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IMPACT OF LDEF PHOTOVOLTAIC EXPERIMENT FINDINGS UPON SPACECRAFT SOLAR ARRAY DESIGN AND DEVELOPMENT REQUIREMENTS

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SUMMARY

Photovoltaic cells (solar cells) and other solar array materials were flown in a variety of locations on the Long Duration Exposure Facility (LDEF). With respect to the predicted leading edge, solar array experiments were located at 0° (row 9), 30° (row 8), and 180° (row 3). Postflight estimates of location of the experiments with respect to the velocity vector add 8.1° to these values. Experiments were also located on the Earth end of the LDEF longitudinal axis. Types and magnitudes of detrimental effects differ between the locations with some commonality. Postflight evaluation of the solar array experiments reveal that some components/materials are very resistant to the environment to which they were exposed while others need protection, modification, or replacement. Interaction of materials with atomic oxygen (AO), as an area of major importance, was dramatically demonstrated by LDEF results. Information gained from the LDEF flight allows array developers to set new requirements for on-going and future technology and flight component development.

INTRODUCTION

Emphasis in this paper is placed on the experiments for which the author was directly responsible. However, where appropriate, references to other LDEF experimenters' results will be made. In particular, the Marshall Space Flight Center (MSFC) portion of the Solar Array Materials Passive LDEF Experiment (SAMPLE-A0171) and the MSFC portion of the Advanced Photovoltaic Experiment (APEX-S0014) will be discussed. SAMPLE was located 30° off the LDEF leading edge. APEX was located on the leading edge.

The longer than planned (5.8 years versus 1 year) LDEF flight provided an environment that caused considerable change to most experiments. That environment, derived from references 1 and 2, is summarized in Table I. Figure 1 is a preflight picture of SAMPLE. Figure 2 is a picture of SAMPLE taken by a shuttle crew member at the time of retrieval. Considerable damage and contamination can be seen in Figure 2. The MSFC solar cell experiments can be seen in Figure 1 as 4 modules and 5 single cells on one of the SAMPLE plates. The descriptions of these experiments are given in Figure 3. A top-to-bottom assembly sketch of the MSFC SAMPLE solar cell test articles is given in Figure 4. Table II describes the cells and coverslides that are used on MSFC SAMPLE and APEX experiments. All of these experiments were built for MSFC by the Lockheed Missiles and Space Company (LMSC).

Two single-cell concentrator assemblies were also tested on APEX for MSFC. These assemblies, identified as Concentrators 1 and 2, utilized a cell/coverslide stack mounted between 2 planar reflectors at 60° to the cell plane. This arrangement provides an ideal concentration ratio of two (2/1). The reflector

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material was 1,200 Å of aluminum deposited on 1.0-mil Kapton and 1.0-mil Mylar film for Concentrators 1 and 2, respectively. The cell and coverslide are described under the APEX column in Table II. The objective of these experiments was to determine how well the materials selected as reflectors would perform in the actual outer space solar spectrum, i.e., what is the effective concentration ratio for solar arrays which use this configuration and these materials in space?

VISUAL OBSERVATIONS

Atomic Oxygen Interaction Effects

At first observation, the most striking changes to materials resulted from interactions with AO. Erosion of polymeric (Kapton) substrates on the SAMPLE experiments resulted in loss of two out of the four MSFC multicell test articles (modules) to space (see Fig. 2). Module 2 (Fig. 3) was missing upon shuttle rendezvous with LDEF. Module 3 drifted away upon grapple with the shuttle arm. Module 5 (Fig. 5) had lost structural attachment at three out of four points and was recovered from the floor of the shuttle cargo bay when LDEF was removed at Kennedy Space Center. The MSFC single-cell test articles (Cell 6 through Cell 9) in Figure 3 also showed considerable erosion to their Kapton substrates. Some parts of these substrates showed less erosion than others, apparently as a result of shading from the AO flux offered by adjacent test articles.

Exposed silver metalization showed differing effects of AO interactions depending upon application. SAMPLE cell "Cell 6," which was flown without a coverslide, leaving its silver gridlines exposed to the AO flux, exhibited oxidation of grid lines but no noticeable erosion. Removal of the oxide layer revealed that it composed only about 10 percent of the gridline thickness. Some cells on Module 5 exhibited considerable erosion (Fig. 6) of the silver metalization that wraps the front side electrical connections of the solar cell to the cell rear surface. This erosion manifests itself in severe electrical performance degradation, to be discussed later in this paper. APEX cells B32 to B35, which had polymeric cover materials, showed differing oxidation effects. Cells B32 and B33, which employed a 1-mil silicone (Dow-Corning 93-500) protective cover had gridlines that were still bright even in areas where the cover layer had been peeled from the cell. Cells B34 and B35, which had cast fluorinated ethylene propylene (FEP-LMSC Spraylon) covers showed apparent oxidation of the gridlines with no observable cover peeling. Considerable cracking of the Spraylon covers was observed under 32× magnification. Differences in the level and type of AO interactions with silver in applications which are similar must be attributed to synergistic effects.

Postflight visual inspections of the MSFC concentrator modules revealed discoloration in S-glass epoxy solar cell substrates, wire insulation, and wire staking adhesives. The most striking damage occurred in the aluminized reflector film as a result of AO attack upon the polyimide substrates. One reflector side was missing on Concentrator 1 which employed the aluminized 1-mil Kapton as the reflector material. The other side had become loose at three out of four attachment points and was severely distorted and torn. Concentrator 2 with the aluminized 1-mil Mylar was in about the same condition with two of four attachment points detached on each reflector and the reflector material also distorted and torn. The aluminum layer for both concentrators still appeared bright and shiny. The scenario for these failures is not readily apparent since the aluminum side of the reflectors faces outward into the velocity direction. It appears that AO could interact with the polymers only by AO bouncing off adjacent structures and/or penetration through pin holes in the aluminum reflective layer. Study of electrical performance data taken by the APEX recorder indicates that reflector material failure probably occurred after APEX quit taking reliable data (328 days).

