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Space Station Freedom Structure Floating Potential and the Probability of Arcing

Daniel E. Hastings,* Mengu Cho,† and Jiong Wang†
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

The interaction between a space system and the space environment has been one of the driving questions for the design of spacecraft since the dawn of the space age. The Space Station Freedom will represent a significant increase in spacecraft size, power, and activity relative to spacecraft that are currently in orbit. The structure floating potential on Space Station Freedom is studied with simple analytical models of the current collection. The probability of arcing due to dielectric breakdown is assessed.

Introduction

PLASMA interactions with Space Station Freedom will determine the charge and voltage distribution on the surface of the station, the grounding of the station to the ambient plasma, arc formation from one part of the station to space or to another part of the station, and the sputtering of surfaces under the impact of the ionic species.

The effect of the plasma on the grounding of Space Station Freedom has recently been studied in a workshop report[1] and several conference papers.[2–4] In the report the current baseline for the station of negative grounding was studied. It was shown that the bulk of the station would be at a negative potential with respect to space and that it would be subject to damaging sputtering and arcing as a result of this choice. Consequently, a choice of a positive grounding scheme was suggested.

In a negative grounding scheme the structure is connected to the most negative end of the solar array and therefore primarily collects ions. The solar arrays collect both ions and electrons so that the net current to the combined structure and arrays is zero. The largest current collection areas on the structure are the radiator panels, which are covered with a conductive paint. For both these panels and the solar arrays the physics of the ion collection is the collection of ions from a supersonic stream to a quasi-two-dimensional body. This is a difficult problem that is not well described by classical probe theory. This problem has been studied recently,[5,6] and simple semianalytical expressions are available for the ion current collection. The physics of the electron collection to the solar array is the collection of magnetized electrons from a subsonic stream to physically small but highly biased areas. This difficult problem is also not well described by classical probe theory. In this work we shall use an approximate numerical fit to computer simulations for the collection of the electrons to Space Station Freedom solar arrays.

With semianalytical expressions for the ion and electron current collection, we calculate the structure potential for a simple model of the Space Station Freedom. This model space station consists of six solar array wings generating power with 82 strings of cells per wing and with 400 cells in a string. The wings are connected to a conductive structure that is covered by an insulating coat. The structure is also connected to conductive radiator panels. The plasma interactions can be analyzed on two different levels. First, on a global scale that is large compared to the space station dimensions, the station will be in a plasma composed of the ambient ionosphere and any additional plasma from a plasma cloud generated by the ionization of neutrals emitted from the station. This large-scale density field will provide the pool from which the current to the station will be drawn. The potential distribution of the space station will be determined by the condition that there be no net current to the structure. Second, on a microscale the buildup of charge in the insulation on the structure will lead to discharges that may be harmful to the coating on the structure. The discharges can occur as a result of dielectric breakdown of the dielectric coating material. In this paper, we calculate both the structure potential and the probability of arcing on the space station structure.

Calculation of the Potential of the Space Station Structure

The model for the space station is of a conductive structure, parts of which are insulated, electrically attached to a voltage-generating set of solar array wings. We will take the structure to be a conductor with an insulating coat and a set of conductive radiators. We define A_{ex} as the area of the underlying conductor on the truss and modules that is exposed to the space plasma environment. We define A_r as the area of the conductive radiators. The current collection to the exposed area will be from ambient ions and any plasma cloud ions as well as from the electrons in the vicinity of the structure. We will model the ambient ions as cold with a Mach number M_0, the plasma cloud ions as warm with an ion temperature T_i but with no relative drift with respect to the station, and the electrons as warm with a temperature T_e. This is a reasonable model of the ionospheric plasma in low Earth orbit since the space station will move supersonically with respect to the ions but subsonically with respect to the electrons. Since the significant dimensions of the exposed area and the truss and modules (A_{ex}) are expected to be small compared to the structure and sheath dimensions, we will take the current collection to the structure as being orbit limited. However, this will not be true for A_r. The current collection to the radiators will be that for space charge limited flow to a flat plate. The baseline for the space station is to attach the entire structure to the negative end of the solar array. Hence, the structure potential for the truss, modules, and radiators must be negative. Therefore, we can write the current to the truss and modules on the structure as

$$I_s(\phi_s) = \left(en_i^a V_0 \frac{A_{ex}}{2} + en_i^c c_{s_i} A_{ex}\right) f(\phi_s) - en_e \frac{\bar{c}_e}{4}\frac{A_{ex}}{2}\exp(e\phi_s/T_e) \quad (1)$$

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*Associate Professor, Department of Aeronautics and Astronautics. Member AIAA.

