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Solar Cell Degradation During the 26-Kilowatt Electric Propulsion Space Experiment Flight

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The Electric Propulsion Space Experiment (ESEX) was launched and operated in early 1999 to demonstrate the compatibility and readiness of a 30-kW class ammonia arcjet for satellite propulsion applications. As part of this flight, an array of onboard contamination sensors assessed the effects of the arcjet on the spacecraft. The sensors consisted of microbalances to measure material deposition, radiometers to assess material degradation due to thermal radiation, and solar cell segments to investigate solar array degradation. During firings, the solar cell segments showed decreasing open-circuit voltages, probably due to additional electrical load imposed by currents through the plume plasma. Over eight firings of the ESEX arcjet, and 33-min, 44-s operating time, the solar cells exhibited a 3% decrease in short-circuit current, attributable to decreased solar transmission of the cover glass. The spacecraft's main solar arrays, however, exhibited no degradation in performance. Contamination affected only the solar cell sensor segments placed near the thruster exhaust nozzle. In the backplane of the thruster, where the main arrays are located, no deleterious effects occurred, indicating that although engineering measures may be required for equipment in the immediate vicinity of the thruster, the arcjet environment is generally benign.

I. Introduction

MATERIAL deposition can impair the operation of thermal control and optical surfaces on a spacecraft. Excessive heat flux can degrade the emissive and absorptive properties of spacecraft materials changing the thermal balance of the satellite. The presence of a conductive plasma exhaust can degrade solar cell operation. Understanding the coupling of these effects with high-power electric propulsion is critically important to the development of next-generation large space assets. A major goal of the Electric Propulsion Space Experiment (ESEX)[1] was to explore these issues by measuring the contamination effects of a 26-kW arcjet in flight. ESEX was launched on 23 February 1999 as one of nine experiments aboard the Advanced Research and Global Observation Satellite (ARGOS).[2]

A series of sensors was positioned at strategic locations of the ESEX package to assess the contamination effects. A pair of gallium–arsenide (GaAs) solar array segments placed near the arcjet nozzle were used to investigate the impact on the satellite power generation capability. Thermal surface degradation due to the arcjet firing was measured using radiometers.[3] Mass deposition was measured with thermoelectric quartz crystal microbalances.[4] Electromagnetic interference was characterized using a set of onboard antennas and ground stations.[5] This paper focuses on arcjet interference and degradation of the solar array segment. Measurements from the other onboard sensors can be found in companion papers within this issue.[3–5]

II. Solar Array Segment Sensors

Possible effects of arcjet operation on solar array performance is a matter of understandable concern to spacecraft designers. To address this issue, two small solar array segments were mounted on top of the ESEX diagnostic tower as shown in Figs. 1 and 2. The cells were positioned 43 cm from the arcjet exhaust plane, slightly downstream of the thruster exit plane. Each segment consisted of four 2 by 4 cm GaAs cells in series, with each cell under a 0.15-mm-thick cerium-doped borosilicate cover glass. This cover glass overhangs the edge of the cells by 0.2 mm, but the interconnects between cells in an array were exposed for a length of approximately 0.8 mm. The cells were mounted at a 42-deg angle to allow direct exposure to both incident sunlight and to the arcjet body and plume. One segment was connected to an open-circuit voltage sensor, the other to a short-circuit current sensor, allowing independent measurement of both parameters. A thermocouple is mounted to the base of the solar cell test assembly to monitor solar array temperature with an accuracy of $\pm 1^\circ$C.

Under direct solar illumination and at temperatures experienced in on-orbit operation, the GaAs solar cells produced a closed-circuit current of approximately 200 mA and an open-circuit voltage of approximately 4.5 V. Unfortunately, the sensing circuit for the open-circuit voltage could not read values greater than 4.2 V, and so the voltage readings were truncated at that value during periods of direct solar illumination.