Micrometeorite/Space Debris Effects

Micrometeorite/space debris craters were observable on MSFC SAMPLE solar cells, under 25× magnification, ranging from very small up to approximately 100 microns (three each). Density of impacts was calculated to be 0.135 per square centimeter (cm). Data reported by Paula Stella in reference 4 were consistent at 0.148 impacts per square cm. One of the largest impacts to the MSFC SAMPLE experiments caused a crack diagonally across one of the two 0.002-in microsheet coverslides on Module 4. The other two large craters were caused by impacts to the rear side of Module 5. The particles penetrated the Kapton substrate causing craters in two cells (PC1L and PC2R) that left their signature at the front surface of the cells (cell/coverslide interface). Figure 7 is a picture taken at 100× by an optical camera of the front surface of cell PC1L. A crater made by impact of a particle on the rear surface of cell PC2R on Module 5 is shown in Figure 8. The impacting particle had to first penetrate the Kapton that composes the cell substrate before impacting the cell. The crater in PC1L appeared very similar, causing about the same level of visual damage. Looking at Figure 7, it is obvious that impact energy causing the crater also caused cleavage along crystal planes in the vicinity of the impact. This type of damage has to result in some level of electrical performance degradation which will be discussed later in the report.

Cell to Interconnect Bonding

Solar cell to solar cell interconnect bonds on the MSFC SAMPLE test articles were made by parallel-gap welding of the rolled annealed copper interconnects to the silver metalization on the rear surface of the cells. All cells had wrap-around contacts so that both bonds could be made on the same side of the cells (Fig. 4). With the interconnects an integral part of the cell substrate, this approach simplifies manufacturing processes. The bonds were subjected to approximately 32,000 thermal cycles within the range –85 °C to +80 °C. There were no failed bonds found on any of the test articles. Pull tests to separate the cell from the interconnect resulted in yield in the copper interconnect or divoting in the solar cell. Previous ground testing of the same technology for over 50,000 thermal cycles in a thermal vacuum chamber at the MSFC provided the same results.

Solar Cell Coverslides

Conventional (glass) coverslides as described in Figure 3 and Table II were flown as part of the solar cell assemblies on the MSFC SAMPLE experiments. The APEX contained MSFC provided cells with conventional and polymer covers as described in Table II. Comparing the postflight electrical performance of the MSFC SAMPLE cells Cell 6 through 10 (C6 through C10 in Figure 9), it can be observed that conventional covers provided considerable protection against the space environment. The extra degradation experienced by Cell 6 (no coverslide) can be attributed largely to the proton/electron radiation environment. Postflight visual (no magnification) comparison of Cell 6 antireflective coating with the antireflective coating of Cell PC1L with its coverslide removed did not reveal any differences.

Reference 3 reports contamination on solar cell coverglasses flown on LDEF leading and trailing edges with the higher degree of contamination being found on the trailing edge. Evaluation of MSFC test articles flown on SAMPLE and APEX confirm that contamination layers exist but electrical performance degradation from contamination was not discernible in MSFC illumination testing of coverglass/solar cell assemblies. Reference 3 also reports changes in coverglass magnesium fluoride antireflective coatings. Early tests and evaluations at MSFC confirm changes but work remains to be performed before the changes can be properly characterized. Results of MSFC coverglass evaluations will be reported in a later report.

ELECTRICAL PERFORMANCE

MSFC SAMPLE Photovoltaic Test Articles

Figure 3 describes the layout and characteristics of the MSFC SAMPLE test articles. Module 5, the only SAMPLE 12 cell module not lost to space, was first illumination tested as a module showing approximately 32-percent degradation in its maximum power capability from the preflight value. It was then dissected into individual cells (PC1L, PC2L, ..., PC4R in Fig. 9), and performance curves of the individual cells were taken under a flash solar simulator. Degradation in the maximum power point power (PMP) of the individual cells ranged from 4.6 to 80 percent (Fig. 9). Although not visually discernible, it was originally thought that the high electrical performance degradation in Module 5 must have resulted from its fall to the shuttle cargo bay since test articles that stayed in place exhibited much lower degradation. Current/voltage (I/V) curves indicated a dramatic increase in series resistance of the poorly performing cells. Figure 10 shows I/V curves for the three highly degraded and the least degraded cells from Module 5. There were also slight indications of decreased cell shunt resistance in some Module 5 cells. Low power optical inspections did not reveal any clues as to the cause of the increased series resistance. However, the Kapton module substrate had been eroded to the extent that holes/cracks were made that would allow AO flux to impinge upon the silver back-surface metalization and wraparound contacts. It was postulated that interaction of the AO with the wraparounds could cause erosion which would result in increased series resistance. Coverslides were removed on four of the most degraded cells, and scanning electron microscope images were made on the wraparounds to confirm this postulate. These images showed a high percentage loss of material in the wraparound metalization (Fig. 6). Electrical resistance measurements were taken across the wraparound and found to be high. Cell PC2C (PMP degraded 80 percent) resistance measured 2.78 ohms. A resistance test on the wraparound of the same type cell that had not flown showed 0.007 ohms. Bridging of the wraparounds with a small wire soldered on the front and rear surfaces restored good performance on the cells that were evaluated in this manner (see Fig. 11). Another observation of data from these tests is that degradation is proportional to the series resistance increase, further indicating that it is the major contributor to the degradation in the highly degraded cells. Modern cells with all contacts on the rear surface of the cells would not have this problem because the wraparound would be replaced by a wrap-through or be protected with a coating. A comparison of electrical performance of cells with impact craters (PC1L and PC2R) with that of cells without craters (Cell 7 to Cell 10) in Fig. 9, indicates that the crater damage could cause 2- to 4-percent degradation in PMP. However, since these cells have not been evaluated in terms of other performance degradation mechanisms, these values can only be taken qualitatively, i.e., craters up to 100 micron in diameter cause relatively small performance degradation. Electrical performance degradation caused by small craters on the cell coverslide was not discernible in measurement.

