CASE FILE COPY

NASA Technical Memorandum 87259

IN-13223

The Voltage Threshold for Arcing for Solar Cells in LEO—Flight and Ground Test Results

(NASA-TM-87259) THE VOLTAGE THRESHOLD FOR ARCING FOR SOLAR CELLS IN LEO: FLIGHT AND GROUND TEST RESULTS (NASA) 22 p HC A02/MF A01 CSCL 10B

N86-28125

Unclas

G3/20 43387

Dale C. Ferguson
Lewis Research Center
Cleveland, Ohio

March 1986

NASA

To: Philip N. French
From: Sue E. Butts
Subject: Formal reports held for DAA from Lewis Research Center

July 28, 1986

After our conference call July 15, 1986, I compiled the following information on the DAA's STIF requested.

TM number	Date DAA sent to STIF
87338	12-11-85
87347	12-5-85
87304	4-12-85
87302	4-21-86
87191*	
87277	3-24-86
87294	3-24-86
87297	2-2-86
87303*	
87346	5-30-86
87311	3-31-86
87326	5-2-86
87259*	
87293*	
87334	4-11-86
87329	5-2-86
97682	Not a Lewis number
87333*	
87251	2-10-86
87321*	
87255	11-12-85
87316	3-24-86
87318	1-24-86
87320	3-10-86

CR number	Date DAA to STIF
3992*	
174970	3-28-86
174788	6-25-86(2nd time)
174967*	

CP number	
2392*	
2409*	

TP number	
2602*	
2570*	
2571*	
2590*	
2591*	
2529*	
2596	1-7-86
2597	1-21-86

The asterisk (*) indicates reports for which approval was received either before the DAA was required or before the Lewis procedure was in place for processing DAAs. There should be a completed COSATI page in the back of each of these reports. According to Kay Vogelweide at Headquarters, since these reports are already for sale it is superfluous to sent to Headquarters for additional approval. If your system must have a DAA let me know and I'll make them up from our records here.

I hope this helps clear your records.

Sue

Sue Butts

THE VOLTAGE THRESHOLD FOR ARCING FOR SOLAR CELLS IN LEO - FLIGHT AND GROUND TEST RESULTS*

Dale C. Ferguson
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

E-2951

SUMMARY

Ground and flight results of solar cell arcing in LEO conditions are compared and interpreted. It is shown that an apparent voltage threshold for arcing may be produced by a strong power-law dependence of arc rate on voltage, combined with a limited observation time. The change in this apparent threshold with plasma density is a reflection of the density dependence of the arc rate. A nearly linear dependence of arc rate on density is inferred from the data.

A real voltage threshold for arcing for 2 by 2 cm solar cells may exist however, independent of plasma density, near -230 V relative to the plasma. Here, arc rates may change by more than an order of magnitude for a change of only 30 V in array potential. For 5.9 by 5.9 cm solar cells, the voltage dependence of the arc rate is steeper, and the data are insufficient to indicate the existence of an arcing threshold. There are indications in the data that the arc rate is significantly increased by an atomic oxygen plasma, as is found in LEO, and by arcing from the backs of welded-through substrates.

INTRODUCTION

It has been known for many years that solar arrays exposed to a plasma similar to that found in low Earth orbit (LEO) arc into the plasma when biased to high negative potentials relative to the plasma. Initial tests of solar array segments in ground based vacuum tanks showed arcing at negative potentials of a few hundred volts and higher, with the exact voltage of arcing onset being quite variable from experiment to experiment. Recent tests done with configurations somewhat similar to solar cells in construction have shown that arcing may occur at some voltage whenever the negatively biased conductor is adjacent to an insulating surface. Again, the onset of arcing occurred at quite different voltages for different configurations. This arcing is important because it could limit the useful operating voltage of solar arrays in LEO, placing constraints on the cable mass and design of such solar arrays.

The ground-based results have been corroborated by two flight experiments to date, PIX I and PIX II. Both saw arcing on negatively biased solar array segments in LEO. Thus, the arcing results were not merely an artifact caused by interactions with the vacuum tank walls, for example, but occurred in the larger plasmas of LEO, and pose a real threat to high voltage power systems in LEO.

*Material previously presented at 24th AIAA Aerospace Sciences Meeting, Reno, Nevada, January 6-9, 1986 as AIAA Paper 86-0362.

The arcs, being not merely arcs between conductors in the solar arrays, but blowout arcs into the plasma itself, must depend on some surface properties of the conductors and/or insulators. A model proposed by Jongeward et al. (ref. 1) uses surface layers of oxides on the conductors to build strong electric fields, leading to enhanced electron tunneling through the surface layers and arcs when ion collection can no longer be neutralized by the electrons tunneling out. It is important that this model be verified or other models be produced to explain the observed arcs. This paper is an attempt to present new data and to review all of the ground and flight data on the incidence of negative bias arcs on solar arrays in LEO conditions.

Flight Results

PIX I. - The PIX I flight experiment was launched into a 920 km polar orbit in March 1978. The 4 hr of data obtained showed that a plain metal disk and a metal disk on Kapton did not arc at negative biases relative to the spacecraft of up to 1000 V, while a 100 cm^2 solar array segment arced into the plasma at negative biases of 734 and 1000 V, relative to the spacecraft. The solar cells were of the conventional interconnect type, 2 by 2 cm in size. Although the spacecraft had no plasma diagnostics, the current collected by the biased surfaces indicated a plasma density of about $2x10^4$ electrons/cm^3. In all, only about 6 min of data were recorded for each configuration at each voltage. The arcing indicator used was a shutdown of the high voltage power supply, indicating a current surge of more than 3 mA. For further information about the PIX I experiment, see reference 2.

Stevens (ref. 3) plotted the potential at which arcs were observed on PIX I versus the plasma density, along with ground-test data which had been obtained on solar cells up to that date. A relationship between the potential at which arcing occurred and the plasma density was apparent, with arcing occurring at lower voltages for higher plasma densities. This potential at which arcing first was observed for a given set of conditions has been called a "threshold" for arcing by some. It shall be called the "onset" voltage in this paper, for reasons which will become apparent in the discussion of the PIX II data.

