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ULTRAVIOLET IRRADIATION AT ELEVATED TEMPERATURES AND THERMAL CYCLING IN VACUUM OF FEP-A COVERED SILICON SOLAR CELLS

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ABSTRACT

Experiments were designed and performed on silicon solar cells covered with heat-bonded FEP-A in an effort to explain the rapid degradation of open-circuit voltage and maximum power observed on cells of this type included in an experiment on the ATS-6 spacecraft. Solar cells covered with heat-bonded and adhesive-bonded FEP-A were exposed to ultraviolet light in vacuum at temperatures ranging from 30° to 105° C. The samples were then subjected to thermal cycling from 130° to -130° C. These conditions were used in an attempt to simulate the conditions during the early stages of the ATS-6 flight. Inspection immediately following irradiation indicated that all the covers remained physically intact. However, during the temperature cycling heat-bonded covers showed cracking. The test showed that heat-bonded FEP-A covers embrittle during UV exposure and the embrittlement is dependent upon sample temperature during irradiation. The results of the experiment suggest a probable mechanism for the degradation of the FEP-A cells on ATS-6. Four months exposure to UV in orbit, at cell temperatures in excess of 60° C embrittled the FEP-A, leading to cracking during the thermal cycling experienced in the first eclipse period. The cracks allowed low energy protons to damage the junction as evidenced by the more rapid degradation of open-circuit voltage and maximum power of the FEP-A covered cells. In the same laboratory tests adhesive-bonded FEP-A covers showed partial separation from the cell surface but no cracking, suggesting that such damage might be avoided with an optimized adhesive bonding technique.

INTRODUCTION

Fluorinated ethylene propylene (FEP-A) has been proposed for use as a silicon solar cell cover in space (1 to 3). Laboratory test reports (4 to 7) on the radiation damage properties of FEP-A indicated that it could provide the cover material for a high power-to-weight ratio flexible array for long duration space missions. In the laboratory tests, it was not possible to simulate the conditions of the space environment. Consequently, the ultimate qualification test had to be the actual performance of FEP-A covered cells during a space flight. Such an opportunity for a real-time environmental test for FEP-A covered cells was offered on board the ATS-6 communication satellite, which was placed in synchronous orbit in June 1974. Analysis of the data from this in-flight experiment showed that during the earliest stages of the flight, FEP-A covered cells behaved the same as other experimental and monitor cells mounted on the test panel. The degradation rate of short circuit current (I_{sc}), open circuit voltage (V_{oc}) and maximum power (P_{max}) of all samples were similar. However, the FEP-A covered cells began to show a relatively higher degradation rate of V_{oc} and P_{max} during the first eclipse period of the satellite which started 90 days and ended 132 days after launch (8). This type of degradation has been previously observed when either bare cells or cells with minute uncovered areas were exposed to low energy proton irradiation (9).

It has been shown (7) that FEP-A cracks when flexed, following electron irradiation in vacuum. However, it has never been observed at such a low absorbed dose as that received by these cells during the initial portion of the ATS-6 flight. It was theorized therefore that the FEP-A covers became embrittled due to UV exposure at the reported cell temperatures range of 56° to 91° C. Subsequent thermal cycling, about 36 cycles, during the eclipse period caused cracks to develop, allowing low energy proton damage to occur.

To test this theory FEP-A covered silicon solar cells were subjected to UV radiation in vacuum at various temperatures and subsequently thermal cycled in the same vacuum chamber. For the experiments described in this report, the majority of specimens were prepared in the same manner as the heat-bonded samples on ATS-6. A few samples with FEP-A bonded to the cells with a silicone adhesive were also included to determine if the heat-bonding procedure contributes to the damage subsequently induced by the UV radiation and thermal cycling.

Test conditions were adjusted to simulate the early stages of the in-flight experiment. The effects of UV exposure and subsequent thermal cycling were assessed by cell I_{sc} measurements and by visual observation of the physical integrity of the cell covers. Measurements and observations were performed while the cells remained in the vacuum chamber.