Cells 6 through 10 were flown on SAMPLE to determine the space environmental effects upon different types of coverglasses and the resulting changes in electrical performance of the cell/coverglass stack. Changes in the coverglass light transmission qualities from space environmental exposure between Cells 7 through 10 were not discernible from electrical performance measurements. The 20.7-percent degradation in PMP experienced by Cell 6 (no cover) can be attributed mostly to charged particle radiation damage which was equivalent to approximately 5E14 1.0 MeV (million electron volts) electrons per square centimeter.

MSFC APEX Photovoltaic Test Articles

Comparison of pre- and postflight test data taken on the MSFC APEX experiments revealed that the preflight data taken on contract to the Lewis Research Center (LeRC) was obviously in error. The average difference between MSFC and LeRC postflight data was slightly less than 1 percent. For cells with conventional coverslides that provide a high degree of cell protection against the charged particle environment, pre- and postflight open circuit voltage (VOC) data agreed within 1 percent. However, for these cells, preflight short circuit current (ISC) values ranged from 5 to 9 percent below postflight values, indicating that preflight values were in error since any change outside experimental error should be performance degradation. In addition, preflight fill factor [(ISC x VOC)/PMP] values were less than postflight values, which indicates an undesirable series resistance in electrical current instrumentation used in preflight testing. Comparison of the preflight I/V curves for the APEX cells with the preflight curves of SAMPLE cells reveals that the APEX cells were the poorer performer, having lower ISC and VOC.

Figure 12 shows the pre- and postflight maximum power point (PMP) data taken for the MSFC solar cells flown on APEX. The postflight data shown in Figure 12 are the average of the MSFC and LeRC data. Three observations are readily made from this figure: (1) relative performance between cells was the same for pre- and postflight data; (2) except for B35, unadjusted preflight measurements of PMP were lower than postflight of all the cells; and (3) cell assemblies with polymer covers (B32 to B35) degraded more than assemblies with conventional covers. In order to obtain degradation data for the cells with polymer covers, it was assumed that performance of cells with conventional covers (B36 to B57) did not measurably degrade. Using this assumption, postflight data could be used as preflight data for these cells, allowing correction factors to be developed for the actual preflight data. This is a reasonable assumption to use since the configuration of APEX had the cells recessed in aluminum structure, providing protection over most of the 4 pi solid angle against charged particle radiation, micrometeorite space debris impact, and ultraviolet radiation. Preliminary analyses of APEX flight data provided by LeRC reinforces this assumption about B36 to B57 by giving flight data over the first 328 days of LDEF flight that agrees closely with MSFC and LeRC postflight data. Using this approach, correction factors were developed and applied to cells B32 to B35 preflight data to determine their electrical performance degradation. The following observations were made for the polymer-covered cells: (1) cells B32 and B33, which used Dow Corning 93-500 adhesive as protective covers, underwent mostly current degradation. Adhesive darkening is the most probable major contributor. (2) Cells B34 and B35, which had LMSC FEP Spraylon protective layers, degraded in VOC and fill-factor; an indication of decreased shunt resistance. The cause of this degradation was not determined. In reference 4, data are also reported on solar cells with polymer covers that were flown on LDEF as part of the JPL SAMPLE experiment. Degradation (ISC) reported therein was substantially higher than that observed for the MSFC cells on APEX. Reference 4 reports ISC degradation values for cells with silicone and FEP Teflon covers averaging 13 and 22 percent, respectively. These higher values can be justified to an undetermined extent by the fact that SAMPLE cells were not recessed in structure as were APEX cells, thereby allowing them to be exposed to a harsher ultraviolet and charged-particle radiation environment. The SAMPLE environment would more closely represent the flight solar array environment supporting the higher degradation values for polymer covers. In either case, polymer covers for typical space solar array applications are not presently adequate, requiring further development and demonstration.

Electrical performance evaluations of the concentrator assemblies flown on APEX for MSFC are in the preliminary stage. Scatter in flight data and lack of preflight data has made determination of the effective concentration ratio difficult. In order to obtain preliminary values, the concentrator cells were illumination tested in the laboratory after the flight without the reflector assemblies. The short circuit currents (ISC) from these tests were then divided into the ISC from flight data. Results gave a concentration ratio of 1.57 for Concentrator 1 and 1.86 for Concentrator 2. This large difference was not expected and is still in question. However, the results obtained from flight supports the viability of the use of low-concentration solar arrays in space.

