cylinder, to the ground plane in meters, and

ϵ_0 = the permittivity of free space or air = 8.85×10^{-12} farads per meter.

Applying this formula for the person/ground plane separation distances of 1 centimeter to 1000 meters results in the curve shown in Figure 2. The maximum capacitance for either the cylindrical model person or the machine to the nearby ground plane at a 1-centimeter distance is approximately 51 picofarads. The capacitance reduces to 41 pf at a distance of 100 meters or at remote earth.

The total capacitance of the person to the ground plane and to earth is therefore 51 pf + 41 pf = 92 pf, neglecting the relatively large capacitance $C_{3,4}$, between the ground plane and earth. Reference [4] shows the capacitance of a horse above a ground plane to be 180 pf. Reference [5] shows the measured capacitance of a human, 1.75 meters tall, weighing 68 kg, to ground at 60 Hz as 100 pf, and higher values for vehicles such as automobiles, etc.

The maximum electrostatic energy on the person, at the remote distance from the machine, is therefore 1/2 CV^2 or $1/2 \times 92 \times 10^{-12} (30 \times 10^3)^2 = 41.4$ millijoules. The maximum charge that can be stored on the person in the remote position is $Q = CV = 92 \times 10^{-12} \times 30 \times 10^3 = 2.8$ microcoulombs.

PHASE 2, INDUCTION PROCESS — A charged body affects the potentials of all other bodies in its vicinity as shown in Equations (1) thru (4). It shows that the charge on the machine is: $q_2 = C_{2,1}, V_1$. The capacitance $(C_{2,1})(C_{1,2})$ between the person and the machine varies as a function of the geometry of the person and the machine, and the distance between them. As the person approaches the machine, the capacitance increases.

However, the capacitance $C_{1,3}$, (51 pf) and $C_{1,4}$, (41 pf) between the person and the machine to the ground plane and earth, respectively, and the capacitances $C_{1,4}$, (51 pf) and $C_{2,3}$, (41 pf) between the machine to the ground plane and to earth, respectively, remain unchanged as the person moves toward the machine. These capacitances result in an additional effective capacitance of 46 picofarads between the person and the machine through the earth and ground plane for the very rapid transient currents. Since the earth and the ground plane are relatively large, their resistances and inductances are ignored in this study for reasons of simplification. In addition, $C_{3,4}$, the relatively large distributed capacitance between the ground plane and earth, will have a tendency to short circuit the very small inductance of the ground plane (see Figure 3 for the equivalent ESD circuit).

Reference [2] shows how the capacitance $C_{1,2}$ between the person and the machine is calculated by using two identical cylinders whose axes are parallel to each other. The results of the calculations are shown in Table 1 of reference [2]. We will use the maximum calculated capacitance of 200 picofarads for $C_{1,2}$. This results in a total effective capacitance of 246 picofarads between the person and the machine. The machine for this model is grounded to earth, hence q_2, the charge on the machine, is constantly changing as the charged person approaches. However, the potentials V_2 on the machine and V_3 on the ground plane remain zero. For our model, it is assumed that triboelectric charging will continue until arc discharge takes place. In other words, the 30 kV is maintained on the person. This will cause the effective person-/machine capacitance (246 pf) to be charged to its maximum of $Q = CV = 7.4$ microcoulombs, with an electrostatic energy of $1/2\ CV^2 = 111$ millijoules. This compares to 89.9 millijoules without the ground plane.

For this model, with about a 1-centimeter gap between the person's body or his fingertip and the machine, discharge will take place for the 30 kV on the person. The electric field of corona discharge, or when the air ionization process takes place, is 3×10^6 volts per meter. At this point, the maximum surface charge density on the person and the machine is $\rho_s = \epsilon_o E = 2.66 \times 10^{-6}$ coulomb/meter^2, where ϵ_o is the permittivity of free space (or air), or 8.85×10^{-12} farads per meter, and E is the electric field, or 3×10^6 volts per meter. A very large ground plane under the system may completely shield the system from the earth, hence the capacitances $C^{1,4}$ and $C^{2,4}$ may vanish.

If a positive charge is assumed to accumulate on the person at the remote position, the charge will tend to be packed or concentrated in the region of the bottom of the feet, especially if a ground plane is used. As the person approaches the machine, the charge will have a tendency to be stored predominantly on the surfaces of the person and the machine which are mutually facing each other. This means that some charges are going to travel much farther than others when arcing occurs.

Reference [1] shows that if the person is positioned at about 15.3 cm (6 in.) away from the machine with his hands at his sides, the mutual capacitance $C_{1,2}$ is reduced to 48 picofarads. However, the effective capacitance between the two bodies, for determining the electrostatic energy in the system, and the total discharge circuit impedance is 48 pf + 46 pf (the capacitance between the person and the machine through the ground plane and earth) = 94 pf. If a person is positioned away from the machine but reaches out with his hand to touch the machine, the capacitance between his arm, hand, and finger to the machine would also be considered. We are now ready to consider Phase 3, or electrostatic discharge of the stored electrostatic energy.

PHASE 3, ELECTROSTATIC DISCHARGE — Everyone has experienced the very unpleasant sensation of ESD shock. We would like to know just how severe the energy density really is in order to design electronic equipment to withstand the shock and also protect the person from potential harm. The most usual discharge into an electronic device is that of a human being, however, other bodies may be much more severe from the standpoint of discharged power, such as a charged metallic cart, chair or table pushed against an electronic device. Not only will the capacitance be significant, but the resistance of the discharge path will be lower than through a human body.

The pulse shapes upon discharge have been characterized by W. Michael King and David Reynolds for various human and hardware models in reference [6]. The study includes measurements of the waveforms of discharges to simulated electronic systems through mobile office furnishings and hand-held metallic objects. From this paper, it is clear that the waveform rise times and the discharge current levels vary greatly, depending upon the setup used in the testing. We now proceed to characterize the discharge circuit parameters and wave shapes.

Figure 1 shows the position of the person with respect to the machine at the moment of arcing. The worst case situation would be a person brushing against the machine. A very large electric field between the two bodies causes the air in the gap to ionize, thus drastically reducing the insulation resistance between them at the point of the arc. This essentially causes the virtual short circuit through the arc. The equivalent circuit is shown in Figure 3. Electrons in the machine are drawn with a strong force of attraction by the electric field toward the positive charges on the person, hence, the large electrostatic energy stored in the person/machine capacitor is suddenly dissipated in the circuit with the current flow in the form of an arc. It is this initial rapid redistribution of charge which is of the most interest because of the severity of the conducted power between the two conductive objects. The arc continues until the voltage across the person/machine capacitor reaches a sufficiently low level to quench itself through the arc. The current during this rapid equalization phase is governed by the R, L, C of the conduction path. The resistance and inductance are derived primarily from the high-frequency characteristics of the person's body and the machine. During the initial charge redistribution, the bulk of the current is flowing from the person to the machine. Before arcing, all of the available free charge resides on the person's skin. The general circuit parameters are shown in Figure 3.

The inductance of the green wire to earth impedes the higher-frequency components of the current, hence, these currents flow in a common mode manner into the low-impedance structure. A slower discharge to earth through the safety wire takes place for the lower-frequency components of the spectrum. At arcing, the distribution current flows as a pulse having a very fast wave front or rise time.