PIX II. - Preliminary discussions of the PIX II experiment are given in references 4 to 6. PIX II, launched into a 900 km polar orbit in January 1983, was a more sophisticated version of PIX I. It incorporated a Langmuir probe for plasma diagnostics, a larger (2000 cm^2) solar array which could be biased in four individual segments and a storage system allowing more of the data obtained to be recorded on the ground. In all, about 18 hr of data were recorded.

It has been shown (ref. 6) that the Langmuir probe of the PIX II satellite was sometimes accidentally in the spacecraft wake because the spacecraft was tumbling. Thus, the Langmuir probe readings were an unreliable indicator of plasma density. For lack of another plasma density indicator, in this paper the currents collected by two of the 500 cm^2 array segments at -190 V bias are used as a plasma density indicator. The -190 V currents collected have been calibrated against preflight ground tests of the PIX II hardware where the plasma density and temperature were known through Langmuir probe sweeps. Here, the numbers have been corrected for the difference in ion mass collected (presumed to be oxygen, instead of the argon used in the ground tests) and for a difference in electron temperature (presumed to be 0.2 eV, instead of the typical 1.0 eV of the ground tests). It was found that in the flight data the two segments had similar negative bias collection currents independent of whether the other segments were biased, and consistent with the Langmuir probe readings for times when both the array and the Langmuir probe were known not to be in the spacecraft wake. A linear dependence of collection current with density is inferred.

A further problem in interpreting the data from the PIX II experiment was power supply shutdowns. When an arc occurred on one of the arrays on PIX II, the high voltage power supply was often shut down for the rest of the data taking cycle, when the biased array segment(s) should have been biased to ever-increasing negative potentials. This was inevitable when an arc occurred at biases greater than -500 V relative to the spacecraft, but at lower voltages the power supply usually recovered. This had three effects on the arcing statistics; it decreased the number of arcing occurrences (and valid chances to arc) at the higher voltages, it restricted arcing at the high voltages to one arc per voltage when an arc occurred, and it affected the average plasma density for valid arcing chances at the high plasma densities. This last effect can be understood in terms of an increased likelihood of arcing at low voltages when the plasma density was high (as in Stevens' diagram of ref. 3) and therefore a decreased chance that the high voltages would ever be reached before power supply shutdown. Thus, when the high voltages were reached, it was more often when plasma densities were low. The arc indicator used on PIX II was the occurrence of a significant drop in the recorded power supply output voltage, indicative of a current surge of more than 4 mA.

Figure 1 shows the onset voltage versus plasma density for the PIX II data for two of the six configurations in which the array segments were biased to the same voltage. The configurations were: (1) all segments biased (shown in fig. 1), (2) one outer segment biased (shown in fig. 1), (3) one inner segment biased, (4) both outer segments biased, (5) both inner segments biased, and (6) all segments but one outer segment biased. Other combinations besides those shown in figure 1 showed similar behavior, i.e., the onset of arcing always occurred at lower voltages when plasma densities were higher. Besides depending on the plasma density, the arcing onset voltage also depended on time in the flight. After removing the dependence on plasma density, four of the six configurations showed a correlation of arcing onset voltage with time during the flight significant at greater than the 90 percent level, with three being at the 98 percent or better level of significance. The correlations were in the sense that the arcing onset voltage increased with time during the flight. Fitting a function of the form

$$\frac{V}{V_{avg}} = A - Be^{-t/T} \qquad (1)$$

to the corrected arcing onset voltages produced values of A ranging from 1.075 to 1.26, B from 0.36 to 0.65, and T from 220 to 507 min. Thus, four of the PIX II array configurations seemed to improve their arcing onset voltages significantly on a timescale of 4 to 8 hr. Fitting a linear function to the first and last halves of the data showed that the rate of onset voltage change was much greater in the first half of the data than in the second half, lending credence to the saturating exponential form of the function above.

It is important that one does not identify the onset voltage for arcing with the arcing threshold. A low but nonzero arc rate could yield zero arcs at a given voltage if the measurement does not extend for a sufficient length of time. Likewise, arcs are first likely to be seen when the probability of an arc occurring during the measurement time interval becomes appreciable. One would then find that the onset voltage of arcing was a function of the measurement time at each voltage. Plots such as Stevens' original diagram (ref. 3), combining measurements made with various waiting times at each voltage, will then show a scatter due solely to this probabilistic effect. In any set of measurements of this type, there will be a scatter of the same order as the voltage step interval. In order to avoid these difficulties, the PIX II data were further analyzed for arc rates as a function of voltage, rather than for arcing onset voltages.

If the arcing onset voltage V_{on} is taken to be the voltage at which the probability of an arc occurring equals 0.5, then the arc rate $R(V)$ and the voltage for arcing onset are related to the measurement waiting time at each voltage t by:

$$R(V_{on}) \times t = 0.5 . \tag{2}$$

The negative bias voltages used in the PIX II arcing experiment were -31, -63, -94, -125, -188, -250, -344, -500, -688, and -1000 V. In the following analysis, the voltages are rounded off to -190, -250, -350, -500, -700, and -1000 V. The error introduced here is probably smaller than the amount of spacecraft charging due to the current collection. No arcs were observed at negative voltages smaller than -250 V.

At voltages smaller than -500 V, the arc rate was simply derived as the number of arcs counted divided by the total measurement time at each voltage. The average plasma density for all of the arcing chances at these voltages was 6.3×10^3 cm^{-3}. At voltages of -500 V and higher, high voltage power supply shutdowns required that the possibility of multiple arcs occurring during one valid arcing chance be considered. Since only the first such arc would be counted, the data were corrected using Poisson statistics. For unrelated arcs, the probability that r arcs will occur in a time when m are expected is

$$P\left(\frac{r}{m}\right) = e^{-m} \frac{m^r}{r!} . \tag{3}$$

If the arc rate is R, then in a time t one expects $m = Rt$ arcs, and

$$P\left(\frac{r}{Rt}\right) = e^{Rt} \frac{(Rt)^r}{r!} . \tag{4}$$

The probability that no arcs will occur is $P(0) = e^{-Rt}$. Thus, the probability that one or more will occur is

$$f = 1 - e^{-Rt}, \text{ and} \tag{5}$$

$$R = \frac{-\ln(1 - f)}{t} . \tag{6}$$

To obtain the true arc rate R for the high voltages, the observed percentage of time that arcs occurred (f) was corrected by this formula. The average density for valid arcing chances at the high voltages was affected by power supply shutdowns. At -500 V, the average plasma density for valid chances was 5.2×10^3 cm^{-3}, at -700 V, it was 3.0×10^3 cm^{-3}, and at -1000 V, it was 1.6×10^3 cm^{-3}. Arc rates given in this paper at the high voltages have been normalized to a density of 6.3×10^3 cm^{-3}, assuming that the arc rate is proportional to density (see below).