†Research Assistant, Department of Aeronautics and Astronautics.

where ϕ_s is the structure potential; n_i^a the ambient ion density; $V_0 = M_0 c_s$ the ion velocity with c_s the ambient ion acoustic velocity; n_i^c the cloud ion density and c_{s_i} the ion acoustic velocity of the cloud ions; $\bar{c}_{i,e}$ the ion (electron) mean random velocity; $n_e = n_i^a + n_i^c$ the electron density and $f(x)$ the ion focusing factor. The ion focusing factor measures the spread of the sheath out from the holes that make up the exposed area and can be determined by simulation or estimated by semianalytical methods. We have determined this factor by a two-dimensional particle in cell (PIC) simulation for the case where the aspect ratio (length to depth) is large. The result is shown in Fig. 1 as a function of voltage.[7]

The first term in Eq. (1) is the ambient ion current to the exposed area. Since the exposed area will probably be distributed uniformly, only half of it will be struck by the supersonic ions at any one time. The second term is the random ion current from any plasma cloud. The third term is the (repelled) random electron current to the exposed area of the structure. The factor of two arises in this case since the electrons are constrained to flow along the magnetic field; if the holes in the insulation are uniformly distributed then on average half of them will be accessible to flow along the magnetic field.

To obtain the current to the solar arrays, we construct a model of each array wing in the following manner. We suppose that there are N sites on each panel that can collect current. On the Space Station Freedom panels, each site corresponds to the sides of a solar cell where the high voltage is exposed to the space environment. We order the sites and associated areas as $[A_0, A_1, A_2, \ldots, A_N]$ such that for sites A_0 to A_m the associated potentials satisfy $\phi_0 < \phi_1 < \phi_2 \cdots < \phi_m \leq 0$ and for sites A_{m+1} to A_N we have $0 < \phi_{m+1} < \phi_{m+2} \cdots < \phi_N$. Hence, there are m sites with a potential that is negative or zero and $N-m$ with a potential that is positive. As the space station orbits the Earth, the arrays will always point so that their unit normal is in the direction of the sun. This means that they will see several different angles of attack with respect to the ambient ion flow. If we define θ as the angle that the space station subtends around the orbit measured from local midnight and take an orbital period of 90 min with 36 min in eclipse, then the station will be in eclipse for $-\theta_s < \theta < \theta_s$, where $\theta_s = 2\pi/5$. We define the angle of attack of the arrays as α, where $(\pi/2) - \alpha$ is the angle between the unit normal to the array from the surface of the array and the direction of the incoming ion flow (measured in a frame attached to the array). With this definition the relationship between α and θ is

$$\begin{aligned} \alpha &= \theta, && \theta_s < \theta < \pi/2 \\ &= |\pi - \theta|, && \pi/2 < \theta < 3\pi/2 \\ &= 2\pi - \theta, && 3\pi/2 < \theta < 2\pi - \theta_s \end{aligned} \tag{2}$$

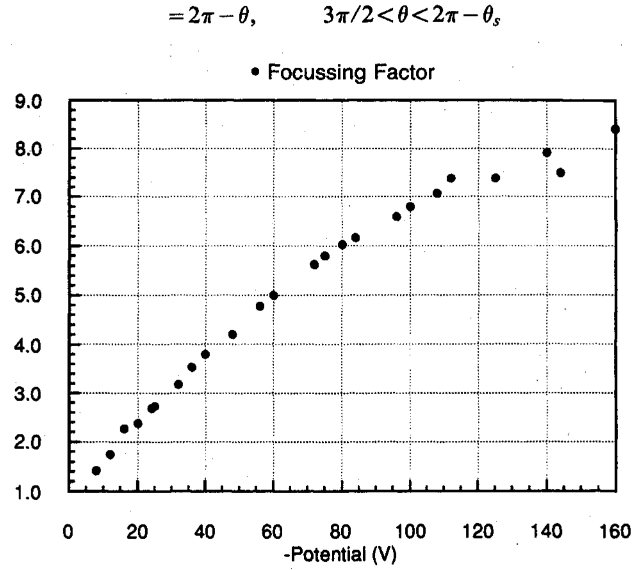

Fig. 1 Focusing factor for ion current collection.

