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INVESTIGATION OF RESINOUS MATERIALS FOR USE AS SOLAR CELL COVER GLASS ADHESIVE

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ABSTRACT

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Various polymeric adhesives – whose intended use is for bonding protective cover glass to solar cells – were subjected to typical prelaunch (temperature storage), launch (vibration, thermal shock and cycle), and simulated orbital space environmental conditions (thermal vacuum, electron, proton and ultra violet irradiation). Comparative degradation effects on the adhesives are shown by transmission loss curves and tables.

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SUMMARY

The improper selection of protective cover glass and adhesive systems can be detrimental to solar array output in space by reducing the energy transmitted to the cells. This transmission loss is caused by irradiation degradation of both the cover glass and adhesive, delamination or crazing of the bond and cover glass breakage occurring from thermal and vibrational shock during the prelaunch, launch and orbital phases of the spacecraft life.

The effort of this paper was to select adhesives which would perform satisfactorily during all operational phases of the spacecraft by a comparative study.

The transmission loss results of proton and electron irradiation exposure of the adhesives (up to 10^{15} elec/cm^2 at 1 Mev energy level for electron irradiation, and up to 4×10^{11} proton/cm^2 at 4.6 Mev level for proton irradiation) indicate little to no degradation of the selected adhesives.

Thermal and vibrational shock damage resulting from simulated environmental exposures clearly shows that silicone-based adhesives are superior to the epoxy based adhesives.

Exposure to ultra-violet irradiation resulted in transmission degradation of all of the adhesives with a leveling off of degradation at 150 hours of exposure for the Sylgard 182 adhesive.

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INTRODUCTION

In June, 1963, it was decided that the solar cell experiment for the EPE-D (S-3C) satellite was to be fabricated by the Solar Power Sources Section of Goddard Space Flight Center. At that time, it was apparent that several studies would have to be made before fabrication of the flight units could begin. These studies were necessary to provide reasonable assurance that, when the flight units were finally fabricated, they would perform satisfactorily under prelaunch, launch, and flight environments. Primary among these studies was the study of cover glass adhesives, since those previously used were of questionable stability, ref. (1), under the anticipated environments, or were unavailable because of proprietary limitations.

The two factors that prompted the adhesive study were first, a report, ref. (1), indicating a loss of solar power output as high as 18% attributable to deterioration of cover glass and cover glass adhesive, and secondly, breakage of cover glasses and delamination and crazing of the bond under thermal shock and thermal cycling due to the inflexibility and expansion differential of the bonded materials.

A limited program was, therefore, undertaken to find a suitable adhesive for the intended application. To perform this investigation, several "off the shelf" adhesives were selected. They were subjected to proton, electron and ultraviolet radiations and also used in the fabrication of two pre-prototype solar cell experiments which were subjected to simulated pre-launch, launch, and orbital environments. These included temperature storage, thermal shock and cycle, and thermal-vacuum cycling; thus providing a use test for the adhesives as well as other panel components. (NOTE: It must be emphasized that no presumptions are meant or implied by the scope of this evaluation. Neither the selection of the adhesives nor the test procedures is considered ultimate. Rather, this was an effort to find a suitable adhesive in a limited time and with a limited equipment availability. It is hoped that the results of this study will encourage more inclusive and more definitive investigations in an area where very much needs to be done and where fruitful results are both needed and attainable.)

EXPERIMENTAL PROCEDURE AND RESULTS

Initial Selection of Adhesives

The primary criterion in the initial selection of adhesives for this study was transmission in the wavelength range from 0.35 microns to 1.2 microns which include the range of solar cell response. Adhesives ordinarily used for clarity in the field of optics are thermo-plastic in nature, e.g., styrene, acrylic, acetate, etc. and depend on solvents, plasticizers or high temperatures for thin film application. Because of these additives and the molecular structure of these polymers, this category of adhesives is subject to severe outgassing, rapid degradation and excessive embrittlement when exposed to levels of vacuum, radiation, and temperature extremes encountered in space. However, epoxy-based and silicone-based adhesives, because of their high solids content, lack of additives and polymeric structure, perform well in space environments, and because of their low viscosity are easily applied in thin films.

