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EFFECT OF ELECTRON IRRADIATION IN VACUUM ON FEP-A SILICON SOLAR CELL COVERS

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EFFECT OF ELECTRON IRRADIATION IN VACUUM ON FEP-A SILICON SOLAR CELL COVERS

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SUMMARY

Fluorinated ethylene-propylene-A (FEP-A) covers on silicon solar cells were irradiated with 1-MeV electrons, in vacuum, to an accumulated fluence of 2.5x10^15 electrons/cm² (6.75x10^7 rads of absorbed dose for FEP-A material) equivalent to approximately 28 years in synchronous orbit. The effect of irradiation on the light transmittance of FEP-A was checked by measuring the short-circuit current of the cells after each dose increment, immediately after the irradiation and again after a minimum of 16 hours of elapsed time. The cells remained in vacuum for all these measurements. The results indicate no apparent overall loss in transmission due to irradiation of FEP-A. However, filter window measurements revealed a "darkening" of the FEP-A at the blue end of the spectrum, as evidenced by a small loss of current at the short wavelengths. The FEP-A solar cell cover was also tested for embrittlement. Although no delamination from the cell surface was observed while in vacuum, embrittlement of FEP-A occurred at this accumulated dose. The electron fluence at which the FEP-A cover embrittles and cracks when subjected to bending tests was determined to be about 2.5x10^15 electrons per square centimeter (6.75x10^7 rads of absorbed dose).

EXPERIMENTAL APPARATUS AND PROCEDURE

Fluorinated ethylene-propylene-A (FEP-A) has been proposed as a solar cell cover for use in outer space (Ref. (1)). The radiation damage properties of FEP-A must be determined before it can be considered for use as a solar cell cover material in a radiation environment. One of the most important properties to be evaluated is its light transmittance after radiation exposure. In general, organic materials tend to darken upon exposure to heavy doses of ionizing radiation. It is, therefore, important to determine whether FEP-A film darkens when it is exposed to radiation. Another important property to be examined after exposure to radiation is the brittleness and the strength of the material. This information is required of the FEP-A to be used for solar cell array packaging which have to be folded or rolled up after exposure to ionizing radiation.

For the experiments described in this report, a thickness of 0.0127 centimeter was chosen because it is the closest commercially available thickness to the standard 0.015-centimeter (6-mil) cover glass. In previous investigations of this material the results were either obtained from testing in air after irradiation in vacuum (Refs. (1) and (2)) or not directly related to light transmittance (Refs. (3) and (4)). Most of the investigators concur that the absence of oxygen during the irradiation and the evaluation of the effects of irradiation in air are responsible for marked changes of the physical, electrical, and optical properties of FEP-A. To preclude any unknown effects that may occur if the simulated exposure is done in one environment and the measurements are made in another, the measurements should be performed in the same environment as the exposure. This report presents in-vacuum measurements of the effects of 1-million-electron-volt (1-MeV) electron irradiation on FEP-A light transmittance and observations of the physical integrity of FEP-A after irradiation. The 1-MeV electron fluence at which the brittleness of FEP-A begins in a completely encapsulated package was also determined and is included in this report.

The effects on the light transmittance were measured by comparing the radiation-induced loss in short-circuit current of the FEP-A covered cells with the corresponding loss experienced by an uncovered cell of the same type. During each measurement, the FEP-A was observed for possible loss in adherence to the cell surface. After the final irradiation the FEP-A was also tested for embrittlement and delamination in an argon atmosphere before exposure to air.

The electron fluence at which the brittleness begins was determined by flexing of the FEP-A encapsulated package in which FEP-A backed by Teflon was used as a hinge.

EXPERIMENTAL APPARATUS AND PROCEDURE

The tests for the FEP-A light transmittance and for its embrittlement, while in vacuum and subjected to ionizing radiation were conducted in a vacuum-tight chamber especially equipped with necessary ports for electron beam irradiation and solar simulator measurements and with electrical and thermocouple read-throughs (Fig. 1). The chamber can be sealed while under high vacuum, decoupled from the beam transport pipe of the electron accelerator, and transported to the solar simulator facility for measurements of various parameters.

The vacuum leak rate of this apparatus is approximately 2x10^-5 torr per minute. This allows almost 1 hour for handling in transport after decoupling from the vacuum system before the pressure within the chamber rises above the 10^-5 torr range. This was only necessary to transport the chamber when performing light transmittance evaluation at the solar simulator facility. In this experiment the time in transport was less than 15 minutes, and the chamber was immediately connected to another vacuum system. The pressure inside the vessel during the irradiation was 1x10^-6 torr. Thus, during this experiment the samples were not subjected to a pressure higher than 3x10^-4 torr until after the final irradiation and measurements.

