ELECTRON PENETRATION OF SPACECRAFT THERMAL INSULATION*

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ABSTRACT

The International Solar Polar Mission spacecraft is designed to use Jupiter's large mass to project it into an orbit perpendicular to the ecliptic plane to enable it's onboard scientific experiments to collect data over the north and south poles of our sun. The spacecraft will approach as close as 5 or 6 Jupiter radii during the critical day of maximum orbit change and must be designed to survive the high electron flux surrounding the planet.

Most of the electrons striking the spacecraft will be stopped within the various materials and produce an increasing negative potential and possibly hazardous electric fields, except for a few electrons of extremely high energy which pass on through and those which are sputtered off as secondaries and those which are repelled by the increasing negative potential. If the electrons deposited in insulators produce electric fields which exceed the dielectric strengths, i.e., fields of the order of 10^6 volts/cm, then undesired internal discharging can occur. When energetic electrons penetrate or are stopped in a nonconductor they reduce its bulk electrical resistivity by increasing the number of electron-hole carriers rendering it more of a semiconductor, a phenomena known as radiation induced conductivity. This then permits more of the electrons to flow through the dielectric toward nearby conductors and away from the regions of high deposited electron density, thereby reducing the accompanying electric field and perhaps avoiding any troublesome arcings and flashovers.

In this study we have taken the external thermal blanket to be 13 mils of polyethylene which has known range and stopping power as a function of electron energy, applied the most recent omnidirectional peak Jovian electron flux at 5 Jupiter radii, calculated the electron current penetrating the thermal blanket and allowed this to impinge on a typical 20 mil polyethylene insulator surrounding a wire. The radiation dose rate to the insulator is then calculated and the new electrical conductivity found. The results demonstrate that the increased electronic mobility is sufficient to keep the maximum induced electric field two orders of magnitude below the critical breakdown strength.

CALCULATIONS

A thermal blanket 13 mils thick consisting of 22 layers of Sheldahl, kapton, mylar, teflon, and vacuum deposited aluminum is approximated in this study by a 13 mil layer of polyethylene. The polyethylene parameters used in this calculation are: a dielectric constant of 2.3, a density of 0.92

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gram/cm^2, a volume resistivity of 10^{17} ohm-cm, and a dielectric strength of 0.5×10^6 volts/cm.

Figure 1 displays the electron range in polyethylene as a function of electron energy plotted from data in Reference 1. For a 13 mil or 0.033 cm. thickness we find that electrons with energies below 0.16 Mev are stopped within the thermal blanket. In this study we are concerned with the electrons which penetrate this blanket and reach a typical insulated wire within the spacecraft; the insulation around this wire is taken to be polyethylene with a thickness of 20 mils or 0.051 cm. We find from Figure 1 that electrons with energies greater than 0.29 Mev pass on through this 0.051 cm. of insulation.

Figure 2 illustrates the total stopping power in polyethylene as a function of electron energy plotted from data in Reference 1. The electrons with energies between 0.16 Mev and 0.29 Mev which are deposited in our 20 mil insulator of interest lose an average of 2.6 Mev/cm.; therefore, they impart an energy to this dielectric equal to their initial energy minus the energy they lost while traversing the 13 mils of thermal blanket. This average 0.22 Mev electron loses an average of 2.6 Mev/cm. times 0.033 cm. or 0.086 Mev traversing the thermal blanket, and has remaining 0.22 Mev minus 0.086 Mev yielding 0.134 Mev for deposit in our inner insulator. The electrons having energies greater than 0.29 Mev which pass through our inner dielectric lose approximately 2.2 Mev/cm.; therefore, they impart 2.2 Mev/cm. times 0.051 cm. for 0.112 Mev per electron to the polyethylene.

Figure 3 gives the Jovian electron omnidirectional integral peak flux as a function of energy at a distance of 5 Jupiter radii plotted from data in Reference 2. This omnidirectional flux needs to be divided by 4 to obtain the correct number crossing unit surface per second according to Reference 3. Values from Figure 3 are 2.8×10^8 electrons/cm^2-sec at 0.16 Mev and 1.7×10^8 electrons/cm^2-sec at 0.29 Mev. After appropriately dividing by the necessary 4, these fluxes become 7.0×10^7 electrons/cm^2-sec at 0.16 Mev and 4.2×10^7 electrons/cm^2-sec at 0.29 Mev.

