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FEP COVERS FOR SILICON SOLAR CELLS

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ABSTRACT

The results of a program designed to evaluate the feasibility of utilizing FEP (fluorinated ethylene propylene) as a replacement for conventional silicon solar cell covers are presented. Techniques for heat sealing FEP to individual solar cells and modules are described with emphasis upon the effects of processing parameters on the optical and electrical characteristics of the cells. Evaluation of the effectiveness of the processing based on visual examination of bond integrity, solar cell damage, bond strength tests, and electrical output under simulated sunlight is discussed.

The effects of environmental testing on single cell and module performance are documented. Tests consisted of exposure to high humidity and temperature, thermal shock, ultraviolet, proton and electron irradiation.

A direct comparison between FEP and conventional glass cover materials is provided with respect to optical and physical properties, application techniques, environmental stability and economic considerations. Test results of this program indicate no apparent drawbacks to the use of FEP covers for solar cells. Potential advantages appear to be realizable.

ONE OF THE MAJOR CONSIDERATIONS facing the designers of future large solar cell arrays is cost. Conventional solar cell covers and their application procedures tend to add a sizeable amount to solar array fabrication costs. The primary purposes of solar cell covers are to provide protection from penetrating radiation and to lower the operating temperature of the cells via high infrared emittance. Conventional solar cell arrays employ covers composed of 6-20 mil glass or fused silica, adhesive bonded to the cells. In order to protect the adhesive from damage induced by solar ultraviolet radiation, it is generally necessary to coat the cover glass with a multilayer film which does not transmit UV radiation. In addition, the front surface of the cover glass is provided with a low refractive index coating in order to obtain lower front surface reflectance losses.

The Lockheed Missiles and Space Company's Palo Alto Research Laboratory has developed a novel approach to solar cell radiation protection and temperature control, using FEP (fluorinated ethylene propylene) as a solar cell cover material. The flexible dielectric film is suitable for application to large area solar arrays by direct heat sealing techniques. The favorable cost, simplicity and fabrication ease can provide a marked advance in the state-of-the-art of solar array manufacturing. In an effort to evaluate the feasibility of utilizing FEP as a replacement cover for conventional silicon solar cells a contract was initiated. Concurrently with this contract NASA Lewis has an in-house program to evaluate FEP as a silicon solar cell cover material and as an adhesive for mounting the solar cells to a flexible substrate. (1)*

The contract program was designed to optimize the process for heat sealing FEP to individual solar cells and modules and determine the performance and integrity of the FEP/solar cell packages under simulated conditions typical of space applications. The effects of time, temperature, pressure, cleaning and other controllable processing parameters were investigated during the optimization phase. Evaluation of the process was based on visual examination, optical transmission, cell damage, bond strength and electrical output of the solar cells. The effects of environmental testing on single cell and module performance were also investigated.

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*Numbers in parentheses designate References at end of paper.

Abbreviated testing of covered individual cells included exposure to high humidity and temperature, thermal shock, ultraviolet, proton and electron irradiation. More extensive environmental tests of the same parameters were also conducted and provided detailed performance data of individual cell and modules as a function of exposure duration. Evaluation was based on the characteristics noted above. The results reported are primarily those from the contract program. In-house program results are included where applicable.

A direct comparison between FEP and conventional glass cover material is presented with respect to optical and physical properties, application techniques, environmental stability and economic considerations.

APPARATUS AND TESTS

The investigation was limited to heat sealing 5-mil Type C FEP film. The Type C film is treated on one surface for better bonding at temperatures above 210° C without significant flow of the material. Initial studies on heat sealing of FEP were conducted on Class II (with cosmetic defects) solderless silicon solar cells with good electrical performance. Efforts were restricted to platen press procedures using silicone pads in conjunction with a polyimide parting sheet. Prior studies have substantiated that polyimide is an excellent parting material which separates easily from the FEP surface, imparts a smooth surface finish and does not affect the FEP transmission.

To optimize the heat sealing process, cells were covered at pressures between 50 and 5000 psi at temperatures between 230° C and 270° C. The cells were held at temperature for times between 15 sec. and 30 min. Cleaning of the cells and FEP was made according to recommendations by the FEP manufacturer. To evaluate the heat sealing process, current-voltage curves of the cells under simulated sunlight were measured prior to and subsequent to the heat sealing operation. The integrity of the bond was evaluated by probing with a scalpel and manual pull tests.

The techniques discussed above were extended to multicell modules which were fabricated in the following manner. Two-mil soft-rolled copper foil was first laminated to a one-mil layer of polyimide using one-mil FEP film as the adhesive. The foil was then photoexposed and chemically etched to form interconnects, soldering points for the back contacts and soldering tabs for the front contacts. Next, another one-mil layer of polyimide, prepunched to expose soldering points and tabs, was laminated on top using one-mil FEP as the adhesive. The soldering points and tabs were then coated with a nominal 1 μm thick film of electroless tin. This then formed a flexible substrate with integral interconnects. A string of five solar cells with FEP covers and flux-treated back surfaces were positioned on the substrate and the back contacts induction soldered in place. The top contact tabs were then bent in place and connected using solder preforms and reflow solder techniques. Three five-cell strings are installed on a substrate to form a fifteen-cell module configured with five cells in parallel and three strings in series (fig. 1).

Environmental tests on the FEP/solar cell packages included the following:

HIGH HUMIDITY AND TEMPERATURE - This test exposed FEP-covered cells simultaneously to 90 percent relative humidity and 40° C temperature.