Data on the actual or even just expected potentials of various components in the solar cell test circuit relative to the spacecraft chassis and to the space plasma would clearly have been useful in understanding some observed effects. Unfortunately, this need was not anticipated at the time the experiment was designed. Post hoc attempts to obtain such information were unsuccessful because the

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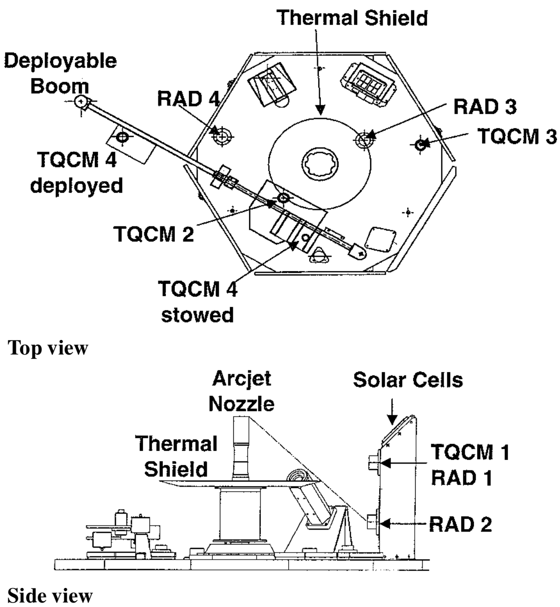

Fig. 1 ESEX showing the locations of the contamination sensors.

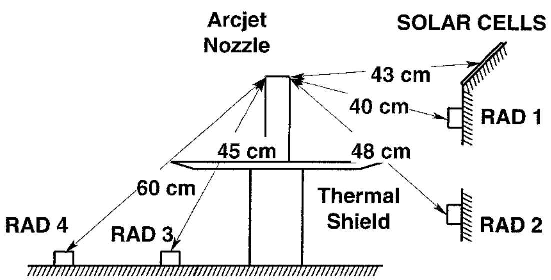

Fig. 2 Locations of the solar cell segments relative to the arcjet nozzle.

ground-test model of the sensor package could not be located for examination.

III. Flight Data

The ARGOS host spacecraft for ESEX was launched 23 February 1999 from Vandenberg Air Force Base using a Delta II launcher into a 97-deg, near-polar orbit at 846-km altitude. The ESEX contamination diagnostics were powered to receive data starting 1 h, 25 min after launch. A total of eight ESEX firings were performed between 15 March 1999 and 21 April 1999. Following the sixth firing, battery degradation occurred that impeded further full-power arcjet operations. The last two firings were terminated before reaching full power operation by excessive battery voltage drop, and when the battery failed completely, the experiment was terminated. The ESEX events, including the battery anomaly, are described in detail in Ref. 1. A summary of the ESEX events related to the contamination measurements is shown in Table 1.

Figure 3 shows the solar cell voltage and current during all six successful arcjet firings. Three of these firings, those on days 80, 85, and 90, occurred while the spacecraft was in eclipse. The firings on days 74, 78, and 82 occurred while the spacecraft was in sunlight, but the orientation was such that the test solar cells were shaded by the arcjet heat shield and/or the ESEX package deck. Illumination by scattered and/or reflected sunlight was sufficient to produce a modest open-circuit voltage in the solar cell segment so instrumented, but could not drive a detectable current through the short-circuit segment.

In all six firings, the current rises above zero about 2 min after arcjet start, reaching a nearly constant value in an additional 2 min, and dropping rapidly to zero after arcjet shutdown. This is consistent with illumination of the solar cells by the glowing arcjet body. Solar cell voltage also follows the same general pattern during the three

Table 1 Contamination events during ESEX flight experiment

Firing (F) or event	Date/Time (zulu)	Julian date (1999)	Duration
Boom deployed	9 March 1999 14:59:57	68.62497	
F-1C	15 March 1999 21:55:55	74.91383	2 m, 21 s
F-2	19 March 1999 22:32:23	78.93916	5 m, 1 s
F-3	21 March 1999 12:24:41	80.51714	5 m, 33 s
F-4	23 March 1999 21:27:57	82.89441	8 m, 2 s
F-5	26 March 1999 12:45:25	85.53154	6 m, 4 s
F-6	31 March 1999 13:05:37	90.54557	4 m, 29 s
F-7	2 April 1999 22:09:03	92.92295	53 s 38 s
F-8	21 April 1999 12:22:12	111.51542	42 s
Battery anomaly	22 April 1999 15:18:37	112.63793	

