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3. Induced Charging of Shuttle Orbiter by High Electron-Beam Currents

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Abstract

Emission of high-current electron beams that has been proposed for some Spacelab payloads requires substantial return currents to the Orbiter skin in order to neutralize the beam charge. Since the outer skin of the vehicle is covered with ~ 1300 m^2 of thermal insulation which has the dielectric quality of air and an electrical conductivity that has been estimated by NASA at 10^{-9}-10^{-10} mhos/m, considerable transient charging and local potential differences are anticipated across the insulation. The theory for induced charging of spacecraft due to operation of electron guns has only been developed for spherical metal vehicles and constant emission currents, which are not directly applicable to the Orbiter situation. Field-aligned collection of electron return current from the ambient ionosphere at Orbiter altitudes provides up to ~ 150 mA on the conducting surfaces and ~ 2.4 A on the dielectric thermal insulation. Local ionization of the neutral atmosphere by energetic electron bombardment or electrical breakdown may provide somewhat more return current. During electron gun operation, differential charging between the outer surface of the dielectric insulator and the internal metal conductors creates large potentials and electric fields across the insulation. Estimates of the transient behavior and potential magnitude are obtained by solving electric circuit analogies. For an electron beam charge of 1 coulomb (10 A for 100 msec), the potential across the insulator rises to 10^3-10^5 volts depending on the induced external ionization. Since electrical breakdown across the insulation occurs at 50,000 volts, high gun currents may cause arcing through the insulation.

I. INTRODUCTION

Electrical charging of spacecraft in the ionosphere and magnetosphere is a consequence of different fluxes of thermal electrons and ions striking the surface of the vehicle. Normally, a very small equilibrium potential is established over the skin of the vehicle which does not affect the operation of sensors and electronic instrumentation. However, the Space Shuttle Orbiter may acquire appreciable charge differentials and local electric fields due to its large airplane shape and its nonconducting outer skin. As the vehicle assumes different attitudes in the course of its mission, various outer surfaces will be shadowed from particle and/or photon bombardment. Owing to alignment of charged-particle trajectories along the geomagnetic field and the relatively large difference in electron and ion speeds, there are many more regions of the spacecraft surface that are accessible to electrons than to ions. In addition, the photoemission of electrons from the surface by solar ultraviolet will depend on spacecraft attitude. Thus, the local current flow to the skin of the vehicle will vary widely from point to point. The dielectric skin of the vehicle prevents rapid flow of surface current to neutralize the differential charging and as a consequence, potential differences and attendant electric fields may be anticipated. During normal passive operations of the vehicle, potential differences of several volts are expected between adjacent areas of the vehicle where the surface contour changes abruptly (edges of wings, payload bay door edges, and around corners).

Active experiments planned for the Orbiter Spacelab include ejection of large amounts of electrical charge in the form of electron beams that must be compensated by a return current to the vehicle. Relatively slow collection of return electron current from the ambient ionosphere prevents rapid neutralization of the electron-beam charge. Proposed gun currents of up to 10 A for 100 msec are predicted to cause transient excursions of the vehicle potential that exceed many thousands of volts, unless appropriate compensating return current is available. Since operation of an electron gun at keV energies from the AMPS Spacelab is a vital part of the overall mission objective, it is important to determine the magnitude of the transient potentials and their dynamic characteristics.

The published literature on ambient charging of spacecraft in the ionosphere and magnetosphere is quite thorough for vehicles with conducting outer skin. Only a few papers have treated the problem of large-electron current ejection from spacecraft, and their applicability to a realistic pulsed mode of operation is open to question. The Shuttle Orbiter presents additional complications due to its non-conducting outer skin which can only be discharged by the ambient plasma medium. For example, an electron gun pulse will drive the skin potential positive until enough return current is collected to neutralize the overall potential of the vehicle;

but by that time the skin will have built up a negative charge which must be neutralized by ion bombardment, photoemission, and conduction leakage to the interior structure.

The results presented here are based on a preliminary analysis of the Shuttle-Orbiter charging problem that is published elsewhere.[1] This earlier work includes summaries of the ambient ionospheric environment at Shuttle-Orbiter altitudes, the electrical characteristics of the vehicle skin, the disturbed atmospheric environment due to gas leakage from the vehicle, the local potential differences that are anticipated during passive operations, and the dynamic potentials that are expected during electron-gun operation. Only this latter topic is considered in detail here.