TEMPERATURE CYCLING - Temperature cycling tests were of three types. The first or abbreviated test is a thermal shock test which consisted of exposing FEP-covered cells and bare cells alternately to dipping in liquid nitrogen for five minutes and holding in room air for a similar period. The samples were held in a loose wire cage so as not to impose mechanical restraints on the cells. The second test consisted of exposing FEP-covered cells and bare cells, mounted on a copper block, to thermal cycling in a vacuum of 10^{-6} torr. Each cycle consisted of cooling the copper block to a nominal temperature of -190° C, a five-minute soak, heating the copper block to a nominal temperature of 25° C, and another five minute soak. The third test consisted of exposing samples to thermal cycling in a vacuum where radiative heating and cooling were employed. Each cycle consisted of heating to 87° C in simulated sunlight for one hour and cooling to -108° C in darkness for one-half hour.

ULTRAVIOLET IRRADIATION - FEP-covered cells and bare cells were simultaneously exposed to ultraviolet radiation. The samples were maintained in a vacuum of 5×10^{-7} torr during exposure. The UV source was a 1000-watt high-pressure, Hg-Xe, AH6-type, water-cooled lamp. The intensity was nominally equivalent to a 10 "sun" level as specified by the lamp output between 0.2 and 0.3 micrometers at the sample distance.

PROTON IRRADIATION - FEP-covered cells and bare cells were exposed to 2-keV protons in a vacuum of 5×10^{-7} torr at room temperature. The proton flux was measured periodically using

Faraday buttons mounted on the rear of a rotatable sample table. The proton flux was relatively constant throughout the exposure.

ELECTRON IRRADIATION - FEP-covered cells and bare cells were subjected to electron irradiation using the Gulf Radiation Technology 25-MeV L-Band Linear Accelerator operating in pulsed mode at 2 MeV. Dosimetry was performed using a series of graphite Faraday buttons distributed over the geometrical position of the samples. The flux was within ± 5 percent over the total sample area. Samples were mounted on a water-cooled plate whose temperature rose to a maximum value of 23° C during irradiation. The sample chamber was maintained at a vacuum of $6\text{-}8\times10^{-7}$ torr during irradiation.

The results of the environmental tests were evaluated by current-voltage curves of the FEP-covered cells prior to and following the tests. Measurements were made at 25 ± 1° C using a high-pressure xenon lamp filtered to simulate the solar spectrum. The light source was calibrated with a balloon-flown standard solar cell to give the equivalent of AMO sunlight at an intensity of 140 mw/cm^2. Visual observations were made of the cells and bond integrity was determined by probing and pull tests of the covers.

RESULTS AND DISCUSSION

The results of the optimization of the heat-sealing process indicate that the process is rather insensitive to processing parameters if a critical temperature and pressure are exceeded. Quench-cooling of coated cells at zero load was found to provide somewhat superior adhesion compared to cooling under pressure, although qualitatively both techniques yield strong bonds. The processing parameters as determined from this effort are given in table 1.

The reproducibility of the heat-sealing process was demonstrated by measuring current-voltage curves of a number of solar cells before and after coating under optimum conditions. A typical curve is shown in figure 2. Characteristics before and after coating are identical within the limits of experimental reproducibility of the solar simulator and recording facility.

In order to assess the effect of surface finish on the electrical and optical properties of the FEP coating, one cell was coated with intentional gross surface defects produced by melting the FEP and deformation of the surface. Although the coated cell had non-uniform thickness, wrinkles and bubbles there was no appreciable reduction of transmission as noted from the values of short circuit current. To further assess the effect of surface finish, comparisons were made between a smooth-finish-coated cell (optimized) and a matte-finish-coated cell produced by interposing a nickel mesh during heat sealing. The relative short circuit current (SCC) for smooth and matte finish cells as a function of angle of incidence of illumination is shown in table 2. The relative SCC is defined as the ratio of the SCC of the FEP-covered cells, measured at the various angles, to the SCC of the uncovered cell.

The relative SCC for the smooth and matte finish cells are identical, indicating that transmission is independent of surface condition. The in-house program typically produces cells with a matte finish. Their results agree with those shown above.

The results of the environmental tests were as follows:

HIGH HUMIDITY AND TEMPERATURE - In an abbreviated test, twenty-five silicon solar cells with heat-sealed FEP covers were subjected to 90 percent relative humidity at 40° C for 72 hours. No indication of delamination or incipient bond failure was noted for any cell. In order to establish the effects of the exposure conditions, the cells, which were prepared with the FEP covers extending beyond the cell dimensions, were subjected to peel tests. The average value for peel strength for the twenty-five cells was 2.75 lbs/cell. The high and low values observed were 3.83 lbs/cell and 1.10 lbs/cell, respectively. All other cells had peel strengths between 2.0 and 3.5 lbs. A set of fifteen control cells prepared under the same conditions showed an average peel strength of 4.71 lbs/cell.

Although the adhesion of the tested cells degraded to approximately 60 percent of the initial average value under the severe conditions of temperature and humidity, the resulting bond strengths of the exposed cells were still high enough to maintain complete integrity. It is presumed that the reduction in bond strength is a result of water permeation of the FEP. Although the FEP has a relatively low moisture permeability in the "as received" condition (0.40 grams/100 in^2/24 hrs./mil), recent work at Gould, Inc. laboratories on the "Development of Improved CdS Solar Cells" (Contract NAS3-13467) has shown that the heat-sealing process increases the permeability to nearly 40 times greater than the manufacturer's specifications.

In order to assess the effects of long-term exposure to high humidity and temperature conditions, 20 FEP-covered cells were exposed at 40° C and 95 percent relative humidity. After 110 hours, slight delamination was noted on five of the cells and gross delamination on one side of a five cell string was observed. Evidence of some delamination on all cells was observed on all samples after 160 hours of exposure.