After carefully screening seven adhesives for optical clarity and applicability, the following four were selected for further testing.

Resin Trade Name	Type	Manufacturer
LTV 602	Clear silicone rubber	General Electric
Sylgard 182	Clear silicone rubber	Dow Corning
Ciba 502	Clear epoxy	Ciba Plastics
Maraglas 656	Clear epoxy	Marblette Corp.

Ultra-violet Radiation Exposure

Test samples were prepared by laminating two fused silica (Corning 7940) 1 × 2 cm. × 60 mil. thick slips with 1 to 2 Mil thickness of each of the adhesives. Two samples of each of the adhesives were mounted in a glass jig and places in a vacuum chamber with a quartz port at a pressure of 10^{-7} mm. of Hg. The ultra-violet source was a 500 watt Hanovia mercury vapor lamp. The lamp was mounted 20 inches in front of the test samples in order to minimize any pyrolytic effect. The samples were measured for spectral transmission over the wave length range from 0.35 microns to 1.2 microns with a Beckman DK-2A double beamed spectrophotometer prior to exposure, after 150 hours of exposure, and again after 300 hours of exposure. Spectral transmittance curves for the three exposure times are shown for each of the four adhesives in Figures

(1), (2), (3), and (4) respectively. Figure (5) is a plot comparing the 300 hour exposure curves for the four adhesives over the range from 0.35 to 0.8 microns where the major part of the transmission loss occurs.

Electron and Proton Radiations

Additional test samples were prepared with each of the adhesives using two laminate configurations. First, a 6 mil OCLI microsheet cover glass, coated with anti-reflective and blue filter coatings, was bonded to a base of 60 mil 7940 fused silica with 1 to 2 mil of adhesive and secondly, a 60 mil 7940 fused silica OCLI cover glass, coated with anti-reflective and blue filter coatings, was bonded to a 60 mil 7940 fused silica base with 1 to 2 mils of adhesive. One 6 mil and one 60 mil cover glass laminate of each adhesive was irradiated in a vacuum of 10^{-4} mm. of Hg. with a single exposure of 4×10^{11} protons/cm^2 at an energy level of 4.6 Mev. Another set was exposed in air at ambient pressure to 1 Mev. electron irradiations of 10^{13}, 10^{14}, and 10^{15} electrons/cm^2. Spectral transmittance measurements were taken before exposure and after exposure at each of these irradiation levels. A Beckman IR-4U double beamed spectrophotometer was used for the measurements. Tables I and II list the transmittance percentages before and after exposure for the electron and proton irradiation tests respectively.

Upon examination of the transmittance data, it was noted that, in the case of the silicone resin laminates, the degree of transmittance degradation was similar to that of the 6 mil microsheet cover glass control. This indicated that the microsheet cover glass was probably undergoing most of the degradation while the adhesive suffered very little or no degradation. This was checked by delaminating the exposed laminate samples and taking transmittance measurements of each part separately, i.e. the glass filter free of the adhesive and the adhesive free of the glass filter. These measurements are shown graphically in Figures (6), (7), and (8).

Prelaunch, Launch, and Orbital Simulation

Two pre-prototype panels for the Solar Cell Experiment were assembled as shown schematically in Figure (9). They were assembled with both shingled and flat mounted cell configurations and with both 6 and 60 mil glass filterslips attached to the cells. With this arrangement, each adhesive was in two positions on each of the panels – near the edge of the panel, adhering 6 mil glass filterslips to the cells, and near the center, adhering 60 mil glass filterslips to the cells. The arangement was such that on one panel the slips were bonded to flat mounted cells, and on the other panel they were bonded to shingled cells.