The rate of electron density deposited in the inner insulator is $(7.0 - 4.2) \times 10^7$ e$^-$/cm^2-sec = 2.8×10^7 e$^-$/cm^2-sec. This is multiplied by the elecronic charge of 1.6×10^{-19} coulomb to yield a current density of 4.5×10^{-12} amp/cm^2. These 2.8×10^7 e$^-$/cm^2-sec which stay in the insulator impart an average energy of 0.134 Mev per electron for a product of 3.75×10^6 Mev/cm^2-sec. The 4.2×10^7 e$^-$/cm^2-sec of higher energy electrons which penetrate the inner insulator lose an energy of 0.112 Mev per electron for a product of 4.7×10^6 Mev/cm^2-sec. This total of 8.4×10^6 Mev/cm^2-sec is converted to a dose rate by using the identity 1 rad $\equiv 6.25 \times 10^7$ Mev/gram to give:

$$(8.4 \times 10^6 \text{ Mev/cm}^2\text{-sec})(1 \text{ rad-gm}/6.25 \times 10^7 \text{ Mev})$$

$$\times (1 \text{ cm}^3/0.92 \text{ gm})(1/0.051 \text{ cm}) = 2.9 \text{ rad/sec}$$

The radiation induced conductivity is calculated using

$$\Delta\sigma = qK\tau\mu\dot{D} = 5 \times 10^{-17}\,\dot{D}$$

from Reference 4, where q is the electronic charge of 1.6×10^{-19} coulomb, K is the density function for electron-hole pairs of 3×10^{13} pairs/cm^3-rad, τ is the state lifetime of 10^{-11} sec, μ is the mobility of 1 cm^2/volt-sec, and $\dot{D}$ is the dose rate in rad/sec. Our typical inner polyethylene insulator has its conductivity changed near Jupiter by the amount

$$\Delta\sigma = 5 \times 10^{-17}\text{ sec/rad-ohm-cm } (2.9\text{ rad/sec}) = 14 \times 10^{-17}\text{ ohm}^{-1}\text{-cm}^{-1}$$

The new conductivity is expressed as the sum of the initial and the change yielding

$$\sigma = \sigma_o + \Delta\sigma = 1 \times 10^{-17} + 14 \times 10^{-17} = 15 \times 10^{-17}\text{ ohm}^{-1}\text{-cm}^{-1}$$

An electrical model is now constructed for the charge density deposited in the insulator and for the equivalent circuit. It turns out that the assumed shape of the charge density doesn't really matter, i.e., it may be an isosceles triangle distribution with the apex at the center of the insulator, or a sinusoidal distribution with the maximum in the center, or a delta function with all charge deposited right at the center. The maximum value of the electric field produced in the insulator is found from Poisson's equation

$$\frac{d^2V}{dx^2} = \frac{dE}{dx} = -\frac{\rho}{\varepsilon}$$

to be $E_{max}(x,t) = \pm s\,\rho_{max}(t)/\varepsilon$, where s is the insulator thickness and ε is the insulator permittivity. The equivalent electrical circuit is taken to be an insulator having both capacitance and resistance in parallel, grounded on each side, with half the deposited electron current flowing in each direction as shown in Figure 4. This model becomes

$$J_e/2 = J_R + J_C$$

The resistive current density is given by Ohm's equation

$$J_R(x,t) = \sigma(t)E(x,t) = \sigma s\,\rho_m(t)/\varepsilon$$

The capacitive or displacement current density is given by

$$J_C = dQ/dt \text{ where } Q = \int \rho_m(t)\delta(x-o)dx = s\,\rho_m(t)$$

This yields

$$J_e/2 = \sigma s\ \rho_m(t)/\varepsilon + s\ d\rho_m(t)/dt$$

which has the solution

$$\rho_m(t) = \frac{\varepsilon Je}{2\sigma s}\ (1 - e^{-\sigma t}/\varepsilon)$$