CONCLUSIONS

The LDEF flight dramatically demonstrated what can happen to a spacecraft solar array when it is improperly designed for the space environment. Atomic oxygen was especially degrading to solar cell experiments on the SAMPLE and APEX because they were exposed to several times the AO fluence to which they were designed. AO was the most degrading environment to the solar cell experiments, taking its toll on solar cell contact metalization, cover glass coatings, and Kapton substrates. Many of the processes used in the development of these experiments worked very well. Solar cells performed to expectations where they were adequately protected against the environment. Adhesives used to attach glass protective covers to the cells and the cells to the substrates worked very well. There were no failures in the copper interconnects and the parallel-gap welds that bond the interconnect to the cell metalization. Glass cell covers experienced damage to their anti-reflective coating but provided good protection against micrometeorite/space debris and charged particle radiation. However, if polymer-type covers which may be attractive from the cost standpoint, are to replace conventional covers, they must undergo further development.

Evaluation of LDEF solar cell experiment results facilitates the following recommendations for ongoing and future solar array development:

1. Protect solar array components against the AO environment. Where possible, select materials that do not interact strongly with AO. If AO resistant materials are not available, use protective coatings. Replacement of solar cell silver metalization, which has been used extensively in conventional space solar arrays, with copper metalization, should receive attention. This approach not only introduces a less AO interactive material, but could contribute to lower array costs since copper is substantially less expensive than silver.

2. Provide appropriate protection against micrometeorites and space debris. Although LDEF solar cells did not degrade appreciably from micrometeorite/space debris impact, the potential for performance degradation from debris impact damage requires that protection to the front and rear cell surfaces be provided. On the SAMPLE experiment, the protective glass covers provided sufficient protection to the cell front surface, but the thin Kapton substrate on SAMPLE Module 5 allowed the larger particles to penetrate the substrate and cause crater damage to the cells back surface. The trend to reduce the weight of solar arrays by reduction of structure should not neglect protection against this environment.

3. Continue to develop higher performance solar array component and systems technology. The space station requires a high power, light weight, long life solar array. Other spacecraft, while not requiring such high power, require solar arrays that are light weight and have long life. Gallium arsenide (GaAs) cells are being made and used with efficiencies greater than 18 percent. They have lower power performance degradation with temperature and degrade less under charged particle irradiation than conventional silicon solar cells. Although GaAs cells presently cost more per watt as delivered from the manufacturer, their characteristics make GaAs arrays more competitive with silicon arrays when cost per watt-hour for long life missions are taken into consideration. Knowledge gained from LDEF with respect to materials utilization can be used to support development of long life, high performance planar and concentrator arrays. Low to medium concentration concentrator arrays are more viable than in the past when considered in terms of GaAs and silicon solar cell technology now available. Concentrator arrays potentially offer lower costs since the concept trades off use of high cost solar cells against more complex design but lower cost concentrator assembly materials (i.e., reflector materials). For these reasons, future solar array component and systems technology development should address concentrator arrays along with planar arrays.

4. Based on the knowledge gained from LDEF about solar arrays in the space environment, improved solar arrays will be developed. Should reflight of an LDEF occur, it undoubtedly should again contain solar array experiments to space prove the new developments. Solar array developers should support reflight of an LDEF.

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David Brinker (NASA Lewis Research Center) – APEX Flight Data

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2. Bourassa, R.J., Gillis, J.R., and Rousslang, K.W.: "Atomic Oxygen and Ultraviolet Radiation Mission Total Exposures for LDEF Requirements." LDEF 69 Months in Space, Part 2, First Post-Retrieval Symposium, NASA CP-3134, February 1992, pages 653 and 660.

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Table 1. LDEF environmental factors.

ENVIRONMENTAL FACTORS

- o " SAMPLE " (AO171) SOLAR CELL TEST ARTICLES EXPERIENCED THERMAL CYCLING WITH TEMPERATURE LIMITS WITHIN THE RANGE -85 TO + 80 DEG. C. (APPROX. 32,000 THERMAL CYCLES)
- o UV RADATION APPROX. 10,000 EQUIVALENT SUN HOURS
- o ATOMIC OXYGEN FLUENCE APPROX. 6.63 X 10^{21} ATOMS/CM^2
- o CHARGED PARTICLE RADIATION EQUIVALENT TO APPROX. 5 X 10^{14} 1 MEV E/CM^2 FOR CELL 6 (UNGLASSED)
  - 3 X 10^{11} E/CM^2 AT 0.25 MEV
  - 1.0 X 10^{10} E/CM^2 AT 1.0 MEV
  - 1 X 10^{9} E/CM^2 AT 3.0 MEV
  - 4.5 X 10^{8} P/CM^2 AT 0.5 MEV
  - 4.0 X 10^{9} P /CM^2 AT 20 MEV
  - 2.4 X 10^{9} P/CM^2 AT 100 MEV
  - 7.5 X 10^{8} P/CM^2 AT 200 MEV

  → FIRST POST-RETRIEVAL SYMPOSIUM NASA CP-3134, PART 1, PG 220 - 221
- o SPACE DEBRIS/MICROMETEORITE IMPACTS:
  - 15 OBSERVABLE UNDER 10X
  - 3 LARGE ENOUGH TO DAMAGE CELLS

Table 2. Solar cell and coverslide characteristics of MSFC SAMPLE and APEX experiments.