TABLE I

ELECTRON EXPOSURE (10^{15} e/cm^2 -1 MEV)

ADHESIVE AND FILTER	TRANSMISSION (PERCENT)																	
	0.43 Microns		0.5 Microns		0.6 Microns		0.7 Microns		0.8 Microns		0.9 Microns		1.0 Microns		1.1 Microns		1.2 Microns	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
Ciba 502 & 6 Mil Microsheet Filter	82.5	67	90.5	79.5	90.5	84	92.5	88.5	90.5	88	90	88	93	92	92	92	91.5	91
Maraglas & 6 Mil Microsheet Filter	79	72	89	82.5	90	85	91.5	88	90	87.5	90	88.5	92.5	91.5	92	91	90.5	89.5
LTV 602 & 6 Mil Microsheet Filter	86	76.5	92.5	85	93.5	87.5	95.5	91	94	90.5	94	92	95	93.5	94	93.5	93	92
Sylgard 182 & 6 Mil Microsheet Filter	86.5	82	93.5	87	94	88	96	91	94.5	92	94.5	92	94.5	92	94	92	91.5	91
Ciba 502 & 60 Mil 7940 Filter	88	84	93	91	92	90	92	91	92	91	91	91	92	92	92	92	91	91
Maraglas & 60 Mil 7940 Filter	86	85	92	90	90	89	91.5	90.5	90	89	89.5	89	91	91	91.4	91.4	90.5	90.5
LTV 602 & 60 Mil 7940 Filter	87	86	92	91	92	91	93	92	92	92	92	92	92	92	92.5	92.5	92	92
Sylgard 182 & 60 Mil 7940 Filter	87	85.5	92	91	91	90	92	91	92	91	91	90	90	90	92	92	91	91

TABLE II

PROTON EXPOSURE (4×10^{11} p/cm^2 -4.6 MEV)

ADHESIVE AND FILTER	TRANSMISSION (PERCENT)																	
	0.43 Microns		0.5 Microns		0.6 Microns		0.7 Microns		0.8 Microns		0.9 Microns		1.0 Microns		1.1 Microns		1.2 Microns	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
Ciba 502 & 6 Mil Microsheet Filter	84	76	91	86	92	89	95	92	93	91	92	91	95	94	94	93	93	93
Maraglas & 6 Mil Microsheet Filter	82	76	91	86	91	88	93	92	91	91	91	91	94	94	92	92	93	93
LTV 602 & 6 Mil Microsheet Filter	84	79	92.5	89	93	90	95	93	92	91	94	93	95	95	95	94	93	93
Sylgard 182 & 6 Mil Microsheet Filter	84	78	91	86	91	88	93	91	92	90	91.5	90	92	92	92	90.5	89	89
Ciba 502 & 60 Mil 7940 Filter	84	84	90	90	90	90	92	91	90	90	89	89	90	90	91	91	90	90
Maraglas & 60 Mil 7940 Filter	91	91	89	89	89	89	90	90	89	89	88	88	90	90	90	90	89	89
LTV 602 & 60 Mil 7940 Filter	86	87	90	90	91	91	91	91	91	91	91	91	91	91	92	92	92	92
Sylgard 182 & 60 Mil 7940 Filter	83	83.5	91	91	91	92	91	91	91	91	91	91	91	91	92	92	91	91

Each adhesive was thus exposed to any vibrational or thermal variations which may have occurred across the panel and was also exposed to any variations which could have resulted from the difference in cell mounting configurations. Both panels were subjected to the following tests:

Temperature Storage Test – The panels were placed in a temperature chamber and were subjected to a temperature storage test which consisted of a gradual reduction of the temperature from ambient to -30°C in approximately 30 minutes where the temperature was stabilized and held for six hours followed by a gradual elevation of the temperature to +60°C in approximately 30 minutes where the temperature was stabilized and held for six hours. The temperature was then reduced gradually to room temperature in approximately 30 minutes to complete the test.

Vibration Test – The panels were vibrated at the vibration levels shown in Table III.