This is expressed in terms of the maximum electric field as

$$E_m(t) = \frac{Je}{2\sigma}\ (1 - e^{-\sigma t}/\varepsilon)$$

The charging time constant is found by

$$\varepsilon/\sigma = K\varepsilon_0/\sigma = 2.3(8.85 \times 10^{-12}\ \text{coul/volt-m})/(15 \times 10^{-17}\ \text{ohm}^{-1}\text{-cm}^{-1})$$

$$\times\ (1\ \text{m}/100\ \text{cm}) = 1360\ \text{sec}$$

The maximum obtainable electric field is given by

$$E_{max} = Je/2\sigma = (4.5 \times 10^{-12}\ \text{amp/cm}^2)/2(15 \times 10^{-17}\ \text{ohm}^{-1}\text{-cm}^{-1})$$

$$= 1.5 \times 10^4\ \text{volts/cm}$$

The equation for the electric field becomes

$$E_m(t) = 1.5 \times 10^4\ \text{volts/cm}\ (1 - e^{-t/1360\ \text{sec}})$$

This maximum electric field of 1.5×10^4 volts/cm is between one and two orders of magnitude less than 5×10^5 volts/cm, the dielectric strength of polyethylene; therefore, no electric discharges are expected to occur within the insulation surrounding wires beneath the spacecraft's thermal blanket.

An interesting graph, Figure 5, is produced by plotting the equation for the charging time versus the absorbed current for various values of resistivity

$$t = \frac{\varepsilon}{\sigma}\ \ln\ (Je/(Je - 2\sigma E_m))$$

One can locate the appropriate curve for the new radiation induced conductivity or resistivity, locate the deposited current density and therefore find the time to breakdown which for our particular values gives a time of infinity.

One final interesting conclusion is found by inspecting the maximum electric field that would be produced if there were no radiation induced conductivity, i.e., by using the initial conductivity of 10^{-17} $\text{ohm}^{-1}\text{-cm}^{-1}$

$$E_{max} = Je/2\sigma = 4.5 \times 10^{-12}/2\ (1 \times 10^{-17}) = 2.25 \times 10^{5} \text{ volts/cm}$$

This is still less than polyethylene's breakdown strength of 5×10^5 volts/cm; therefore, no breakdown would be expected even without the dielectric degradation. Of course, this applies only to insulation beneath the thermal blanket.