Error bars were also assigned to the measured arc rates using Poisson statistics of small numbers. An observed arc count of r was interpreted to mean a true arc count of between m_{min} and m_{max}, with a 68 percent probability (1 σ), using values given in table I.

The raw data of numbers of arcs and total measurement times are given in table II. For all high voltages, the waiting time at each voltage was 16 sec. In table III are the derived arc rates, after making the corrections given above.

There may be an indication of an effect of the area of the biased array in the data of table III. For the -250, -500, -700, and -1000 V data there are positive (but not statistically significant) correlations between the arc rate and the number of biased segments. Furthermore, the correlations are highest where the arc rate statistics are best (at the two highest voltages). A two parameter logarithmic regression of the arc rate on the number of biased segments and on voltage for all determined data points yields a dependence of only the 0.14 power on the number of segments. Even taking only the two highest voltages, where the apparent dependence of arc rate with segments is highest, yields only a dependence of arc rate on number of segments to the 0.43 power. Furthermore, examining the error bars on the arc rates, it may be seen that the data may be fit with no dependence of the arc rate on number of biased segments. Perhaps the safest thing that may be said is that if there is a dependence of arc rate on area it shows up only weakly in the data, and therefore is probably not a strong dependence. Since statistically there is no significant difference between the arc rates for the different numbers of biased array segments, they may all be lumped together under the column titled "All combs." to improve the statistics. The data lumped together in this way are presented in figure 2. The data at 250 V and higher are well represented by a function of the form.

$$R = 1.4 \times 10^{-10} (-V)^{3.093} \tag{7}$$

with a correlation coefficient between log R and log (-V) of 0.992, significant at more than the 99.9 percent level. However, the absence of arcs at -190 V is below the extrapolation of this function by approximately three times the 1 σ error in the arc rate. Thus, the arc rate appears to have a "threshold" at a voltage between -190 and -250 V.

Assuming that the arc rate is directly proportional to the plasma density as was done for correcting the high voltage data for density, the arc rate may be written as

$$R = 1.4\times10^{-10} (-V)^{3.093} \left(\frac{n}{6.3\times10^3}\right) . \qquad (8)$$

where n is the plasma density in cubic centimeters.

Ignoring for the moment the presence of the "threshold," one can derive from the rate function a relation for the voltage onset for arcing. Setting the rate equal to one half the inverse of the waiting time at each voltage (16 sec for most voltages) as was previously discussed, it may be seen that

$$V_{on} = -8.48\times10^3 \, n^{-0.323} . \qquad (9)$$

Figure 1 shows that this function adequately represents the onset of arcing for the PIX II arrays. Thus, the apparent threshold of arcing as a function of plasma density one might infer from figure 1 and other diagrams such as that of Stevens (ref. 3) may be only an artifact of the form of the arc rate as a function of density and voltage. The true arcing threshold may be related to the voltage only, as appears to be true from figure 2. The reality of this threshold must be confirmed by experiment.

Skylab. - The highest exposed voltages flown on solar arrays in low Earth orbit to date aside from the PIX I and PIX II experiments were the voltages generated by solar arrays on Skylab. Throughout most of the flight, potentials of 75 V were generated, with occasional excursions to 100 V. One can surmise that most of this potential drop was at negative potentials relative to the plasma, because of the difficulty in collecting ions as compared to the more mobile electrons. It is not clear that the Skylab arrays never arced into the plasma. All that can be said is that arcs, if they occurred, did not disable the Skylab electrical power system.

Ground Tests

PIX II Ground Tests. - The PIX II experiment underwent plasma testing as part of its preflight testing program. An argon plasma was generated in a vacuum tank, with electron densities of from 2×10^3 to 2×10^4 cm^{-3}. The PIX II panels were biased with respect to the plasma and arcs were counted. The tests were performed by Norman T. Grier at NASA Lewis. The problem of high voltage power supply shutdown which existed in the PIX II flight data was not present in the ground test data, presumably because it was the result of a change in a capacitor made immediately prior to launch. Therefore, the uncertainty generated by having different plasma densities at different voltages was not present in the ground test data. Furthermore, the plasma densities, although derived from the currents collected at -190 V as in the case of the flight test data, could be calibrated directly from Langmuir probe measurements.

Measurements were made principally at two different plasma densities, about 2×10^3 and 1.5×10^4 cm^{-3}. Results from these two regimes were analyzed separately. In order to maximize the statistical reliability, all combinations of array segments were lumped together, as was done for the final results reported herein for the PIX II flight test results. An attempt was made to analyze the data in as similar a fashion to the flight results as possible. No arcs were seen at biases smaller than -505 V. At the low density, there were no arcs seen at -505 or -675 V in a total time of 1408 sec each, 3 arcs at -845 V in 1408 sec, and 14 at -1010 V in 1344 sec total time. At the high density, there were 2 arcs at -505 V in 1408 sec, 25 arcs at -675 V in 1408 sec, 55 arcs at -845 V in 1376 sec, and 78 arcs at -1010 V in 1120 sec. Putting statistical error bars on the numbers of counts, one can derive the arc rates in table IV. Here, all combinations of biased array segments are lumped together. The high density data are at a mean plasma density of 1.5×10^4 cm^{-3}. The ion temperature at both densities was about 1 eV. The low density data have here been normalized to the same density assuming a linear dependence on density. At voltages of -320 V and smaller, the high density upper limit to the arc rate was 0.00078 arcs per second. The high density data at -505 V and higher can be fit by the formula

$$R = 1.82 \times 10^{-18} (-V)^{5.57} \tag{10}$$

with a correlation coefficient of 0.968, significant at the 97 percent level. Here, in the ground test data, the exponent of the power law is much higher than in the flight data.

