N91-30249

LEO SPACE PLASMA INTERACTIONS

Dr. Dale C. Ferguson
NASA Lewis Research Center
Cleveland, Ohio

Photovoltaic arrays interact with the low Earth orbit (LEO) space plasma in two fundamentally different ways. One way is the steady collection of current from the plasma onto exposed conductors or semiconductors. The relative currents collected by different parts of the array will then determine the floating potential of the spacecraft. In addition, these steady state collected currents may lead to sputtering or heating of the array by the ions or electrons collected, respectively. The second type of interaction is a short timescale arc into the space plasma, which may deplete the array and/or spacecraft of stored charge, damage solar cells, and produce EMI. Such arcs only occur at high negative potentials relative to the space plasma potential, and depend on the steady state ion currents being collected. New high voltage solar arrays being incorporated into advanced spacecraft and space platforms may be endangered by these plasma interactions. Recent advances in laboratory testing and current collection modeling promise the capability of controlling, and perhaps even using, these space plasma interactions to enable design of reliable high voltage space power systems. Some of the new results may have an impact on solar cell spacing and/or coverslide designs. Planned space flight experiments are necessary to confirm our models of high voltage solar array plasma interactions. Finally, computerized, integrated plasma interactions design tools are being constructed to place plasma interactions models into the hands of the spacecraft designer.

INTRODUCTION

The standard power source for space applications continues to be photovoltaic arrays. Standard space arrays have used low voltages, such as 28 V, and have had minimal interactions with the ionized plasma of the earth's upper atmosphere. With no exposed high voltages, such systems will come to an equilibrium potential not far from the potential of the surrounding plasma. However, with the advent of large space power systems, and the necessity of large distributed areas for array photon collection, there has come a desire for high efficiency power transmission. To electrical power system designers, this implies high voltage systems, because the distribution losses go up as the square of the necessary current. With high voltage systems, the same amount of power may be distributed at lower current levels, and concomitant higher efficiencies.

Modern large solar array designs for high power space applications typically use end-to-end voltages of 160 to 200 V (eg. Space Station Freedom [SSF] and Advanced Photovoltaic Solar Array [APSA]). With such high distributed voltages, some parts of the array must be at relatively high potentials, with respect to the ambient plasma potential. Ground tests and theories concur that solar arrays at high potentials will interact with the surrounding plasma in two fundamentally different ways. Firstly, they will collect steady currents from the plasma onto exposed conductors (such as cell interconnects) or semiconductors (such as cell edges).

These currents will act as a drain on the power system, and for that reason are sometimes called parasitic currents. High potentials will pull in larger parasitic currents than the low potentials on solar arrays flown to date. The absence of a hard electrical ground in the space plasma will require that the power system, and solar arrays, will take on potentials (called floating potentials) such that electron currents collected by the more positive parts of the system will be balanced by the ions collected by the negative areas. In general, only connected electrical conductors must obey a "global" current balance condition. Insulators and isolated conductors exposed to the plasma will locally balance the electron and ion currents to their surfaces, resulting in a slightly negative surface potential. This potential is necessary to repel enough of the fast-moving electrons to restrict the electron current to match the slow-moving ion current collected at small negative potentials.

When applied globally to a space power system, the current balance condition requires that for unimpeded electron and ion current collection, the entire system will float with about 95% of its area negative, and about 5% positive of the plasma potential. For a 160 V solar array hooked to an insulated structure, this means that the most negative end of the array will be at about 152 V negative of the plasma potential, and the positive end at only 8 V positive. High negative potentials relative to the surrounding plasma may lead to undesirable interactions, among them sputtering and arcing into the plasma.

If parts of the solar array are forced to be at high positive potentials relative to the surrounding plasma, other undesirable effects may occur. At potentials above about 100 V positive of the plasma, solar cells and arrays may collect anomalously high currents, tantamount to the currents one might expect if the insulating surfaces were collecting current as well as the conducting or semiconducting surfaces. This effect is called "snapover", from the belief that it is caused by the high surface potentials on the conductors "snapping over", because of secondary electron effects, onto the surfaces of the adjacent insulators. It might lead to unacceptably high parasitic current power losses. One other possible undesirable effect might be localized heating due to snapover currents onto small exposed areas, which could lead to pyrolysis of Kapton® surrounding the exposed conductor.

Ion current collection by conducting surfaces at high negative potentials is implicated in the second fundamental type of environmental interactions. The interaction of interest here is arcing from surfaces to the space plasma (or to other spacecraft surfaces). These transient arcs may discharge the entire electrically connected surface of the spacecraft or array, and are therefore potentially destructive of solar cells and/or array current traces. Solar array arcs into the plasma occur where conductors or semiconductors collecting ion current from the plasma are adjacent to insulating materials, such as coverslides or Kapton®. They are very short (microsecond) localized transients, emitting heat, radio frequency interference, light, and a very dense localized plasma, and causing a rapid positive swing of all spacecraft potentials. There seems to be a threshold voltage for solar array plasma arcing, at around -230 V, although it may vary with materials used.

The advantages of using high end-to-end voltages on space photovoltaic power systems must be weighed against the risks of damage due to plasma interactions. There exist possibilities of tailoring the system plasma interactions so that they may be ameliorated, or in

some instances even used to control vehicle potentials. An understanding of the phenomena is necessary in order to explore these possibilities.