REFERENCES

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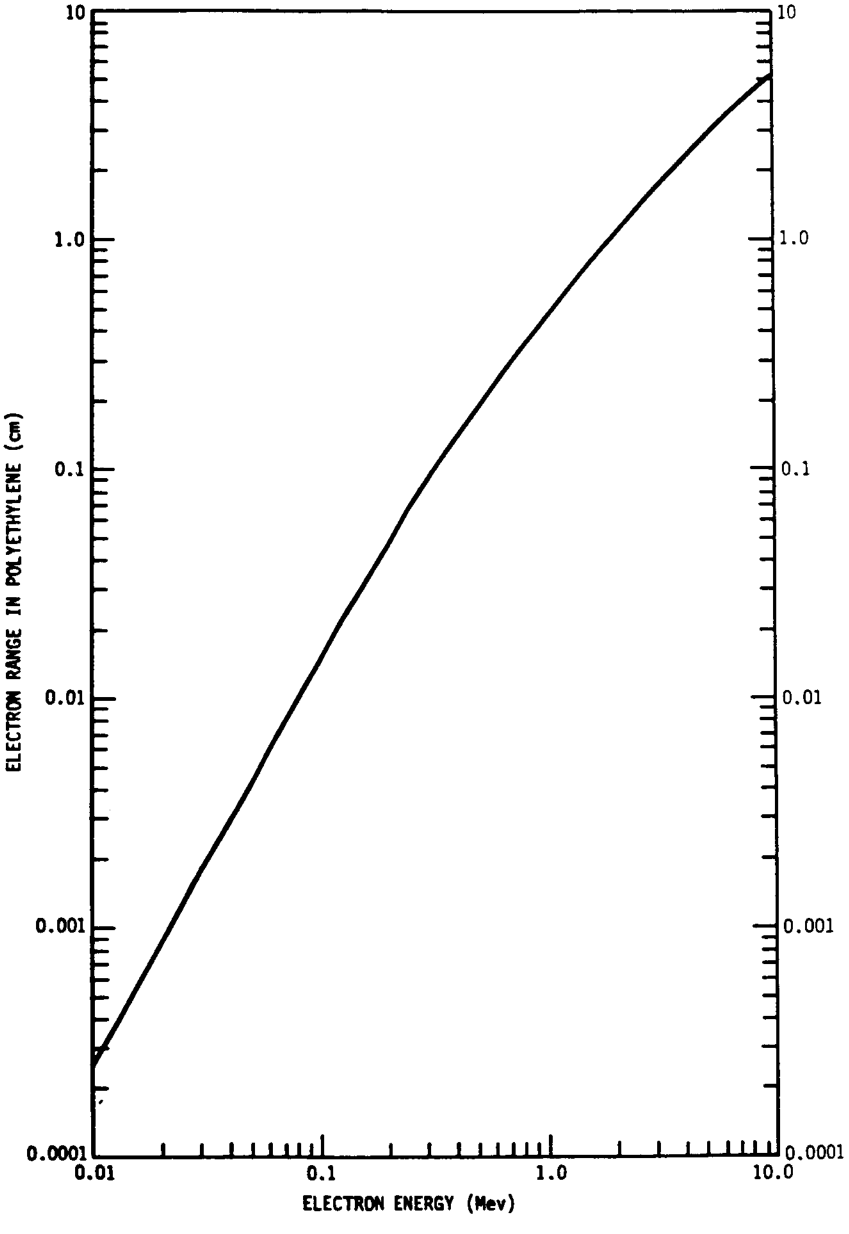

10
1.0
0.1
0.01
0.001
0.0001
10
1.0
0.1
0.01
0.001
0.0001
0.01
0.1
1.0
10.0
ELECTRON RANGE IN POLYETHYLENE (cm)
ELECTRON ENERGY (Mev)

FIGURE 1.