SOLAR CELL CHARACTERISTICS	SAMPLE	APEX
o MANUFACTORER	ASEC	SAME
o TYPE	N ON P, 2 OHM-CM	SAME
o JUNCTION DEPTH	APPROX 0.3 MICRON	SAME
o SURFACE FINISH	UNREPORTED	CHEM ETCHED
o CONTACTS	CVD DIELECTRIC, SIDE WRAP-AROUND	CVD DIELECTRIC, END WRAP-AROUND
o METALIZATION	Ti-Pd-Ag	Cr-Pd-Ag
o CONTACT THICKNESS	4 To 8 MICRON	SAME
o AR COATING	DUAL AR	TANTALUM PENTOXIDE
o BACK SURFACE REFLECTOR	ALUMINUM	NONE
COVERSLIDE TYPES	**SAMPLE**	**APEX**
o NONE	CELL 6	
o DOW CORNING 93-6000		B32, B33
o FEP TEFLON (LMSC SPRAYLON)		B34, B35
o OCLI, 6 MIL, MICROSHEET, ARC & UVF	MODULE 5, CELL 8	
o OCLI, 6 MIL, MICROSHEET, ARC	CELL 7	
o OCLI, 6 MIL, FUSED SILICA (FS), FROSTED, ARC & UVF	CELL 9	
o OCLI, 6MIL, FS, ARC & UVF	CELL 10	B38, B41, CONC'S 1 & 2
o PILKINGTON P. E., 2 MIL, MICROSHEET,	MODULE 4	
o PILKINGTON, 5.5 MIL, CERIA STABILIZED MICROSHEET, ARC		B36, B37

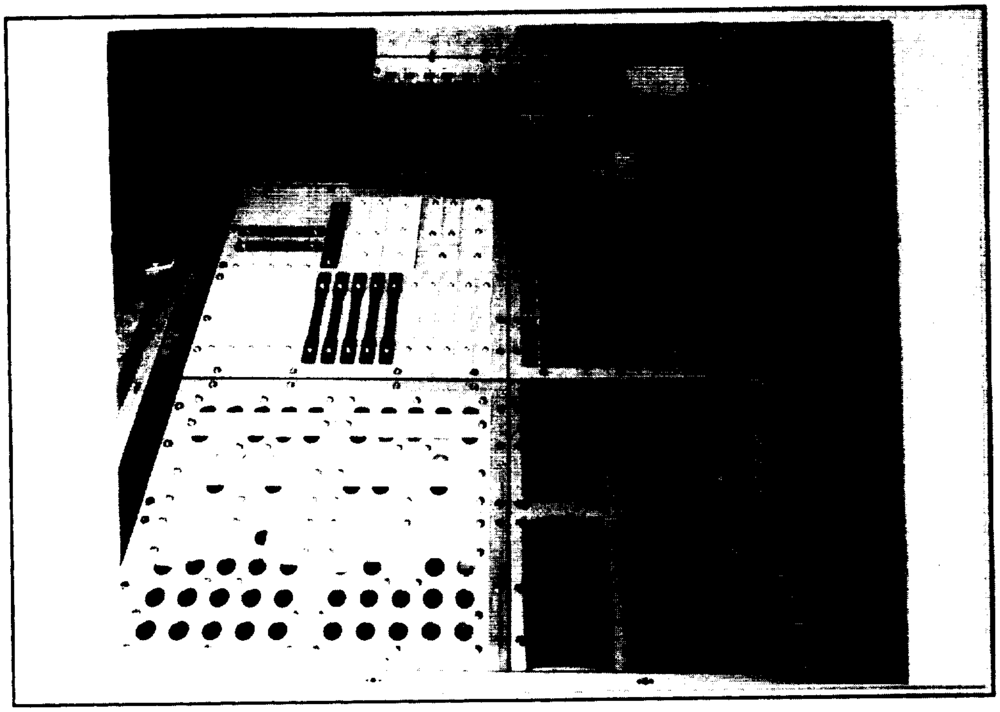

Figure 1. Picture of SAMPLE in laboratory before installation on LDEF.

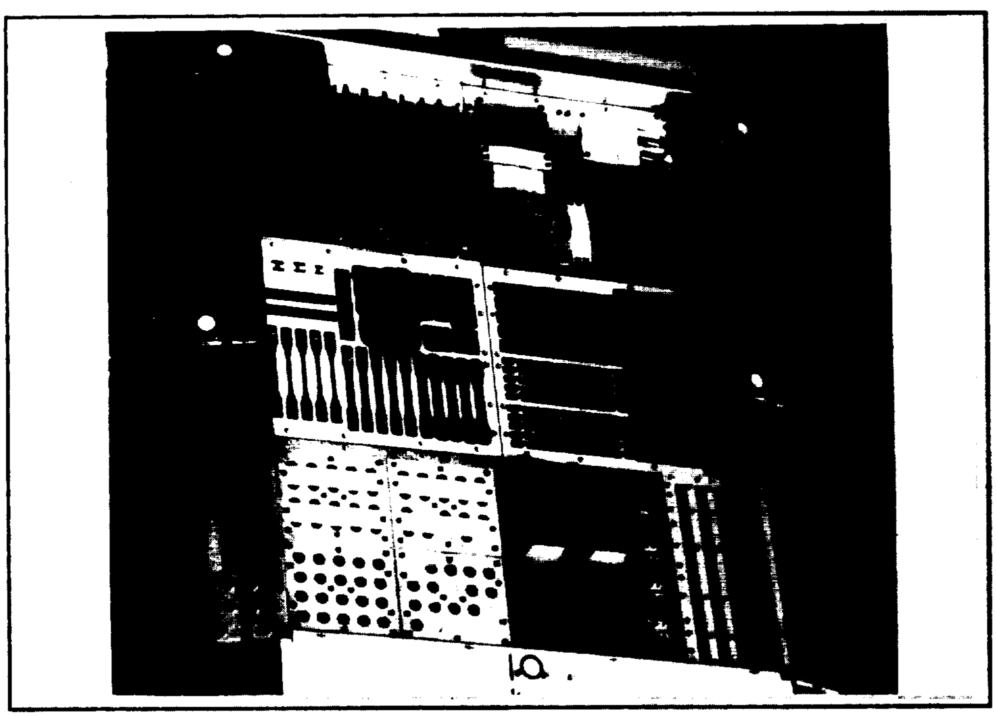

Figure 2. Picture of SAMPLE upon shuttle rendezvous.