<u>Miller's Results</u>. - Miller (ref. 7) arc tested several configurations of conductor-insulator interfaces in a vacuum bell jar with an argon plasma density of 10^3 to 10^5 cm^{-3}. The solar array which he tested was four 2 by 2 cm cells of conventional interconnect design. His figure 8(b) shows that there was a dependence of the arc rate on plasma density at a voltage of -600 V, but the data allow power laws of exponent anywhere from the 0.4 to 0.9 power of the density. Because of the large error bars on his data, they may be consistent with a linear dependence on density.

Figure 8(a) of Miller's paper, however, gives the arc rate as a function of voltage. Plotting his values on a logarithmic scale yields figure 3 of this paper. One can see that Miller's data also show a power law dependence of arc rate on voltage, with the exponent in this case being about 5.5. These data were obtained at a plasma density of 1.64×10^5 cm^{-3}. The ion temperature during the data-taking period was about 16 eV, found from examining results of diagnostics performed during data-taking and recorded in the original experiment logbooks. The results are similar to the PIX II ground test results in the exponent of the power law.

Miller also saw a change of arc rate with time. The arc rate at a given voltage (-700 V) decreased to a near constant value on a time scale of about 1 hr. Interpreting this in terms of an onset voltage, with an arc rate proportional to $(-V)^{5.5}$, it is clear that the timescale for onset voltage change would be about 5.5 hr. This timescale is similar to the 4 to 8 hr timescale for onset voltage change found here for the PIX II orbital data.

<u>Leung's Results</u>. - Under contract to NASA Lewis to perform arc testing of solar array segments for the VOLT-A flight project, Philip Leung obtained data on the arc rates and EMI generated from the arcs of small segments of PIX II type cells and 5.9 by 5.9 cm cells of wraparound interconnect design. The experiments were conducted in a lithium plasma of densities from 10^4 to 6×10^5 cm^{-3}. The ion temperature in the runs was between 6 and 12 eV. In further analysis herein, a temperature of 10 eV is assumed. The PIX II type array segment consisted of 24 cells wired in series. The 5.9 by 5.9 cm cell segment had 4 cells wired in series. Leung's final report is reference 8. Reported here is a more complete set of his data than given in the final report. First given are the data on the PIX II type cells. For plasma

densities of $5x10^4$ and $6x10^5$, Leung measured two sets of arc rate data, given in table V.

Here it can be seen that for the data taken at the higher density the arc rate has dropped considerably between the first run and the second. This may be identical to the change of arc rate with time seen in both the PIX II flight data and Miller's ground test data. In order to minimize the time effect in the high density data, analysis continues herein using only the second run data, presumably taken after the arc rate has dropped to its stable value. For the low density data, where the change in arc rate between runs is not so strong, the data have been lumped together to improve statistics. The second run high density data are shown in figure 4. Here it can be seen that the high density data at voltages of -250 V and higher show a correlation of log R with log (-V) of 0.952, significant at about the 99 percent level, with a power law of 4.8, close to that found in the PIX II and Miller ground test data.

Important to note in figure 4 is the upper limit to the arc rate at -218 V. This upper limit lies well below the arc rate extrapolated from higher voltages, and may signify a real threshold in the arc rate between -218 and -250 V. This is strikingly similar to the situation in the PIX II flight data, where a similar "threshold" is seen between -190 and -250 V. Thus, the flight results and lab simulation on 2 by 2 cm solar cells of conventional interconnect design are both consistent with an apparent arcing threshold at a voltage between -218 and -250 V. One must advise caution in applying these results to solar cells of different sizes and/or designs, however, because the physics of the arcing phenomenon, and in particular its dependence on cell design and construction, is not well understood.

Using only Leung's data at voltages of -438 V and larger, a linear correlation of the arc rates at the two densities yields a correlation coefficient of 0.992, significant at the 94 percent level, with a slope of 10.74. The ratio of densities is 8.33, so if the arc rate is a power law in density, the exponent is about 1.1. This is within the errors of being a linear dependence of arc rate on density.

Leung also took data on 5.9 by 5.9 cm cells of wraparound interconnect design. Although the cells had welded-through technology, exposing conductive material on the back of the substrate, in Leung's setup the segment was mounted on fiberglass, limiting the exposure of the back conductor to the plasma. Leung's array consisted of four cells. Plotting the highest density data from his table IV, one obtains figure 5. Here again the arc rate at high voltages follows a power law dependence on voltage, this time with an exponent of about 5.3. Now, however, the extrapolation to low voltages does not allow the presence or absence of a threshold to be determined. The arc rate for the large cells is sufficiently lower than that for the 2 by 2 cm cells that the power law extrapolation to low voltages yields arc rates too small to have been measured with Leung's waiting times.

<u>Grier's Results</u>. - Norman T. Grier, of NASA Lewis, has performed arc rate measurements on a panel of 5.9 by 5.9 cm solar cells supported by their Kapton substrate. Grier's panel had 36 cells for a total area of about 1250 cm^2. The plasma was an argon plasma, generated at low densities by four standard ion sources, and at high densities by an ion thruster. Here only a brief account is given of Grier's experiment, as Grier intends to publish a fuller account and analysis at a later date.

One set of Grier's data, obtained at a plasma density of 4.9×10^4 cm^{-3} and an ion temperature of about 0.5 eV, is shown in figure 6. Again, the arc rate as a function of voltage may be represented as a power law of the voltage, with the exponent in this case being 8.1. Other sets of data obtained by Grier at different plasma densities also show this steep power law dependence, with exponents ranging from about 8 to about 10.