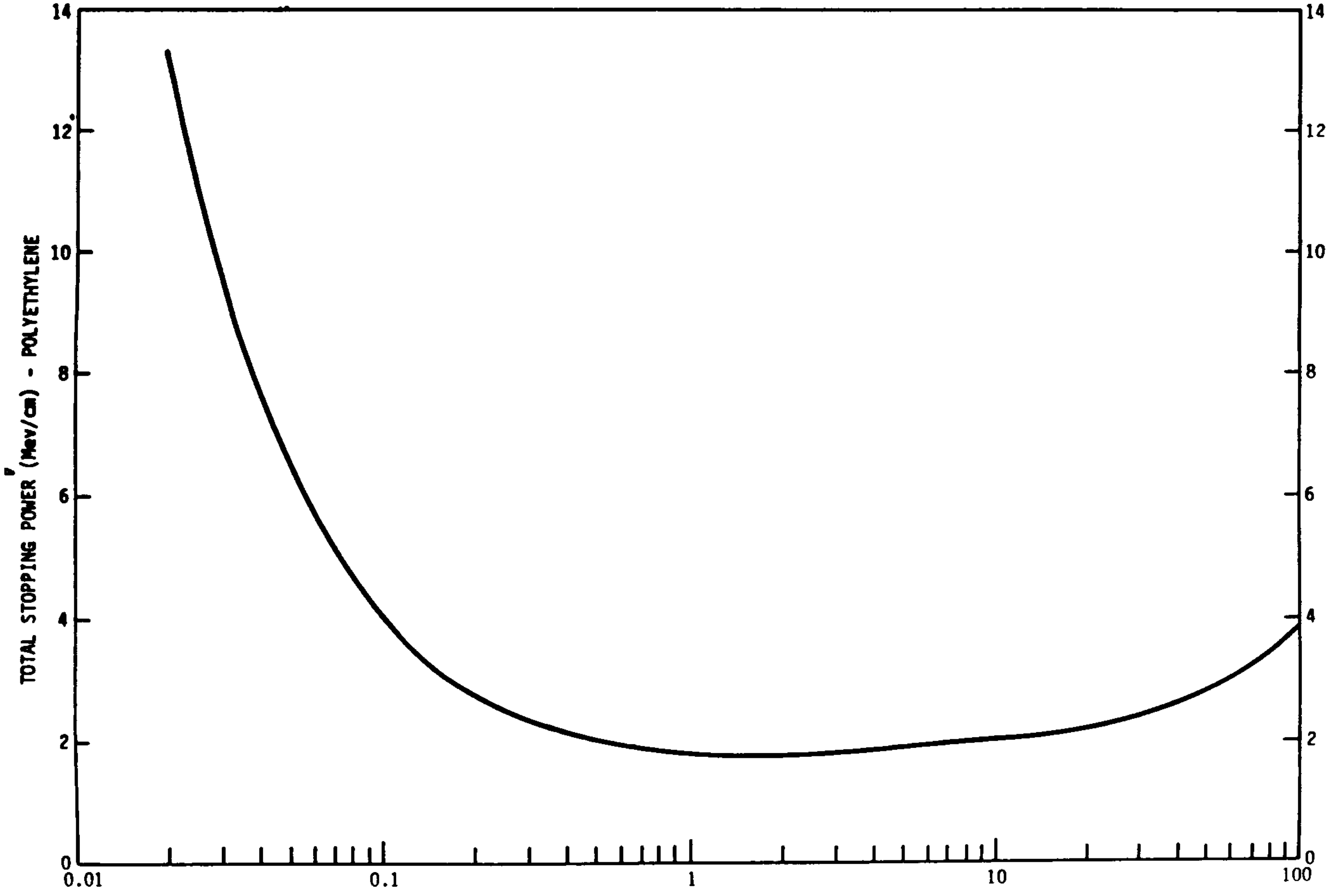

TOTAL STOPPING POWER (Mev/cm) - POLYETHYLENE
14
12
10
8
6
4
2
0
0.01
0.1
1
10
100
ELECTRON ENERGY (Mev)

FIGURE 2.