EXPERIMENTAL APPARATUS AND PROCEDURE

The test consisted of irradiation of the covered cells with ultraviolet light at elevated temperatures followed by thermal cycling, all conducted in a 10^{-6} torr vacuum. Two separate runs were performed. The irradiation was performed at an intensity of 11 AMO UV energy equivalent solar constants. The apparatus is equipped with two UV sources (fig. 1). Three medium pressure "U" - shaped lamps, Hanovia type Z1500-211 approximately 800 watts each, are housed in Suprasil quartz tubes which extend to the center of the vacuum chamber and are spaced 120° apart. These lamps, located approximately 10 cm above the specimen holder, are cooled during the operation with gaseous nitrogen. Ten high pressure "U" shaped lamps, Hanovia 616A-13, type SH, 100 watts each are housed in a ring with an aluminum reflector, above a fused silica plate window at the top of the chamber. The lamps are approximately 25 cm above the specimen holder, and the ring is enclosed by an exhaust hood. The combined intensity of the two UV sources was measured at the specimen holder at the center of the chamber, by a Hy-Cal Engineering Rapid Response Radiometer with a 0.4 μm filter. The initial intensity was 11.6±5% AMO UV energy-equilvalent solar constants, and at the completion of a 300 hr run, the intensity was 10.5±5% AMO UV equivalent solar constants. It is estimated that the 300 hr exposure at an average intensity of 11 AMO UV energy equivalent solar constants in this experiment was equivalent to the UV dose absorbed in about 137 days (approx. 4-1/2 months) in synchronous orbit.

Twenty silicon solar cells with heat-bonded FEP-A covers were prepared in the same manner as those on ATS-6. Details of the preparation can be found in reference 3. Two silicon cells with 0.0127 cm thick FEP-A covers and 0.0025 cm thick Kapton substrates, bonded together with GE574 silicone adhesive were also prepared for this experiment, to determine if the heat-bonding contributes to the damage possibly induced by UV exposure and thermal cycling.

Prior to irradiation, the short circuit current (I_{sc}) of the cells was measured in-situ using three externally mounted tungsten halogen lamps. Two bare monitor cells were mounted on the speciment holder to serve as reference cells. The samples were then irradiated in one uninterrupted exposure. They were held in place by individual clamps which were electrically insulated from the mounting block. These clamps also served as contacts for electrical measurements. Several cells were instrumented with thermocouples for temperature monitoring during the experiment. Specimen holder cooling could be adjusted to the requirements of the test. Different temperatures were achieved by mounting cells on intermediate layers of Kapton. The following temperatures were measured during the irradiation:

(a) Specimen holder: 28°-32° C

(b) Bare-back cells: 30°-35° C

(c) Cells with one layer of Kapton: 55°-75° C

(d) Cells with two layers of Kapton: 85°-105° C

Short circuit current measurements and visual inspections were made after irradiation without removal from the vacuum system. The cells were then subjected to 70 thermal cycles, with low temperatures ranging between -110° and -130° C, and high temperatures ranging between 110° and 130° C. Visual inspection was conducted throughout the thermal cycling.

RESULTS AND DISCUSSION

The results of the two runs were essentially the same and are discussed here together.

Visual inspection immediately following the UV irradiation indicated that most of the covers had darkened to various degrees, but all remained physically intact. In-situ measurements of I_{sc}, whose accuracy was no better than ±5%, indicated I_{sc} reductions of about 4%, comparable to those previously observed (3) for cells kept at about 30° C during irradiation. However, in this experiment samples irradiated at higher temperatures showed greater reductions in I_{sc} as high as 9% for those irradiated at 85° to 105° C.

During thermal cycling, the heat-bonded FEP-A covers showed cracks which varied in width and appeared at different stages of thermal cycling, depending on specimen temperature during UV irradiation. These results are shown in table I. The heat-bonded FEP-A cracked sooner and more severely when the irradiation temperature was higher. It is assumed from these results that the heat-bonded FEP-A solar cell cover becomes brittle when exposed to UV radiation and that the embrittlement is worse the higher the cell temperature during exposure. Figures 2 to 4 are actual photographs of irradiated and thermal-cycled cells.

In contrast, the adhesive bonded FEP-A covers, showed a partial separation from the surface of the cells but no cracking (fig. 5). This suggests that the cracking of the cover and subsequent proton damage to the cells might be avoided with an optimized adhesive bonding technique. Lower temperature cover application would be beneifical since it avoids possible built in stresses, and the possibility of changes in the FEP-A, that could occur during heat bonding.