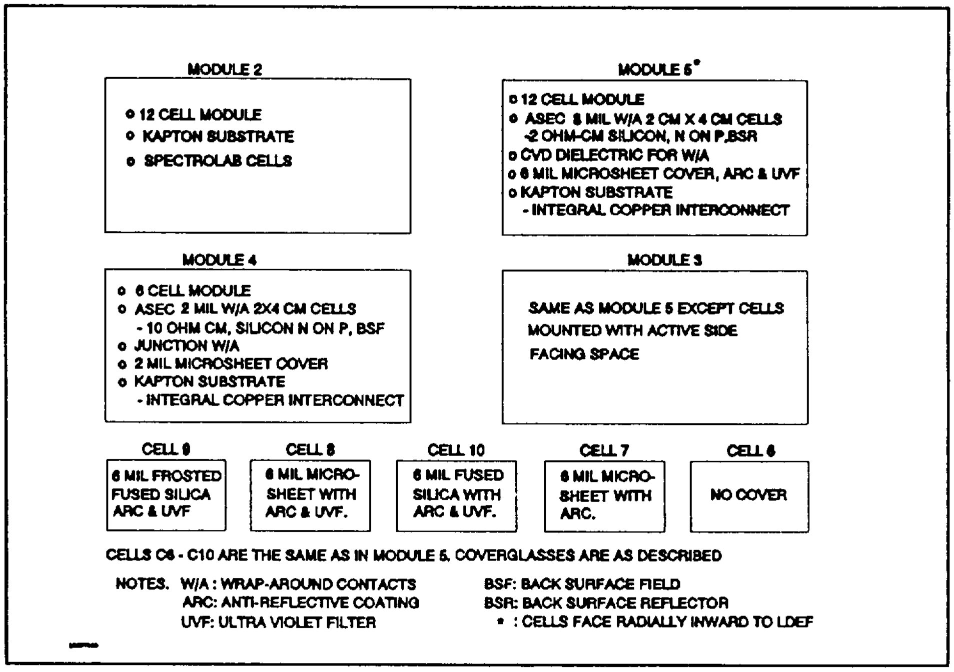

Figure 3. Description of MSFC SAMPLE solar cell test assemblies.

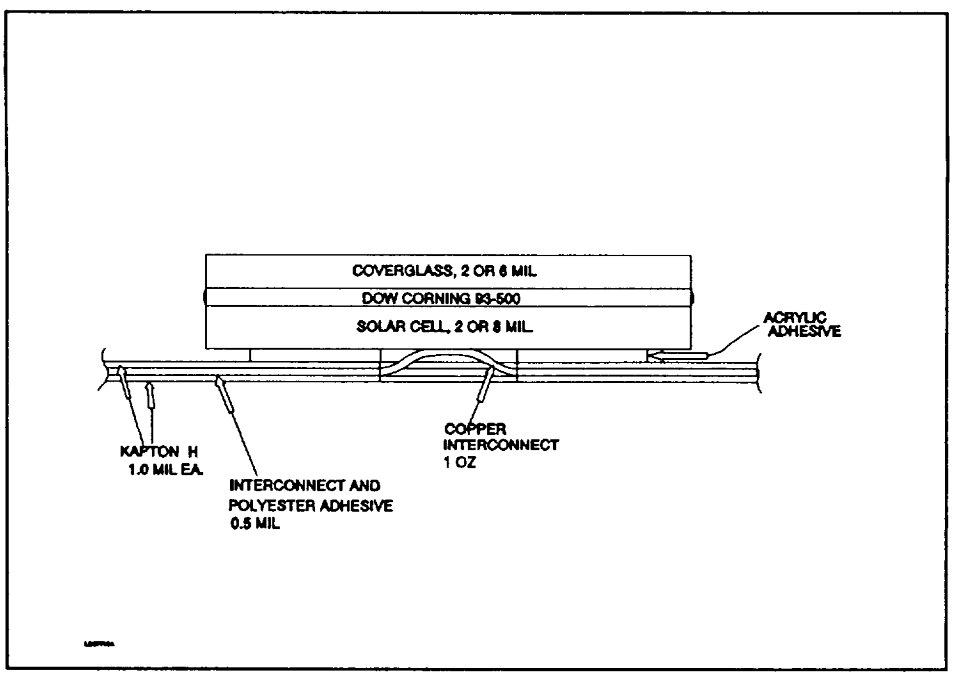

Figure 4. Cross-sectional sketch of MSFC SAMPLE solar cell test assemblies.

