N90-25558

SOLAR ARRAY ARCING IN PLASMAS

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ABSTRACT

Solar cells in space plasma conditions are known to arc into the plasma when the interconnects are at a negative potential of a few hundred volts, relative to plasma potential. For cells with silver-coated interconnects, a threshold voltage for arcing exists at about -230 V, as found in both ground and LEO experiments. The arc rate beyond the threshold voltage depends nearly linearly on plasma density, but has a strong power-law dependence on voltage, such that for small increments in operating voltage there is a large increment in arc rate. The arcs generate broadband radio interference and visible light. In ground tests, interconnects have been damaged by arcs in cells having insufficient isolation from a source of high current. Models for the arcs are highly dependent on the choice of interconnect conductor material exposed to the plasma and possibly on the geometry and choice of adjacent insulator material. Finally, new technology solar cells use copper for the cell interconnects, a material which may have a lower arcing threshold voltage than silver. It is expected, from ground tests of simulated solar cells, that any junction of conductor and insulator exposed to space plasma conditions will arc into the plasma at a few hundred volts negative potential, relative to the local plasma.

INTRODUCTION

The prospect of flying large structures in space brings with it a need for space power systems capable of generating large amounts of power. To keep cable masses low, with no loss of efficiency, high voltages must be used; much higher than the 28 V systems typically orbited until now, and even higher than the occasional 100 V used on Skylab.

Solar cells, which individually generate low voltages, are typically strung together in series for high power applications, so that the total voltage across the array may become quite large. The connections from one cell to another are called interconnects. In standard technology solar arrays, the interconnects are coated with silver, for ease in soldering, and are exposed to the surrounding environment. Newer technology cells are welded to a copper trace from the back, so that little conductor is exposed in front. If the cell backs are not well insulated, copper will contact the space plasma.

Early plasma testing of solar cells in simulated low Earth orbit (LEO) plasmas (Cole et al 1968, Stevens 1978) revealed that at high positive array potentials of a few hundred volts relative to the plasma, even the insulating cover glasses collected electrons from the plasma as if they were conductors. This effect, known as "snapover", has been understood in terms of secondary electrons generated on the cover glasses "hopping" over to be collected at the conductor.

At high negative potentials of a few hundred volts relative to the plasma, solar cells were observed to arc into the surrounding plasma, first in ground tests (Kennerud 1974) and later in orbital flight tests (PIX-I and PIX-II, Grier and Stevens 1978, and Grier 1983). PIX-I, because of limited plasma diagnostics, essentially only confirmed that arcing was not an effect caused by the plasma chamber walls. PIX-II, however, yielded information about arcing voltage thresholds and arc rates, as well as about the "snapover" electron currents, in LEO conditions.

Because of the obvious implications of arcing and anomalous current collection on systems exposed to the space plasma, it is of some interest to understand these plasma interactions with spacecraft systems. This paper reviews current progress in understanding solar array arcing in plasmas.

ARC RATE AND THRESHOLD MEASUREMENTS

Ferguson (1986) shows that the onset of arcing in solar array plasma tests may not accurately reflect the voltage threshold. If, for example, the arc rate at some combination of plasma conditions and bias voltage is very low, the experimenter may move on to higher voltages before arcing is observed. When arcs were observed in ground tests, and arc rates could be obtained (Miller 1983, Leung 1985, and Grier 1984), it was found that the arc rate depended on the conditions in the following approximate way:

$$R = C_1 \, n \, T^{0.5} \, m^{-0.5} \, V^x, \quad (1)$$

where C_1 is a constant, n is the plasma density, T is the plasma temperature, m is the plasma ion mass, V is the interconnect voltage relative to the plasma potential, and x is approximately equal to 5 for 2x2 cm cells, 2x4 cm cells, and the fronts of 5.9x5.9 cm cells in ground tests, and x is about 8 for the fronts and backs of 5.9x5.9 cm cells together, in ground tests. The PIX-II flight results yielded a value for x of about 3 for 2x4 cm cells in orbit. The difference between the fronts of 5.9x5.9 cm cells only and the fronts and backs together may be caused by a difference in the exposed conducting materials on the cell fronts and backs as will be discussed later. The difference between x for the 2x4 cm cells in ground tests and x in space may be due to the presence of atomic oxygen in space, as contrasted with other gases used in ground tests.