2. ENVIRONMENTAL CHARACTERISTICS

2.1 Ambient Ionosphere

The Shuttle Orbiter that carries the Spacelab payloads is scheduled to operate in a nominal altitude range between 250 and 400 km. The natural environment is described in great detail in many aeronomy textbooks.[2-6] At these F-region altitudes, the charged constituents consist principally of oxygen ions and electrons and the primary neutral constituent is atomic oxygen. Large variations in both density and temperature for these constituents are attributed to source and transport mechanisms that vary diurnally as well as with season and solar cycle.

As a consequence of the plasma temperature, the spacecraft speed is considerably greater than the mean thermal speed of the ions but significantly less than the mean thermal speed of electrons, which has important consequences for current collection by particle flux at the vehicle skin. The gyroradius for ions is a few meters, whereas for electrons it is a few centimeters so that plasma motion is field-aligned. Due to the geometrical configuration of the vehicle and the variety of attitudes it may assume during a mission and its cross-field orbits, many areas will be routinely shadowed from ion and electron bombardment as well as photon flux.

The mean free path of the ions, electrons and atoms is orders of magnitude greater than the Shuttle-Orbiter dimensions so that collisional effects may be ignored. However, collective plasma properties significantly influence the flow of charge to the vehicle. Electrical conductivity of the plasma is highly anisotropic due to the presence of the geomagnetic field. Along the field direction the conductivity is about 20 mhos/m, but normal to the magnetic field the conductivity is several orders of magnitude less, virtually prohibiting current flow unless the

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electric field is very large. Thus, for most vehicle attitudes, there is very little electrical connection through the plasma between different parts of the vehicle.

2.2 Vehicle Surface

Less than 5 percent of the outer surface of the Shuttle Orbiter and Spacelab consists of good metallic conductor. More than 95 percent of the surface is good thermal insulating material consisting of fibrous silicon dioxide tiles, coated felt, and adhesives. The composite material has extremely high electrical resistivity, between 10^{-10} and 10^{-13} mhos/m. The dielectric constant of these thermal insulators is comparable to that of air, and breakdown potential of the tiles has been measured at 50,000 volts by NASA/JSC. Since the thickness of the sample is presumably a few centimeters, the corresponding limiting electric field at break-down is taken as 10^6 volts/m. Such fields and potentials would not occur for ambient conditions; however, vehicle charging during electron gun operation may exceed these limits by substantial amounts as will be shown.

There are some metallic exterior surfaces that provide "shorted" electrical contact between the interior metal supperstructure of the Orbiter and the external plasma. The largest area is provided by the metal rocket motor nozzles. Other substantial surface areas are provided by the antenna boom, pallet instruments, and the manipulator arm. Since the pallet is graphite epoxy which is a poor conductor, there is some question about the electrical contact between these latter instrument related conductors and the interior superstructure. However, for purposes of the present analysis, all of the external metal surfaces are assumed to be in contact with each other and the internal superstructure.

The electrical properties of the primary external surfaces of the Orbiter and Spacelab are tabulated in Table 1. The insulation data was provided by Mr. John Lobb, NASA/JSC, Houston, in private communications. Of special interest for scientific researchers is the lack of an effective external ground plane; the Space-lab pallet and control room have graphite epoxy exterior surfaces which are not conductors. Overall, the metal surfaces amount to about 60 m^2 whereas noncon-ductor surfaces cover 1300 m^2.