The discharge phase is seen as three subphases: (1) the very fast charge redistribution between the person and the machine through a relatively low-impedance path, (2) a high-frequency coupling between the remaining person/machine capacitance to earth and the ground plane, and (3) the much slower bleed-off of the built-up net charge of the system to earth.

In order to create a circuit schematic for determining the wave shapes, we must determine the electrical characteristics of the person and the machine. The following discussion of the human body is taken generally from reference [2].

The electrical impedance of the human body is very complex, as man is composed of materials of varying resistivity, such as tissue, supporting structure, and outer covering. Within the body, inside the outer covering, resistivities vary from approximately 100 ohm cm (1 ohmmeter), for most vascular tissue, up to 900 ohm cm for bone, and as great as 5000 ohm cm for fatty tissue. The live body, because of the effect of saline liquids, can be viewed, for very low-frequency considerations, to be a uniform mass with an approximate resistivity of 100 ohm cm and a dielectric constant no greater than unity [7]. The dielectric constant changes greatly at higher frequencies.

In vivo (living body) experiments performed upon cats by Maria Stuchly, et.al. [8] show that the value of approximately 1 ohmmeter resistivity, taken on the average of organic tissue, is satisfactory at 1 to 2 GHz. From the foregoing, we will use a value of resistivity of 1 ohmmeter. The dielectric constants at 1 GHz varied over the range of 43 for kidney to as high as 59 for skeletal muscle. [8]

The effect of the permittivity or dielectric constant of the body upon the current is not considered in this paper. It is a subject of further investigation.

The model of the main frame of the body for the purpose of capacitance calculation is shown under "Electrostatic Discharge Model." The capacitance was estimated under "Phase 1, Initial Charge Buildup" and is summarized for various conditions in Table 1. Figure 4 shows the possible current flow routes in parts of the human body for two conditions of discharge: (1) midsection body discharge, and (2) discharge through the finger. The shape of the body suggests the cylinder as a basic building block for the parts of the body through which current may flow.

For the discharge electrical impedance, we now determine the estimated resistance and inductance of the parts of the body most likely to influence the discharge current. These are the main frame, the arm and the finger, all modeled as cylinders.

In order to determine the impedance of the human body we must determine the "skin depth," or limit of depth within the body tissue through which current can flow. Because of the fast rise times involved, some in the order of a few nanoseconds, we must consider the frequency for the ESD currents to be as high as 1 to 2 GHz. Some rise times as fast as 500 ps have been observed. The frequency is needed to determine the skin depth for the currents in the body. Rutherford Peck [9] shows the skin depth in meters for a conducting media to be $S = \sqrt{2/\mu g \omega}$ where μ is the permeability or $4\pi \times 10^{-7}$ H/m, or the same as free space; g is the conductivity in mhos per meter, and ω, the angular velocity $= 2\pi f$. For 1 ohmmeter resistivity, this results in 1.12×10^{-2} meters at 2 GHz, and 1.59×10^{-2} meters at 1 GHz. We will use 1 cm since the faster rise time of 500 ps has been observed.

The resistance and the inductance of the human body main frame depend upon the point of discharge as suggested by Figure 4. The body is modeled as a hollow cylinder with a shell thickness of 1 centimeter, as shown in Figure 5 for the finger or arm discharge. The cylinder is divided into two half shells because the current, in this case, will have the tendency to take parallel paths around each side of the body while traveling from the feet to the shoulder, arm and fingertip. Refer to the specific discharge, Cases 1 through 6, for determining the discharge path and resulting conditions, series or parallel arrangements, for resistance and inductance calculations.

In the case of a human midsection discharge, the model is shown in Figure 6. Here, the current has generally four parallel current paths; from the head downward to the midsection, from the feet upward to the midsection, and around each half perimeter of the body. Hence, 4 half shells, each 1 cm thick, are used.

For the model of the human arm, refer to Figure 7. The resistance is determined by calculating the resistance of a hollow cylinder where the thickness of the shell is 1 centimeter (the skin depth).

For the model of the human finger, refer to Figure 8. The resistance is determined by calculating the resistance of a solid cylinder, since doubling the skin depth exceeds the diameter of the finger. The skin depth is 1 centimeter. The resitance of the components may be calculated by $R = \rho(\ell/A)$, where R is the resistance in ohms, ρ is the volume resitivity (1 ohmmeter), ℓ is the length of the component in meters and A is the cross-sectional area in (meters). [10]

The resistance of the finger was determined by considering the resistance of the finger bone in parallel with the more conductive outer sheath of the finger, taken as 1/8 in. thick.

The outer skin layer, the epidermis, has a resistivity of up to 10^6 ohm cm and may be taken as about 1 mm thick. [7] For this reason, it will be considered a thin layer of insulation carrying relatively little current.

An area of uncertainty lies in the effect of the relatively high resistive epidermis portion of the skin. Just before discharge, the free charge resides on the surface and the electric field is perpendicular to the skin. At discharge, the current takes the path of least resistance, which is below the skin in the region of the saline structure. The skin is only 1 mm thick, hence the charge would be influenced by the skin for only a very short portion of the rise time, considering the length of the discharge path for each charge. If the skin resistance effect were continuous, the resistance of the skin over the body surface would be $R = \rho(\ell/A) = 55.7$ ohms, where ρ is the resistivity of the skin or 10^4 ohmmeter, ℓ is the skin thickness or 1 mm, and A is the surface area of the body or 1.8×10^{-1} m² for a cylinder. It appears, therefore, that the skin acts only as a delaying factor, and not as a continuous circuit resistance during the discharge process.

The self inductance is determined by considering each component as a cylindrical conductor. Terman [10] shows the inductance of straight round wires for intermediate frequencies as $L = 0.00508\ell\,(2.303 \log_{10}(4\ell/d) - 1 + \mu\delta)$ microhenries, where ℓ is the length in inches, d is the diameter in inches, μ is the permeability, and δ is a skin depth factor, which, for higher frequencies, is inversely proportional to the square root of frequency, and for very high frequencies approaches zero. Hence, the term $\mu\delta$ will be taken as zero, since the frequency (2 GHz) is very high. Terman states that "the changes of inductance with frequency are comparatively small." [10] Therefore, the value of inductance used is:

$$0.00508\ell\left(2.303 \log_{10}\frac{4\ell}{d} - 1\right) \qquad (10)$$

H.C. Barnes, et al. [7] arrived at values of 0.1 microhenry for inductance and 1 ohmmeter resistivity for the human body, modeled as a prolate spheroid, at 60 Hz. These compare favorably with our values. Ronald J. Spiegel [11], uses various cylinders for parts of the human body in his work relating to current induced into the body for high voltage power lines.

In this paper, there are 6 specific conditions taken for discharge. (The case of a metallic intervening object, e.g., a person seated in a metal chair or pushing a metal cart of some configuration are not included in this paper.) The values of resistance, inductance, and capacitance for each case are shown in Table 1. The cases are as follows:

Case 1. A charged person with 30 kV on his body approaches a large, low-resistive machine such as in Figure 1, with his arms close by his body, and he brushes up against the machine (see Figure 10 for the wave forms).

Case 2. This case is similar to Case 1, which is for a person approaching within a very close distance from the machine, e.g., 1 cm, (0.4 in.) allowing the full capacitance development between the person and the machine. The difference is that he touches the machine with his finger instead of brushing by it (see Figure 11).