STEADY STATE CURRENT COLLECTION

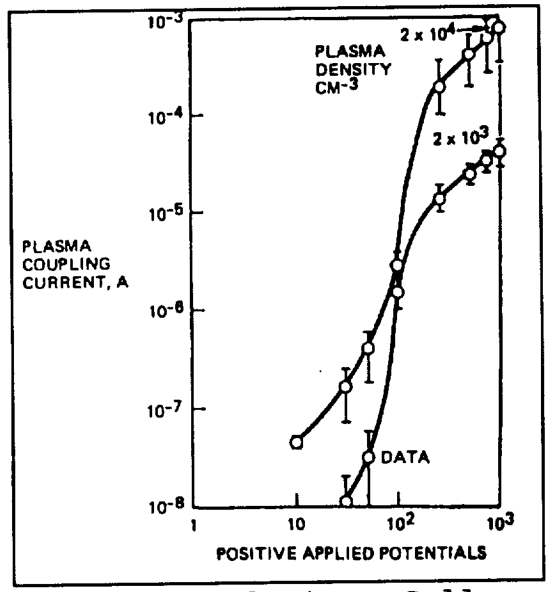

Figure 1. Electron Collection

Figures 1 and 2 show the current collection behavior of a typical solar array immersed in the space plasma, when its conductors (or semiconductors) are at a potential V relative to the plasma potential (Stevens and Stillwell, 1989). It may be seen that for electron current collection, there is a region of depressed plasma current collection for low potentials (less than about 100 V). This is because the insulating surfaces which surround the exposed conductors have a slightly negative potential, to be able to locally repel fast-moving electrons to allow the slower ions to balance current locally. These potentials, typically three to five times the plasma electron temperature (that is, 0.3 to 1.0 volts), extend into the region of space above the conductor, and may partially choke off the electron current to the conductor, depending on the exact geometry. Above about 100-200 V, there is a transition to anomalously high electron current, corresponding to the snapover phenomenon mentioned in the introduction. Here, it almost seems like the entire coverslide surface has become a conductor, for the purposes of electron collection. Although there is disagreement about the mechanism of the snapover phenomenon (Gabriel *et al*, 1983, Thiemann and Schunk, 1990), it may be due to charging of the adjacent insulators by secondary electron emission, where emitted electrons hop across the insulator until reaching the conducting surface, or perhaps by other surface conduction processes.

By way of contrast, notice the extremely small ion collection currents at the same plasma densities and potentials negative of the plasma. Here the ion collection currents appear to be approximately linear with voltage up to the voltage range where arcing typically occurs. The great differences in the size and effects of electron and ion currents is due primarily to the difference in the ion and electron mass, which is a factor of 1836 even for the lightest positive ion, hydrogen. In low Earth orbit (LEO), most of the ions are atomic oxygen, sixteen times more massive still. Spacecraft speeds are typically much less than electron thermal speeds, so that the electrons are collected from all directions, at the thermal flux as modified by local potentials. However, the positive ions move much slower than the spacecraft,

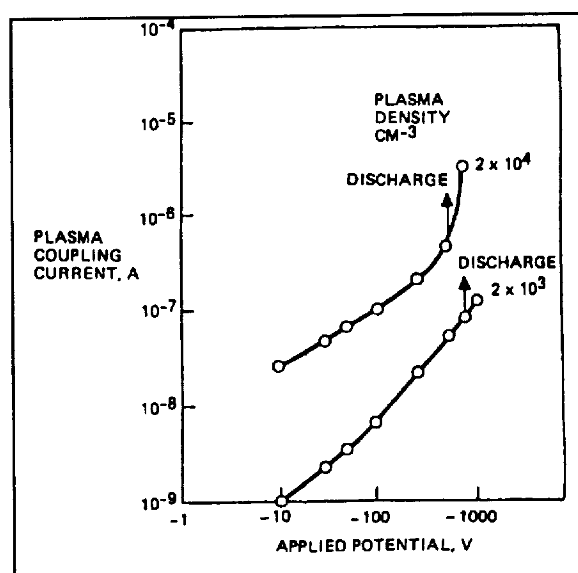

Figure 2. Ion Collection

and so their flux is the ram flux, again modified by local potentials. Current collection in the wake of a large structure or array is complicated by the supersonic wake, depleted of ions, and also depleted of electrons by small space charge built up from the absence of ions. Electron and ion current densities may be orders of magnitude lower in spacecraft or array wakes than in the undisturbed plasma.

By balancing electron and ion currents collected by the entire structure and arrays, one may determine the spacecraft floating potential. Simple models balancing the electron and ion currents to an array yield about a 95% negative floating fraction. It is reasonable, therefore, in the absence of very large ion collecting areas on the spacecraft, to assume that the array floats wholly negative, its most positive part at 0 volts relative to the plasma. This will be modified by vxB potentials due to the spacecraft motion through the ionosphere, and by changes in the relative conducting areas for electron and ion current collection. However, it does show that for steady state conditions, a distributed voltage in contact with the space plasma will be more liable to ion-collection problems than those due to electron collection. Paramount under these problems are sputtering, dielectric breakdown, and arcing to or through the space plasma. I will treat dielectric breakdown and arcing to the space plasma in the next section on transient events.