If we assume that each string on each array wing will have solar cells, each of which generates a voltage $\Delta\phi_c$, then we can write

$$\phi_j - \phi_{j-1} = \Delta\phi_c, \qquad 1 < j < N \tag{3}$$

The current to the positive parts of the array can be written as

$$I_{ap} = en_i^a V_0 \sin \alpha H(\pi - \theta) \sum_{j=m+1}^{N} H\left(1 - \frac{e\phi_j}{\mathcal{E}_0}\right) A_j + en_i^c c_{s_i} \times \sum_{j=m+1}^{N} \exp\left(\frac{-e\phi_j}{T_i}\right) A_j - en_e \frac{\bar{c}_e}{4} \sum_{j=m+1}^{N} A_j f_{\text{eff}}\left(1 + \frac{e\phi_j}{T_e}\right) \tag{4}$$

where $H(x)$ is the Heaviside unit function defined as $H(x) = 1$ for $\chi \geq 0$ and $H(x)$ is zero otherwise. In the first part of Eq. (4) the cold ambient streaming ions are repelled and never get to the array if the biased side is in the wake or if the potential at location A_j is larger than the directed energy $\mathcal{E}_0$ of the ambient ions. In the second term in the equation the cloud ions are repelled, and only the tail of the distribution gets through.

The question of the high-voltage electron current collection in a low Earth orbit to a solar array is poorly understood. It is not well described by classical probe theory because of the relatively small and geometrically complex collection area, as well as the presence of nearby dielectric surfaces that can emit secondary electrons under primary electron bombardment. The latter effect is known under somewhat simpler geometries to give rise to enhanced electron current collection at voltages > 100 V. This phenomenon has been termed "snapover" and has been extensively studied.[8] The numerical correlation that we use does show increasing electron collection with voltage, although it does not show any sudden jump or snapover. Furthermore, no such sudden jump has been seen in the tank test on actual Space Station Freedom solar arrays. This may be due to the substantially different geometry for the electron collection to the Space Station Freedom solar cells compared to the simple geometries where snapover was seen. Therefore, in the third term in Eq. (4) we use an approximate numerical correlation for the electron current collection as a function of voltage, with $A_j f_{\text{eff}}$ being the effective electron current collection area of each cell. This correlation was determined by detailed particle tracking simulations[9] at NASA Lewis. The effective electron current collection area arises due to the "choking" of the electron orbits by the geometry of the Space Station Freedom solar cells. The electrons must enter the gap between coverslides to strike the biased solar cell. For high voltages the presence of a positive charge on the coverslides causes some of the incoming electrons to be repelled; therefore, the current collection system acts like it has a smaller aperture. This approximate correlation neglects the effect of the Earth's magnetic field. For low voltages ($e\phi_j/T_e \ll 1$), the effect of the Earth's magnetic field can be neglected, since the average gyroradius (3 cm) is much larger than the height of the solar cell edges that are collecting electrons. Therefore, on the scale of the solar cell edge the electrons are not seen to turn due to the magnetic field, and the effect can be neglected. For high voltages ($e\phi_j/T_e \gg 1$), the sheath will be much larger than an electron gyroradius. Hence, the electron collection will be magnetically limited. However, for a large quasihemispherical sheath (sheath radius r_{sheath} much larger than an ambient electron gyroradius), the maximum variation in current collection due to magnetic limitations is a factor of two (a current collection area of $4\pi r_{\text{sheath}}^2$ compared to $2\pi r_{\text{sheath}}^2$). Furthermore, the relatively small variation in the magnetic field direction on a 28.5 deg inclined orbit around the Earth compared to the unit normal to the array surface over a typical orbit will constrain the variation due to magnetic field limitations even more than a factor of two. Given the less than factor of two variation in electron current collection due to magnetic field limitations, we will neglect it in this analysis.