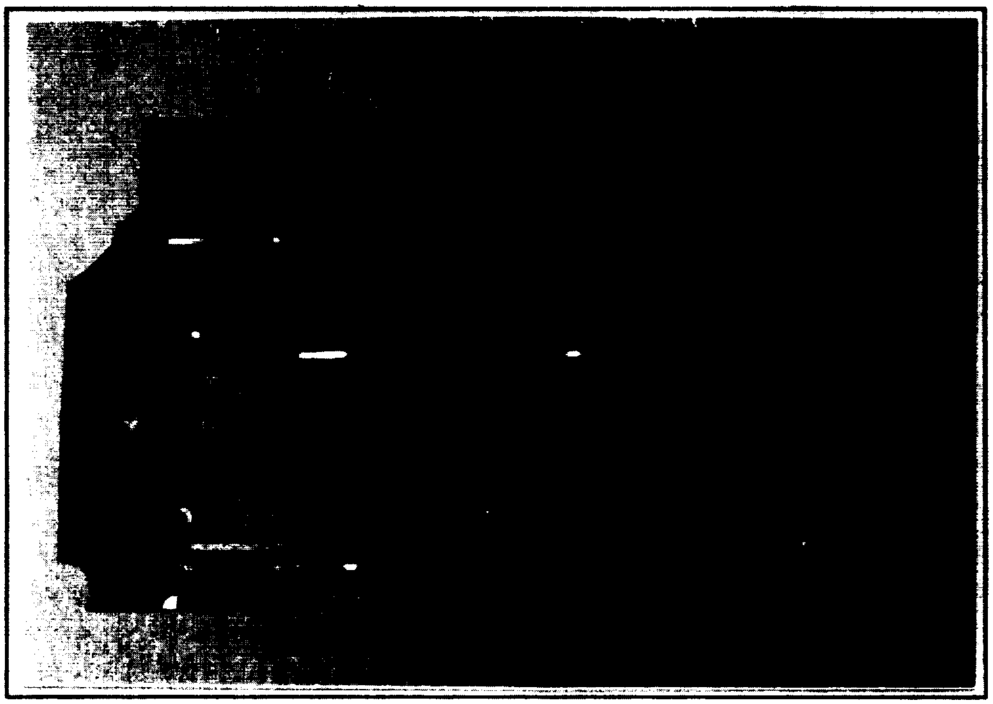

Figure 5. Postflight picture of SAMPLE Module 5 showing AO erosion of Kapton H substrate.

Figure 6. Scanning electron microscope image of SAMPLE solar cell wraparound contact erosion from AO.

Figure 7. Front surface damage to SAMPLE solar cell PC1L from micrometeorite/space debris impact to rear surface.

Figure 8. Scanning electron microscope image of micrometeorite/space debris crater on the rear surface of SAMPLE solar cell PC2R.

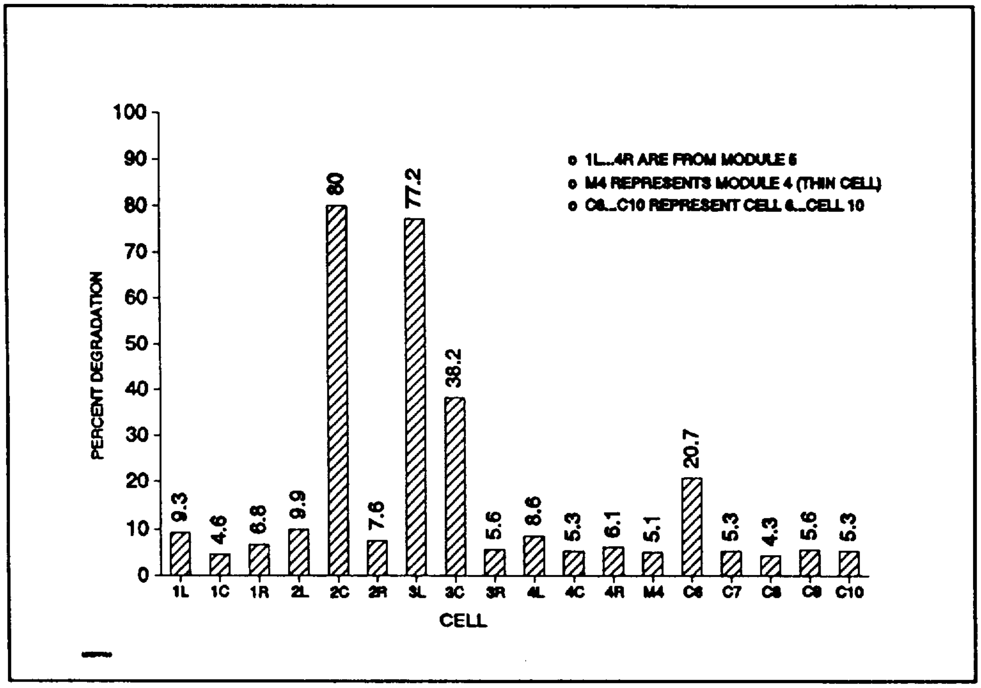

Figure 9. MSFC SAMPLE solar cell maximum power point degradation.