Sputtering is the physical removal of material from a surface by impact of incoming atoms or ions. Sputtered material may be redeposited on other surfaces, contaminating those surfaces with a thin film coating. Sputtering at negative potentials starts occurring when exposed conductors are at the sputtering threshold below the plasma potential. For most materials, this is between 10 and 30 volts. Sputtering yields are, however, small for energies less than about 100 electron volts, so sputtering only becomes a serious problem for negative potentials greater than this. Near holes in insulating coatings, the sputtering ions will be focussed to fluxes perhaps 17 times their undisturbed flux, exacerbating the problem. See Figure 3 (courtesy of Joel Herr, Sverdrup Technology, Inc.). All previous space power systems have generated end-to-end voltages much less than about 100 volts, so sputtering was not considered in their design. However, for Space Station Freedom, it has been estimated that sputtering may produce a loss of (or contamination of) about 0.4 mils of material per year (Ferguson *et al*, 1990). Atomic oxygen protective coatings are typically much thinner than this, and one might expect that if they were sputtered (as, for instance near the edges of solar cells), their lifetime would be much less than one year. Even coatings as thick as 5 mils might be eroded away during the lifetime of SSF. Sputtering problems are especially severe on rapidly switched components, because all of their insulating surfaces directly above conductors will spend most of the time at very negative potentials, as the plasma ions find it impossible to react quickly enough to neutralize the surfaces. Sputter coating may be a particularly difficult problem for solar cell coverslides, for their anti-reflective coatings may lose their efficiency if covered with transparent sputter effluent, or lose transparency altogether if coated with an opaque sputter product.

Electron collection problems are likely to become important only if the most negative end of the array is somehow elevated to a potential near the plasma potential. This may occur on negatively grounded arrays through thruster firings or other effluent dumps from the spacecraft, during arcs, or through purposeful increase of ion collection or decrease of electron