The current to the negative parts of the array must be considered in three regions.[5] The first region is where the ion flow is directly striking the biased surface of the array but the angle of attack is larger than the Mach angle. The Mach angle is defined as $\theta_0 = \sin^{-1}(1/M_0)$ and is the angle that the flow will turn through as it expands around the edges of the array.[5] Hence, we define in region I ($\theta_s \leq \theta < \pi - \theta_0$) the current to the negative part of the array as

$$I_{an} = (en_i^a V_0 \sin\alpha + en_i^c c_{s_i}) \sum_{j=0}^{m} A_j f(\phi_j) - en_e \frac{\bar{c}_e}{4} \sum_{j=0}^{m} \exp\left(\frac{e\phi_j}{T_e}\right) A_j \qquad (5)$$

The second region for the ion flow to the array is when the angle of attack is almost zero and the ion flow is always within the Mach cone. Therefore, we define in region II ($\pi - \theta_0 \leq \theta \leq \pi + \theta_0$) the current to the negative part of the array as

$$I_{an} = \left(0.82 en_i^a V_0 \frac{\lambda_D}{L} |\phi_0|^{3/4} + 0.37 en_i^a c_s + en_i^c c_{s_i}\right) \times \sum_{j=0}^{m} A_j f(\phi_j) - en_e \frac{\bar{c}_e}{4} \sum_{j=0}^{m} \exp\left(\frac{e\phi_j}{T_e}\right) A_j \qquad (6)$$

In Eq. (6) λ_D is the Debye length based on the ambient electron density and temperature and L is the length of the panel in the direction of the flow. The assumption in the equation is that the most negative end of the array is on the leading edge of the array and turned into the flow. With this assumption, the first term is the ion current collection to the leading edge of the array and the second term is the ion collection to the rest of the array surface. We have assumed that the sheath edges overlap at some distance from the array so that the incoming ion flow sees a uniform sheath.

The third region for the ion flow to the array is when the biased surface is in the wake. In this case the ions get caught by the sheath edge as they pass near the array and are swept around into the wake. Therefore, we define in region III ($\pi + \theta_0 < \theta \leq 2\pi - \theta_s$) the current to the negative part of the array as

$$I_{an} = [en_i^a V_0 \sin\alpha C_w(\alpha, M_0) + en_i^c c_{s_i}] \sum_{j=0}^{m} A_j f(\phi_j) - en_e \frac{\bar{c}_e}{4} \sum_{j=0}^{m} \exp\left(\frac{e\phi_j}{T_e}\right) A_j \qquad (7)$$

In Eq. (7), $C_w(\alpha, M_0)$ is the function representing how much of the ram current is pulled around to the wake. In general, this function has to be determined numerically. In Fig. 2 we show $C_w(\alpha, M_0 = 8)$ against α. This was determined from a hybrid particle in cell simulation.[6]

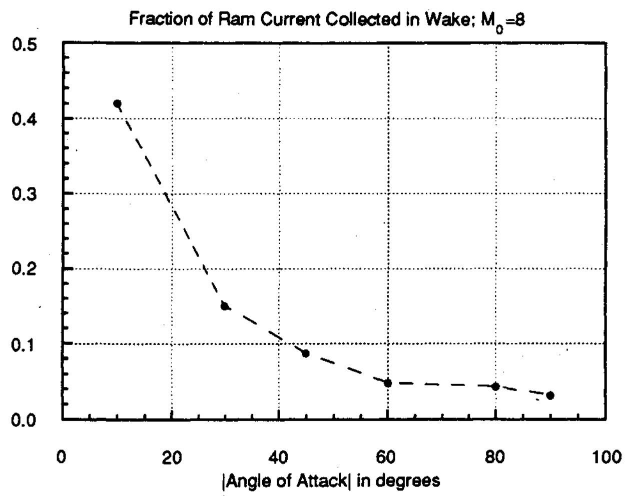

Fig. 2 Fraction of ram current collected in wake for $M_0 = 8$.