The quartz view ports were protected from radiation damage by 0.3-centimeter-thick aluminum shields fitted on the inside along the contour of the vessel. These shields, the specimen holder, and all other accessories involved in these experiments were mounted on a rotatable platform. The rotation of the platform was controlled electrically from the outside of the vacuum chamber.

The 1-MeV electron beam was provided by the Dynamitron potential-drop accelerator. The beam was focused to a vertical line of good uniform density and then moved to scan a 4- by 10-centimeter rectangular area uniformly. This allowed simultaneous irradiation of up to four 2-cell modules. The dose received by the cells was measured directly by a Faraday cup behind a 0.3-centimeter-diameter entrance aperture. The charge intercepted by the Faraday cup was measured by a cur-
Solar cell electric output measurements were made by using individually insulated contacts, which also served to hold the cells in place. No attempt was made to control the temperature of the specimen holder; however, this temperature and the temperature of the cells were monitored with thermocouples. The specimen holder arrangement is shown in Fig. 2.

For each set of electrical measurements the light-beam intensity was set for air-mass-zero conditions at the test plane by monitoring the short-circuit current of two reference cells positioned on the specimen holder outside the electron-beam target area and further protected by a moveable shield during the irradiation. The reference current value for these cells was established before the experimental measurements by using Lewis filter wheel solar simulator currents (Ref. 1). The reference cells were rechecked after the experiment to ensure that air-mass-zero conditions were maintained.

Procedure for the Light Transmittance Test

Prior to the experiment the following 10 ohm-centimeter, 0.0035-ohm-centimeter (12-Mev) thick silicon solar cells with silicon monoxide (SIO) antireflection coating were selected at random: three 2- by 2-centimeter FEP-A covered cells prepared by a siliola

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cause of the omnidirectional nature of space radiation. This additional effect can be reasonably estimated from Table 6.2 of Ref. (7), which gives the absorbed dose in air under a shield in a synchronous, zero-inclination orbit. With a shield of FEP, Kapton, silver contact, and silicon having a combined thickness of 0.1206 gram per square centimeter, the absorbed dose under this shield is approximately 2.5x10^5 rads per year. Thus, the total dose in the FEP cover in synchronous orbit is about 2.4x10^7 rads per year. Thus, the absorbed dose in this experiment, corresponding to an accumulated 1-MeV electron fluence of 2.5x10^16 electrons per square centimeter, would be equivalent to the dose absorbed in about 28 years in orbit.

For comparison purposes Fig. 3 shows data from this Investigation superimposed on the normalized Iac data from Ref. (7) for uncovered 7- to 13-ohm-contact FEP cells, 0.0205 centimeter thick illuminated at 135 milliwatts per square centimeter. The spread of the experimental data points may be attributed mainly to measurement reproducibility errors. The uncertainty of the accumulated fluence, based on previous experience, is a maximum of 10 percent.

No Iac changes were observed between measurements taken immediately after irradiation and those taken after a minimum time lapse of 16 hours. This agreement indicates no annealing in vacuum of either the FEP-A cover or the cells.

The FEP-A cover does not change its transparency, as indicated by total Iac measured under the solar simulator, even at an accumulated 1-MeV electron fluence of 3.5x10^16 electrons per square centimeter (6.75x10^5 rads of absorbed dose).

A photograph of the cells inside the vessel was obtained after the final irradiation increment, while they were still in vacuum, and it is shown in Fig. 2. No delamination of FEP-A or any other visible damage occurred to the cells. The cells were fully supported and subjected to no extraneous stresses, and they remained in this state until probed with a sharp object in an argon atmosphere. Probing revealed that the FEP-A film was brittle after the 1-MeV electron fluence of 2.5x10^15 electrons per square centimeter. Attempts to lift and peel the FEP-A from the surface resulted only in removal of the cover immediately under the probe.

Measurements and Observations in Air Following the Light Transmittance Test

Upon removal of the cells from the argon atmosphere, Iac and V0C measurements were again made. The readings were in very close agreement with those obtained while the cells were still in vacuum. These measurements were repeated at about 0.5 rad per hour. No changes were observed, which indicated that no annealing had taken place in several hours. Measurements made on the quartz glass windows revealed that no disorientation of the glass occurred during irradiation.