The electrical conductivity of the thermal insulation materials is a vital parameter for the conclusions in this study and, unfortunately, its value is in doubt at this time. The value 10^{-9}-10^{-10} mhos/m quoted in Table 1 is the current best NASA/JSC estimate, but no official experimental measurements have been made to date. An independent measurement of HRSI tiles has been made by Mr. Paul W. Edwards at Rockwell International who found a bulk conductivity of 10^{-13} mhos/m. Such discrepancies are well within the range of conductivity values for different types of silica (10^{-7}-10^{-14} mhos/m) as the manufacturing process,

Table 1. Orbiter/AMPS-Spacelab Outer Skin Materials

Location	Material	Area (m^2)	Thickness (m)	Electrical Conductivity (mhos/m)	Dielectric Constant (κ)
Topside (low temp.)	FRSI	300	0.011	10^{-10}	~1
Topside (high temp.)	LRSI	280	0.010-0.030	10^{-9}-10^{-10}	~1
Underside (reentry shield)	HRSI	475	0.024-0.107	10^{-9}-10^{-10}	~1
Nose and Wing Edge	RRC	37.5	0.006	10^{-6}	~1
Rocket Exhaust Nozzles	Inconel 718	~30	--	6×10^6	--
Interior Bay Door Radiators	Teflon	~100	--	10^{-10}	~1
Spacelab Pallet	Graphite Epoxy	~90	--	10^{-10}	~1
Spacelab Control Room	Graphite Epoxy	~25	--	10^{-10}	~1
Spacelab Pallet Instruments	Aluminum	~10	--	3×10^7	--
Antenna Boom	Beryllium Copper	~15	--	1×10^7	--
Manipulator Arm	Aluminum	~5	--	3×10^7	--

purity of the material, and environmental conditions (handling and aerosols) all affect electrical insulation quality. However, there is a clear need for more accurate estimates of the electrical conductivity for the thermal insulation. For the present, the NASA values will be used, but effects of different values will be noted where appropriate.

Some external conditions or modes of experimental operation require conduction through the insulation to establish equilibrium. Under most situations, however, the thermal blanket acts as a dielectric capacitor which efficiently stores

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charge on its external surfaces. The capacitance and resistance of the blanket per unit area are $\kappa\epsilon_o/\Delta h$ and $\Delta h/\sigma$, respectively, where κ is the relative dielectric constant, ϵ_o is the permittivity of free space (8.85 $\mu\mu f/m$), σ is the electrical conductivity, and Δh is the blanket thickness. The e-folding time constant for discharging such an electrical circuit is $\tau_{RC} = \kappa\epsilon_o/\sigma$. According to Table 1, this discharge constant is 0.01 - 0.1 sec for the thermal blanket. The total area of the thermal blanket gives an overall capacitance of 0.5 μf and an overall resistance of 2×10^4 to 2×10^5 ohms using an average blanket thickness of 2.5 cm. This time constant is a critical parameter for estimating discharge rates, particularly during electron gun firings. According to the previous discussion, the thermal insulation may conceivably yield time constants from 10^{-4} sec to 10^3 sec. The low end would provide welcome relief from charge buildup and its attendant hazards whereas the high end raises grave concerns about arcing, and its side effects.

2.3 Vehicle Gas Releases

There is considerable neutral gas released by the Shuttle Orbiter that may contaminate its natural environment. A comprehensive study of contamination control has recently been completed for NASA.[7] Results reported here are based on the conclusions in this report. Both passive releases from the outer skin materials and cabin atmosphere leakage, and active exhausting from vernier rockets and fuel-cells cause localized enhancements of the neutral gas around the vehicle. Outgassing is the steady release of heavy molecules (M ~ 100) from the nonmetallic skin materials exposed to the vacuum environment of space. Offgassing is the prompt release of adsorbed volatile species primarily from the nonmetallic materials (M ~ 18). Cabin atmosphere leaks from various seals around doors, windows, and skin joints. There are two flash evaporator vents near the rear of the fuselage that periodically expell large amounts of water vapor from the fuel cells. There are six 25 lb (nominal) thrust vernier control rocket engines that are used for vehicle attitude control. Outgassing of the main rocket engine following orbit insertion is not treated in the study because the exhaust product is water vapor that promptly dissipates.

Comparison of the ambient oxygen density at Orbiter altitudes with predicted offgassing and cabin leakage densities, shows that the Shuttle Orbiter is generating its own atmosphere. The principal source is cabin leakage which is one or two orders of magnitude greater than the natural oxygen density. In the first few hours offgassing of volatiles is comparable, but after the first day it is a minor contributor. The evaporators and vernier engines produce narrow rayed plumes that are several orders of magnitude denser than ambient, but these exhaust plumes move radially away from the vehicle and do not contribute appreciably to the total density adjacent to the skin.