TABLE III

Vibration Schedule

a. Sinusoidal Tests

Frequency (cps)	Acceleration ± g	
	Thrust Axis (Z)	Transverse Axis (X & Y)
5-50	2.3	0.9
50-500	10.7	2.1
500-2000	21	4.2
2000-3000	54	17
3000-5000	21	17

Constant sweep rate of 2 octaves/minute

b. Random test (each axis)

Frequency Range (cps)	PSD (g^2/cps)	Amplitude g-rms	Duration Min.
20-2000	.07	11.5	4.0

Thermal Shock and Cycle Test – The panels were placed in a temperature chamber which was preheated to +90°C for the thermal shock test. In this manner, the panels were temperature shocked from ambient to +65°C in two minutes. The temperature was then lowered gradually to -65°C in approximately 45 minutes to start the thermal cycling. This consisted of two full temperature cycles, each going from -65°C to +40°C and back to -65°C, and a half cycle ending at +40°C, with each half cycle taking approximately 30 minutes. Finally the temperature was lowered from +40°C to ambient.

Thermal Vacuum Test – The panels were placed in a tank which was then sealed and placed into the temperature chamber. The tank was then evacuated to as low a pressure as possible (nominally 0.1 mm. Hg.) by means of a continuously operating mechanical vacuum pump and the temperature was gradually reduced to -65°C in approximately 90 minutes and held at this value for 16 hours. The temperature was then raised gradually to +40°C in approximately 90 minutes and held at this value for 48 hours. Finally the temperature was lowered and the pressure was raised gradually to ambient in approximately 30 minutes.

The condition of each panel was determined before and after each of these environmental tests. This was done by measuring the electrical output (complete voltage-current curves) of each solar cell string and by making microscopic examinations of the panels. Table IV shows the damage observed during microscope examination, resulting from each of the environmental tests.

DISCUSSION

Effects of Ultra-Violet Radiation

Figures (1) through (4) give a graphical picture of the rates of degradation showing a continuing rate with all the adhesives excepting Sylgard 182 (Figure 2). The major effects in all cases appeared within 150 hours of exposure duration.

Examination of the curves in Figure (3) indicates a degradation variation even with the same categories (silicone or epoxy) of adhesives. Figure (5) also confirms previous observation, Ref. (1), that polymeric adhesives degrade severely in transmission at the shorter wave length regions (below 0.8 microns) but beyond this there is very little degradation.

Electron and Proton Degradation

In Figure (6, 7, & 8), where the transmittance curve of the original laminates before exposure to irradiation is compared to the curves of the separate

TABLE IV

ADHESIVE PERFORMANCE UNDER ENVIRONMENTAL TESTS

	SHINGLE MOUNTING				FLAT MOUNTING			
	6 Mil Slips		60 Mil Slips		6 Mil Slips		60 Mil Slips	
Adhesive	Type of Damage	Test No.	Type of Damage	Test No.	Type of Damage	Test No.	Type of Damage	Test No.
Ciba 502	1 Cracked Filter 2 Cracked Filters 2 Cracked Filters	1 2 3	1 Chipped Filter	2	3 Cells With Small Bubbles	3	1 Chipped Filter	2
Maraglas 656	1 Cracked Filter 2 Cracked Filters 1 Cracked Filter 1 Cracked Filter	1 2 3 1	3 Delam. Filters	3	2 Cracked Filters	3	No Change After All Tests	
LTV 602	1 Delamination	2	4 Delamination	3	1 Cracked Filter	3	1 Delamination 3 Delaminations	3 4
Sylgard 182	1 Cracked Filter	3	No Change After All Tests		No Change After All Tests		1 Delamination	3

Test Index:
1. Temperature Soak
2. Vibration
3. Thermal Shock and Cycle
4. Thermal Vacuum

components (adhesive and glass slip) after exposure, it is apparent that little or no degradation is experienced by the silicone adhesives and that most. if not all, of the degradation has occurred in the 6 mil micro-sheet cover slip. Upon analyzing Tables I and II in conjunction with the above facts (noting that little or no transmittance loss is observed with the 60 mil 7940 fused silica slips) it can be concluded that little or no transmittance loss is attributable to any of the selected adhesives. It can also be concluded from the above data that microsheet is an inferior cover glass material.