Similarly to Leung's data, Grier's data at low voltages yield arc rates too low to measure, leaving the question of the existence of a voltage threshold for the 5.9 by 5.9 cm cells an open question. In contrast to Leung's results with similar solar cells, the exponent of the power law Grier found was much larger than that seen for the 2 by 2 cm cells. Since Leung's exponent for the 2 by 2 cm cells was similar to that found by other investigators (Grier in the case of the PIX II ground tests), one may infer that the difference in plasma composition between Leung's experiment and the others did not cause a difference in the power law exponent for those cells. If it also did not cause the difference for the 5.9 by 5.9 cm cells, then one must look for another explanation. A likely possibility is that in Grier's experiment, both sides of the array were exposed to the plasma, and that arcs could then occur on the exposed conductors in the welded-through backs, as well as on the fronts of the cells. In order to test this hypothesis, which implies that there should be a greater arc rate at all voltages when both sides are exposed to the plasma, one must investigate the relationship between arc rate and plasma density, ion mass, ion temperature, and array area, in order to be able to scale the results from different investigations.

Comparison and Interpretation of Results

Some theoretical guidance in interpreting the various results comes from the arc model of Yongeward et al. (ref. 1). In their model, high electric fields built up in thin dielectric contaminant layers on the surface of exposed conductors leads first to enhanced electron emission from the surface, and finally to puncture of the layer by an arc when ion collection has progressed to the point where electrons tunneling through the layer are insufficient to neutralize the ions being collected.

In its simplest form, assuming that a solar array collects current as an infinite plane and that the array is entirely discharged in an arc, the model predicts that the arc rate should go as

$$R \sim n\ T^{0.5}\ m^{-0.5}\ , \qquad (11)$$

where n is the plasma density, T is the ion temperature, and m is the ion mass. Since a large array will not reach arcing conditions before a small array, the array area should not matter for the arc rate. Also, under the assumption of planar collection, the voltage should not be important. It is obvious that the data contradict this last assumption, and this contradiction will be further examined later.

To investigate the influence of all of these parameters, the data sets of Miller, Leung (high plasma density), and the PIX II ground test data (all on 2 by 2 or 2 by 4 cm cells) were used. Here, the cells are all of the same type, but there are variations in ion mass, plasma density, ion temperature, number of cells (or interconnects), and voltage. Performing a multidimensional logarithmic least squares fit of the arc rate on these five "independent" variables, one finds that the coefficient of determination is 0.948, and the standard error of estimate is 0.528 in the natural logarithm.

The variables here are not truly independent, there being strong correlations between, for example, the temperature and the number of cells. Remembering that there was no strong correlation of the arc rate with the number of biased segments in the PIX II flight data, one may perform the same analysis as above, but omitting the number of cells as a variable. When this is done, the coefficient of determination remains 0.948, but now the standard error of estimation improves to 0.498. The conclusion is that including the number of cells as a variable does not improve the fit. The remaining four variables take on the power law exponents given in table VI. The exponents are close enough to those predicted by the simple model of reference 1 to justify a test of the quality of a fit assuming that the power law exponents of 1 for n, -0.5 for m, and 0.5 for T. Dividing the rates by these quantities raised to the proper exponents, it may be found that now the logarithms of the corrected rates are correlated with the logarithm of voltage with a correlation coefficient of 0.978, a standard error of estimate of 0.463, and a power law in voltage of exponent 5.34. It may be concluded that the dependences of arc rate on density, temperature, and ion mass are very well predicted by the model.

Correcting the rates to a density of 6.3×10^3 cm^{-3}, a temperature of 5 eV (the ram temperature in LEO), and an ion mass of 16 (for atomic oxygen in LEO), one obtains figure 7. Here the ground test data on 2 by 2 cm cells are directly compared with the PIX II flight test data, with least squares logarithmic fits superimposed. It may be seen that the ground test arc rates are everywhere lower than the flight test arc rates, as well as having a steeper power law dependence on voltage. The most likely cause of the discrepancy is that in LEO the oxygen ions which are collected may react chemically with the surface, creating their own oxide layer and thereby increasing the arc rate. The great difficulty of using oxygen in ground tests because of the fire hazard and the oxidation of tank seals and components may make flight testing the most attractive way of testing this hypothesis.

A difficulty with the arc model as it has been used herein is that the ion collection is assumed to be like that of an infinite plane. Therefore, there should be no voltage dependence of the arc rate (the collection being independent of voltage for an infinite plane). The real ion currents collected in both flight tests and ground tests show a dependence on voltage more like spherical, collision-free collection, with the current going as the first power of the voltage. Simply substituting this type of collection law for the planar collection assumed in reference 1 results in a dependence of the arc rate on the first power of the voltage, and puts the square root of the ion temperature in the denominator, instead of in the numerator, where the data seem to agree it should be. Further work on the model seems to be necessary, although the agreement the simple model imposes on three very disparate sets of data is encouraging.

Turning now to the ground test results on 5.9 by 5.9 cm cells, the data from the two experimenters have very different voltage dependences. As remarked earlier, this difference may be due to both sides of the panel being exposed to the plasma in Grier's new experiment. If this is true, then the arc rate for Grier's experiment should be higher at every voltage than that in

Leung's experiment, after correction for the differences in ion mass, temperature, and density. Using the dependences on mass, temperature, and density, from the simple model of reference 1 which fit the 2 by 2 cm data so well, one can correct Leung's data of figure 5 to the conditions of Grier's data of figure 6. The normalization factor for Leung's data is 9.17×10^{-3}. Multiplying the arc rate law of figure 5 by this factor, one finds for Leung's data a normalized arc rate dependence of

$$R = 1.3 \times 10^{-18} (-V)^{5.3} , \tag{12}$$

to be compared with Grier's dependence of

$$R = 3.6 \times 10^{-23} (-V)^{8.1} . \tag{13}$$

Setting these rates equal, one may find the voltage above which Grier's rates exceed Leung's. This yields (-V) = 42 V. Thus, for all voltages of -42 V or larger, Grier's rate exceeds Leung's, and might be expected from the hypothesis of backside arcing. Although neither set of data reveals an arcing threshold, comparison of the data sets gives a voltage which may correspond to a threshold. Further data, especially in an atomic oxygen environment, is sorely needed.