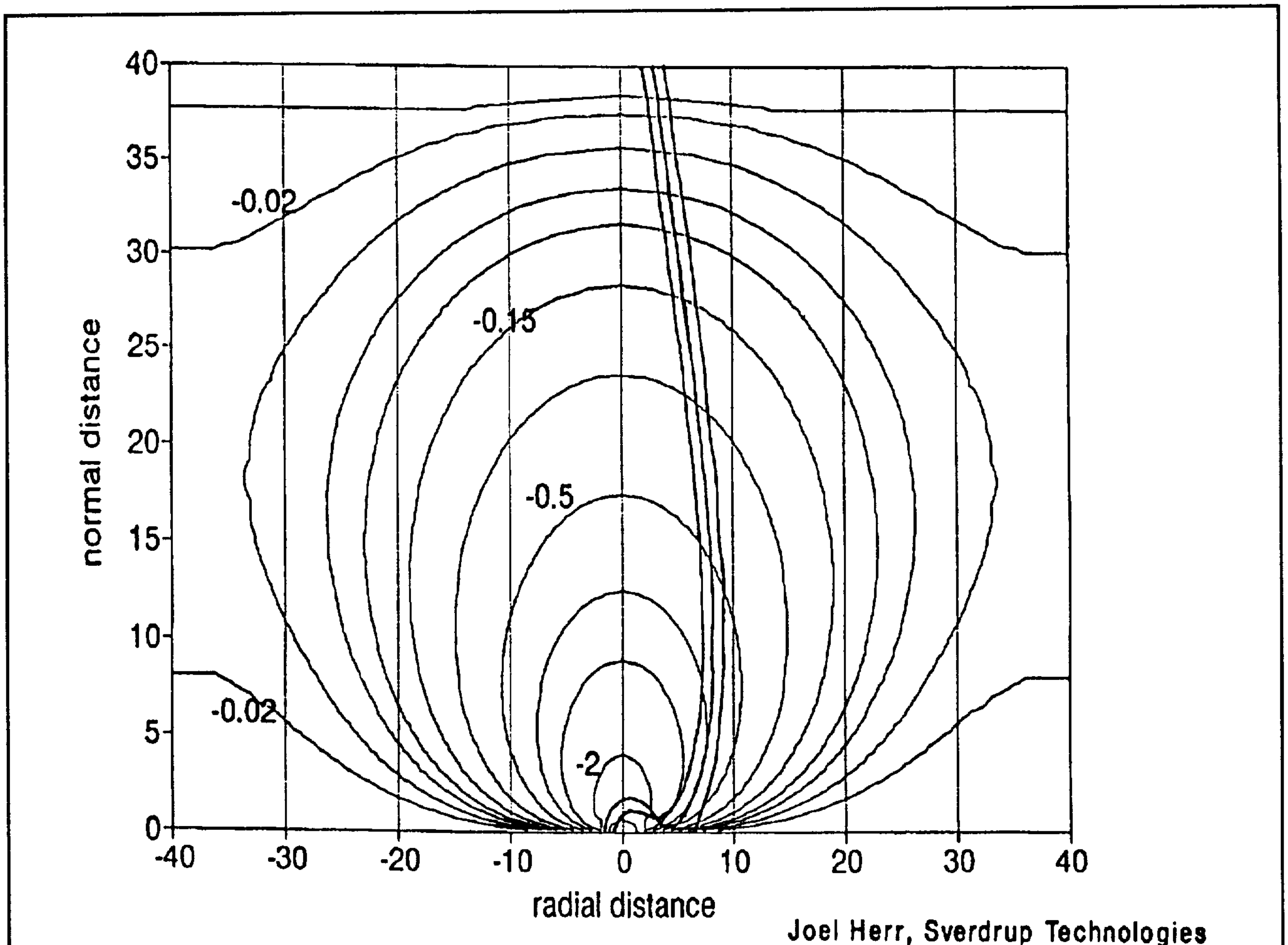

Figure 3. Ion Paths and Equipotentials Near an Insulation Pinhole

current collection. These mechanisms may decrease the relative electron to ion collection current ratio, and push the spacecraft potential more positive. It is estimated that under thruster firings on the negatively grounded SSF, the arrays may collect 10 amps of current or more (Ferguson *et al*, 1990). This current drain will show up as a 1.6 kW parasitic loss in the power system. More importantly, however, large temperature increases may occur in thin power system traces, leading to pyrolysis (charring) of Kapton® or melting of copper or aluminum (as recently found by T. Morton, Sverdrup Technology, Inc.). This is only likely to occur if all of the following conditions are met:

1. The current-carrying trace is thin and covered with a poor heat conductor.
2. A hole large enough to prevent current chokeoff (about 60 mils, Chock, LeRC) but small enough to collect high snapover currents exists in the insulator covering.
3. The conductive trace is exposed to a high density LEO plasma in the ram direction.
4. The trace is above +100 V with respect to the LEO plasma.
5. All above conditions obtain for several seconds (perhaps 10 seconds).

Kapton® pyrolysis was seen to occur on a test panel-pair of SSF arrays in a vacuum chamber at +450 volts (Felder, 1990). The charred area did not spread from the vicinity of the trace,

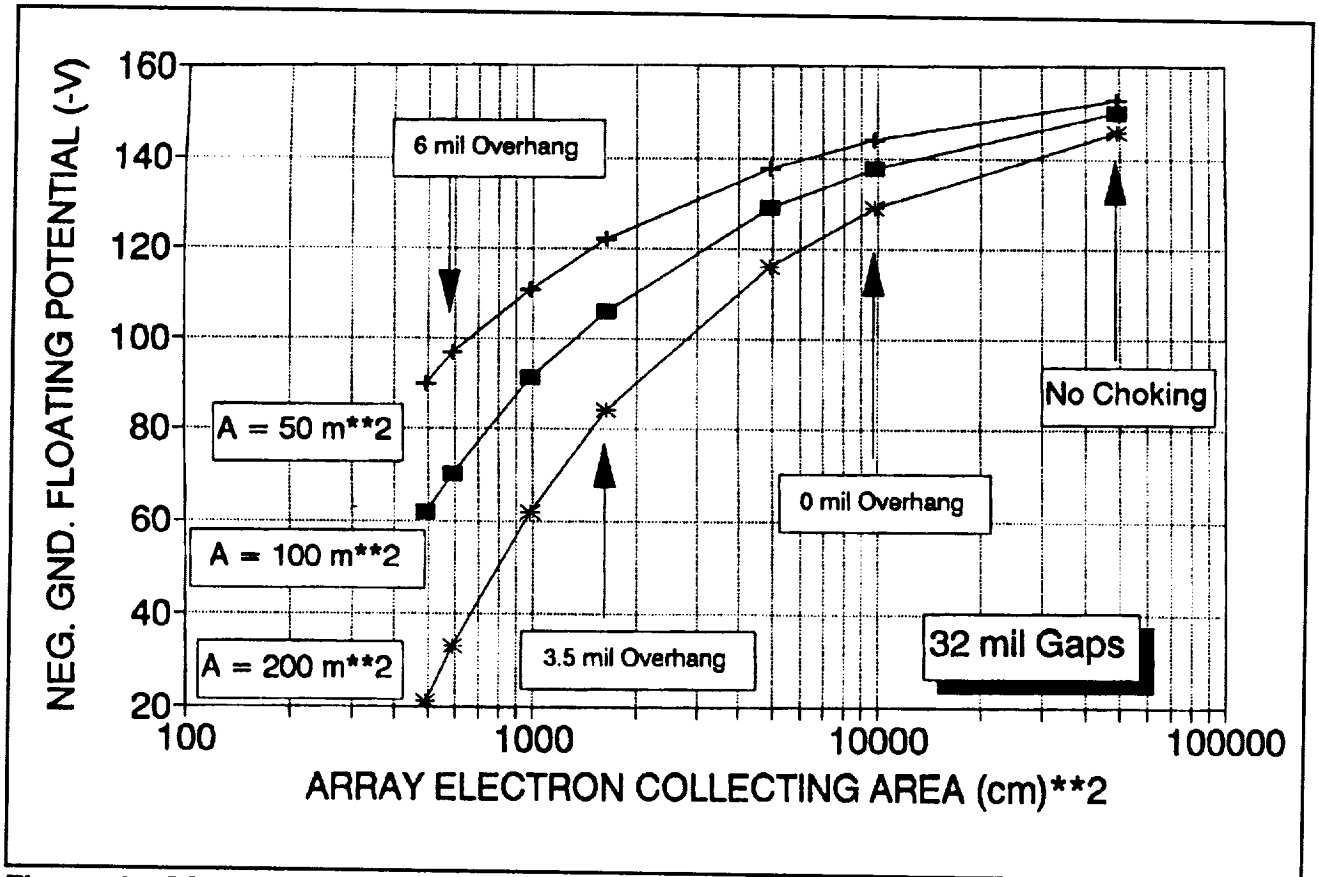

Figure 4. SSF Floating Potentials with Ion Collecting Area A vs. Electron Collecting Area

but did significantly increase the effective electron current collecting area of the array until it was repaired with a Kapton® patch. In the tank tests, the array was artificially biased to high potentials under dark conditions. It is not known whether arc-tracking of the pyrolysis might occur when current-carrying traces undergo pyrolysis in daylight. In space, holes for pyrolysis might be created by sputter or atomic oxygen enlargement of debris impact holes, or other array blanket defects.