Pre-launch, Launch and Orbital Simulation Test Results

In Table IV, it is apparent that the use of epoxy type adhesives resulted in glass filter cracking during thermal and vibrational shock exposure because of the associated rigidity of these adhesives. However, the silicone-type adhesives, because of their flexibility, did not cause serious amounts of glass filter cracking. The LTV 602 did show serious amount of delamination with the 60 mil glass slips, whereas the Sylgard 182 survived the environmental tests with very few delaminations. (Delaminations could be possibly caused by a higher degree of cure shrinkage in the LTV 602 resin).

CONCLUSIONS

Upon examination fo the four selected adhesives, from the standpoint of ultra-violet. proton and electron irradiation degradation, environmental "use" tests. and ease of application, it can be concluded that Sylgard 182 (silicone-type adhesive) is the most suitable adhesive for the intended application on the S-3C Satellite Solar Cell Experiment. The properties that are outstanding in this adhesive are (a) optical clarity, (b) flexibility over wide ranges of temperature, (c) generally good properties for application such as low viscosity. long pot life, little to no bubble occlusion in the cell-adhesive-filter laminate. and rapid cure cycle at reasonably low temperatures and (d) low shrinkage during curing stage.

Even with the Sylgard 182 adhesive. there is more to be desired in the ultra-violet resistance properties. In Figure (2). it can be noticed that there is a transmittance loss of from 40% to 50% in the region of .410 microns to .6 microns.

From the standpoint of stability. the use of 7940 type cover glass is preferable to the use of microsheet.

RECOMMENDATIONS

For any future studies, it is recommended that:

1. The above properties be used as criteria for the selection of cover glass adhesives,

2. Investigations into the synthesis of a more ultra-violet resistant resin be undertaken,

3. A more intensive program be carried out to test all available clear resins with particular emphasis on silicone resins.

4. Fused silica 7940 be used rather than 0211 micro sheet as a substrate for the U-1 filter and for radiation protection.

ACKNOWLEDGEMENTS

The author wished to thank Mr. Frank Campbell of NRL for the tests and measurements performed at the NRL facilities. The author wishes also to thank the Thermal Systems Branch of GSFC headed by Mr. Schach for the use of their equipment and assistance in the test performance and measurements.

REFERENCE

1. "Effects of Space Radiation on Solar Cell Cover Materials" by F. J. Campbell, Insulation Section, Electromagnetic Materials Branch, Solid State Division, U.S. NRL, Washington, D. C.