All cells exposed during this test were laminated at a nominal temperature of 250° C. Under these conditions the bond between the Type C FEP and the solar cell is created by the treated FEP surface rather than direct fusion of the FEP. Since the nature of the surface treatment is proprietary to DuPont, it is difficult to speculate on the cause of the bond failure. However, the following results indicate that heat sealing at higher temperatures improves the moisture resistance of the FEP cover assemblies.

Seven cells with FEP bonded at 290° C were exposed to 92 percent relative humidity and 28° C for one month with no bond failure. The same cells were then exposed to 90 percent relative humidity at 40° C for another month. Again no bond failure was observed.

TEMPERATURE CYCLING - Three FEP-covered cells and bare cells were exposed to ten thermal shock cycles in an abbreviated test. Evaluation of the cells following the test revealed no loss of adhesion or any other changes in the FEP/solar cell packages. Pre- and post-test measurement of electrical properties indicated no alterations due to thermal shock for either the bare or coated cells. The nature of this test, which is more severe than the thermal cycling experienced by solar cells during spaceflight, substantiate the integrity of the heat-sealed bond of FEP to silicon solar cells, despite the poor thermal expansion match for the materials.

Four FEP-covered cells were subjected to thermal cycles in vacuum between -190° C and 25° C. No evidence of mechanical or electrical output degradation was observed after 150 such cycles for single FEP/solar cell packages. However, for FEP-covered cells zone-soldered to flexible substrates, a catastrophic shearing of the solar cell has been observed. In this case, failure occurs within the silicon, the FEP and solder remaining bonded. Preliminary evidence indicates that the failure mode can be averted by uniform solder coverage on the solar cell back contact.

FEP-covered single cells and modules utilizing FEP both as the cover material and as an adhesive for mounting the solar cells to a flexible substrate were exposed to over 2000 temperature cycles between 87° C in simulated sunlight and -108° C in darkness at a pressure of 10^{-7} torr (2). The cells in the modules were interconnected without solder. The equilibrium temperature of the FEP-covered cells was within 2° C of commercial glass covered cells exposed in the same test. Pre- and post-test measurements showed no effect on the FEP/solar cell packages.

ULTRAVIOLET IRRADIATION - In an abbreviated ultraviolet radiation test, three FEP-covered cells and one bare cell were simultaneously exposed for 52 hours. The FEP-covered cells and bare cell behaved essentially identically with changes in short-circuit current, open-circuit voltage and maximum power being less than 1 percent as determined from pre- and post-test current voltage curves. It was concluded that the FEP cover suffered no optical degradation due to the abbreviated ultraviolet exposure and no mechanical property changes were observed upon subsequent evaluation.

Four FEP-covered cells and two bare cells were exposed to 2000 equivalent sun hours of ultraviolet radiation in a vacuum of 2×10^{-7} torr. Measurements of electrical output under simulated sunlight were performed prior to test and at nominal 500 equivalent-sun-hour intervals.

A typical set of I-V curves for an FEP-covered cell is shown in figure 3. It is evident that the bulk of the degradation occurs in the early stages of exposure and tends to saturate. The 3 percent reduction in short-circuit current is attributed to a slight reduction in transmission of the FEP in the ultraviolet and near-visible region. Bare cells exposed simultaneously exhibited no change in output characteristics. The slight reduction in cell output is not considered serious enough to compromise the utility of the FEP covers.

Subsequent periodic remeasurement of the irradiated cells over a period of 7 days showed no change from the characteristics measured within one hour from removal of the cells from the vacuum chamber. The lack of recovery effects tends to validate the measurement technique based on "in air" evaluation. No evidence of delamination or mechanical deterioration of the exposed cells was noted.

Four FEP-covered cells were exposed to 3600 ESH under ultraviolet radiation of about 7.5 "suns" in the in-house program. Pre- and

post-test measurements indicate that the SCC decreased by about 3 percent.

PROTON IRRADIATION - Three FEP-covered solar cells and one bare cell were exposed to 2-keV protons in an abbreviated test. The total integrated flux for the exposure was 2.08×10^{17} protons/cm^2 incident on the front surface of the samples. Figure 4 shows the effect of the proton exposure on the current-voltage characteristic of the bare cells. The well defined "knee" of the pre-test curve is lost upon irradiation indicating substantial radiation damage to the cell. A reduction in short-circuit current of 27 percent, in open-circuit voltage of 8 percent and in maximum power of approximately 67 percent is observed. In contrast, the FEP-covered cells retained their initial current-voltage curve structure while averaging reductions of 5 percent for short-circuit current, 2 percent for open-circuit voltage and 6 percent for maximum power (fig. 5). The losses are attributed to slight reductions in the transmission properties of the FEP induced by the large proton dose equivalent to over 30 years exposure in a synchronous orbit.

FEP-covered and bare cells were simultaneously exposed to 2-keV protons in vacuum, at an average dose rate of 1.3×10^{12} p/cm^2-sec. Using a rotatable sample table exposures of 1×10^{13} p/cm^2, 1×10^{15} p/cm^2, 1×10^{17} p/cm^2 were performed on four separate sets of samples consecutively. Upon termination of the test all samples were measured within a period of two hours.

Figure 6 summarizes the results in terms of reduction of short-circuit current as a function of proton fluence. Appreciable degradation was evident only for the 1×10^{17} p/cm^2 and 2×10^{17} p/cm^2 FEP-covered cells, the I-V curves for the cells exposed to lower proton doses being identical with pre-test measured values. The bare cells simultaneously exposed degraded substantially more than the covered cells, even at the 1×10^{15} p/cm^2 dose.