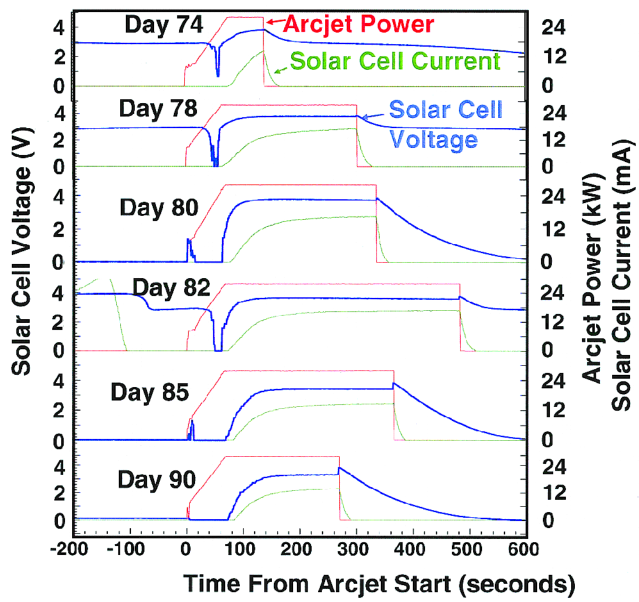

Fig. 3 Solar cell response to the six primary ESEX arcjet firings.

firings that occurred during eclipse (on days 80, 85, and 90), with the rise occurring slightly earlier, and the postshutdown dropoff substantially slower, than is observed for the current. Although not apparent in the scale used in Fig. 3, voltage also drops off very slightly during the near-equilibrium phase of the longer firings, which is expected as the temperature of the solar cells increases.

Two other effects are observed in Fig. 3. During the firings on days 80 and 85, there was a small voltage spike 20 s after ignition peaking at about 1 V. Also, immediately after shutdown in all six firings, there is a small instantaneous jump in voltage, after which the voltage trails off as the arcjet cools. The magnitude of this jump increases from approximately 0.2 V after the first firing to 0.6 V after the last in the sequence.

Slightly different behavior is seen for the three firings that occurred while the solar cells were exposed to indirect sunlight. The day 82 firing occurred less than 2 min after the solar cells went into shadow, explaining the current seen in the early period of that data set. Solar cell current during these firings followed the same pattern as with the eclipse firings, and so, too, did solar cell voltage after the first 2 min of the firing, with the obvious exception of falling off to the original steady-state voltage due to indirect illumination, rather than to zero, after shutdown. The instantaneous postshutdown jump is observed in these firings, again increasing in magnitude with each successive firing.

The substantial difference between the indirect-illumination firings and the eclipse firings is in the behavior of the solar cell voltage during the first 2 min. In all three illuminated cases, the voltage begins to fall off from the original steady-state value about 40 s into the firing, and drops precipitously at about 60 s. Voltage recovers equally rapidly about 10–20 s later, shortly before the current rise and at approximately the time the voltage is observed to rise from zero in the eclipse firings. Both the magnitude and duration of the voltage transient increase in successive firings.

In light of the observed effect of arcjet operation on solar cell voltage, it is instructive to examine the V–I curve for the solar cells while the arcjet is firing to that observed when the arcjet is inactive. The illumination of the solar cells by the incandescent arcjet body, which continues for some time following arcjet shutdown, offers an opportunity for such a comparison. Figure 4 shows open-circuit voltage vs short-circuit current data for all six full-length arcjet firings. With the arcjet shut down, the data fall on a single curve, and even very small currents correlate with open-circuit voltages in excess of 3 V. When the arcjet is operating, however, the V–I curve is shifted down in voltage from the arcjet-off case, with the amount of the shift increased at each firing. The shift is most pronounced for low current values and is much less significant at currents of 10 mA or greater.

Long-term degradation of the solar cells is shown in Fig. 5, where the solar cell current is plotted over several days at three sample times during the flight: before the arcjet is fired, after the arcjet firings, and after the battery failure. Before the arcjet firings, an average short-circuit solar cell current of 214 mA is observed. After the eight firings, the average current drops to about 207 mA. Following the battery failure, a smaller decrease to 205 mA is observed. This indicates that during the arcjet firings a 3% decrease in solar cell current and power occurs. The source of this decrease is probably

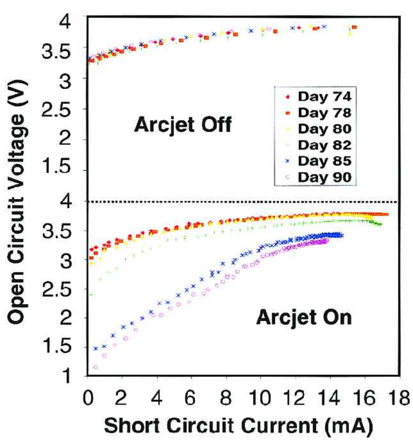

Fig. 4 Solar cell I–V curves during the six ESEX arcjet firings.