It is possible to change the current-collection characteristics of solar cells and arrays through design practices. It has been found by modeling SSF array current collection with 3-D computer codes (NASCAP/LEO, R. Chock, LeRC) that the narrow spacing of the cells acts very well to choke off electron current collection in ground tests, and is predicted to do so somewhat under space conditions. Chock has shown that it may be possible to increase the overhangs of solar cell coverslides beyond the cell edges, and to decrease the gaps between solar cells, to produce an array which collects electrons no more efficiently than ions, and thereby to significantly influence the floating potential behavior of large space arrays. Figure 4 shows these results. The manufacturing feasibility of these solutions is now being evaluated by major solar cell manufacturers. Caulking the gaps between cells, or painting the edges of cells, on the most positive segments of solar arrays may be alternative methods of decreasing array electron collection and producing a more 50%-50% distribution of array potentials.

TRANSIENT EVENTS

Classical solar array arcing to the plasma is well documented in both ground test and space flight conditions (eg. Snyder, 1984, Grier, 1983). Figure 5 (Ferguson, 1986) shows the voltage dependence of the sporadic arc rate for 2x2 cm and 2x4 cm standard silicon solar cells on the ground and in space. The same threshold seems to apply to all available data, about -230 V. Somewhat disturbing is the tendency of the space results to lie above the ground test results at all voltages above the threshold. The cause for this effect is not known. SSF solar arrays arced into the plasma during tank tests at voltages of -205 V (Nahra *et al*, 1990). Whether this is the threshold voltage for them is not yet known, since accurate rate vs. voltage data were not obtained. Theories predict that the threshold voltage should be a function of the conducting material exposed to the plasma, and there are some supportive test data, but the predictive ability of the existing theories is just now being explored (eg. Hastings *et al*, 1990).

The arc rate for 2x2 standard cells depends linearly on the ion current collected and as a steep power-law of the voltage (at voltages above threshold). The arcs occur (usually) directly into the plasma, rather than to adjacent conductors. There seems to be no strong dependence of arc rate on number of possible arc sites (number of cells), and this has been interpreted as a reset phenomenon occurring after each arc. In both ground and space testing, the arc rate has decreased to a constant level on a timescale of hours after immersion into the vacuum. It has been found (Upschulte *et al*, this conference) that this is most likely due to outgassing of solar cell adhesives, and a significant reduction in arc rate has been achieved by modifying solar cell coverslide adhesion and cleaning techniques. Increas-