SUMMARY OF RESULTS AND CONCLUSIONS

An investigation was conducted in which silicon solar cells covered with FEP-A were irradiated in vacuum with ultraviolet light at an intensity of 11 AMO UV energy equivalent solar constants for 300 hr and then subjected to thermal cycling. These accelerated laboratory conditions are believed to be equivalent to those experienced by FEP-A covered cells on the ATS-6 spacecraft during the early stages of its flight.

The following results were obtained:

(a) FEP-A heat-bonded covers cracked during thermal cycling following the UV exposure.

(b) The severity and onset of cracking during thermal cycling was a function of the temperature of the cells during irradiation.

(c) FEP-A covers, adhesive bonded, partially separated from the cell surface during thermal cycling but did not crack.

The results indicate a probable mechanism for the faster degradation of the FEP-A covered cells on the ATS-6 satellite. Heat-bonded FEP-A covers apparently embrittle sufficiently when exposed to four months of space UV radiation at elevated temperatures, to crack when subjected to thermal cycling during the eclipse period. Low energy proton radiation can then penetrate to the junction of the cell and cause degradation of the open circuit voltage and maximum power to occur. An alternate method of application of FEP-A [illegible]h as with adhesives, may prevent such cracking from occurring.

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TABLE I. - COMPARISON OF EXTENT OF DAMAGE TO FEP-A COVERS, CAUSED BY UV IRRADIATION AT VARIOUS TEMPERATURES FOLLOWED BY THERMAL CYCLING

Description of sample	Temp. during UV irradiation, °C	Number of samples	Number of thermal cycles before onset of damage	Number of samples damaged	Extent of damage
Heat-bonded FEP-A	85-105	3	4-6	3	Wide cracks after 4-6 cycles; Very severe cracking and peeling after 70 cycles.
Heat-bonded FEP-A	55-75	2	26	2	Wide cracks after 26 cycles; Severe cracking and blistering after 70 cycles.
Heat-bonded FEP-A	30-35	15	70	3	Very slight cracking and indication of blisters after 70 cycles.
Adhesive-bonded FEP-A	85-105	2	11	2	Partial separation from surface of cell after 11 cycles; no cracking after 70 cycles.

APPARATUS FOR ACCELERATED UV IRRADIATION AND IN-SITU MEASUREMENTS

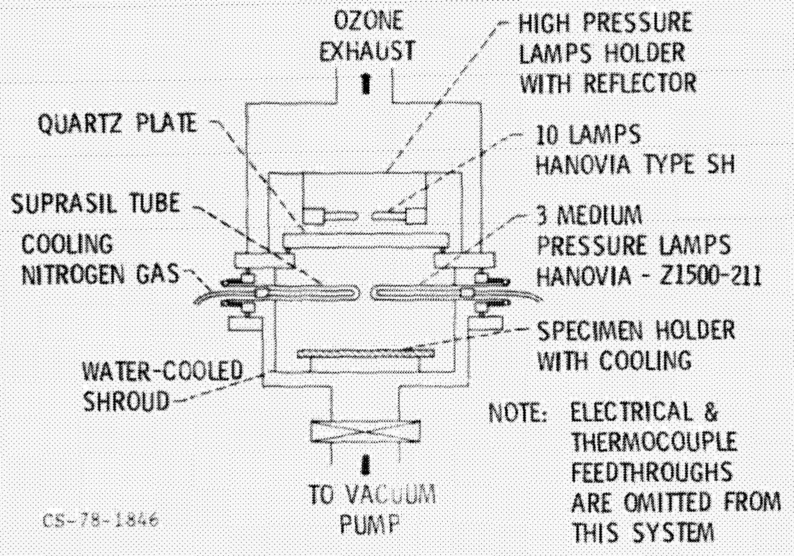

Figure 1.