ELECTRON IRRADIATION - Six FEP-covered cells and three bare cells were subjected to 2-MeV electron irradiation. The flux was measured at 1.3×10^{12} electrons/cm^2-sec. and was applied for 7.7×10^3 seconds to give an integrated dose of 1×10^{16} electrons/cm^2. This is considered to be a severe test and the dose is equivalent to over 50 years exposure to synchronous orbit electrons of energy between 0.5 and 3.0 MeV. Following exposure of the samples in vacuum, the chamber was opened and the samples observed. Three of the six covered cells exhibited catastrophic failure in which the FEP and silicon oxide coatings on the cells separated exposing bare silicon surfaces. The grids remained bonded to the cells' front surfaces while the silicon oxide remained on the FEP. The three other cells showed simple delamination of the FEP-solar cell bond. The bare cells appeared unchanged. The separated FEP covers did not substantially embrittle and were capable of repeated flexing. However, embrittlement of the separated covers increased with time after removal from the vacuum chamber.

In order to establish a threshold for bond failure, similar tests were repeated for groups of 4 cells (3 covered and 1 bare) to fluences of 1×10^{15} and 1×10^{14} electrons/cm^2. For the 1×10^{15} electrons/cm^2 test, initial removal from the vacuum chamber indicated no delamination. However, over a period of 30 minutes delamination became increasingly severe under laboratory ambient conditions. After 24 hours complete delamination of all covered cells resulted. For the 1×10^{14} electrons/cm^2 fluence initial observations indicated no delamination. After 24 hours in air, however, probing with a tool showed there was negligible bond strength.

A typical pre- and post-exposure current-voltage curve for the 10^{16} electrons/cm^2 exposure with catastrophic failure is shown in figure 7, where a severe loss in output is evident. Figure 8 shows the results for a cell suffering simple delamination following exposure to 10^{16} electrons/cm^2. The post test measurements were made with the separated cover overlaying the cell and being held in place by the screws used for mounting to the sample plate. Some of the loss in short-circuit current may be due to reflection losses related to the incomplete FEP/solar cell bond. Comparison with a bare cell exposed to the same conditions (fig. 9) shows that the loss in performance was primarily due to the electron damage to the cell. A 5-mil cover of either FEP or fused silica does not provide much protection against 2-MeV electrons because the electrons have a range much greater than the thickness of the material. The FEP apparently suffered little loss in transmission. Similar results were seen after exposure to 10^{14} and 10^{15} electrons/cm^2.

One-MeV electron irradiation tests in the in-house program show essentially the same results. In one test however, silicon cells with a non-oxide antireflection coating were covered with FEP and exposed to 10^{16} electrons/cm^2 at 1 MeV in vacuum. There was no delamination of the FEP when the cells were removed from the vacuum chamber. However, some cracking of the

FEP was noted on one sample. The cells were immediately stored in a vacuum desicator and periodically observed. After four months the cells were removed and examined. The FEP did not delaminate. When the covers were probed with a scalpel, the FEP tended to crack into small pieces indicating embrittlement; however, the bond integrity was not adversely affected. It is well known that free radicals are formed in FEP when it is exposed to ionizing radiation. If the free radicals combine with oxygen in the bond layer of the FEP/solar cell package chains can be broken and affect the bond strength. In the bulk material, cross linking appears to cause embrittlement.

COMPARISON OF FEP AND CONVENTIONAL COVERS - As stated earlier the primary purposes of solar cell covers are to provide protection from penetrating radiation and to lower the operating temperature of the cells via high infrared emittance. Although conventionally protected solar arrays have been successful in providing reliable power for numerous spacecraft missions, many limitations exist. For many missions, the use of 2-4 mil covers would be adequate for both thermal control and radiation protection. Although this would provide significant weight savings, especially for large arrays, it is not feasible since such thin fused silica is not currently available on a production basis at a reasonable cost. Even 3-mil-thick cover glasses provide a significant price penalty compared to 6-mil fused silica. An additional factor is the tendency of conventional solar cell cover application procedures to add a sizeable amount to solar array fabrication costs.

Many of the problems described above can be overcome by the use of FEP as the solar cell cover material. In addition to providing equivalent radiation and temperature control properties, significant savings in cost, weight and manufacturing operations can be effected.

Availability of the FEP film in thicknesses ranging from 0.5 to 20 mils offers a wide range of temperature control, radiation protection and array weight so that suitable tradeoffs can be made within the current state of technology. The direct heat sealing eliminates the necessity for adhesives which add weight, fabrication complexity and require UV radiation protection. The low refractive index ($n = 1.34$) insures low front surface reflection losses without the need for antireflection coatings.

Material and installation costs provide a major advantage over conventional cover glasses. FEP is commercially available in large area rolls at a cost of \$0.08/square foot (0.5 mil) to \$0.53/square foot (5.0 mils). The cost of coated fused silica cover glasses is about \$250/square foot. Installation costs add another \$200-300/square foot. Since current production solar arrays provide approximately 10 watts/sq. ft., a 10 kilowatt array would cost in the vicinity of \$500,000 more for adhesive-bonded 6-mil silica cover glasses than for a 5-mil FEP film covering. Requirements for thinner cover slide application would result in even greater economies using FEP covers.

A comparison of FEP and fused silica cover material is presented in table 3.

CONCLUSION

The results of this investigation indicate that FEP may provide a viable alternative to conventional fused silica cover glasses for silicon solar cells. With regard to economic, processing, handling and environmental considerations the heat-sealed FEP covers have been shown to have characteristics equivalent or superior to conventional glass covers. The test conditions that were used were more severe than would be expected in actual use. These were chosen, in this early state of development, to show up any weaknesses in the FEP cover system. However, they do not seriously diminish the potential utility of this system. On the contrary, the efforts, to date, strongly indicate that the approach justifies substantial further research and development. It is anticipated that the use of FEP solar cell covers will be a major milestone in solar cell technology.

REFERENCES

1. A. F. Forestieri and J. D. Broder, "Improvements in Silicon Solar Cell Coverglass Assembly and Packaging Using FEP Teflon." NASA TM X-52875, July 1970.