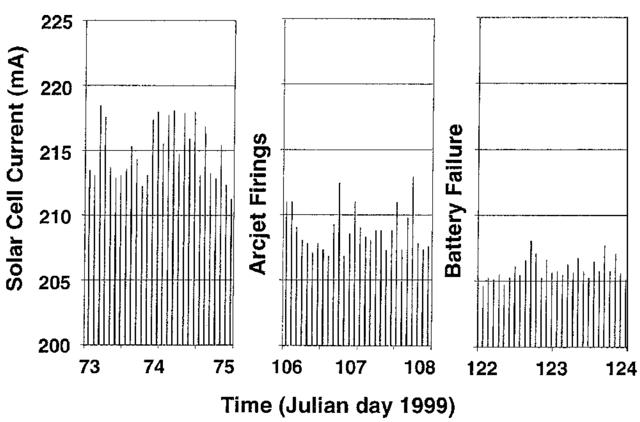

Fig. 5 Solar cell current at selected times during the ESEX flight.

a decrease in the solar transmissivity of the solar cell cover glass. Radiometer[3] and thermoelectrically cooled quartz crystal microbalance (TQCM)[4] sensors similarly exposed to the arcjet plume do show some detectable effects over the same period, but cannot be characterized in detail. No degradation of the main ARGOS arrays was reported as a result of the ESEX arcjet firings.

IV. Discussion

The small jump in closed-circuit solar cell voltage following arcjet cutoff, as seen in Fig. 3, is consistent with the shift in V–I curve observed in Fig. 4. The current is driven primarily by radiation from the incandescent arcjet body, which cannot change instantaneously due to its substantial thermal inertia. Figure 4 shows that the open-circuit voltage associated with any particular short-circuit current is reduced when the arcjet is in operation. The solar cell current is nearly constant at and immediately following the conclusion of any firing long enough to reach steady-state operation, and so, at the moment of shutdown, the voltage will revert from the depressed value associated with arcjet operation to its normal, higher value. The magnitude of this effect is observed to increase over subsequent firings, at approximately the same rate with each firing, in both Figs. 3 and 4.

The observed reduction in the solar cell voltage during arcjet operation is most likely a result of the plasma forming an alternate, shorting current path. The exposed interconnects between solar cells provide an attachment surface for an external glow discharge across the cell face, once arcjet operation has established a sufficient plasma density in the vicinity of the array.

Such a short would be limited in current by the finite density of charge carriers in the plasma. At low-power levels early in the arcjet start sequence, plasma density seems to be inadequate to shunt a significant fraction of the current the solar cells are capable of driving when illuminated by indirect sunlight. As the arcjet reaches full power, the plasma density increases to the point where most or all of this current is drawn through the short, so that the transducer can no longer read the true open-circuit voltage. Finally, as the arcjet reaches full power, radiation from the incandescent arcjet body drives enough current in the array to saturate the plasma short and to restore normal array operation with only a very minor current drain and measured voltage reduction. These three phases of operation correspond with the observed voltage loss and subsequent recovery during arcjet start. The small voltage jump immediately following shutdown results from the elimination of the plasma short, allowing true open-circuit voltage measurement without even the minor reduction associated with the saturated plasma short.

This effect is observed to increase with successive firings, possibly due erosion or sputtering of the exposed interconnects increasing the effective surface area of the plasma current connection site. The magnitude of the effect is very small, and so only observable in low-current operation of the solar cells in the immediate vicinity of the arcjet plume. The main ARGOS solar arrays, well in the backfield of the arcjet, reported no degradation of power during arcjet firings. This indicates that the problem can be alleviated through appropriate spacecraft design.

V. Summary

A preliminary analysis of the data from the ESEX flight was performed to assess the spacecraft interactions associated with the use of the 26-kW arcjet. Solar array test segments showed a decrease in output voltage when the arcjet is fired, which is most prevalent during periods of illumination by indirect sunlight at very low intensity. This effect results from impingement of the arcjet plasma on the solar arrays, producing a current-limited short circuit between exposed interconnects in the array assembly. This deleterious effect can be controlled through the judicious placement of the thruster relative to the solar arrays, or by avoiding exposed and uninsulated electrical interconnects in array design. The solar array segment also shows a 3% decrease in current following the eight arcjet firings, probably a result of decreased solar transmission through the cover glass.

Deleterious contamination effects were observed only for sensors placed very near the arcjet nozzle, much closer than would be designed on an operational spacecraft. Sensors showed no contamination effects in the thruster backplane.[3,4] The ESEX data suggest that the contamination associated with the operation of high-power electric propulsion can be controlled through routine design practice.

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