3. POTENTIAL INDUCED BY ELECTRON GUN

3.1 General Problem

Firing large current pulses of high-energy electrons away from the Spacelab produces a net positive charge on the Shuttle Orbiter that must be neutralized by return electron current from the plasma surrounding the vehicle. Several factors affect this neutralization process. If natural return currents are inadequate, large positive vehicle potentials would result, and local electric fields might ionize the neutral atoms increasing the available return current. The rapid motion of the Orbiter relative to the ions produces a positive charge in the spacecraft wake that alters the distribution of return current collection. Finally, the dielectric nature of the thermal insulation means that the neutralization current does not efficiently return to the electrical ground of the electron gun; instead, it causes differential charging between insulator outer surfaces and the inner metallic superstructure. Evidently, the temporal behavior of these processes is critical for determination of the magnitude of local charging and electric fields. Clearly, it is important to avoid generating potentials that do not allow the beam to escape or that cause electrical breakdown and significant arcing in the thermal insulation.

3.2 Metal Satellites

The magnitude of the problem is illustrated by proposed theories for satellite potentials induced by large currents of high-energy electrons that have been developed for spherical metal vehicles.[8-10] Unfortunately, the theories are not directly applicable to the Shuttle-Orbiter configuration, and the results have not been adequately tested with rocket experiments. Furthermore, they represent steady-state solutions that describe continuous electron emission rather than current pulses.

The theories assume that the background plasma is entirely natural; there is no consideration of satellite sources of gas or additional plasma. Any additional ionization of the ambient ionosphere caused by the high electric fields radiating from the vehicle is also ignored. The return current is assumed to be derived from a Maxwellian distribution of electrons. Since the electrons move much faster than the vehicle, the spacecraft is assumed to be stationary and wake effects are ignored. The distinguishing difference between these theories is attributable to the way in which the geomagnetic field effects are handled.

In the initial analysis,[8] the magnetic forces were ignored. A subsequent analysis[9] rigorously included the magnetic field effects and obtained much larger potentials for a prescribed beam current due to inhibited collection of return current. Finally, in an effort to bridge the gap between these two results, a large turbulent region around the vehicle was postulated[10] to increase the collection

cross section while retaining the magnetic constraint. The interesting conclusion is that a 1 m sphere that emits 0.5 A continuously is predicted to have a potential of 10^4-10^6 volts depending on the influence of the geomagnetic field. The magnitude of the induced potential is relatively independent of the size of the vehicle. If such large potentials occur, they would inhibit or destroy beams of 10-100 keV electrons.

3.3 Rocket Experiments

There have been several rocket experiments which fired electron beams, and the data from these experiments may provide some indication of the vehicle potential. However, because the experiments have successfully launched the beams, there has been little investigation or analysis of data pertaining to the ultimate induced potential of the vehicle. The electron echo experiments[11] fired beams upward along the field lines and observed the electromagnetic emissions and electrons after they had echoed back from the other hemisphere. Electron beams from rockets were also fired into the atmosphere to generate artificial auroras.[12] Other rocket experiments involving beam injections into the ionosphere to study excitation processes, have also been successfully performed by Air Force Cambridge Research Laboratories (H. Cohen, private communication). These electron guns had nominal power levels of a few kilowatts and used accelerator voltages of 1-40 kV. Currents of 5-500 mA were fired in short pulses (tens of milliseconds) at the rate of several times per second. Thus, these experiments are not accurate tests of the foregoing theory, although they do indicate a bound on the voltage excursion. Evidently, the electron beams were successfully fired away from the rockets, so their potentials must have been limited to something less than a kilovolt. The return current collection area was just the metal skin of the rocket in most cases (the auroral rocket partially deployed a large conducting "umbrella" to enhance its return current), which is about 20 m^2. Thus, the ambient return current of electrons is perhaps 100 mA maximum. This is sufficient to balance the gun current in most cases so that large potentials are not expected.

3.4 Numerical Estimates

The Shuttle Orbiter has its own peculiar characteristics that distinguish it from the foregoing rocket experiments or satellite theories. First, and foremost, is its enormous size which provides a return current collection area of 1300 m^2 on dielectric and 60 m^2 on metallic conductor (this metal surface area is significantly more than most rockets). The large dielectric area causes more serious discharging problems since the vehicle is no longer an equipotential as in the all-metal case.