The current to the negatively biased conductive radiators must also be considered in several regimes. To minimize the heat load on the arrays, the radiators will always have their unit normal at right angles to the unit normal to the array surfaces (which is in the sun direction). In addition, since both sides of the radiators can collect ions, there will be both a ram ion flow and a wake ion flow. The wake ion flow will be small compared to the ram ion flow (see Fig. 2), except in the Mach cone. Therefore, we will neglect it everywhere except in the Mach cone. With these assumptions and the definition of the angle λ as $\lambda = (\pi/2) - \alpha$, we can write the following.

Region A [$\theta_s < \theta < (\pi/2) - \theta_0$]:

$$I_{s_r} = en_i^a \frac{\bar{c}_e}{4} \left\{ \frac{4c_s}{\bar{c}_e} \frac{A_r}{2} \left[M_0 |\sin(\lambda)| + \frac{(n_i^c c_{s_i})}{(n_i^a c_s)} \right] - \frac{n_e}{n_i^a} A_r \exp\left(\frac{e\phi_s}{T_e}\right) \right\} \qquad (8)$$

Region B [$(\pi/2) - \theta_0 < \theta(\pi/2) + \theta_0$]:

$$I_{s_r} = en_i^a \frac{\bar{c}_e}{4} \left\{ \frac{4c_s}{c_e} \frac{A_r}{2} \left[0.82 M_0 \frac{\lambda_D}{L} |\phi_0|^{3/4} + 0.37 + \frac{(n_i^c c_{s_i})}{(n_i^a c_s)} \right] - \frac{n_e}{n_i^a} A_r \exp\left(\frac{e\phi_s}{T_e}\right) \right\} \qquad (9)$$

Region C [$(\pi/2) + \theta_0 < \theta < 3(\pi/2) - \theta_0$]:

$$I_{s_r} = en_i^a \frac{\bar{c}_e}{4} \left\{ \frac{4c_s}{\bar{c}_e} \frac{A_r}{2} \left[M_0 |\sin(\lambda)| + \frac{(n_i^c c_{s_i})}{(n_i^a c_s)} \right] - \frac{n_e}{n_i^a} A_r \exp\left(\frac{e\phi_s}{T_e}\right) \right\} \qquad (10)$$

Region D [$(3\pi/2) - \theta_0 < \theta < (3\pi/2) + \theta_0$]:

$$I_{s_r} = en_i^a \frac{\bar{c}_e}{4} \left\{ \frac{4c_s}{\bar{c}_e} \frac{A_r}{2} \left[0.82 M_0 \frac{\lambda_D}{L} |\phi_0|^{3/4} + 0.37 + \frac{(n_i^c c_{s_i})}{(n_i^a c_s)} \right] - \frac{n_e}{n_i^a} A_r \exp\left(\frac{e\phi_s}{T_e}\right) \right\} \qquad (11)$$

Region E [$(3\pi/2) + \theta_0 < \theta < 2\pi - \theta_s$]:

$$I_{s_r} = en_i^a \frac{\bar{c}_e}{4} \left\{ \frac{4c_s}{c_e} \frac{A_r}{2} \left[M_0 |\sin(\lambda)| + \frac{(n_i^c c_{s_i})}{(n_i^a c_s)} \right] - \frac{n_e}{n_i^a} A_r \exp\left(\frac{e\phi_s}{T_e}\right) \right\} \qquad (12)$$

The total current to the arrays and structure is

$$I = I_s + I_{s_r} + N_w N_p (I_{an} + I_{ap}) + I_c = 0 \qquad (13)$$

where N_p is the number of solar cell strings per wing and N_w is the number of wings on the station. I_c represents a current emission due to a plasma contactor that may be operational on the station. In Eq. (13) we set the total current to zero to give the potential distribution along with Eq. (3). If we take all of the areas $A_j = A$, define the total collecting area of the arrays as $A_a = N_w N_p N A$, define a normalization current as $I_n = en_i^a(\bar{c}_e/4)A_a$, and use Eq. (3), then we can write for all regions

$$(I/I_n)(m\Delta\phi_c, \theta; T_i, T_e, M_0, A_{ex}/A_a, A_r/A_a, \delta) = 0 \qquad (14)$$

In Eq. (14), δ is the ratio n_i^c/n_i^a. Equation (14) can be solved for m and ϕ_0 as a function of the angle and parametrically as a function of T_i, T_e, M_0, A_{ex}/A_a, A_r/A_a, and δ.