If the voltage at which arcing is first observed in a test is interpreted as that voltage at which the average time interval between arcs becomes less than the continuous test time at that voltage, it may be shown that (Ferguson, 1986):

$$V_{on} = C_2 \, n^{(-1/x)}, \quad (2)$$

where V_{on} is the apparent onset voltage, C_2 is a constant, and n and x are as defined before. Thus, an apparent density dependence of the arcing threshold may in fact be simply a reflection of the steep voltage dependence of the arc rate.

The true voltage threshold for arcing for 2x4 cm cells with silver-coated interconnects, defined as the potential below which the measured arc rate is several standard deviations below the rate extrapolated from higher voltages, has been found to be about -230 V, relative to the plasma, from all available ground and orbital data. This threshold may be a function of solar cell geometry and materials, and should not be taken to represent the threshold for arbitrary or new solar array designs. Figure 1 shows the arc rate behavior found for several arrays of 2x2 cm and 2x4 cm cells in ground and orbital tests, normalized by the plasma parameters in equation (1). It is worth mentioning that the arc rate observed does not depend strongly on the number of cells or exposed interconnects at high voltage. For a large array with insulated interconnects, one pinhole in the insulation will thus arc effectively as much as if the interconnects were all exposed to the space plasma.

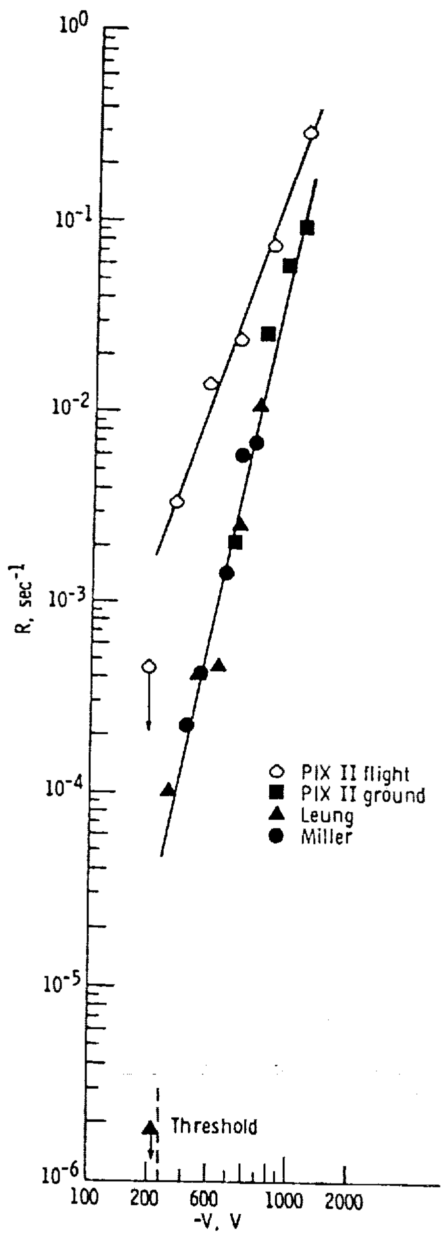

Figure 1 - Arc rate versus voltage for standard interconnect cells, normalized to LEO ram conditions.

EFFECTS OF SOLAR ARRAY ARCS

Of course, it is only necessary to avoid arc occurrence if the arcs may harm spacecraft operations or systems. Leung (1985), as part of the now-defunct VOLT experiment development, measured the radiofrequency noise spectrum of arcing solar cells. Figure 2 shows the spectrum he found. Depending on the strength of the arcs (which depends on the capacitance of the array to space, as also found by Snyder in 1985), the EMI generated may be negligible or quite significant. For arrays large enough to generate the high potentials necessary for arcing, EMI may be significant if it couples to spacecraft electrical systems. Communications between spacecraft, or between spacecraft and telerobotic systems may be disrupted.

In addition to radiofrequency EMI, arcs produce visible light, which may interfere with optical experiments. The visible spectrum of the arcs has not, to date, been measured.

If arcs occur in solar arrays which are insufficiently isolated from a high current source, as in early experiments where a high voltage power supply was used to bias the arrays, the large arc currents may damage materials at the arcing point. Miller (1983) found partially melted interconnect material in arrays which had been repeatedly arced. Since his experience, it has become standard experimental technique to place a large resistance between bias sources and the array to be plasma tested. For large space solar arrays, however, the source of the high negative potentials may be the array itself. In this case, the strength of the arcs will depend on the total array capacitance and on internal array connections (diodes, etc.).