Case 3. This is the same as for Case 2, except the person is about 15.3 cm (6 in.) away from the machine when he reaches out to touch it with his finger (see Figure 12).

Case 4. This is the same as Case 3, except the machine has a high resistance, chosen as 10^6 ohms (see Figure 13).

Case 5. In this case, a person standing 15.3 cm (6 in.) from a low-impedance machine is holding a sharp object such as a key with a radius of 1 millimeter. His body has only 3 kV on it. He then reaches out to touch the machine with his finger (see Figure 14).

Case 6. This is a rerun of Case 4 in reference [2] for the condition of no ground plane, but including the capacitance from the person to the machine through earth (see Figure 15 for the wave forms).

The resistance of the machine was chosen as the relatively low value of 1 ohm for a metal chassis, or 10^6 ohms for an insulated chassis. The inductance of the machine is taken to be the same as the human main frame, both modeled as cylinders. For calculating the predicted wave form, the simplified circuit is shown in Figure 9. The charged capacitance serves as the voltage source. With the current flowing upon arcing, R_T and L_T are the total circuit resistance and inductance, respectively, and C is the capacitance.

In the simplified schematic for the series circuit, the capacitor is the storage element for the initial voltage V_0. When the circuit is completed by closing the switch (low resistance arc), the Kirchhoff voltage law may be used to set up the differential equation:

$$L\frac{d^2i}{dt^2} + R\frac{di}{dt} + \frac{1}{C}\,i = 0, \qquad (11)$$

where i is the instantaneous current.

The solution of this equation and discussion of the factors controlling the wave shape are shown in Reference [2]. The voltage, current and time curves are shown in Figures 10 through 15 for the six cases. These curves were obtained by using an HP 21 MX Minicomputer and an HP 9872A Plotter. Conditions described in the six cases determine whether the curves are overdamped, or underdamped. Case 1 is an example of an underdamped case due primarily to the low value of resistance R in the system. The wave shapes are shown in Figure 10. This shows a rise time of about 6 ns for the "brush by" or midsection discharge case. Case 2 is an example of an overdamped case due to the higher resistance of the finger and the arm as compared to the body.

Recommendations for designing and testing electronic equipment to meet the conditions of ESD are shown in reference [2].

CONCLUSIONS

The results show that Case 1 for the midsection discharge is far more severe than the others from the standpoint of electrical power to be absorbed by the system. The current approaches 589 amps. This represents a peak power of $589^2 \times 11.3$ ohm = 3.9 megawatts. The peak power released for, e.g., Case 3 is $27^2 \times 1083$ ohm = 0.79 megawatts.

The use of the ground plane increases the peak current for Case 1 from 573 amps to 589 amps, as shown in

Figure 10. Hence, it appears that the insertion of the ground plane does not appreciably increase the current and power in the case of a human discharge into a large machine. This is because of the relatively higher capacitance between a person and the large machine, as compared to the capacitance between either the person or the machine to the ground plane.

The current wave form shown in Figure 14 shows that if a person is carrying a sharp object such as a key and discharging with either the key or a finger, the worst case peak power to be absorbed by the system is reduced to $(2.7)^2 \times 1083 = 7895$ watts. Discharge through a sharp object is also much less uncomfortable than through the nerve sensitive finger tip. It is believed by the author that an arc discharge from the body actually burns a small hole through the skin due to the very great current density.

It is apparent that ESD poses a threat to all sensitive electronic equipment, whether enclosed in an electronic machine or present in the human body in the form of biomedical implants. Fortunately, the threat may be greatly reduced through analysis, design and test of systems.

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APPENDIX A — POTENTIAL AND CHARGE ON A NONUNIFORMLY SHAPED BODY

The field strength at the surface of a charged conductor is geometry dependent. Figure 16 shows a charged body on the left with a nonuniform surface such as would be the case of a person with an appendage of relatively sharper radius, such as a finger, or if he were holding a metallic object such as a key. Charge is free to migrate from point to point on the surface. The surface is equipotential in the static case; however, the electric field and surface charge density will be more intense at the sharper radii. It will be shown that the upper limit of voltage that can be sustained on the human body is approximately 30 kV based upon the radius of, e.g., an isolated fingertip which forms a hemisphere with a radius of roughly 1 cm.

The body on the left may be simplified by compressing the neck of the appendage to a short, very small diameter conductive wire connecting two conducting spheres of unequal radii of a and b, respectively.

Since the wire length is held to a small length equal to the approximate length of the neck, the potential of the system will not be appreciably changed. In other words, negligible work is expended in the charge redistribution process. The two spheres are at the same potential $V = V_a = V_b$. The potential on the surface of an isolated sphere is

$$V = \frac{Q}{4\pi\epsilon_0 \text{ radius}}$$

where Q is the charge on the sphere [9] and ϵ_0 is the permittivity of free space (or air). The total charge on the wire is held negligible since it is relatively small. Also, the spheres are assumed to have a negligible effect on each other since sphere radius a is much larger than sphere radius b. It follows that:

$$\frac{Q_a}{4\pi\epsilon_0 a} = \frac{Q_b}{4\pi\epsilon_0 b}$$

Since radius a is much larger than radius b, Q_a is much greater than Q_b. The electric field at the surface of the sphere

$$E = \frac{Q}{4\pi\epsilon_0 r^2} = \frac{\sigma}{\epsilon_0}$$

is derived from the Gauss law of electrostatics. σ is the surface charge density. It follows that:

$$E_a = \frac{Q_a}{4\pi\epsilon_0 a^2} = \frac{\sigma_a}{\epsilon_0}$$

$$E_b = \frac{Q_b}{4\pi\epsilon_0 b^2} = \frac{\sigma_b}{\epsilon_0}$$

Since $E = V/r$ for a sphere,

$$\frac{V_a}{a} = \frac{\sigma_a}{\epsilon_0} \quad \frac{V_b}{b} = \frac{\sigma_b}{\epsilon_0}$$

or

$$V_a = \frac{\sigma_a a}{\epsilon_0} = V_b = \frac{\sigma_b b}{\epsilon_0}$$

Since a is much larger than b, σ_b, the surface charge density on the smaller sphere b, is much larger than that on the larger sphere a. From the rationship $E = \sigma/\epsilon_0$, it follows that the electric field is much greater at the surface of the smaller sphere than that at the larger sphere and is inversely proportional to the radius.

From the foregoing, assuming a radius of a typical fairly uniform appendage such as a fingertip of approximately 1 cm, and considering the Corona breakdown of the electric field $E = 3 \times 10^6$ V/m, V = Er = 30 kV. If the body of the cylindrical model had no sharp radii appendages, a much higher voltage could be maintained on the body. This shows the importance of the natural body appendage or added conductor to the body such as, e.g., a hand-held object. If the object were, e.g., a key with a radius of 1 mm, the highest voltage that could be maintained would be 3 kV. Hence, it appears reasonable that the highest voltage to use for the model is approximately 30 kV.