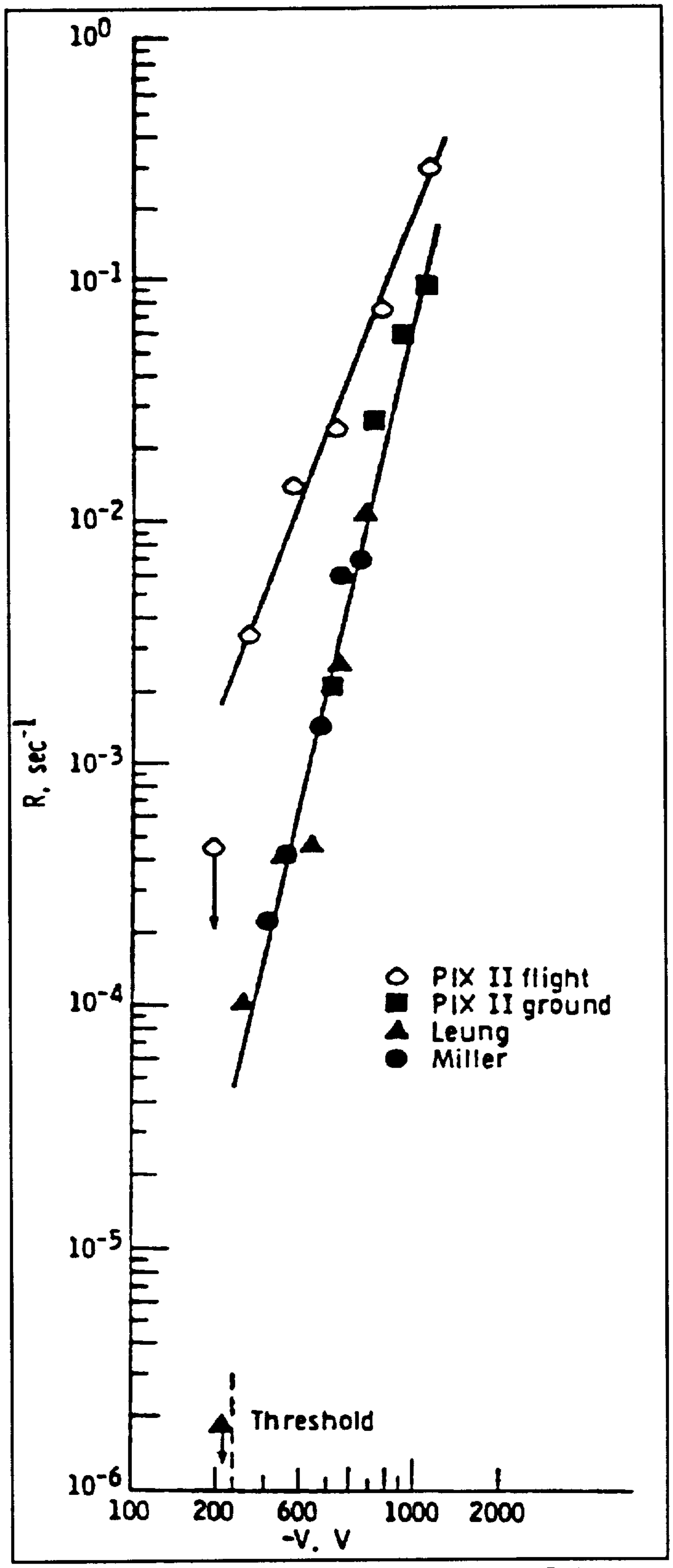

Figure 5. Arc Rate vs. Voltage for LEO Ram Conditions

ing the solar cell coverslide overhangs may decrease the arc rate by decreasing local ion current collection. There is some evidence (Chock, LeRC) that arc sites on the SSF array in ground tests preferentially occurred where coverslide overhangs were small or nonexistent. It is doubtful that such techniques will change the arcing threshold.

Arcs similar to classical solar cell arcs may occur on spacecraft surfaces with an insufficient dielectric strength covering over the conducting material. Anodized aluminum surfaces have been seen in ground tests to arc into the plasma at potentials as small as -80 V. While not directly of concern to spacecraft solar array operations, large negative potentials on spacecraft may be the result of the spacecraft electrical power grounding scheme, the end-to-end voltage on the arrays, and the relative electron and ion current collection characteristics of the solar arrays. They may therefore be controlled by changing the array floating potentials through coverslide and gap specifications, as well as by a proper grounding scheme and properly chosen coatings. Arcs of all types seem to discharge the entire connected capacitance of the power system where they occur, and are therefore powerful current transfer events.

Figure 6 shows new laboratory results of arc strength versus connected capacitance in the system (Snyder, LeRC). For large capacitances, as on very large solar array panels or on large anodized spacecraft structure panels, peak arc currents may extend to thousands of amps. The limiting mechanism for peak arc currents has not yet been found. It is believed

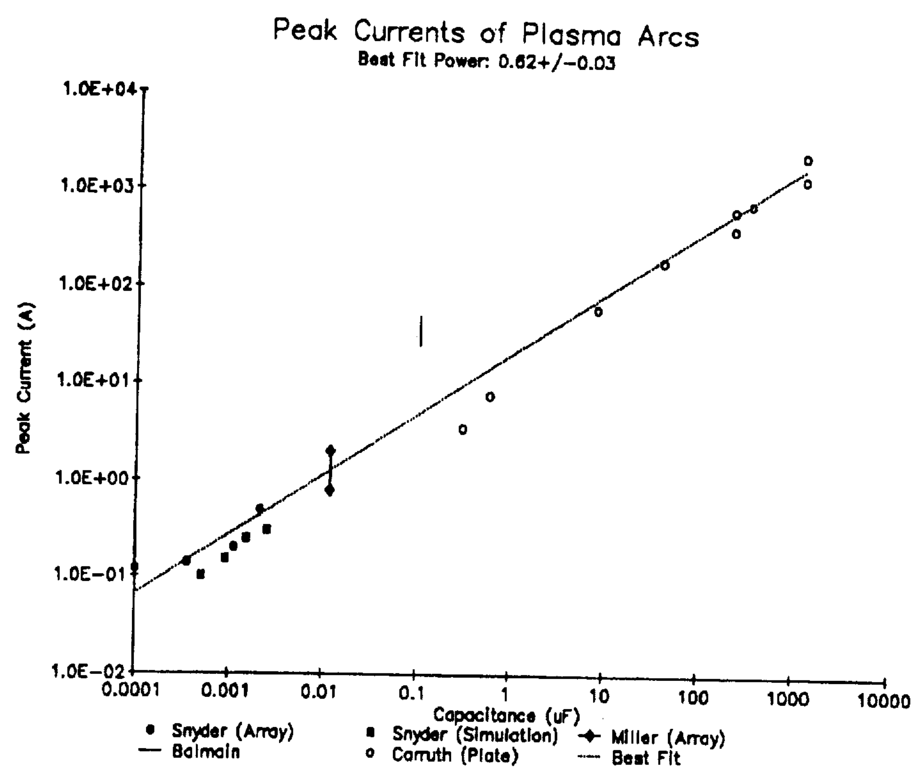

Figure 6. Peak Arc Currents vs. Connected Capacitance

that large arcs produce a local plasma of such density that sufficient charge carriers exist for thousand amp arcs. Large arcs may locally disrupt the surface, interrupt power for a short time, produce prompt contamination, and generate copious amounts of electromagnetic interference (EMI). Figure 7 shows EMI produced by laboratory tests of small solar arrays of a given capacitance in a plasma (Leung, 1985). It is desirable to limit the potential of spacecraft systems and arrays with respect to the plasma in order to prevent arcs, or to at least limit the amount of connected capacitance available to potential arc sites.