For a thin insulator surface, if the potential ϕ_0 becomes too negative, there is the possibility of arcing. Arcing may occur for several different reasons: 1) dielectric breakdown or 2) vacuum flashover[10] in the region near the plasma, dielectric, and conductor interface (the triple junction). In this paper we will only calculate the upper bound for arcing due to dielectric breakdown. The type of arcing discussed in Ref. 10 is unlikely to occur on the structure for the voltages reached on the orbit.

The maximum arc rate for dielectric breakdown can be calculated as the inverse of the time to charge the insulator with thickness d to the electric field E_d, which is the dielectric strength. This rate is given by

$$R_{DB} = \frac{j_{ram}}{\epsilon_d E_d}, \quad \frac{\phi_s}{d} > E_d$$

$$= 0, \quad \frac{\phi_s}{d} < E_d \tag{15}$$

Of course, this assumes that once a dielectric breakdown occurs the surface recovers without any physical damage so that it can arc again. In fact, for intense arcs, it will probably damage the surface to the point that the insulator material is removed. Therefore, the arc rate in Eq. (15) can be regarded as an upper bound on the true arc rate. For the calculations we have used the extreme set of parameters for Al_2O_3 from Ref. 11 and used the structure potential given in Figs. 3 and 5. The set of parameters we choose to evaluate the maximum arc rate is $n_i^a = 10^{12}\ m^{-3}$, $\epsilon_d/\epsilon_0 = 8.4$, $E_d = 6.3 \times 10^6$ V/m, and a dielectric thickness of $d = 5\mu$.

Results and Discussion

To evaluate the structure potential for the Space Station Freedom, we take for the solar array parameters $A = 6.5 \times 10^{-5} m^{-2}$ (this corresponds to the current collection area of the 8 mm × 8 cm gap along each edge of each solar cell[8]), $f_{eff} = 0.5$, $N = 400$, $N_p = 82$, $N_w = 6$, and $\Delta\phi_c = 0.4$ V. This gives an array collection area of $A_a = 12.8\ m^2$. We choose the ambient Mach number of the ionic oxygen as $M_0 = 8$, the cloud ions as molecular nitrogen with temperature $T_i = 0.03$ eV and the electron temperature as $T_e = 0.2$ eV. The choice of molecular nitrogen as the cloud ions would be appropriate for a thruster firing of a hydrazine bipropellant engine where the nitrogen in the exhaust became ionized by some mechanism such as the critical ionization velocity process. The ambient ions have directed energy $\mathcal{E}_0 = 5$ eV. These values for the ambient and cloud give $\bar{c}_i/c_s = 0.46$ and $\bar{c}_e/c_s = 264$. The length of solar array panel in the flow direction is taken as 20 m, which for average ionospheric conditions gives the ratio $\lambda_D/L = 5 \times 10^{-4}$. The current collecting area of the radiators is $A_r = 1100\ m^2$. We solve for the structure potential with A_{ex}/A_a, δ, and I_c/I_n as free parameters. The total area of the structure[1] planned for the Space Station Freedom is 2500 m²; thus a choice of $A_{ex}/A_a = 25$ represents 13% of the insulator punctured or eroded. The fraction of electron collecting area f_{eff} that actively collects is determined approximately from detailed particle tracking simulations[9] and is found to be about one-half.