Immediately upon exposure to air, the FEP-A covered cells were measured in the filter wheel setup. A filter-by-filter analysis of the current indicated that "darkening" of the FEP-A in the violet to blue-violet region of the spectrum occurred. Changes in the selected wavelength interval short-circuit current of the cells are tabulated in Table III and are given as the percent of the initial current. For the FEP-A covered cells the value is the average of measurements of three cells. The uncovered cell value is then for one cell only. Normally the Iac of a cell in the range from 0.4 to 0.5 \( \mu \)m does not change upon irradiation. This can be seen from the values of the uncovered cell for 0.4, 0.5, and 0.6 \( \mu \)m and for the FEP-A covered cells at 0.6 \( \mu \)m. The 103.5% value given for the uncovered cell current change at 0.6 \( \mu \)m should not be interpreted as a real increase in current. It is more probably due to the cell current in determin- ing a small change in current of low current values (approximately 0.1 mA). The decrease for the FEP-A covered cells is indicative of a loss in transparency of FEP-A in the 0.4 and 0.6 \( \mu \)m. This is not unexpected, since most organic materials darken during irradiation.

For FEP-A this darkening affects the ultraviolet and blue portions of the spectrum. Because of the low sensitivity of the cell in this region of the spectrum, the increased short wavelength absorption has a minimal effect on the overall current output of the cell as measured under a Spectrolab X-25 solar simulator.

The current normally associated with the 0.4 \( \mu \)m region is 3 to 6 mA, and thus the loss of 10% shown in Table III would represent about 0.5 mA. An additional loss of 0.5 mA (6% of 8 mA) would be expected from the 0.45 \( \mu \)m spectral region. The total loss of 12% is within the limits of error (70%) of the filter wheel solar simulator system. Since the measurements were made immediately upon removal from the vacuum system, it is assumed that the darkening occurs during irradiation and exists in vacuum. It should be noted that the corresponding loss for high blue response cells would, of course, be greater than that observed in this experiment which employed normally diffused SiO-coated cells.

Within three weeks after exposure to air, other changes were noted in the FEP-A covered cells. One cover cracked and lifted from the cell surface separating at the SiO-to-cell interface. The color of the coatings on the remaining cells faded. Fig. 4 shows the condition of all four cells after 16 days in air. Both phenomena can be explained by the reactions that occur when FEP-A is irradiated and then exposed to oxygen. Electron irradiation causes scission of the long chain molecules with the release of some active form of fluorine (Ref. (8)). When the split chains are exposed to oxygen in the air, they react with the oxygen and further degradation occurs (Ref. (9)). It can be postulated that the active form of fluorine can react with the SiO coating to change its color and optical properties and/or release it from the cell surface. It is quite possible that in attacking the SiO coating the active fluorine species causes the release of some form of oxygen from the SiO coating, leading to damage of the FEP-A even in vacuum. A possible solution to this problem would be the use of nonoxide AR coating such as Siliq which has been shown to be compatible with FEP-A technology (Ref. (10)).

Determination of Electron Fluence at Which the Brittleness of FEP-A Begins

An absorbed dose at which the FEP-A used as a solar cell cover becomes too brittle to be bent through an angle of about 120°, was determined by flexing a mod- ulae. The flexing angle between 10° and 120° led to a result if the solar array was rolled on an 8-inch diameter cylinder. A minimum of two flexes would be re- quired for one operational cycle. The naphs were examined after 2, 5, 10 flexes, etc. Fig. 5 shows the range of flexes for several values of electron fluences, within which a striking crack in the FEP-A occurred. The upper value indicates the number of flexes when a crack was first observed;
the lower value "indicates the number of times at the prior examination." It should be noted that at the electron fluence of 1x10^15 cm^-2 no break was observed after 200 fluxes and no attempt was made to establish the breaking point beyond this number of fluxes. The curve through these data indicates the probabie number of fluxes needed to produce a hairline crack in the PEP-A cover, at various 1-MeV electron fluences. The critical electron fluence at which PEP-A sustains at least two fluxes prior to cracking is about 2.5x10^15 cm^-2, which is equivalent to 6.75x10^7 rads of absorbed dose. At this critical fluence the Kapton-PEP-20C bond also separates. The data in Fig. 5 was obtained from 26 samples. The electron fluence at which the PEP-A embrittles and separates into two pieces, determined by using the "dummy" two-cell module, is between 2.5x10^15 cm^-2 and 5x10^15 cm^-2.

**SUMMARY OF RESULTS**

The following results were obtained from an investigation in which silicon solar cells covered with fluorinated ethylene-propylene-A (PEP-A) were irradiated in vacua by 1-MeV electrons to a fluence of 2.5x10^14 cm^-2 (equivalent dose in the PEP-A cover of approximately 6.75x10^7 rads, equivalent to the dose absorbed in about 28 years in a synchronous equatorial orbit):

(a) The cells showed no delamination and no more loss of short-circuit current than that experienced by an uncovered cell. There was no apparent darkening of PEP-A, which would have reduced the short-circuit current more than the reduction caused by the irradiation of an uncovered cell.