HEAT-BONDED FEP COVER TEST

UV (30^0-35^0 C)/70 THERMAL CYCLES (-130^0 + 130^0 C)

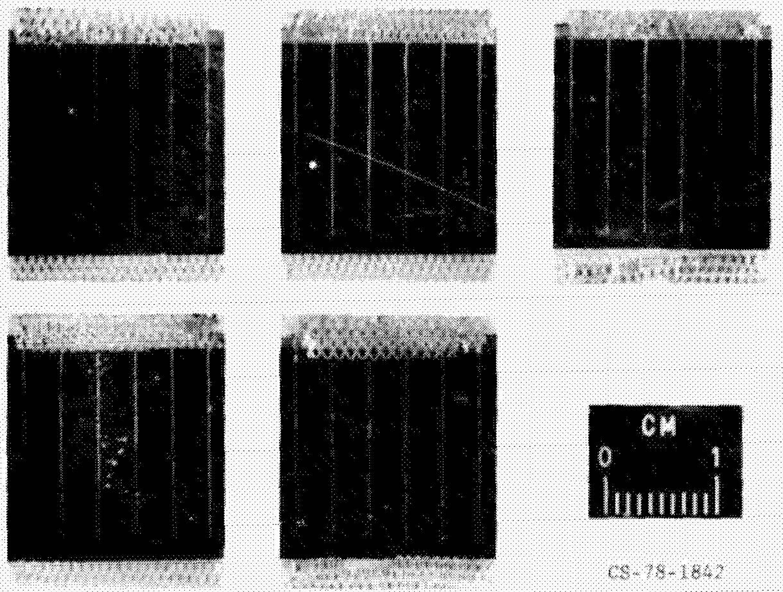

Figure 2.

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HEAT-BONDED FEP COVER TEST

UV (55^0-75^0 C)/70 THERMAL CYCLES (-130^0 + 130^0 C)

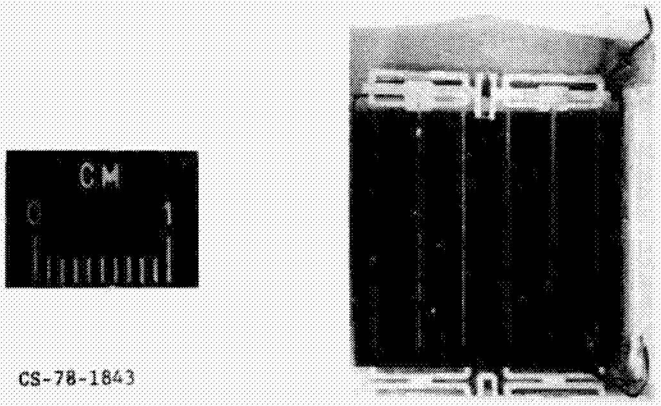

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Figure 3.

HEAT-BONDED FEP COVER TEST

UV (85^0-105^0 C)/70 THERMAL CYCLES (-130^0 + 130^0 C)

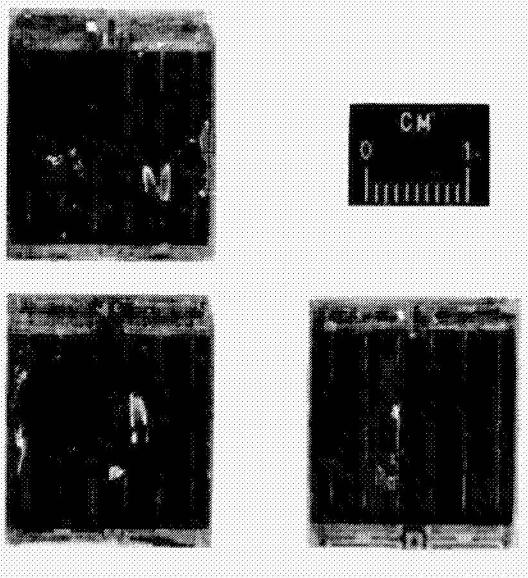

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Figure 4.

ADHESIVE BONDED FEP COVER TEST

UV (85^0-105^0 C)/70 THERMAL CYCLES (-130^0 + 130^0 C)

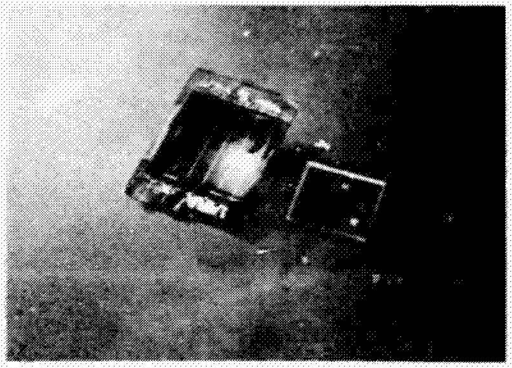

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Figure 5