In Fig. 3 we show the structure potential for the case where there is no low-energy plasma cloud. For the case where there is no or very little exposed area on the structure (other than the radiators), the structure potential is quite negative. It is most negative near the dusk terminator ($\theta \simeq 270$ deg). This is because the array is in the wake; therefore, the structure must float as negatively as possible to attract ions. It is least negative at local noon ($\theta \simeq 180$ deg). Here the radiators are normal to the flow and collect a large number of ions so that a smaller additional ion current to the array is necessary to balance the electron current to the array. The structure potential for 13% of the area exposed is qualitatively similar to the case for no area exposed. However, the magnitude of the potential is everywhere reduced because the increased ion collection of the structure requires a smaller ion collection to the array and therefore a smaller maximum potential. In Fig. 3 we also show the maximum arc rate for the two cases considered. The maximum possible arc rate is independent of angle, since we have taken the maximum value of the ram current. For both cases the structure will suffer an arc at some location several times a second. If the arcs are large, this could potentially damage the thermal coating of the structure and lead to a loss of thermal control of the system.

In Fig. 4 we show the structure potential for the case where there is a dense low energy plasma cloud so that the cloud is 10,000 times denser than the ambient. For the case where $A_{ex}/A_a = 10^5$, the structure potential is quite negative and uniform over the orbit compared to the equivalent case in Fig. 3. This is because the ram/wake differences that drive the morphology of the potential as a function of angle for $\delta = 0$ are not present because the cloud isotropically surrounds the station.

In Fig. 5 we show the structure potential for the case where there is a plasma contactor emitting a normalized current of 0, 1, 100, and 200. For a random ionospheric electron current density of 10 mA/m², we have $I_n = 0.13$ A and $I_c = 0$, 0.13, 13, and 26 A. We see that as the contactor current increases the structure potential becomes less negative and also more uniform as a function of angle. For a contactor current emitted of $I_c/I_n = 200$, the potential of the structure is almost at ground (0 V) and the maximum arc rate is reduced to zero. This suggests that the use of a plasma contactor attached to the negatively biased structure and emitting a net electron current can cause the structure potential to be approximately grounded and minimize the possibility of arcing due to dielectric breakdown.

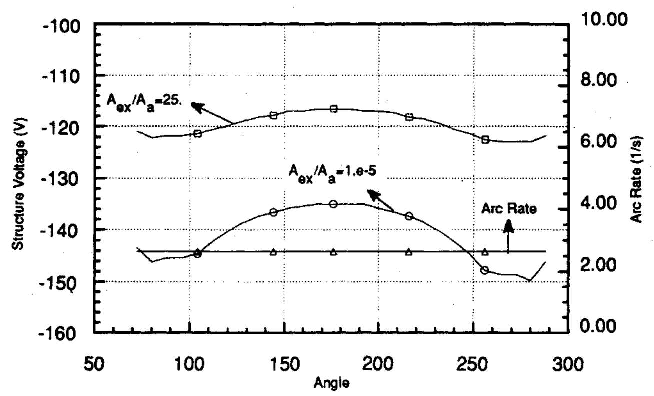

Fig. 3 Structure potential (V) and arc rate (1/s) against angle; $A_{ex} = 10^{-5}$, 25.

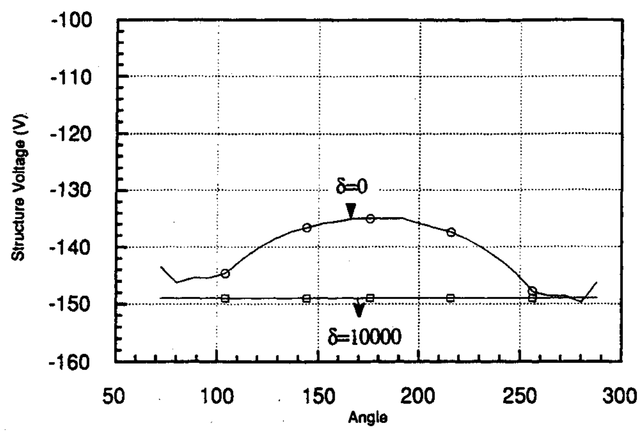

Fig. 4 Structure potential (V) against angle; $\delta = 0$, 10^4.