Table 1
Discharge Circuit Characteristics

		Resistance—Ohms (1 Ohm Resistivity at 2 GHz)					Inductance—Microhenries at 2 GHz					
Case	Voltage kV	Body	Arm	Finger	Machine	Total Circuit	Body	Arm	Finger	Machine	Total Circuit	Capacitance Picofarads
1	30	11.3	—	—	1	12.3	0.16	—	—	0.16	0.32	246
2	30	22.7	211.7	848	1	1083	0.89	0.27	0.054	0.16	1.37	246
3	30	22.7	211.7	848	1	1083	0.89	0.27	0.054	0.16	1.37	94
4	30	22.7	211.7	848	10^6	10^6	0.89	0.27	0.054	0.16	1.37	94
5	3	22.7	211.7	848	1	1083	0.89	0.27	0.054	0.16	1.37	94
6*	30	22.7	211.7	848	1	1083	0.89	0.27	0.054	0.16	1.37	69

*This is a rerun of Case 4 in reference [2] for the condition of no ground plane, but including the capacitance from the person to the machine through earth.

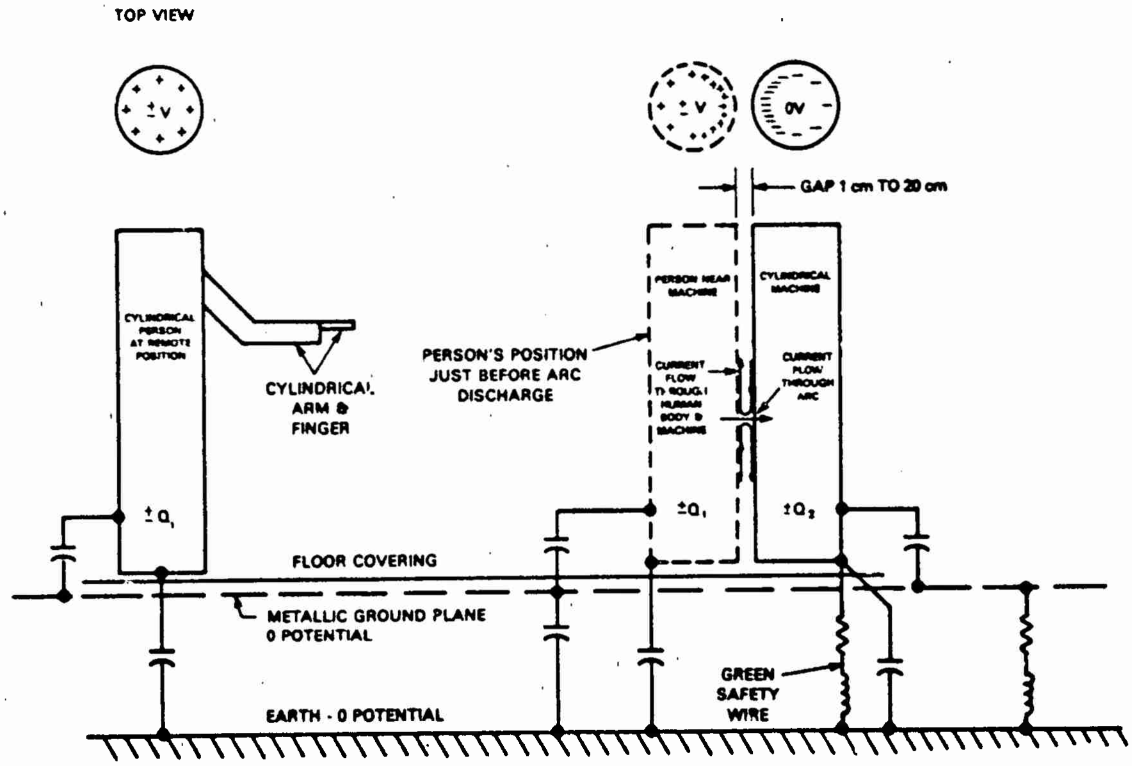


Fig. 1 - Electrostatic buildup and discharge model

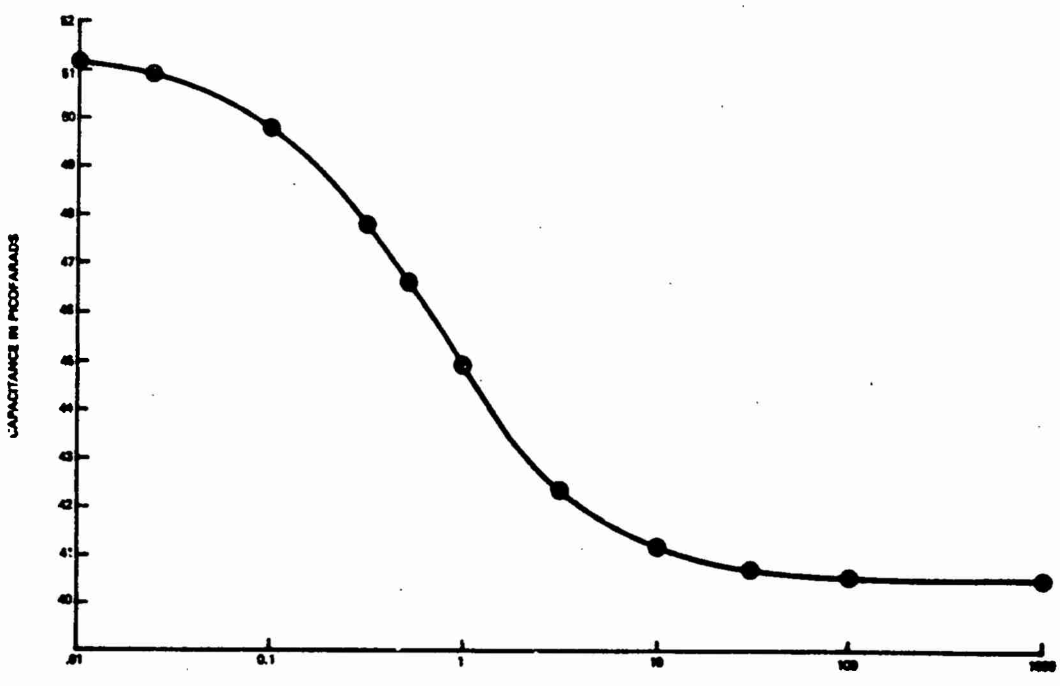


Fig. 2 - Capacitance between simulated person and ground plane

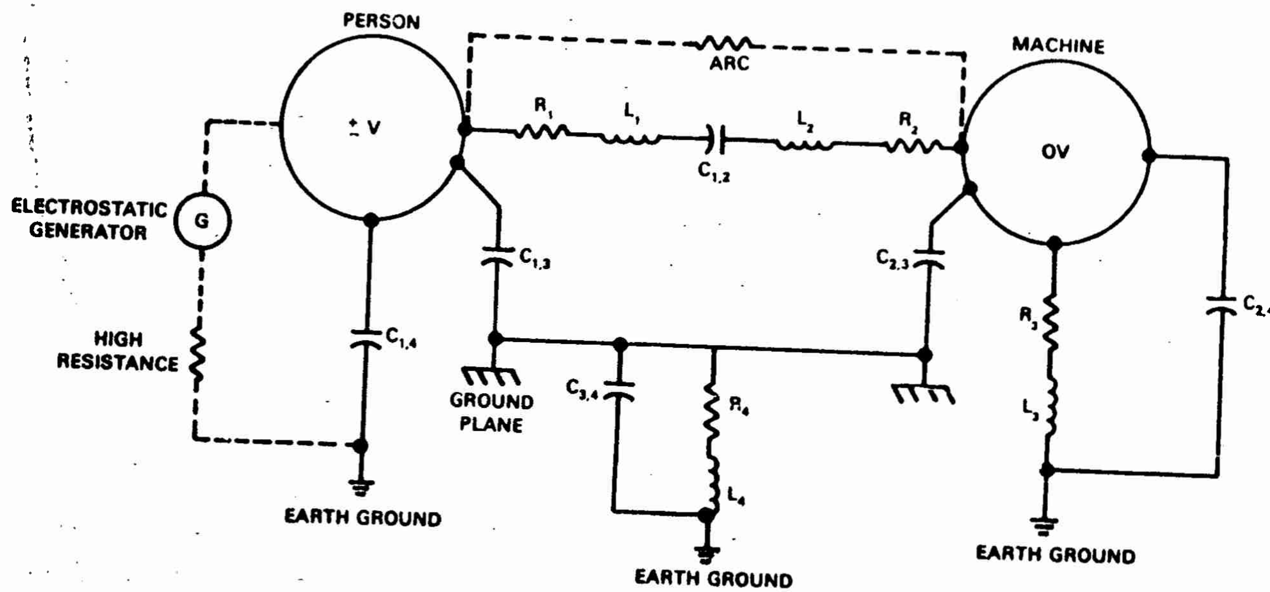


Fig. 3 - Equivalent ESD circuit

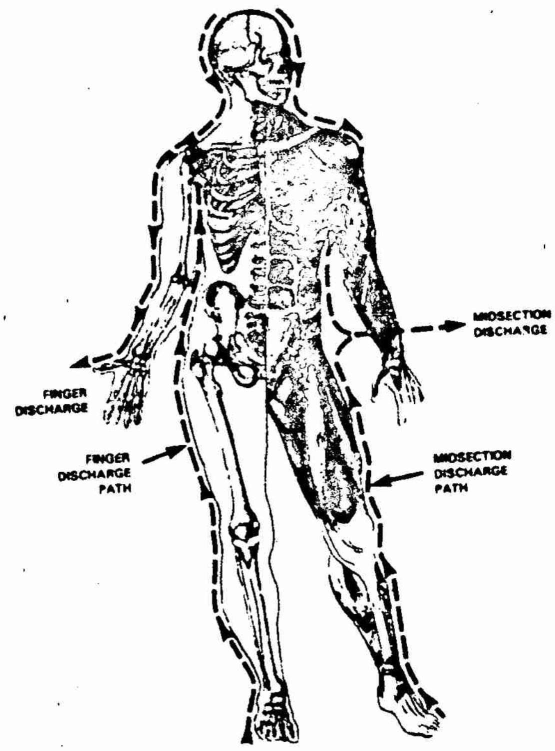


Fig. 4 - ESD current flow through a human body