CONCLUSIONS

The conclusions which may be drawn from the analysis of this paper may be summarized as follows:

1. There appears to be a threshold for arcing of 2 by 2 cm cells into the plasma at about -230 V. A threshold may exist for 5.9 by 5.9 cm cells, but its existence is not proven by the data in hand.

2. What appears to be a dependence of the arcing threshold on plasma density may be a reflection of the power law nature of the arcing rate with voltage above the true threshold.

3. The arc rate decreases after exposure to the plasma (or possibly to arcing) to a steady value on a timescale of a few hours.

4. The arc rate above the threshold may depend on the plasma density to the first power, on the square root of the ion temperature, and inversely on the square root of the ion mass.

5. No strong dependence of the arc rate on the number of cells or inter connects could be found in the data.

6. The arc rate above threshold is greater in the flight test conditions than in ground tests, possibly because of the atomic oxygen plasma in LEO.

7. The arc rate in cells with exposed conductors on the backs, as in welded-through substrates, is higher at all likely arcing voltages than the rate for cells exposed to the plasma only on the fronts.

8. There is a great need for more data, especially in the atomic oxygen conditions of LEO, before an understanding of the arcing phenomenon may be reached.

ACKNOWLEDGMENTS

The author would like to thank Gary Jongeward, Ira Katz, and Philip Leung for their cooperation in providing unpublished information, and Norman Grier for providing newly taken data prior to publication. He also wishes to thank Carolyn Purvis for discussions and support.

REFERENCES

1. Jongeward, G.A., et al.: The Role of Unneutralized Surface Ions in Negative Potential Arcing. IEEE Trans. Nucl. Sci., vol. NS-32, no. 6, Dec. 1985, pp. 4087-4091.

2. Grier, N.T.; and Stevens, N.J.: Plasma Interaction Experiment (PIX) Flight Results. Spacecraft Charging Technology 1978, NASA CP-2071, 1978, pp. 295-314.

3. Stevens, N.J.: Interactions between Large Space Power Systems and Low-Earth-Orbit Plasmas. Spacecraft Environmental Interactions Technology 1983, NASA CP-2359, 1983, pp. 263-276.

4. Purvis, C.K.: The Pix-II Experiment: An Overview. Spacecraft Environmental Interactions Technology 1983, NASA CP-2359, 1983, pp. 321-332.

5. Grier, N.T.: Plasma Interaction Experiment II (PIX II): Laboratory and Flight Results. Spacecraft Environmental Interactions Technology 1983, NASA CP-2359, 1983, pp. 333-347.

6. Ferguson, D.C.: Ram-Wake Effects on Plasma Current Collection of the PIX II Langmuir Probe. Spacecraft Environmental Interactions Technology 1983, NASA CP-2359, 1983. pp. 349-357.

7. Miller, W.L.: An Investigation of Arc Discharging on Negatively Biased Dielectric-Conductor Samples in a Plasma. Spacecraft Environmental Interactions Technology 1983, NASA CP-2359, 1983, pp. 367-377.

8. Leung, P.: Characterization of EMI Generated by the Discharge of a "VOLT" Solar Array. JPL D-2644, Jet Propulsion Lab, California Institute of Technology, Sept. 1985.

TABLE I. - 68 PERCENT CONFIDENCE INTERVALS ON SMALL NUMBERS (POISSON STATISTICS)

r	m_{min}	m_{max}
0	0	1.14
1	.16	1.80
2	.70	3.30
3	1.30	4.60
$r > 3$	$r - r^{1/2}$	$r + r^{1/2}$

TABLE II. - PIX II FLIGHT RAW DATA - ARCING

Volts, bias	Number of biased array segments				All combs.
	1	2	3	4	
-190	0 arcs 1056 sec	0 arcs 1056 sec	0 arcs 480 sec	0 arcs 576 sec	0 arcs 3168 sec
-250	5 arcs 1056 sec	1 arc 1056 sec	0 arcs 480 sec	3 arcs 576 sec	9 arcs 3168 sec
-350	10 arcs 528 sec	7 arcs 528 sec	4 arcs 240 sec	2 arcs 272 sec	23 arcs 1568 sec
-500	5 arcs 464 sec	12 arcs 496 sec	4 arcs 224 sec	5 arcs 256 sec	26 arcs 1440 sec
-700	9 arcs 400 sec	8 arcs 304 sec	6 arcs 160 sec	6 arcs 176 sec	29 arcs 1040 sec
1000	10 arcs 256 sec	9 arcs 192 sec	3 arcs 64 sec	6 arcs 96 sec	28 arcs 608 sec

TABLE III. - PIX II FLIGHT ARC RATES (ARCS PER SECOND), FULLY CORRECTED, NORMALIZED TO PLASMA DENSITY = 6.3×10^{3} cm^{-3}

Volts, bias	Number of biased array segments				All combs.
	1	2	3	4	
-190	<0.0013	<0.0013	<0.0028	<0.0025	<0.00044
-250	.0057 ±.0025	.0011 ±.0010	<.0028	.0063 ±.0036	.0035 ±.0011
-350	.019 ±.006	.013 ±.005	.017 ±.008	.0074 ±.0047	.014 ±.003
-500	+.007 .014 -.007	+.015 .037 -.013	+.017 .026 -.013	+.017 .028 -.014	.025 ±.006
-700	+.027 .059 -.023	+.039 .072 -.030	+.124 .120 -.063	+.089 .103 -.052	.079 ±.020
-1000	+.186 .241 -.104	+∞ .342 -.137	+∞ .342 -.244	>.129	+.19 .32 -.10

TABLE IV. - PIX II ARC RATES (ARCS PER SECOND), GROUND TEST DATA. ALL COMBINATIONS OF ARRAY SEGMENTS BIASED

	Volts, bias			
	-505	-675	-845	-1010
Hi density	0.00142 ±.00092	0.0178 ±.0036	0.0400 ±.0054	0.0696 ±.0079
Low density	<0.0055	<0.0055	0.0152 ±.0081	0.0736 ±.0198

TABLE V. - LEUNG'S DATA

[PIX II type cells, arcs and time.]