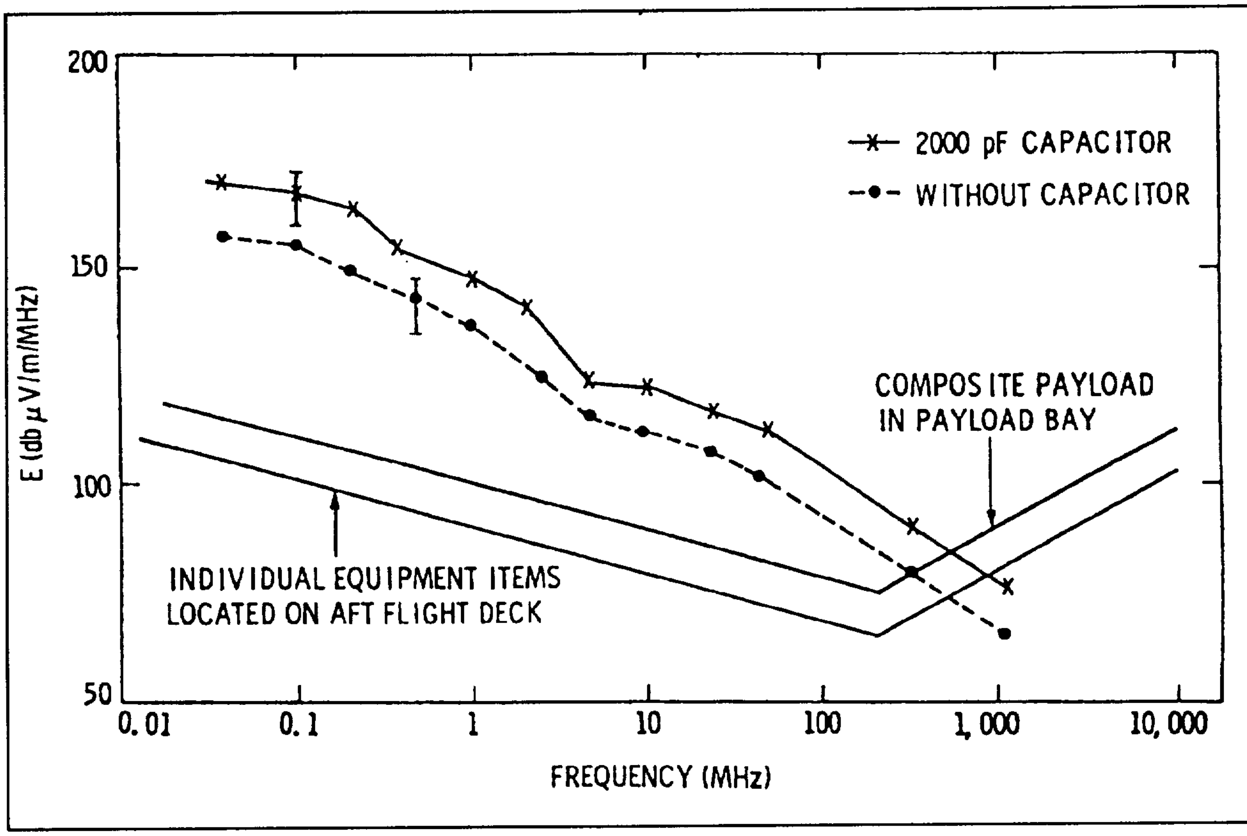

Figure 7. EMI from Solar Array Arcs

SPACE FLIGHT EXPERIMENTS

Several space flight experiments to test the various results and conclusions summarized in this paper are in preparation. I am Principal Investigator on the Solar Array Module Plasma Interaction Experiment (SAMPIE) to fly on Shuttle in 1993. It will investigate arcing thresholds for various materials and configurations, serve as a demonstration flight for the SSF and APSA cells, and investigate arcing and current collection characteristics of several solar cell types and proposed configurations. In addition, it will look for dielectric breakdown on anodized aluminum samples. By using a biased guard ring, we will attempt to simulate the effects of the presence of a large surrounding array on solar cell current collection. SAMPIE has been approved for Phase C/D development, and will incorporate much of worth from the old defunct VOLT flight experiment. SAMPIE will use the large collecting area of the Shuttle main engine nozzles to keep the spacecraft potentials from being pushed far negative when the

small (1000 cm^2) SAMPIE modules are biased to high positive potentials. (That this statement had to be made shows the extreme tendency for negative potentials to predominate). It is believed that real arcing thresholds and valuable space data on other interactions will be obtained from this experiment.

PASP+ is an orbital experiment designed by the Geophysics Laboratory and funded by the Department of Defense. It will look at arcing thresholds and radiation degradation on a variety of solar array types (many of which are of interest mainly to the military). PASP+ will be placed in a highly elliptical polar orbit by a Pegasus launch vehicle, and has a desired lifetime of months to years. NASCAP/LEO modeling (Chock, LeRC) has shown that potentials on PASP+ may be controlled by an electron emitter capable of emitting about 20 mA of current. Power for the experiment will come from operating solar panels of a conventional type. PASP+ is expected to be launched near the end of 1992.