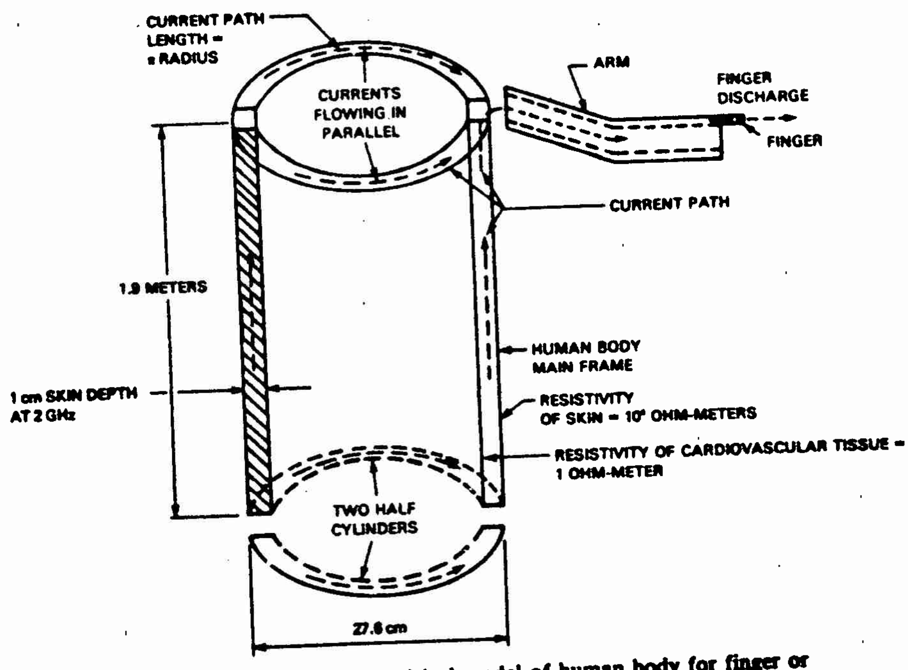


Fig. 5 - Cylindrical model of human body for finger or arm discharge

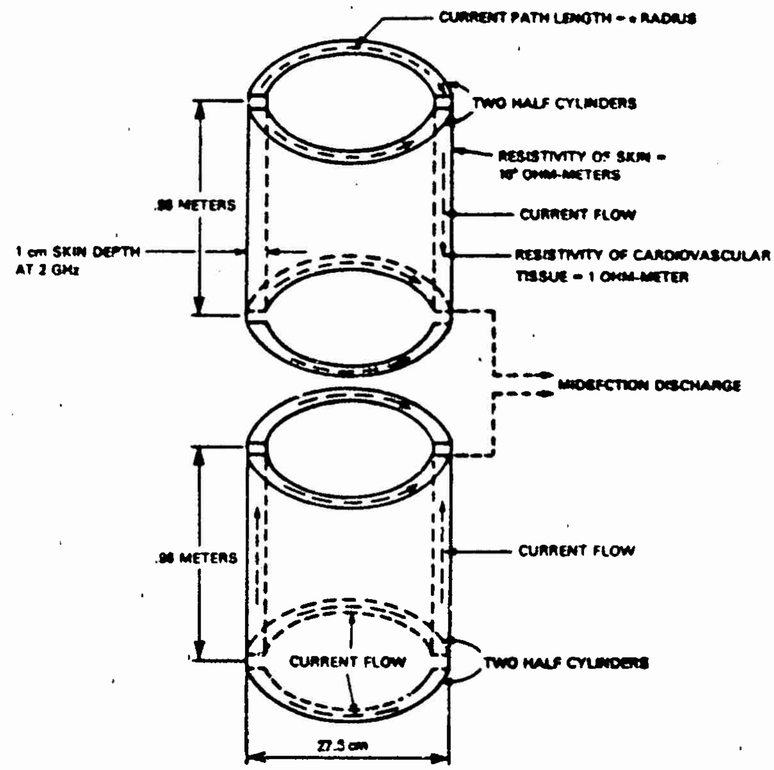


Fig. 6 - Cylindrical model of human body for midsection discharge

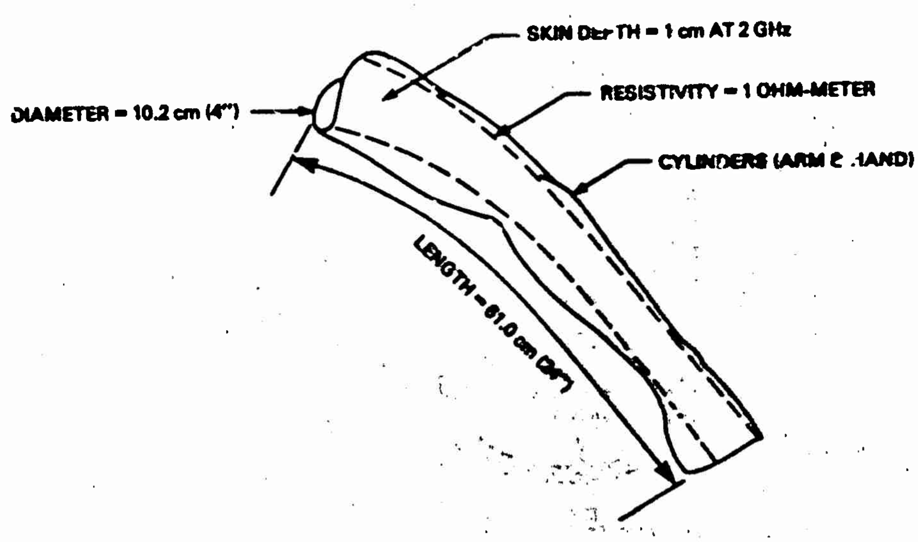


Fig. 7 - Model of human arm

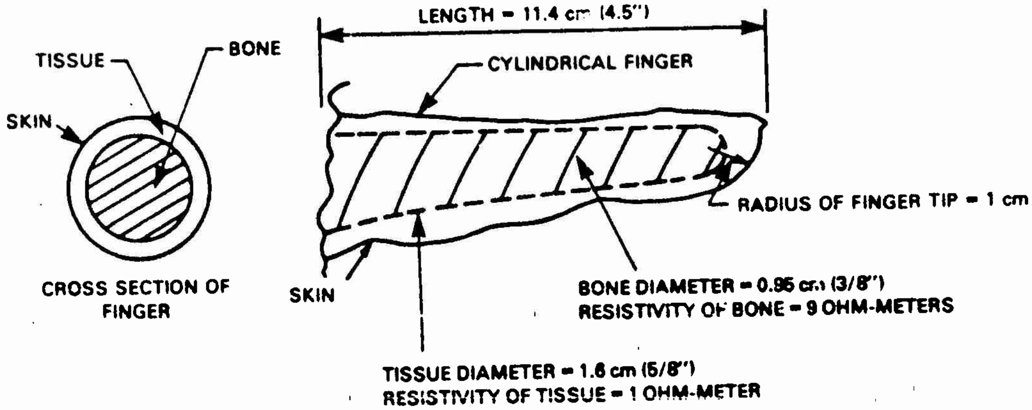


Fig. 8 - Model of human finger

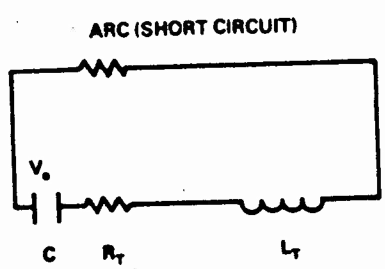


Fig. 9 - Simplified circuit schematic

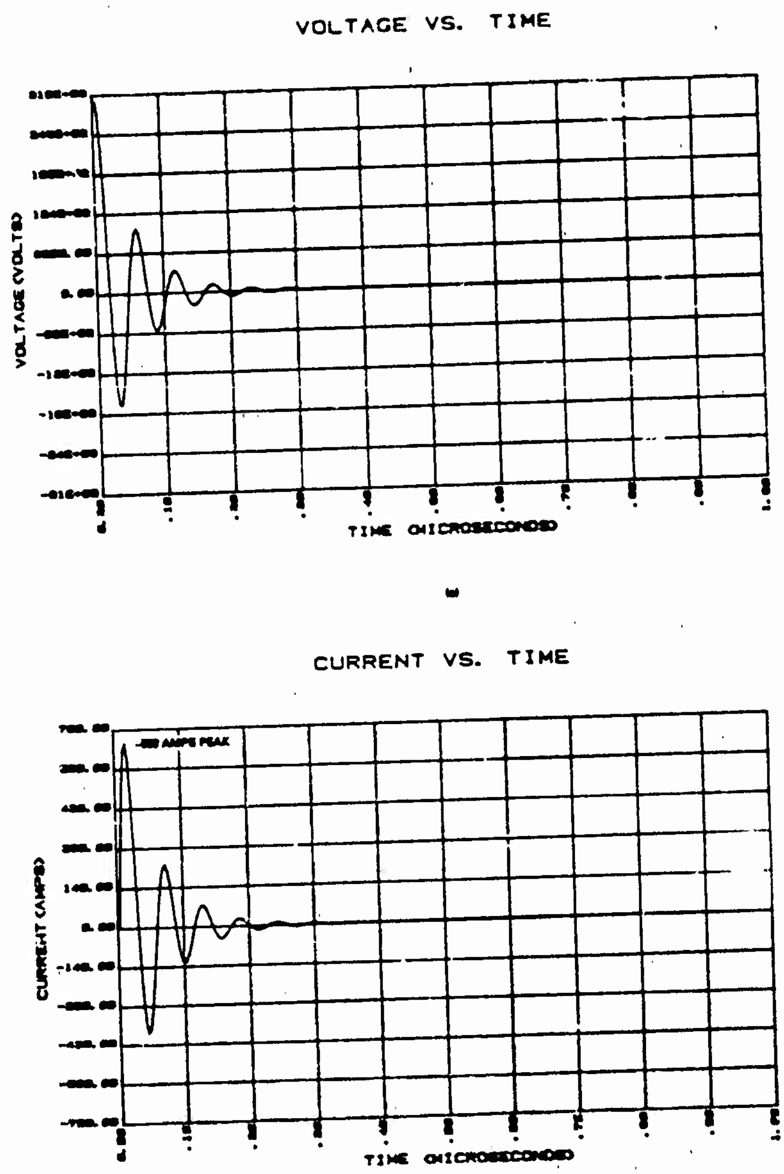
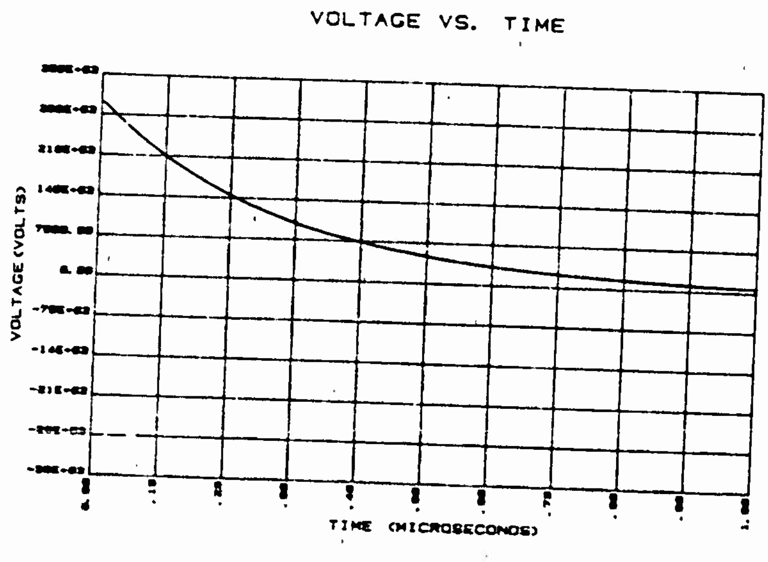
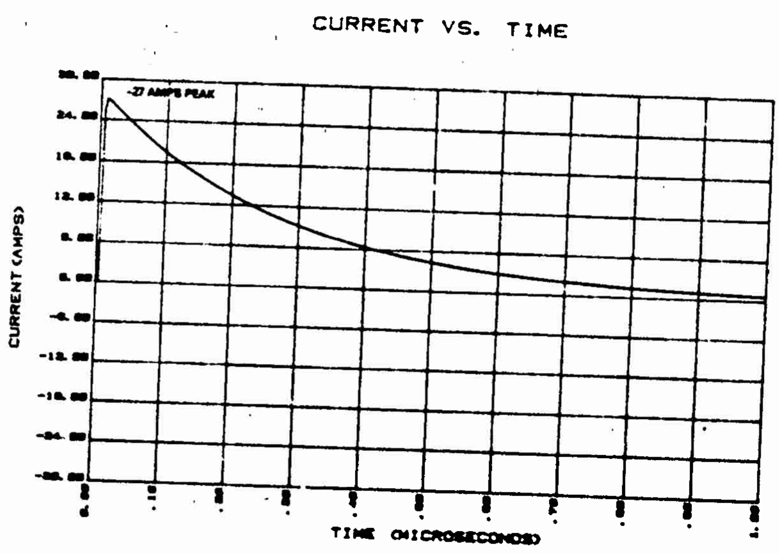