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Second, the shape of the Orbiter-Spacelab has many sharp corners and edges that produce very high electric fields with only modest potentials. Thus, local ionization enhancements and corona are to be anticipated. Third, the neutral atmosphere around the vehicle is well above ambient so that some cascading of electron return current is anticipated during electron gun firing.

When the electron gun is operated, the overall potential of the vehicle is driven positive. For "average" conditions at a nominal altitude of 400 km (near maximum electron density), it has been shown[1, 4, 8] that the ionosphere provides a field-aligned return current of up to 2.4 mA/m^2. The cross section of surface area available to collect the current varies with vehicle orientation relative to the geomagnetic field. An effective collection area of 1000 m^2 is assumed here (500 m^2 each, above and below). Thus, the ambient return current can balance up to 2.4 A of gun current. Unfortunately, the return charge is mostly collected on the dielectric thermal insulation and does not directly neutralize the gun potential.

The electron gun is presumably grounded to the metallic superstructure of the vehicle which has an external surface area of only 60 m^2 or so. Thus, with proper orientation to take full advantage of the conductor cross section, the direct return current to the gun amounts of 150 mA. It is reasonable to conclude that this level of gun current can be accommodated without undue charging of the Orbiter dielectric insulation. For gun currents in excess of 150 mA, the electric potential is expected to increase significantly, large electric fields are generated, and the dielectric is charged up.

To illustrate some magnitudes, consider a 10 A gun current pulse for 100 msec, that is, 1 coulomb of charge. If the return current is limited to ambient ionospheric background levels, it requires 400 msec for the Orbiter skin to acquire a neutralizing charge. Most of this charge is collected on the dielectric insulation and subsequently leaks to the metallic inner structure. The time constant, τ_{RC}, for such current leakage is about 50 msec for overall resistance of 10^5 ohms and capacitance of 0.5 μf. However, over the range of conceivable insulator conductivities τ_{RC} may vary from 250 μsec to 250 sec. —

The effect of large vehicle potentials on the surrounding plasma distribution is uncertain. Some general properties can be surmised, however. If the potential exceeds +4 volts, the ion ram current is stopped. Since electrons are accelerated to the vehicle, there is a net positive charge in the vehicle wake. Its total charge is probably comparable to the charge in the gun current pulse. Again, consider a 10 A gun current for 100 msec. In 100 msec, the Orbiter has traveled 800 m and its wake diameter is at least comparable to its dimensions, say 50 m. Thus, the volume of the wake charge is at least 1.5×10^6 m^3, and the excess charge density is less than 4×10^{12} ions/m^3. At this level the density is an order of magnitude above the ambient plasma density, but coulomb forces and plasma instabilities

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rapidly dissipate the charge as electron return current enters the wake. During operation of the electron gun the increase in Orbiter potential is accompanied by large electric fields, but their local magnitude over the dielectric is difficult to estimate. Over sharply curved regions, however, potentials of 100 volts will generate fields of 10^4 volts/m around 1 cm radii. Protruding metal surfaces are apt to be even more sharply curved. These local areas of high electric fields can accelerate ambient electrons and these electrons cause ionization of the neutral atmosphere. Although the process is insignificant over much of the vehicle, there are locations where the neutral density is high and appreciable electron-ion pair production is feasible..

3.5 Electric Circuit Analogies

A comprehensive theoretical model for the overall vehicle-plasma interaction during the electron gun operation has not been developed. However, some quantitative limits can be deduced from electrical properties of the vehicle skin... Since the charge on the thermal insulator dielectric does not leak to the inner conductor immediately, negative charge builds up on the dielectric and reduces its potential relative to the conductor. As the overall vehicle potential returns to the ambient plasma level, the dielectric potential actually goes negative for a short while. During this interval, ion-ram current discharges forward areas on the dielectric but not the shielded areas. A qualitative illustration of the potential and charging scenario is displayed in Figure 1. Evidently, the vehicle is charge-neutral well before the conductor and dielectric are fully discharged by leakage current.