2. A. F. Forestieri, A. F. Ratajczak and T. M. Klucher, "Thermal Cycling Test of a Flexible Solar Cell Module." NASA TM X-52995, March 1971.

Table 1 - Optimum Processing Parameters

	Operating Range	Nominal Operating Value
Temperature	235° C - 270° C	250° C
Applied Pressure	100 - 5000 lbs/in^2	1000 lbs/in^2
Dwell Time at Temp.	10 sec - 10 min	60 sec
Parting Material	Polyimide (0.5-mil)	
Cleaning	Boiling Ethyl Alcohol	
Solar Cell Type	Solderless	

Table 2 - Relative SCC as a Function of Surface Finish and Angle of Incidence

Angle, degrees	Relative SCC	
	Smooth Finish	Matte Finish
90	1.00	1.00
60	.75	.75
30	.50	.50

Table 3 - Comparison of FEP and Fused Silica Covers

Property	Fused Silica	FEP
Density	2.20	2.15
Refractive Index	1.54	1.34
Front Surface Reflectance	4.2%	2.1%
Handling	Fragile	Flexible
Bonding	Adhesive Required	Heat Sealing no adhesive
Available thickness (mils)	6-40	0.5 - 20
Relative Cost	500	1
Anti-reflection Coating	Required	Unnecessary
Ultraviolet Filter	Required	Unnecessary
Radiation Protection	Equivalent for equal mass per unit area	
Radiation Stability	Good	Appears adequate but further testing required
Emittance	Equivalent	Equivalent
Area	Limited to single cells or small modules	Applicable to large areas - also protects cell edges
Application Cost	High	Low
Solar Transmittance	Equivalent	Equivalent

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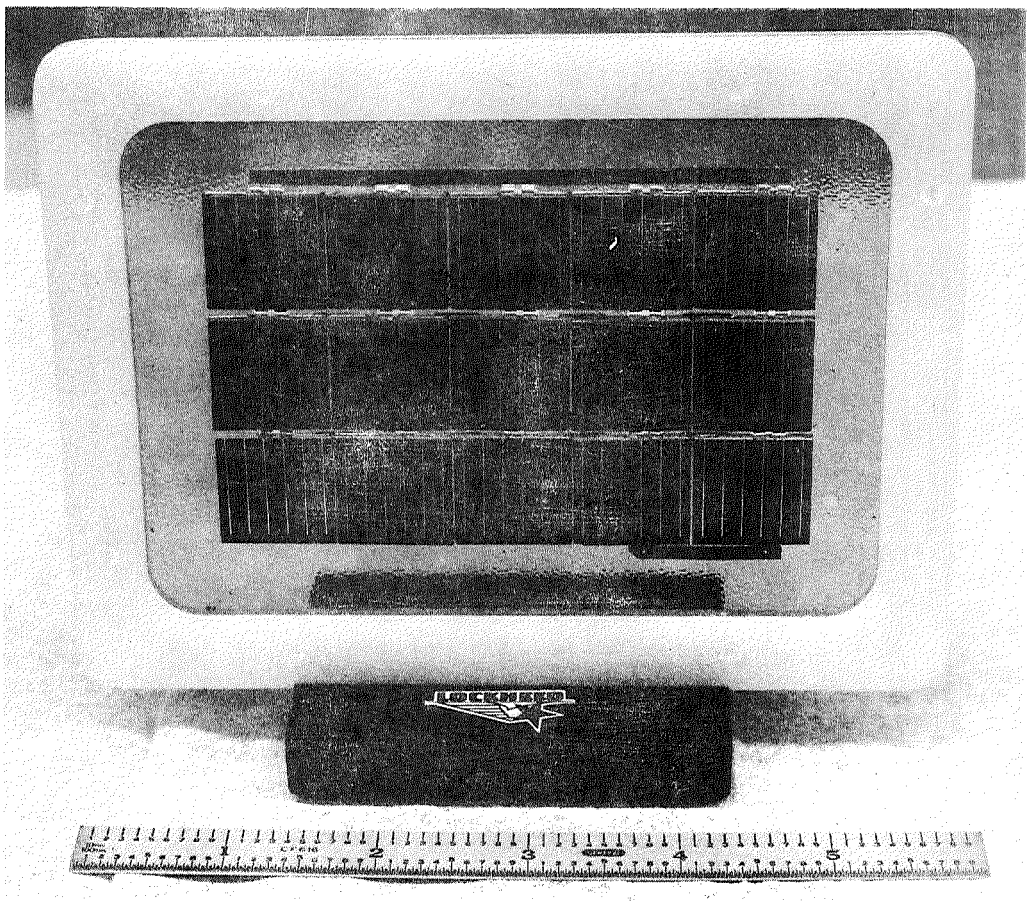

Figure 1. - Fifteen-cell module.