The High Voltage Solar Array experiment (HVSA) is a Japanese satellite, to be launched by a Japanese expendable launch vehicle. It will bias large solar arrays up to various high potentials with respect to the LEO plasma. It is unclear to this author what technique will be used to prevent the vehicle from charging to high negative potentials when the arrays are biased positive. HVSA may fly in 1992.

Other flight opportunities in the near future include SPEAR-3 (for Space Power Experiments Aboard Rockets), an SDIO experiment to investigate very high voltage interactions with space power systems, but which will include some area for solar array tests, and possibly SEDS-2, an orbital experiment which may derive high voltages from an electrodynamic tether.

All of these flight experiments are important to give us more information on the behavior of space photovoltaic plasma interactions, so that our design ideas for preventing arcing and controlling spacecraft electrical potentials may be proven in the space environment.

COMPUTERIZED DESIGN TOOLS

Along with the possibility of designing space power systems to interact compatibly with, or to take advantage of, their space environment must come tools to enable the spacecraft and space photovoltaic designers to benefit from this new knowledge. At present, there are many large 3-D codes which allow detailed designs to be checked out in a computer-simulated space environment. Among these are NASCAP/LEO (a LEO charging and current collection code, see Mandell *et al*, 1990), POLAR (a polar orbit ram/wake charging code), MOLFLUX (a contamination code), and others. However, these codes are more useful for checking out detailed designs or exploring scientific concepts than for from-the-ground-up spacecraft design. In order to make engineering for spacecraft environmental interactions easier, a new generation of codes is being developed, with adequate scientific approximations and real-time operation, to enable the designer to sit down at his PC and have a good design in a short period of time. The first of these codes, called EPSAT (for Environment Power System Analysis Tool, see Jongeward *et al*, 1990), was funded by SDIO, and is now in beta testing. It runs in real-time on a high-end PC, and allows preliminary analysis and design tradeoffs for a

variety of space plasma and system-produced environmental interactions. In EPSAT, space environmental interactions of all major spacecraft systems may be considered in a self-consistent and integrated way. A spinoff of EPSAT, oriented more toward SSF than SDIO systems, is being funded by SSF, and is called Environments WorkBench (EWB). It is expected that this and other codes will bring space plasma and other space environmental interactions out of the experimental stage so that they may be considered by every spacecraft and space photovoltaic designer.

REFERENCES

Felder, M.C. (1990). "PV Plasma Interaction Test: Preliminary Results and Status," Final Report of the Joint Workshop on Evaluation of Impacts of Space Station Freedom Grounding Configurations, Ferguson, Snyder, and Carruth, eds., NASA LeRC, August 21, 1990.

Ferguson, D.C. (1986). "The Voltage Threshold for Arcing for Solar Cells in LEO - Flight and Ground Test Results," NASA TM-87259.

Ferguson, D.C., Snyder, D.B., and Carruth, R. (1990). Final Report of the Joint Workshop on Evaluation of Impacts of Space Station Freedom Grounding Configurations, NASA LeRC, August 21, 1990.

Gabriel, S.B., Garner, C.E., and Kitamura, S. (1983). "Experimental Measurements of the Plasma Sheath Around Pinhole Defects in a Simulated High-Voltage Solar Array," AIAA Paper 83-0311.

Grier, N.T. (1983). "Plasma Interaction Experiment II: Laboratory and Flight Results," in NASA CP-2359, p. 333, 1985.

Hastings, D.E., Weyl, G., and Kaufman, D. (1990). "Threshold Voltage for Arcing on Negatively Biased Solar Arrays," J. Spacecraft and Rockets, 27, p. 539.

Jongeward, G.A., Kuharski, R.A., Kennedy, E., Wilcox, K.G., Stevens, N.J., Putnam, R.M., and Roche, J.C. (1990). "The Environment Power System Analysis Tool Development Program," in NASA CP-3089, p. 352.

Leung, P. (1985). "Characterization of EMI Generated by the Discharge of a 'VOLT' Solar Array - Final Report," JPL Document D-2644, September, 1985.

Mandell, M.J., Katz, I., Davis, V.A., and Kuharski, R.A. (1990). "NASCAP/LEO Calculations of Current Collection," in NASA CP-3089, p. 334.

Nahra, H.K., Felder, M.C., Sater, B.L., and Staskus, J.V. (1990). "The Space Station Photovoltaic Panels Plasma Interaction Test Program: Test Plan and Results," NASA TM-102474.

Snyder, D.B. (1984). "Characteristics of Arc Currents on a Negatively Biased Solar Cell Array in a Plasma," NASA TM-86887.

Stevens, N.J., and Stillwell, R.P. (1989). "Discharge Transient Coupling in Large Space Power Systems," in NASA CP-3059, p. 383.

Thiemann, H., and Schunk, R.W. (1990). "Particle in Cell Simulations of Sheath Formation Around Biased Interconnectors in a Low-Earth-Orbit Plasma," J. Spacecraft and Rockets, 27, p. 554.

® Kapton is a registered trademark of Dupont de Nemours, Inc.