The equivalent electrical circuit for this process can be solved explicitly to get quantitative estimates for potentials and time constants. Initially, the return currents to the dielectric I_D and the conductor I_C are assumed constant. This is reasonable for modest potentials that do not ionize or otherwise enhance current collection. The gun current I_G is also constant during the time interval $0 \leq t \leq t_G$. The dielectric skin may be approximated as a high resistance in parallel with a capacitance. The simple electrical circuit and its current flows are shown in Figure 2. The effective charge on the capacitor is $Q = Q_C - Q_D > 0$ where Q_C is the charge collected by the conductor and Q_D is the charge on the outer skin of the dielectric. The potential across the capacitance is

$$\phi = \phi_C - \phi_D = Q/C \quad .$$

The transient behavior of this circuit is described by Kirchoff's rules for electrical networks. The instantaneous leakage current I_L (positive) across the resistance R is determined by the voltage drop around the circuit
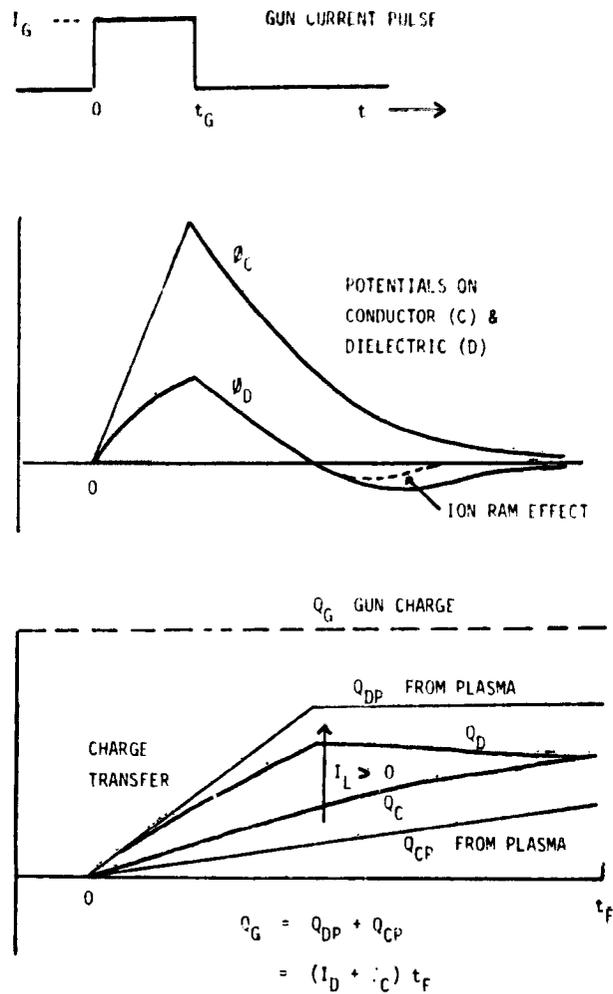
Figure 1. Qualitative Behavior of Potentials and Charges on Conductors and Dielectrics on Orbiter/ Spacelab during Electron Gun Firing

$$-I_L R + Q/C \quad 0 \quad .$$

The sum of the currents to the conductor is

$$-I_L - I_C + I_G \quad dQ_C/dt$$

and the corresponding sum to the dielectric is
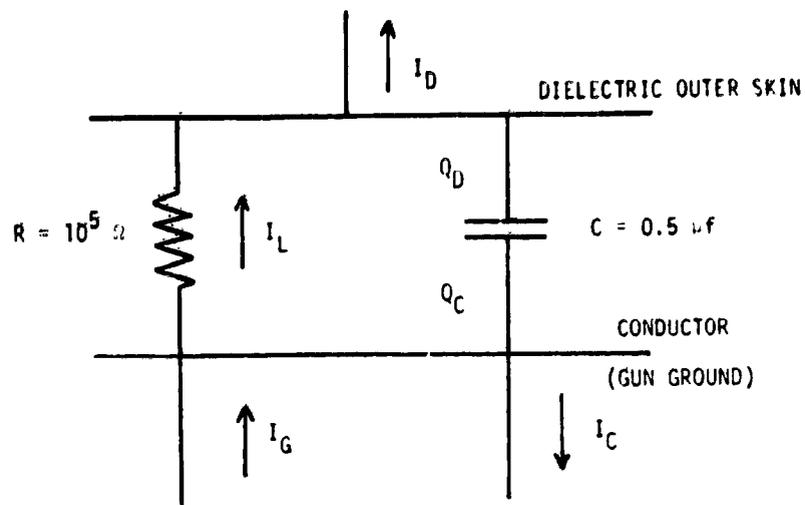
$$I_L - I_D \quad dQ_D/dt \quad .$$

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Figure 2. Equivalent Electrical Circuit for Orbiter Skin Neglecting Plasma Resistance

Together, these equations specify the temporal behavior of Q and ϕ across the dielectric.