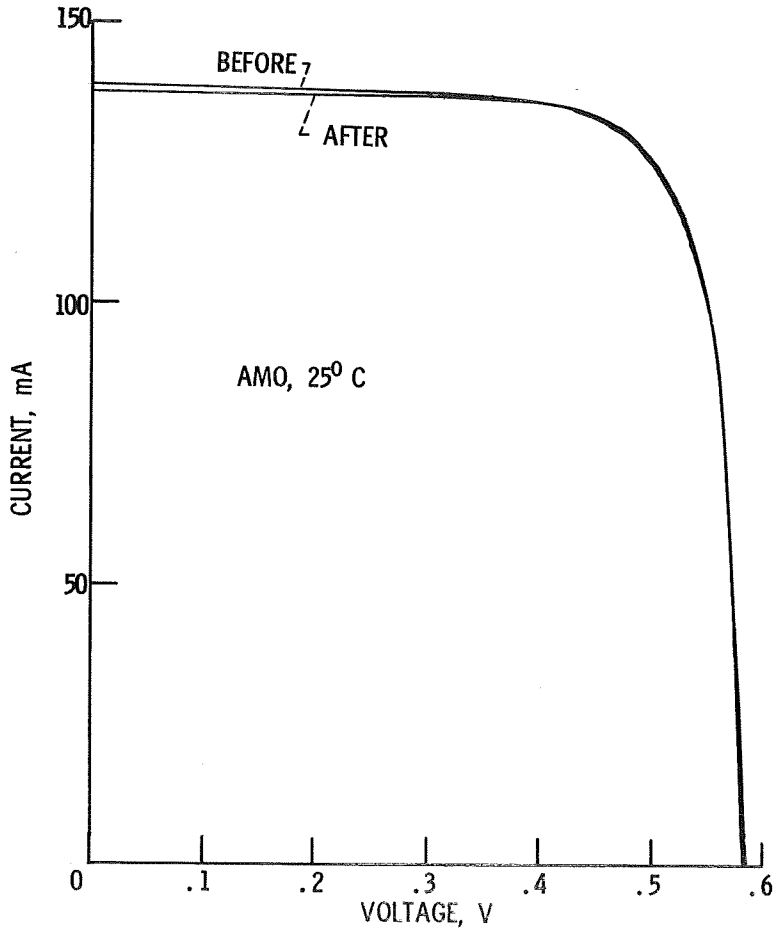

Figure 2. - Typical current-voltage characteristics of silicon solar cell before and after covering with FEP.

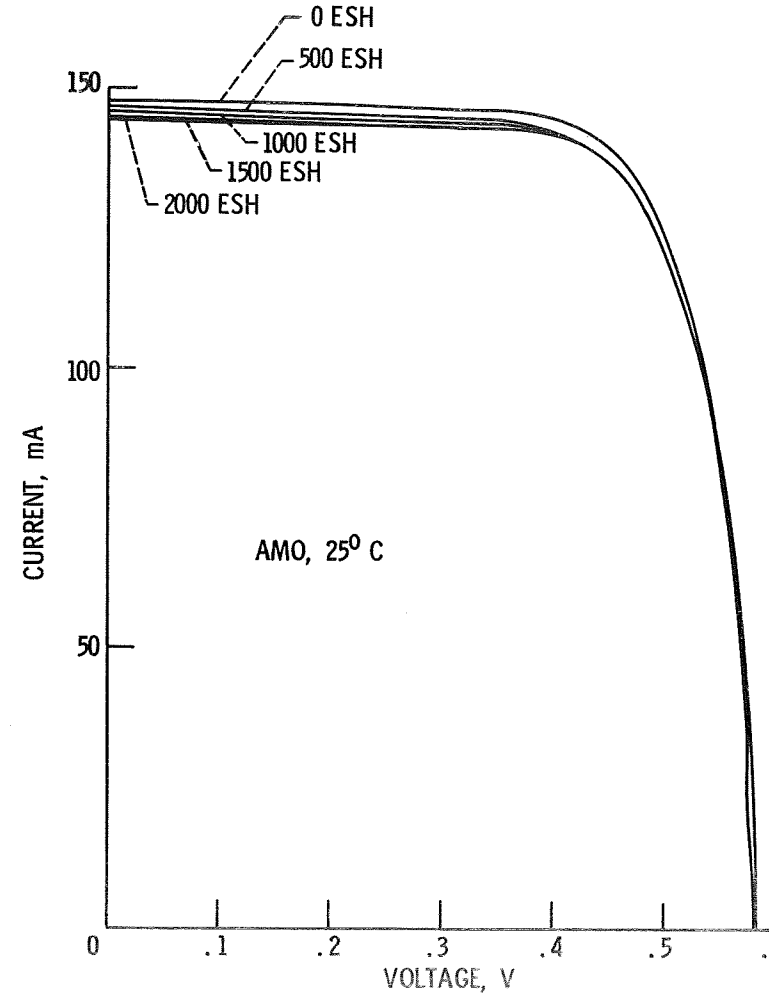

Figure 3. - Effect of UV exposure on FEP covered solar cell.

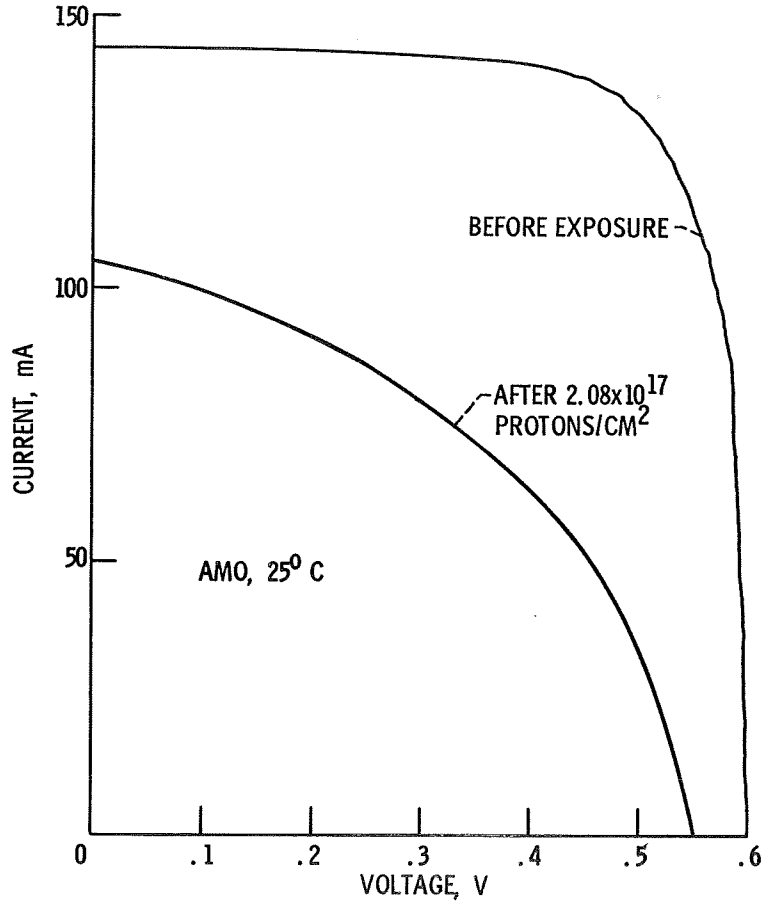

Figure 4. - Effect of proton exposure on a bare solar cell.