Adverse array arcing effects may be mitigated in several ways:

1. Design the system so that high negative potentials relative to the plasma will exist nowhere in the system. This will mean, in practice, one of two design solutions. Either the total array voltage, from end to end, must be limited, or a large current-collecting area is provided at the negative end of the array, so

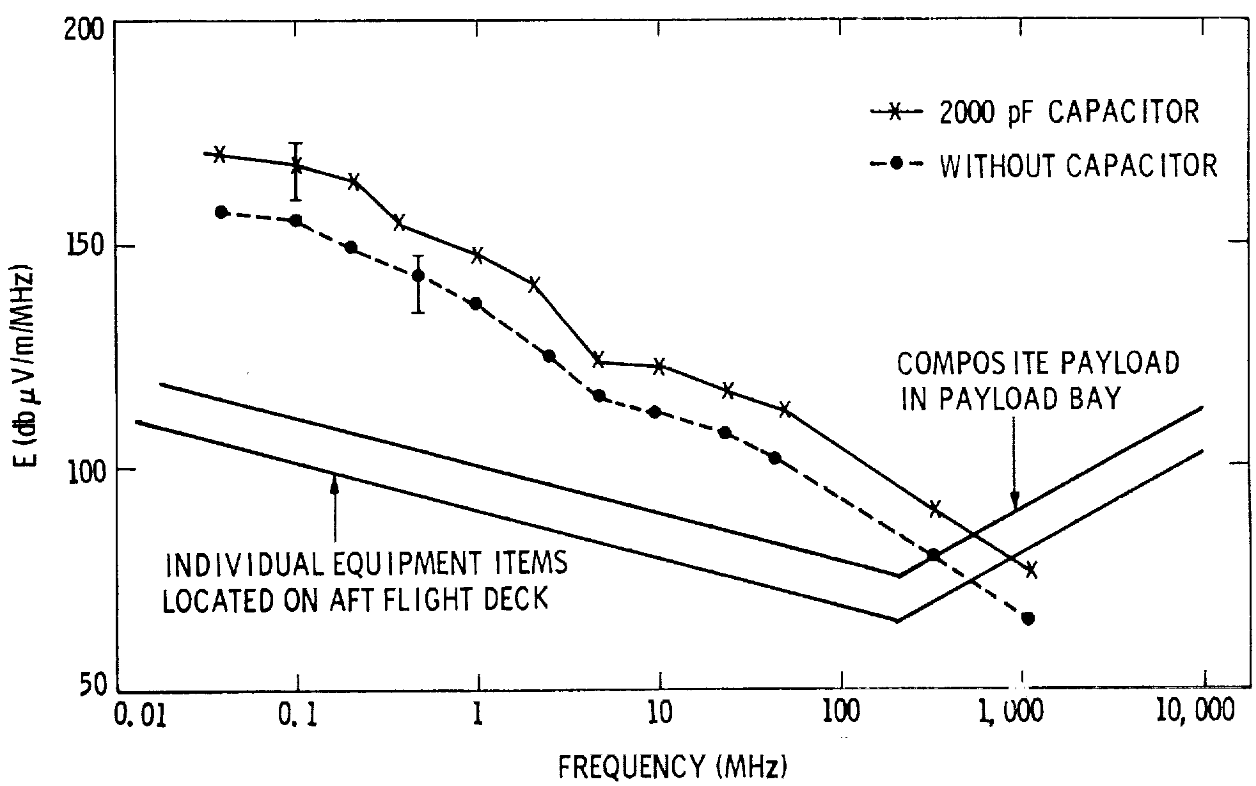

Figure 2 - Spectra of RF radiation generated by a 4 cell array of 5.9x5.9 cm cells, with welded-through interconnects, with and without an added capacitance.

there will be a low potential drop at that end. The first solution will mean that larger cable masses must be used to limit I^2R losses. The second solution will push the positive end of the array up to high positive potentials relative to the plasma, so that snapover problems may become important.

2. Insulate the interconnects so thoroughly that it is certain no plasma contact will be made. For long-lived arrays, micrometeoroids and/or debris may puncture the insulation, nullifying this solution.