Subtracting the current equations gives

$$\frac{dQ}{dt} = I_D - I_C + I_G - 2I_L \quad .$$

Eliminating I_L with the voltage equation leads to the elementary differential equation

$$\frac{dQ}{dt} + \frac{2Q}{\tau_{RC}} = I_D - I_C + I_G \quad .$$

Its solution has the form

$$Q = \frac{1}{2} \tau_{RC} (I_D - I_C + I_G) \left[1 - \exp(-2t/\tau_{RC}) \right] \quad \text{for} \quad 0 \le t \le t_G$$

and

$$Q = \frac{1}{2} \tau_{RC} (I_D - I_C) \left[1 - \exp\left\{ -2(t - t_G)/\tau_{RC} \right\} \right] + Q(t_G) \exp\left[-2(t - t_G)/\tau_{RC} \right]$$

for $t > t_G$.

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where $Q(t_G)$ is the maximum charge difference that occurs at $t = t_G$ when the gun current terminates. During the time interval $0 \leq t < t_G$, the charge Q increases, and afterward it decreases. Discharging continues until the gun charge Q_G is balanced by the plasma return current, $(I_D + I_C) t_F$.

To test the original assumption that I_C and I_D are constant, consider the illustrative case $I_G = 10$ A and $t_G = 100$ msec. If $I_D = 2.4$ A and $I_C = 0.15$ A, the maximum charge is $Q(t_G) \sim 0.3$ coulombs (assuming $\tau_{RC} = 50$ msec). This gives a potential drop across the insulation of

$$\phi_C - \phi_D = Q(t_G)/C = 600,000 \text{ volts} \quad .$$

This enormous potential would create electric fields of 24 MV/m across the insulation which is well above the electrical breakdown field for these materials.

With presently available materials, the original assumption of moderate potentials is not valid and the return current is not constant. Since the conductor is at the higher potential, it is expected to collect more current and ϕ increases. Thus, as an initial estimate, assume I_C is proportional to ϕ or

$$I_C = \phi/R'$$

where R' is a fictitious plasma resistance that simulates the effect of local ionization and enhanced return current. Its value is unknown, but in general $R' < R$ if ϕ is to be smaller. Hopefully, the dielectric insulator potential is not too high so that I_D may be assumed to remain constant for convenience. The new circuit is shown in Figure 3.

For these new assumptions, the differential equation for the charge becomes

$$\frac{dQ}{dt} + \frac{2Q}{\tau_{RC}} + \frac{Q}{\tau_{R'C}} = I_D + I_G \quad .$$

Thus, the same type of solution is obtained with a new time constant

$$\frac{2}{\tau_{RC}} + \frac{1}{\tau_{R'C}} = \frac{1}{\tau_{R'C}} \left(1 + \frac{2\tau_{R'C}}{\tau_{RC}} \right)$$

where it is assumed $R' \ll R$. For $t_G \gg \tau_{R'C}$, the maximum charge built up across the insulator is reduced to