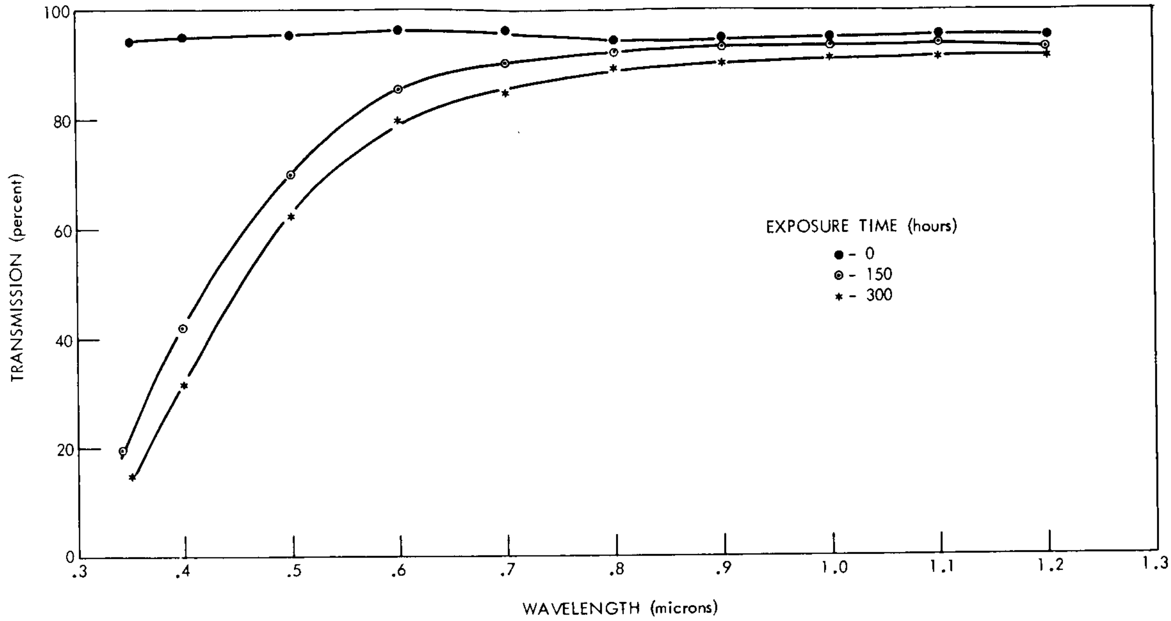

Figure 1–Effects of Ultra-Violet Exposure on LTV-602

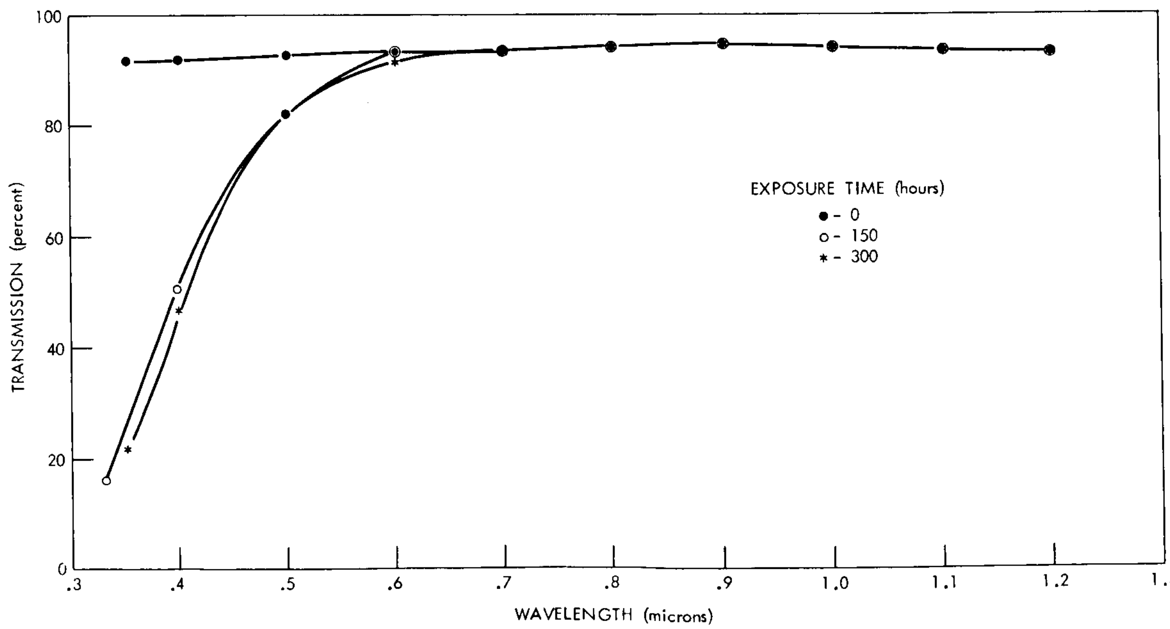

Figure 2–Effects of Ultra-Violet Exposure on Sylgard 182