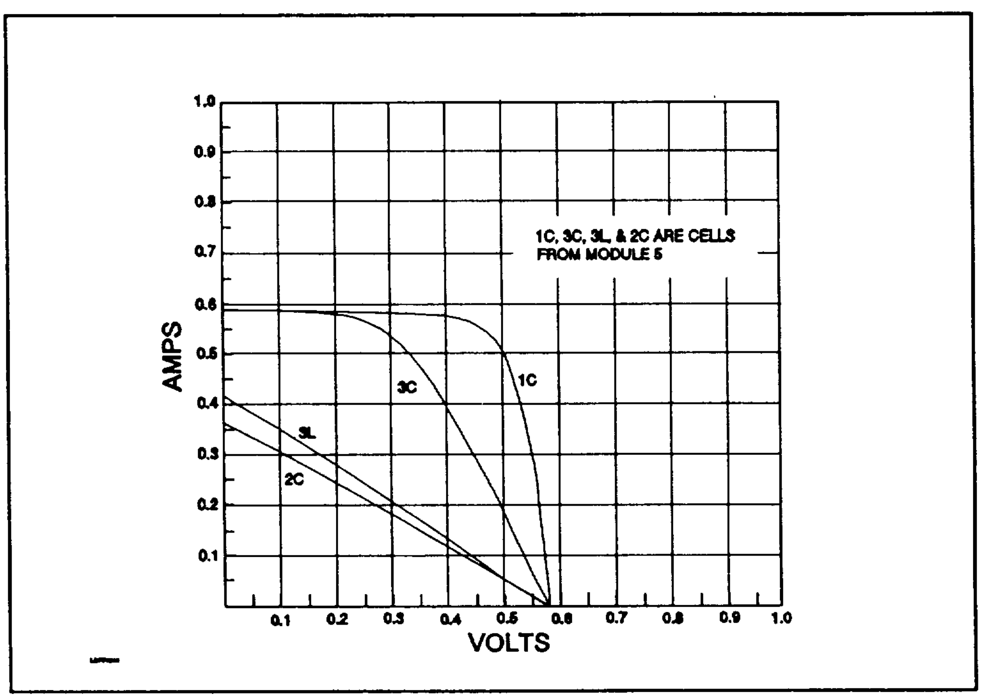

Figure 10. Range of SAMPLE solar cell Module 5 individual cell electrical performance.

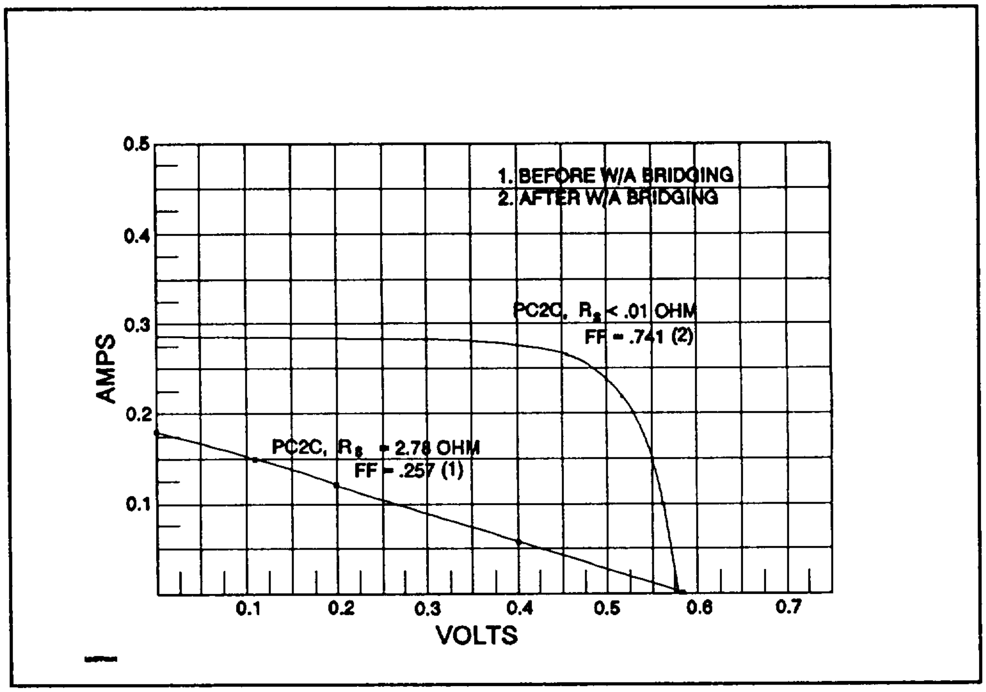

Figure 11. SAMPLE solar cell PC2C series resistance assessment.

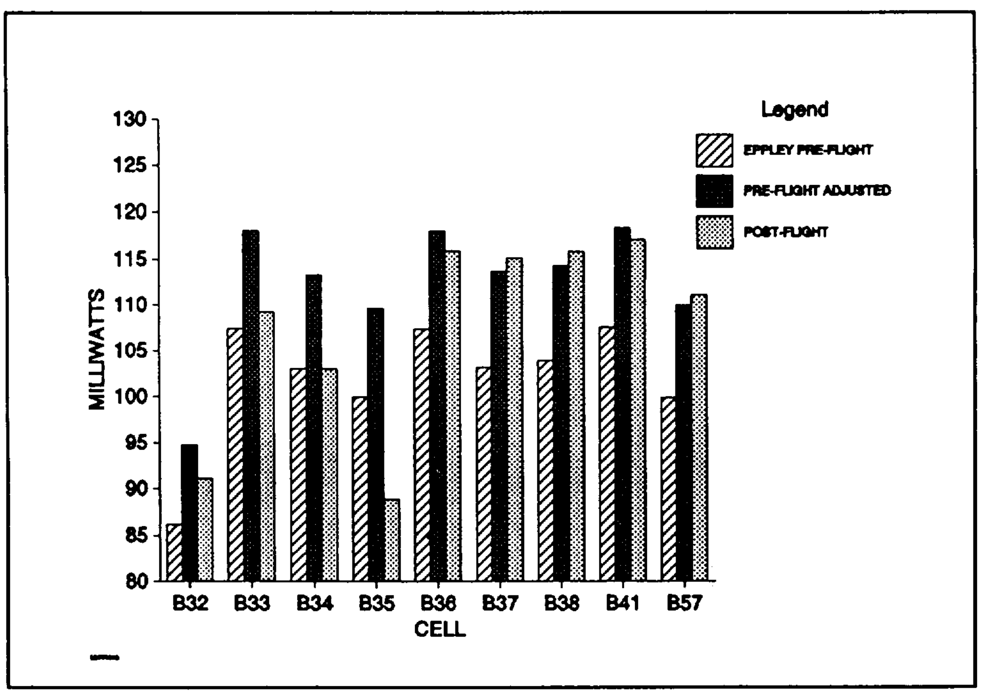

Figure 12. Pre- versus postflight maximum power point performance of APEX MSFC solar cell assemblies.