$$Q(t_G) = \tau_{R'C} \left(1 - \frac{2\tau_{R'C}}{\tau_{RC}} \right) (I_D + I_G)$$
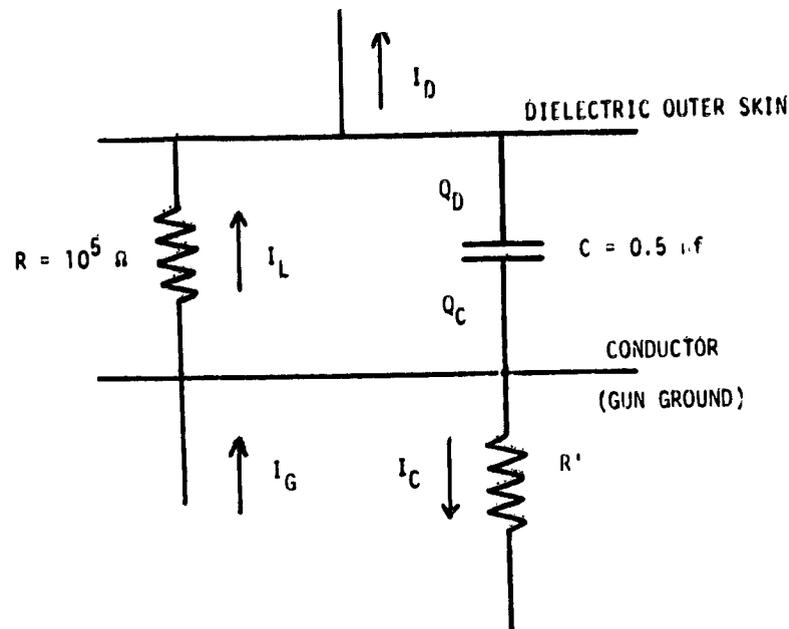
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Figure 3. Equivalent Electrical Circuit for Orbiter Skin Including Plasma Resistance

and the corresponding maximum potential is

$$\phi_C - \phi_D = (I_D + I_G) \, R' \, (1 - 2R'/R) \ .$$

The value of R' seems to be the elusive critical parameter for the process. There is no simple plasma theory for it. A probable range of values may be deduced, however In order to suppress the induced potential, I_C must grow to an appreciable fraction of I_G. It is limited by the condition that the total return current cannot exceed the gun current,

$$I_C + I_D \leq I_G \ .$$

In order for the conducting surfaces to collect most of the return current, their potential must be high enough to cause local ionization. This may be achieved with voltages of 10^2 to 10^4 volts to produce electron ionization or electric fields of $10^6 - 10^7$ volts/m to produce breakdown in the local atmosphere. Such potentials and associated fields around the Orbiter are probably created by gun current pulses of less than 1 A, and, therefore, R' is in the range $10^2 - 10^4$ ohms. For gun currents of 10 A, the conductor potential is probably $10^3 - 10^5$ volts. The

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corresponding plasma time constant R'C for reaching quasi-steady state conditions is 50 μsec to 5 msec. Thus, the rise time on the potential is extremely short compared to typical gun pulses of 10 msec or more.

4. CONCLUSIONS

Generation of large spacecraft potentials externally and internally causes deleterious side effects. Perhaps the most obvious is that the electron beam fails to escape when the spacecraft potential exceeds the electron accelerator potential (around 50 kV). Some experimental objectives require a series of bursts from the electron gun and the transient decay time becomes important. Although one pulse may not build up large potentials, a long series builds up charge if there is inadequate time for decay between between gun pulses.

Another obvious problem is probable arcing through the insulation if voltages exceed 50 kV or more. In addition to minor physical damage along the discharge path, such occurrences generate broadband electromagnetic interference. Another important aspect is local geometry such as sharp edges or bends which have much higher local electric fields and are more prone to discharges. In some locations repeated (continuous?) discharges are conceivable.

In view of the foregoing difficulties, major charging of the Orbiter skin (above 10 kV) should be avoided. Operation of high current electron guns from the payload bay, therefore, requires much better electrical conductivity through the thermal insulation or auxiliary sources of return current. Doping the insulation materials with impurities to improve electrical conductivity may be a feasible solution. A thin coating of conducting material on the exterior surface of the insulation would be desirable if it does not appreciably alter its overall thermal response.

An important criterion for any suppression technique is that the return current it provides should more than equal the electron gun current. Otherwise the dielectric thermal insulation is charged significantly, and the usefulness of the collection system is dubious. As an example, an electron return current of 1 A requires at least 400 m^2 of collector surface in the nominal environment. At lower or higher altitudes, the return current density is sharply reduced to perhaps 0.1 mA/m^2 which requires 10,000 m^2 of collector to balance 1 A. At some point there is a physical limit to the size of the collector no matter what technique is deployed, and this places an upper limit on the gun current that can be used.

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