Bias volts	First run, n(cm-3)		Second run, n(cm-3)	
	60 000	500 000	60 000	500 000
-218	0 arcs 20 min	1 arc 20 min	0 arcs 30 min	0 arcs 1 hr
-250	0 arcs 20 min	24 arcs 5 min	-------- --------	5 arcs 5 min
-344	0 arcs 20 min	36 arcs 5 min	-------- --------	35 arcs 10 min
-438	3 arcs 10 min	45 arcs 5 min	0 arcs 40 min	44 arcs 10 min
-532	6 arcs 5 min	390 arcs 5 min	8 arcs 10.7 min	244 arcs 10 min
-626	69 arcs 5 min	1860 arcs 5 min	96 arcs 10 min	1058 arcs 10 min

TABLE VI. - 2 BY 2 CM AND 2 BY 4 CM SOLAR CELL GROUND TEST DATA FOR ARC RATES

[Least squares fits to logarithms.]

Power law exponents				
Parameter	n	m	T	-V
Exponent	0.56	-0.69	0.86	5.16

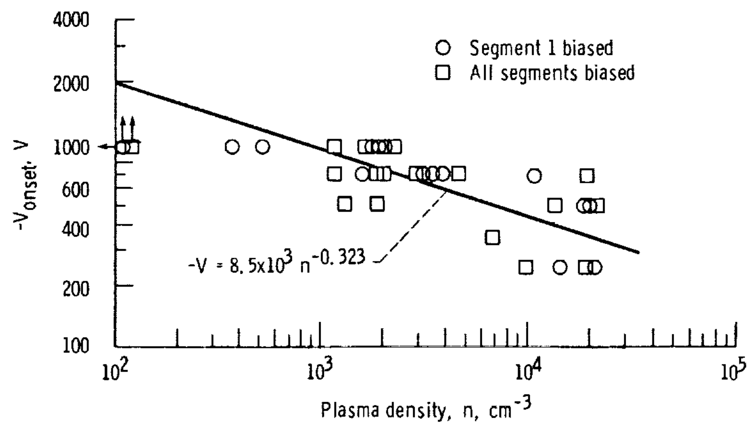

Figure 1. - PIX II flight data. Arcing onset voltage versus plasma density.

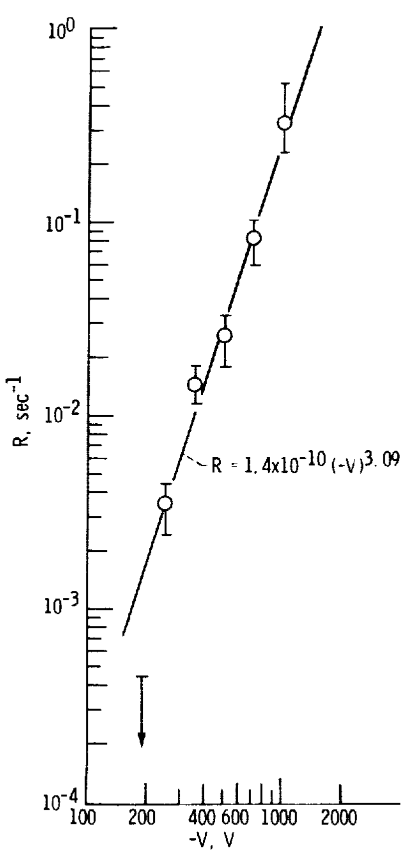

Figure 2. - Pix II flight data. Arc rate versus voltage.

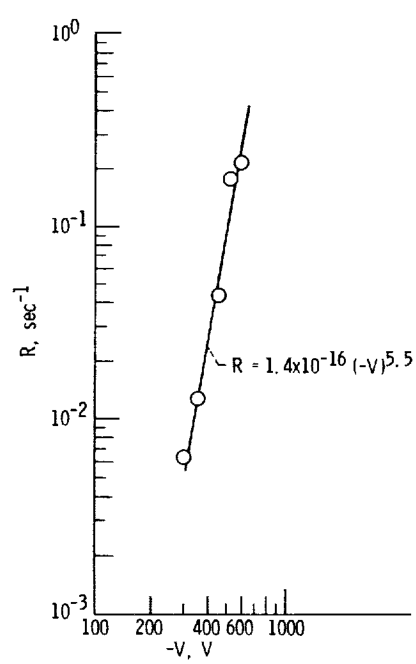

Figure 3. - Miller's data, 2x4 cm cells. Arc rate versus voltage.

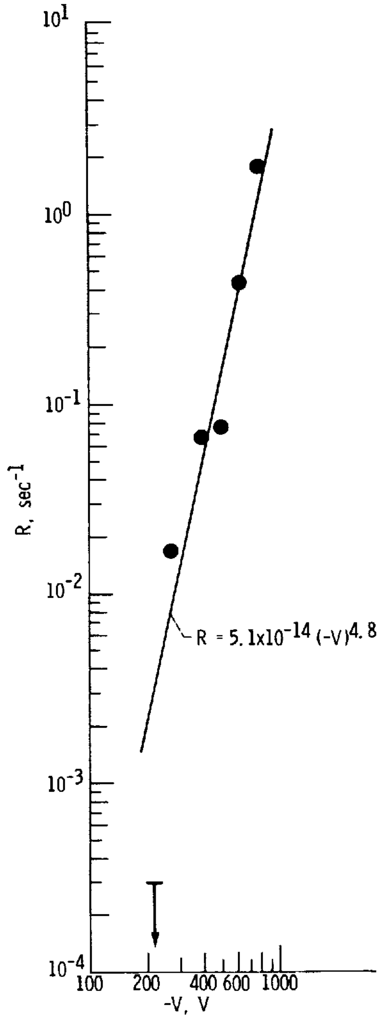

Figure 4. - Leung's data, PIX II type cells. Arc rate versus voltage.