3. Design the arrays so that only a small amount of charge may be dumped when an arc occurs. This may limit the EMI, etc., to tolerable levels. Bear in mind, though, that each independent array segment will arc as one unit, so the total arc rate will go up linearly as the number of arc segments.

4. Use materials for interconnects, coatings, etc., which will not arc at the high negative potentials likely to exist on parts of the array. This option will be further examined in the next section.

POSSIBLE MATERIAL DEPENDENCES

Interesting differences exist in arcing thresholds and arc rates between arrays having different surface materials. For instance, ESA tests (Thiemann and Bogus 1986 and 1988) have shown that arrays having the interconnects coated with an "insulating" material sometimes arced at lower voltages than they did before the interconnects were coated. The effect amounted to hundreds of volts in the onset of arcing.

Solar arrays for the PIX-II experiment had a much higher voltage for the onset of arcing in pre-flight ground test experiments than they exhibited in orbit (Ferguson, 1986). The voltage dependence of the arc rate of the PIX-II arrays was also very different than found in pre-flight testing. In this case, the orbital arrays were likely covered with a thin oxide coating from interaction with the atomic oxygen in LEO, whereas pre-flight testing was done in an argon plasma.

Miller (1983) showed that in ground tests the solar array arc rate started out high, and then decreased to a constant level on a time scale of a few hours, as if the arc sites were cleaning themselves up during testing. Leung (1985) observed the same effect in ground tests using a different background plasma. PIX-II also showed this effect in orbit (Ferguson 1986).

As was already mentioned, the fronts of 5.9x5.9 cm cells arced in ground tests at a slower rate than the fronts and backs together. Here, the significant fact may be that the cell backs had copper exposed to the plasma, rather than silver. Supporting this contention are the ground tests performed by Snyder (1986) on metals partially covered with insulating material, to simulate the conductor-insulator junctions on solar cells. Silver in his tests arced so as to bring the local conductor potential down to about a -230 V level, coincident with the arcing threshold found in other tests. Copper in his tests arced so as to bring the local copper potential in arcs to a value less than about -120 V, possibly indicating a lower arcing threshold voltage for copper than for silver.

All of these results may be understood if the arcing threshold and arc rate depend on the surface properties of the materials at the arc sites. There are two popular models for the onset of arcing at high negative potentials. In one, a thin dielectric layer of contaminant is built up on the surface of the conductor, and sufficiently high electric fields may be produced in the vicinity of the insulator to punch through the layer, triggering an arc (Jongeward et al 1985). In the second model, breakdown of gas emitted by the insulator under electron bombardment may lead to an avalanche into the plasma if the electric fields are high enough (Hastings et al 1989). In both of these models material properties play a strong role, as does the presence of high electric fields near conductor-insulator interfaces. On the basis of these models and the observations they are meant to explain, arcs may be expected at negative potentials of a few hundred volts negative, relative to the plasma, at conductor-insulator junctions, regardless of whether the junction occurs on a solar cell or is part of some other spacecraft system.

Obviously, more work needs to be done in ground tests and space flight experiments, to investigate the material and geometry dependences of the arc rate and arc threshold. Only then can proper mitigation techniques be employed. One approved Shuttle experiment to investigate arcing on solar arrays in LEO is the SAMPIE, or Solar Array Module Plasma Interaction Experiment, a joint NASA/ESA venture now manifested for late in 1994. Ground testing continues at NASA Lewis Research Center, TRW, and elsewhere.

CONCLUSIONS

EMI generated in solar array arcs may generate radiofrequency noise which might disrupt telerobotic communications. High negative potentials on other spacecraft surfaces are a possible threat to the successful operation of spacecraft systems, including automation and robotics electronics and communications. It is necessary to consider solar array arcing and solar-array-type arcing in the design of spacecraft power systems and other systems which may be affected by arcing. Systems should be designed to mitigate the incidence and effects of arcing, whenever possible. Although not the topic of this paper, arcs may also occur during docking, if the potentials of the docking vehicles differ sufficiently. Thus, control of spacecraft potentials is important in spacecraft design, if reliability and communications are important to spacecraft systems. Material dependences of arc rates and thresholds are important factors in system design, and our knowledge of them relies to a great extent on lab and spaceflight experiments, some of which remain to be done.

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