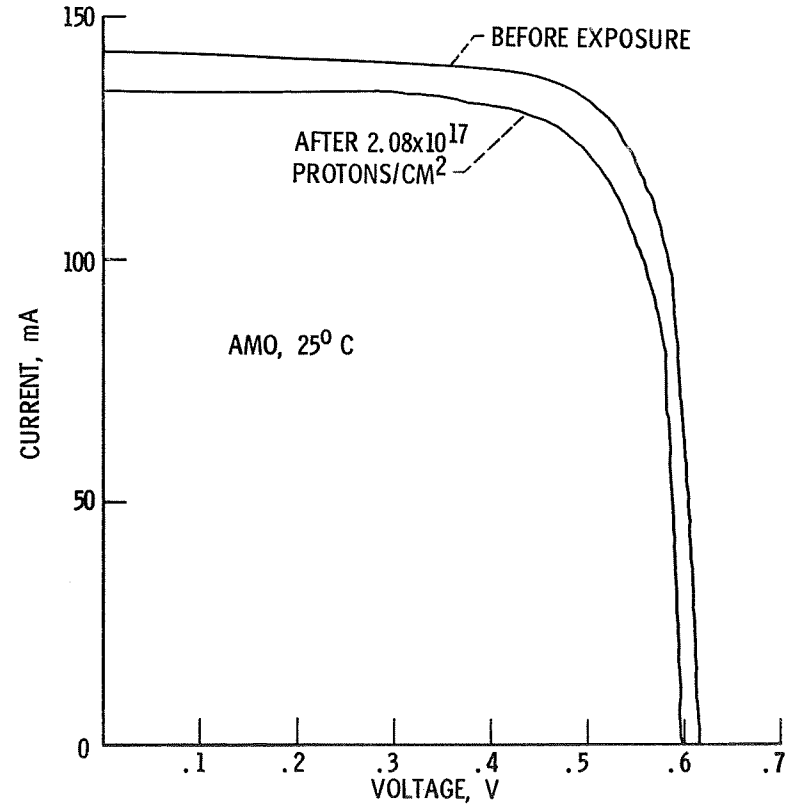

Figure 5. - Effect of proton exposure on FEP covered solar cell.

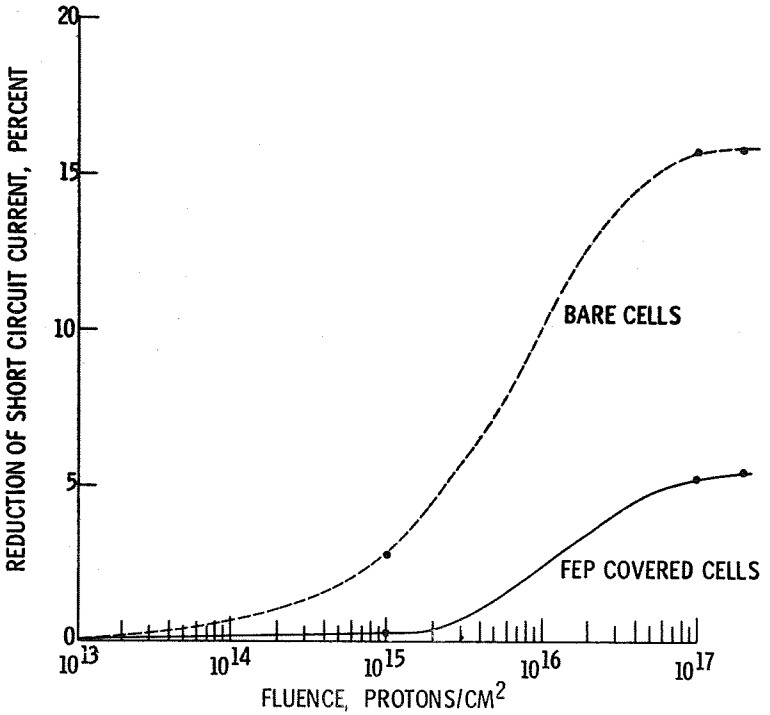

Figure 6. - Effect of low energy protons on solar cell short-circuit current.