(b) Measurements of the currents in air under the filter wheel simulator indicate a loss in transmission of the PEP-A in the violet to blue-violet region of the spectrum.

(c) At a 1-MeV electron fluence of 2.5x10^16 cm^-2 the PEP-A was very brittle. The critical fluence at which the PEP-A cover is too brittle to sustain at least two fluxes comparable to those typical of a "roll-up" array was found to be 2.5x10^15 cm^-2 (6.75x10^7 rads of absorbed dose).

**REFERENCES**


### TABLE I. OPEN-CIRCUIT VOLTAGE OF FOUR SOLAR CELLS BEFORE AND AFTER IRRADIATION

<table>
<thead>
<tr>
<th>Cell</th>
<th>Cover</th>
<th>Open-circuit voltage before irradiation, $V_{oc, 0}$</th>
<th>Open-circuit voltage after irradiation, $V_{oc, 1}$</th>
<th>Ratio of open-circuit voltage, $V_{oc, 1}/V_{oc, 0}$</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>FEP-A</td>
<td>0.55</td>
<td>0.47</td>
<td>0.85</td>
</tr>
<tr>
<td>2</td>
<td>FEP-A</td>
<td>0.54</td>
<td>0.46</td>
<td>0.85</td>
</tr>
<tr>
<td>3</td>
<td>None</td>
<td>0.54</td>
<td>0.46</td>
<td>0.85</td>
</tr>
<tr>
<td>4</td>
<td>FEP-A</td>
<td>0.54</td>
<td>0.47</td>
<td>0.87</td>
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### TABLE II. SHORT-CIRCUIT CURRENT OF SOLAR CELLS BEFORE AND AFTER IRRADIATION

<table>
<thead>
<tr>
<th>Cell</th>
<th>Cover</th>
<th>1-MV electron flux, electrons cm$^{-2}$</th>
<th>Short-circuit current</th>
<th>Percent of initial $I_{sc}$ after Irradiation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$I_{sc, 0}$</td>
<td>$I_{sc, 0}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$I_{sc, 1}$</td>
<td>$I_{sc, 1}$</td>
</tr>
<tr>
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<td></td>
<td>$I_{sc, 0}$</td>
<td>$I_{sc, 0}$</td>
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<td></td>
<td>$I_{sc, 1}$</td>
<td>$I_{sc, 1}$</td>
</tr>
<tr>
<td>1</td>
<td>FEP-A</td>
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<td>1.0</td>
<td>116</td>
</tr>
<tr>
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<td>FEP-A</td>
<td>132</td>
<td>1.0</td>
<td>115</td>
</tr>
<tr>
<td>3</td>
<td>None</td>
<td>137</td>
<td>1.0</td>
<td>112</td>
</tr>
<tr>
<td>4</td>
<td>FEP-A</td>
<td>133</td>
<td>1.0</td>
<td>119</td>
</tr>
</tbody>
</table>

### TABLE III. PERCENT OF INITIAL $I_{sc}$ AFTER IRRADIATION OF CONVENTIONAL SiO COATED AND FEP-A COVERED CELLS

<table>
<thead>
<tr>
<th>Wavelength, $\lambda$, $\mu$m</th>
<th>Percent of initial $I_{sc}$ after Irradiation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FEP-A covered average of three cells, percent</td>
</tr>
<tr>
<td>0.6 - 0.95</td>
<td>86.5</td>
</tr>
<tr>
<td>0.5</td>
<td>99.5</td>
</tr>
<tr>
<td>0.45</td>
<td>93.9</td>
</tr>
<tr>
<td>0.4</td>
<td>90.5</td>
</tr>
</tbody>
</table>
Figure 1. - Top view of experimental apparatus for irradiation.
Figure 2. - Cells in vacuum after last irradiation. Test cells 2 by 2 centimeters; reference cells, 1 by 2 centimeters.

Figure 3. - Normalized short-circuit current as function of 1-MeV electron fluence. Total dose absorbed by FEP-A cover, 6.7x10^9 rads.
Figure 4. - Cells irradiated at 2.5-10^{16} electrons per square centimeter after 14 days in open air. Cell 2 shows cracked FEP-A and delamination, and cell 4 shows effects of probing.
Figure 5. Number of flexes sustained by FEP-A cover at various 1-MeV electron fluences.

- Number of flexes at which FEP-A cracks were not determined at this fluence.