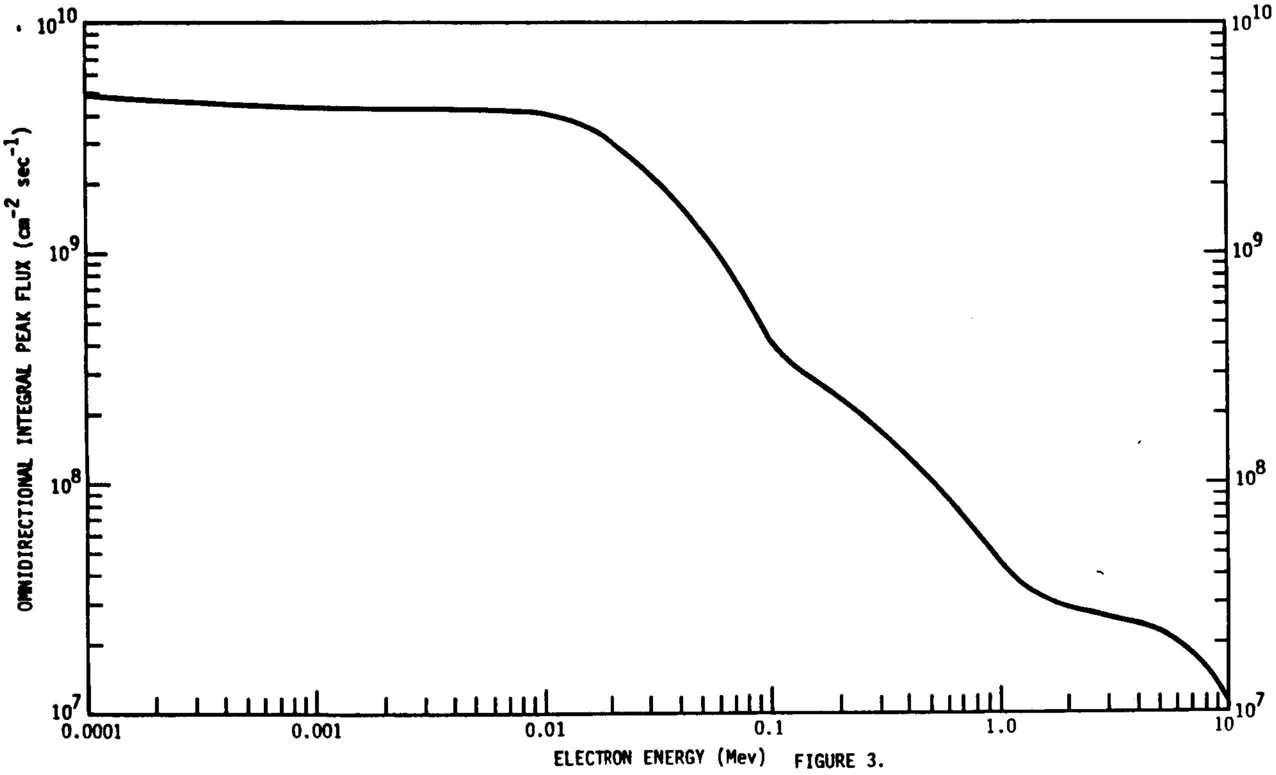
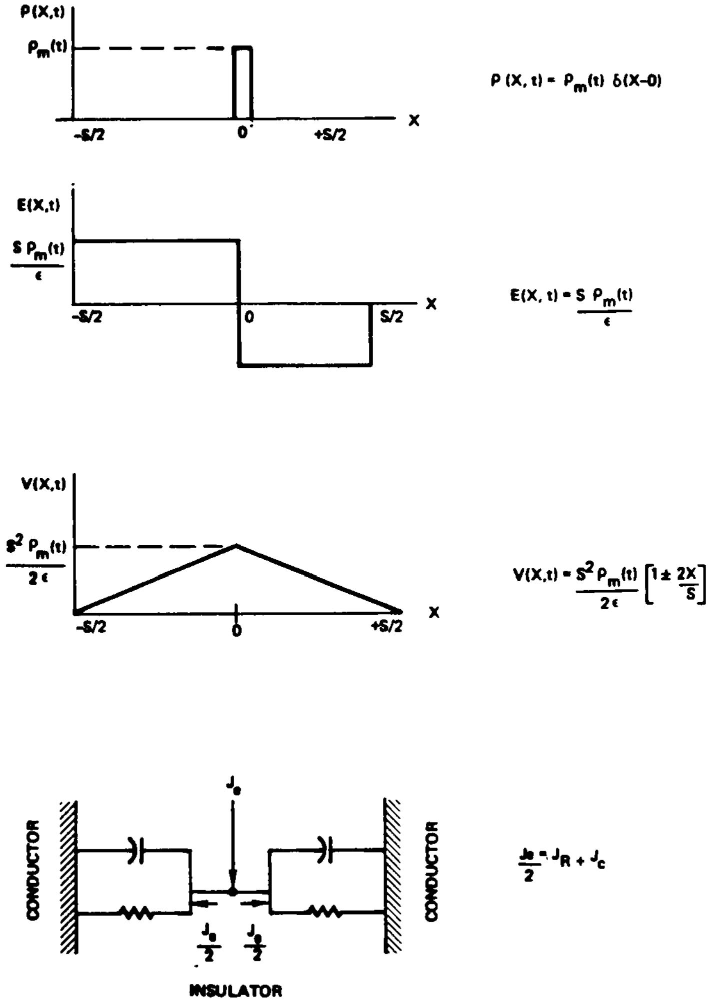

OMNIDIRECTIONAL INTEGRAL PEAK FLUX (cm^{-2} sec^{-1})
10^{10}
10^{9}
10^{8}
10^{7}
10^{10}
10^{9}
10^{8}
10^{7}
0.0001
0.001
0.01
0.1
1.0
10
ELECTRON ENERGY (Mev)

FIGURE 3.



Models for Electron Distribution and Electrical Circuit

FIGURE 4.