Fig. 10 - Case 1 — "brush by" — underdamped — low-impedance machine



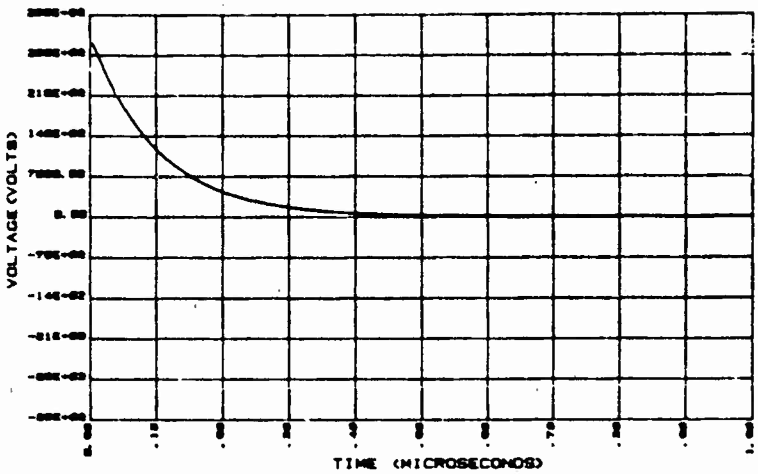
(a)



(b)

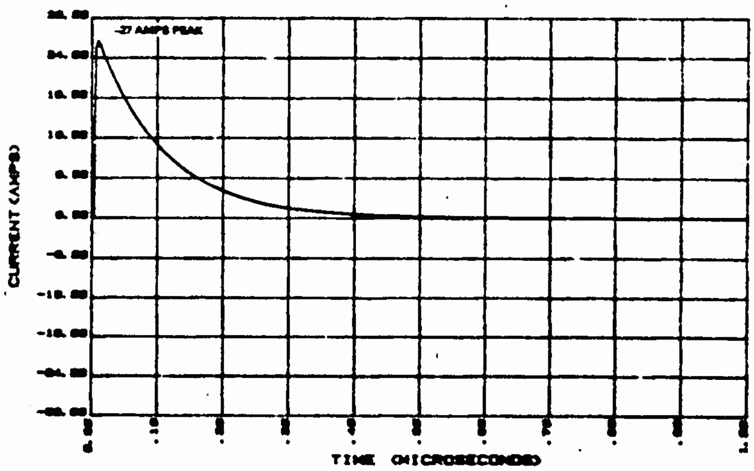
Fig. 11 - Case 2 — contact with finger — person close to low-impedance machine

VOLTAGE VS. TIME



(a)

CURRENT VS. TIME



(b)

Fig. 12 - Case 3 — contact with finger — person standing away from low-impedance machine

CURRENT VS. TIME

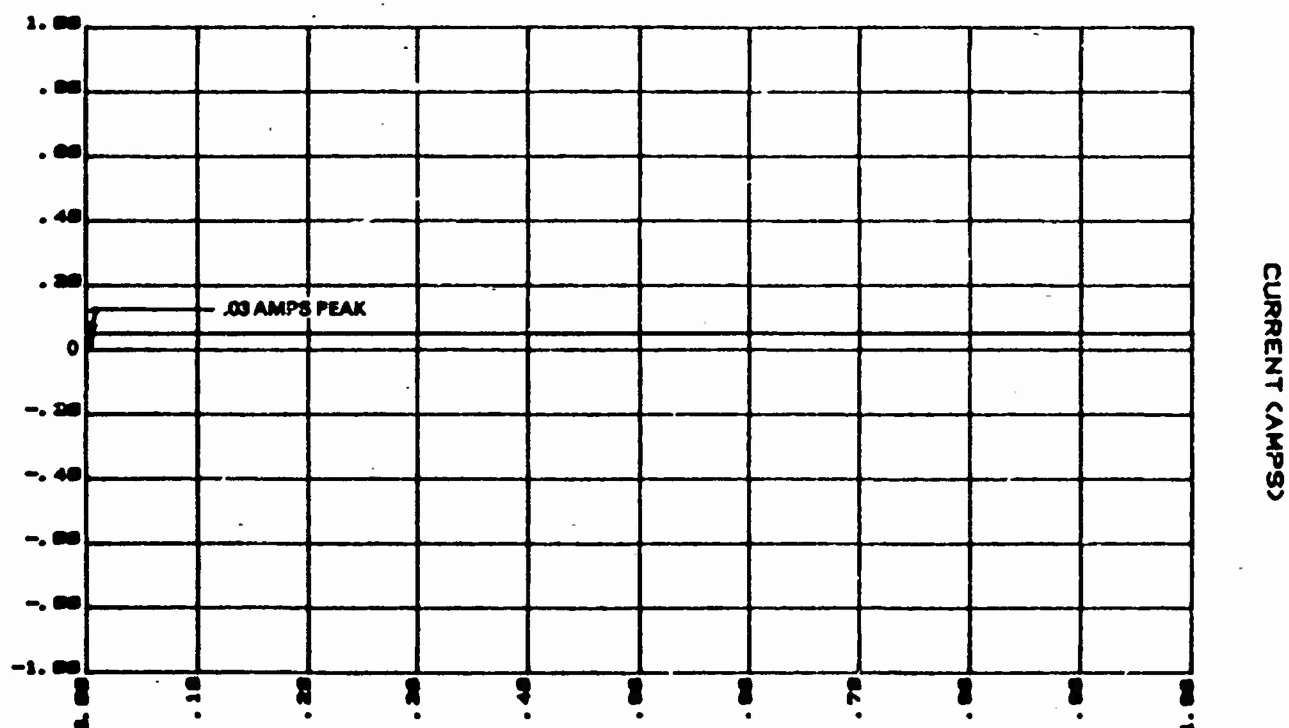
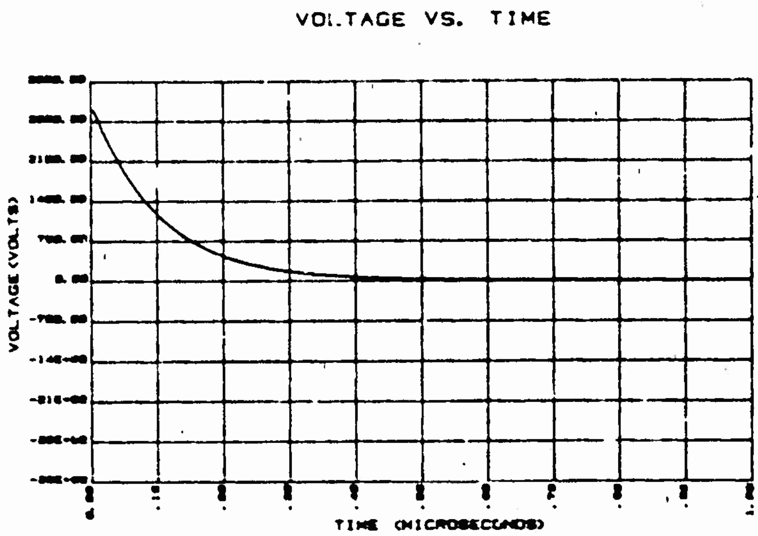