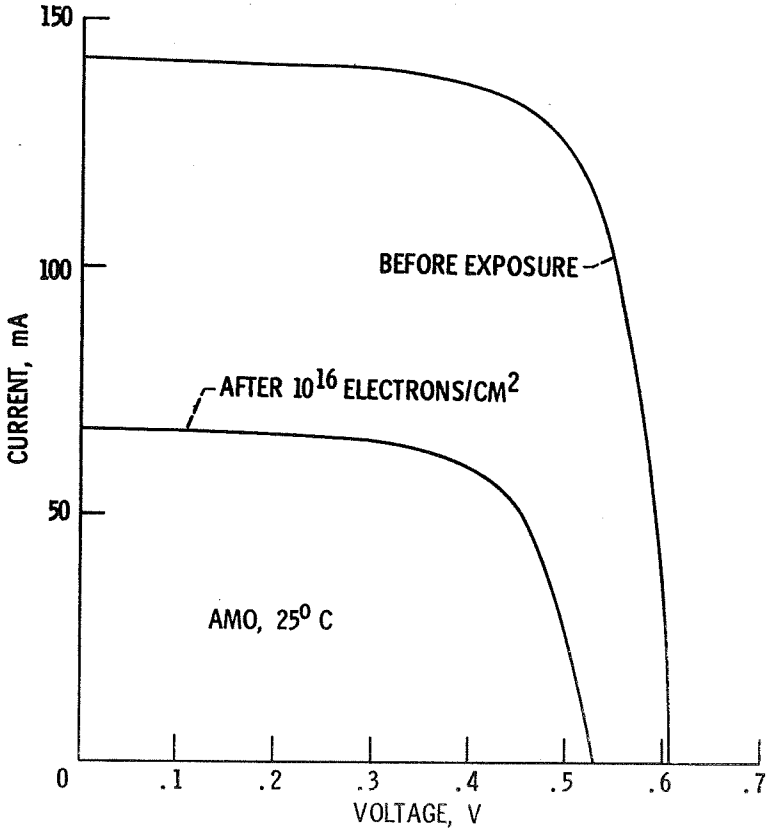

Figure 7. - Effect of electron exposure on FEP covered solar cell. FEP and antireflection coating separated from cell.

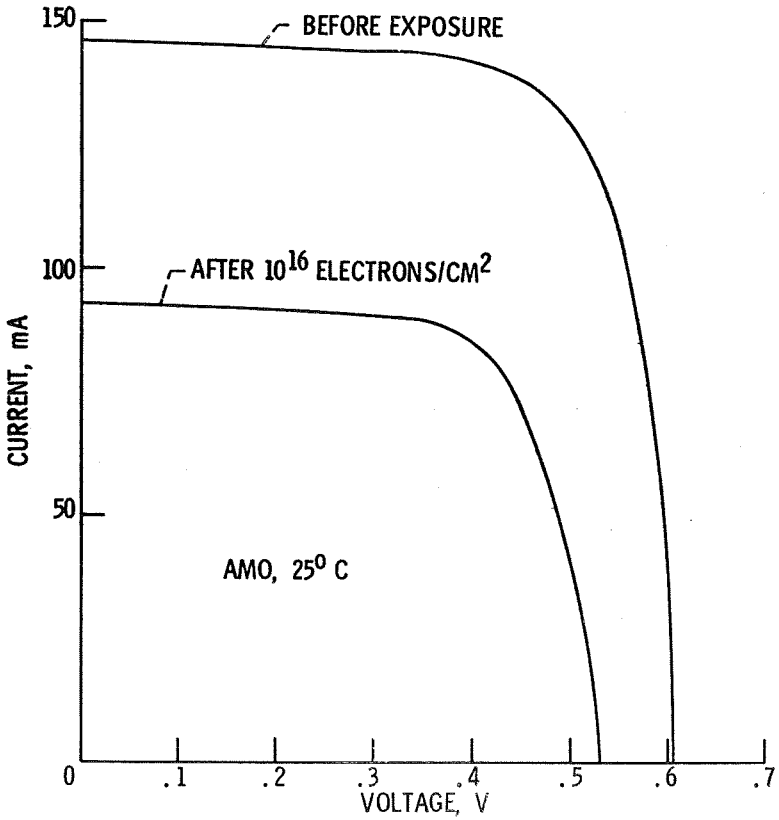

Figure 8. - Effect of electron exposure on FEP covered solar cell. FEP separated from cell, antireflection coating intact.

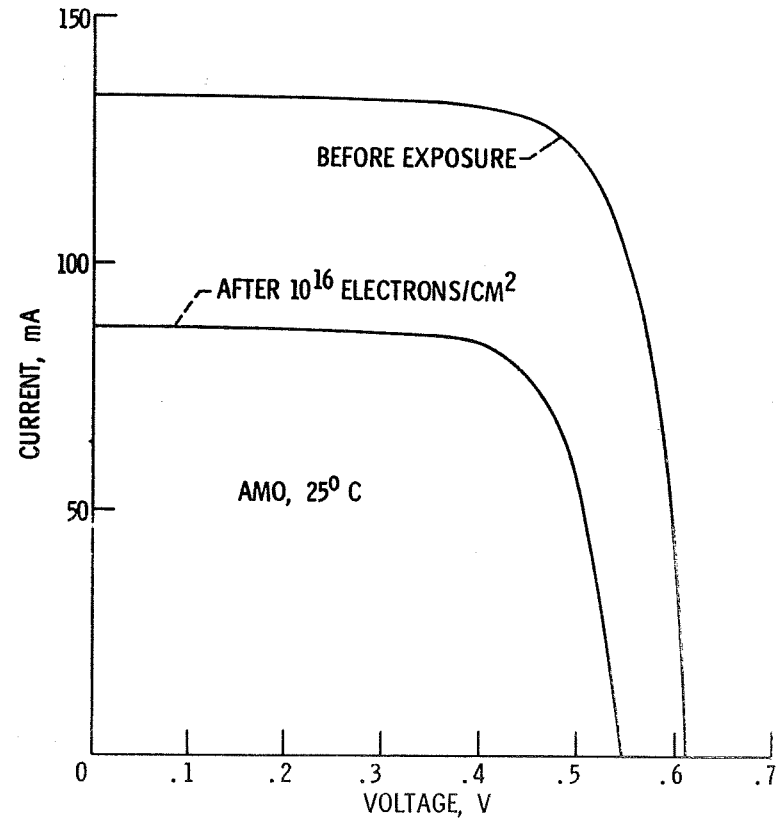

Figure 9. - Effect of electron exposure on bare solar cell.