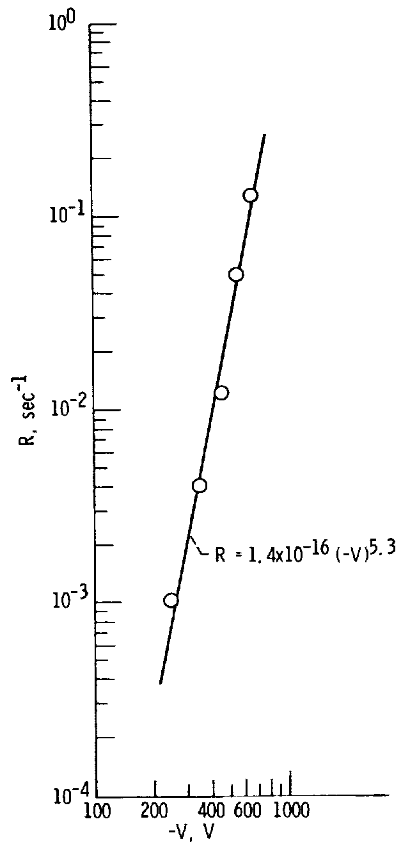

Figure 5. - Leung's data, 5.9x5.9 cm cells. Arc rate versus voltage.

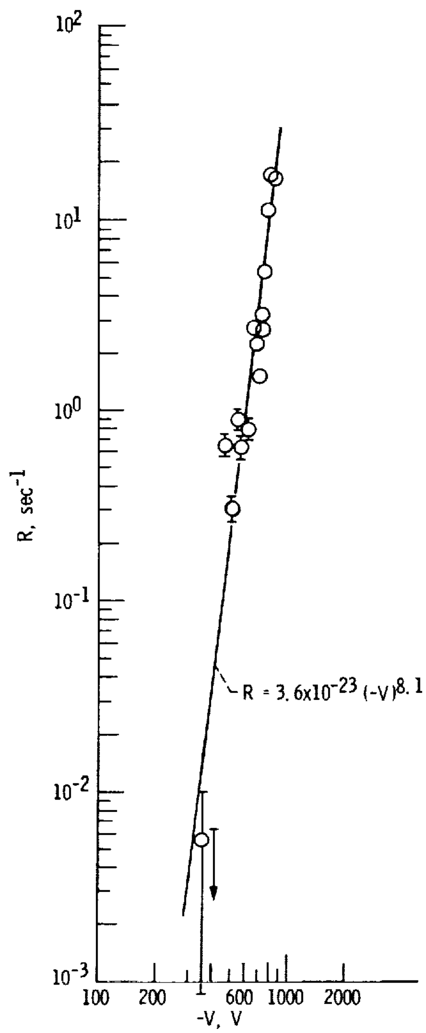

Figure 6. - Grier's data, 5.9x5.9 cm cells. Arc rate versus voltage.

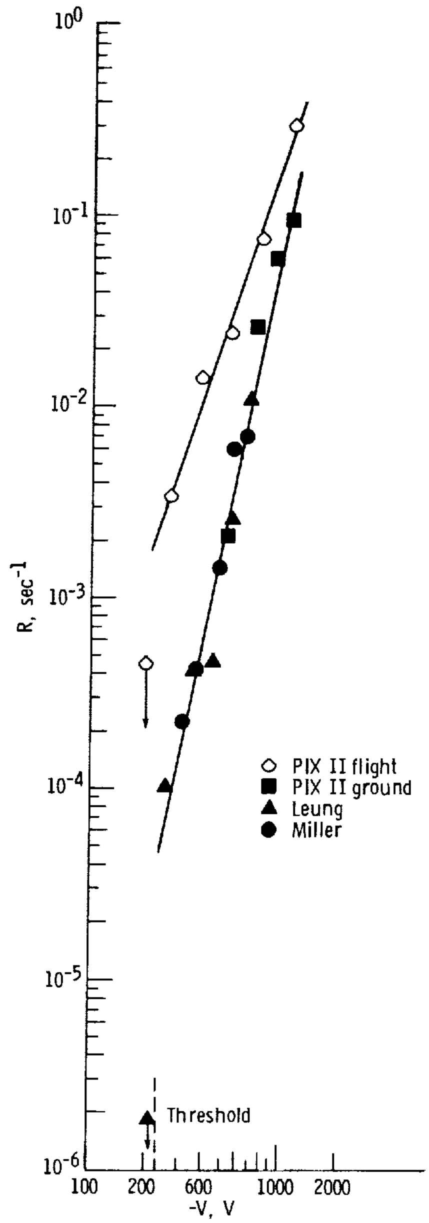

Figure 7. - Arc rate versus voltage for standard interconnect cells. Normalized to LEO ram conditions (see text).

1. Report No. NASA TM-87259	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle The Voltage Threshold for Arcing for Solar Cells in LEO - Flight and Ground Test Results		5. Report Date March 1986
		6. Performing Organization Code 506-41-4C
7. Author(s) Dale C. Ferguson		8. Performing Organization Report No. E-2951
		10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Material previously presented at the 24th AIAA Aerospace Sciences Meeting, Reno, Nevada, January 6-9, 1986 as AIAA Paper 86-0362.

16. Abstract

Ground and flight results of solar cell arcing in LEO conditions are compared and interpreted. It is shown that an apparent voltage threshold for arcing may be produced by a strong power-law dependence of arc rate on voltage, combined with a limited observation time. The change in this apparent threshold with plasma density is a reflection of the density dependence of the arc rate. A nearly linear dependence of arc rate on density is inferred from the data. A real voltage threshold for arcing for 2 by 2 cm solar cells may exist however, independent of plasma density, near -230 V relative to the plasma. Here, arc rates may change by more than an order of magnitude for a change of only 30 V in array potential. For 5.9 by 5.9 cm solar cells, the voltage dependence of the arc rate is steeper, and the data are insufficient to indicate the existence of an arcing threshold. There are indications in the data that the arc rate is significantly increased by an atomic oxygen plasma, as is found in LEO, and by arcing from the backs of welded-through substrates.

17. Key Words (Suggested by Author(s)) Solar cells; Arcing; Voltage threshold	18. Distribution Statement Unclassified - unlimited STAR Category 20

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified		

*For sale by the National Technical Information Service, Springfield, Virginia 22161