Fig. 13 - Case 4 — person standing away from high-impedance machine



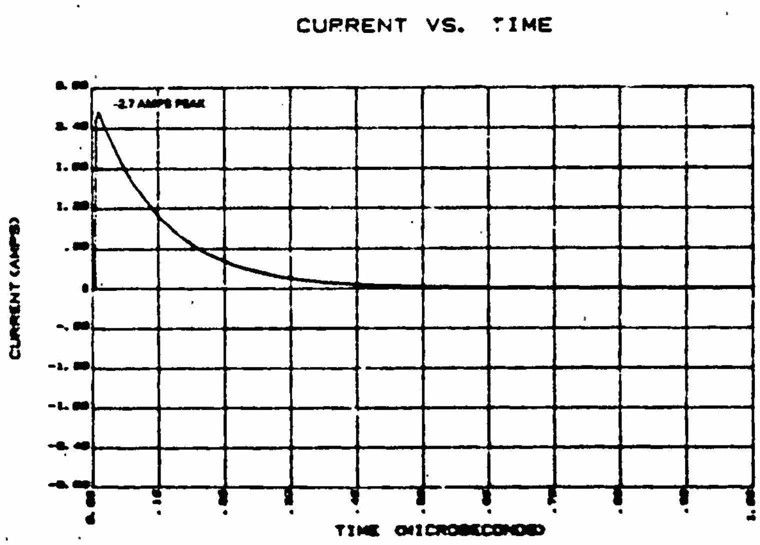
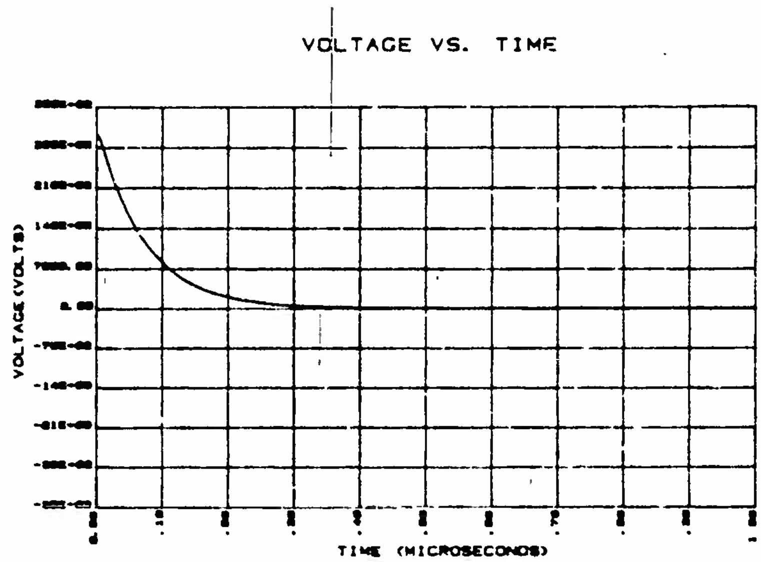


Fig. 14 - Case 5 — contact with finger — person standing away from low-impedance machine — 3kV



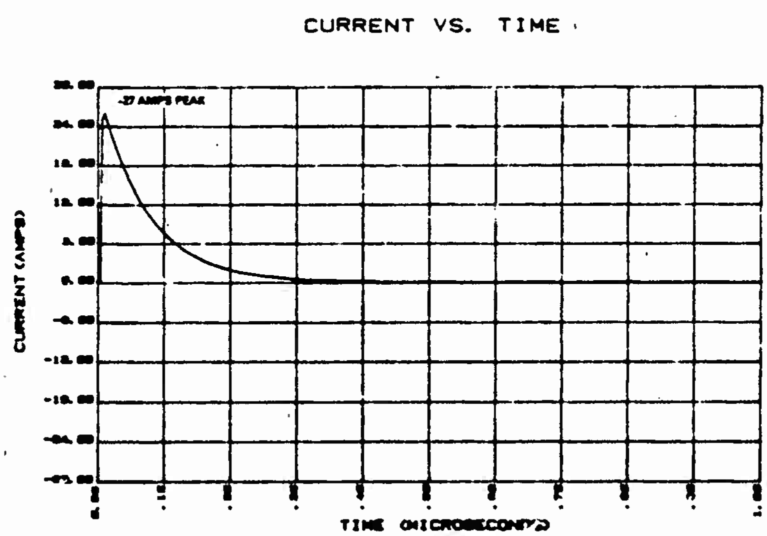


Fig. 15 - Case 6 — contact with finger — person standing away from low-impedance machine — no ground plane

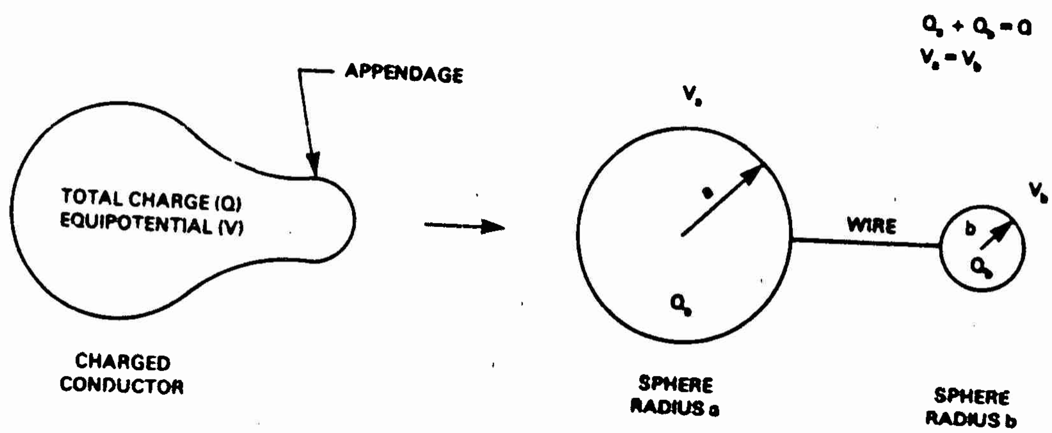


Fig. 16 - Potential and charge on nonuniformly shaped body

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