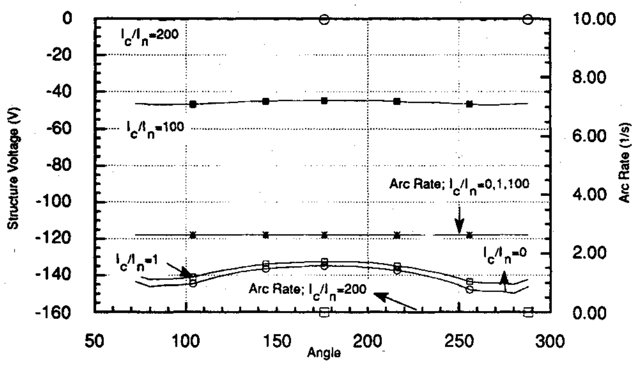

Fig. 5 Structure potential (V) and arc rate (1/s) against angle; $I_c/I_n = 0$, 1, 100, 200.

Conclusions

The potential of the underlying structure for the space station has been calculated. The structure will be negatively grounded and will be at a large negative potential in the early years of operation of the station. As the station ages and more of the structure is exposed, the structure potential will become less negative.

The arc rate of the structure through defects in the insulation has been calculated. The dielectric coating will be sufficiently thin so that a large number of arcs will occur in every orbit. These arcs will lead to damage to the insulating coat and eventual loss of parts of the dielectric. It is shown that use of a plasma contactor will alleviate the problem due to arcing although a plasma contactor may introduce other issues. These will include electromagnetic interference and possible contamination issues.

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References

[1]Ferguson, D. C., Snyder , D. B., and Carruth, M. (eds.), "Evaluation of Impacts of Space Station Freedom Grounding Configurations," *Report of the Joint Workshop of the Space Station Freedom Plasma Interactions and Effects Working Group, the Space Station Freedom Plasma Working Group and the Space Station Freedom EMI/EMC and Electromagnetic Effects Working Group,* NASA Lewis, May 22–24, 1990; also NASA TM 103717, May 1990.

[2]Carruth, M., and Vaughn, J., "Experimental Studies on Spacecraft Arcing and Current Closure Paths," AIAA 30th Aerospace Sciences Meeting, Reno, NV, AIAA Paper 92-0820, Jan. 1992.

[3]Farmer, V., Leung, P., Murphy, G., Croley, D., and Balmain, K., "The Role of External Circuit Impedance in Dielectric Breakdown: Experimental Results and EMC Analysis," AIAA 30th Aerospace Sciences Meeting, Reno, NV, AIAA Paper 92-0821, Jan. 1992.

[4]Katz, I., Jongeward, G., Vaughan, J., and Carruth, M., "Extrapolation of Anodization Breakdown Currents from the Laboratory to Space Station," AIAA 30th Aerospace Sciences Meeting, Reno, NV, AIAA Paper 92-0822, Jan. 1992.

[5]Wang, J., and Hastings, D. E., "Ionospheric Plasma Flow Over Large High-Voltage Space Platforms I: Ion-plasma Time Scale Interactions on a Plate at Zero Angle of Attack" *Physics of Fluids B,* Vol. 4, No. 6, 1992, pp. 1615–1629.

[6] Wang, J., and Hastings, D. E., "Ionospheric Plasma Flow Over Large High-Voltage Space Platforms II: The Formation and Structure of the Plasma Wake," *Physics of Fluids,* 1992, (to be published).

[7]Hastings, D. E., and Cho, M., "Ion Drag for a Negatively Biased Solar Array in LEO," *Journal of Spacecraft and Rockets,* Vol. 27, No. 3, 1990, pp. 279–284.

[8]Hastings, D. E., and Chang, P., "The Physics of Positively Biased Conductors Surrounded by Dielectrics in Contact with a Plasma," *Physics of Fluids B,* Vol. 1, No. 5, 1989, pp. 1123-1132.

[9]Ferguson, D. C., private communication.

[10]Cho, M., and Hastings, D. E., "Dielectric Charging Processes and Arcing Rates of High Voltage Solar Arrays," *Journal of Spacecraft and Rockets,* Vol. 28, No. 6, 1991, pp. 698–706

[11]Weast, R. C. (ed.), *CRC Handbook of Chemistry and Physics,* CRC Press, Boca Raton, FL, 1984.

Paul F. Mizera
Associate Editor