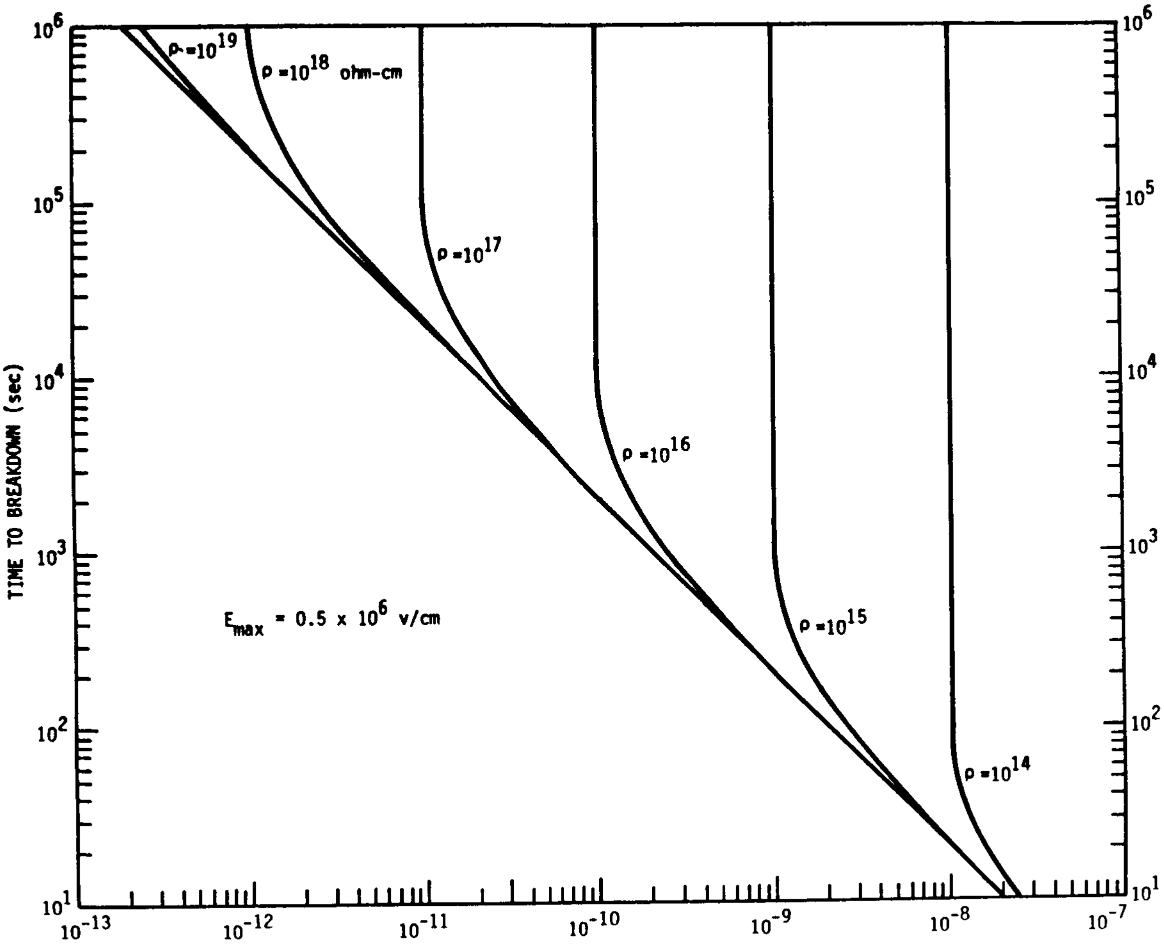

TIME TO BREAKDOWN (sec)
10^6
10^5
10^4
10^3
10^2
10^1
$\rho = 10^{19}$
$\rho = 10^{18}$ ohm-cm
$\rho = 10^{17}$
$\rho = 10^{16}$
$\rho = 10^{15}$
$\rho = 10^{14}$
$E_{max} = 0.5 \times 10^6$ v/cm
10^{-13}
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
CURRENT ABSORBED (amp/cm^2)

FIGURE 5.