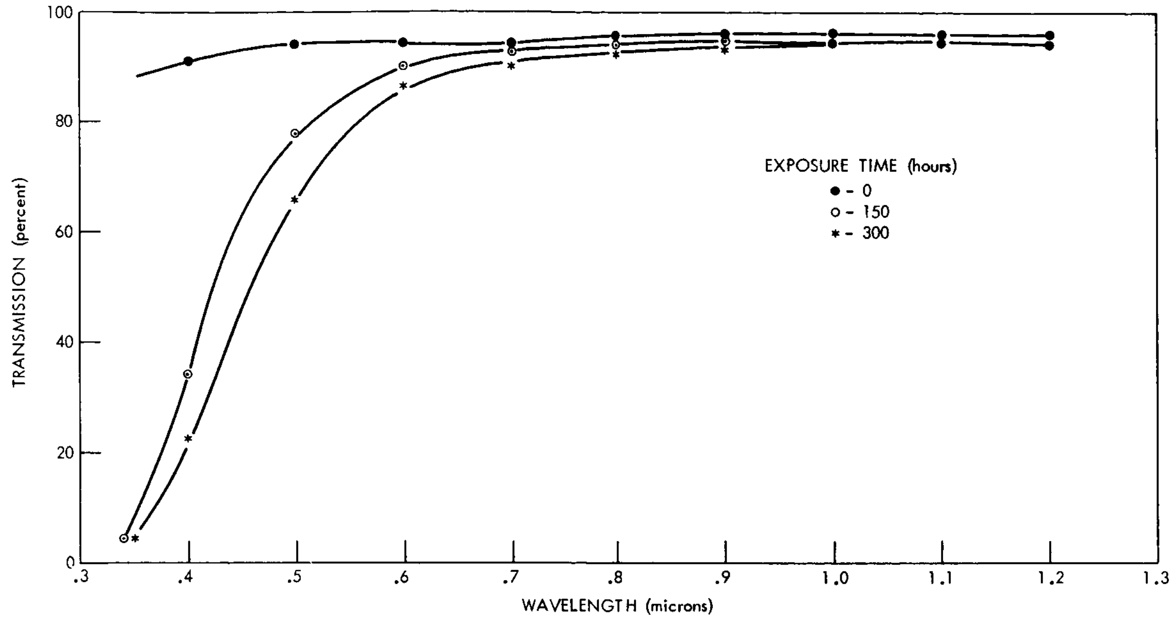

Figure 3–Effects of Ultra-Violet Exposure on CIBA 502

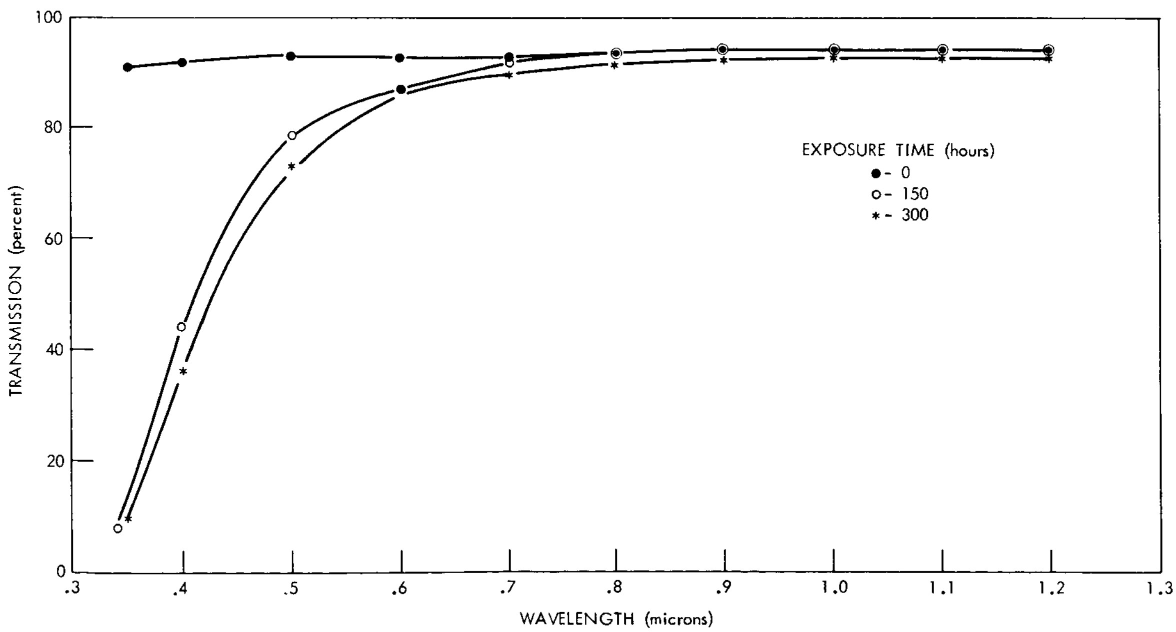

Figure 4–Effects of Ultra-Violet Exposure on Maraglas 655

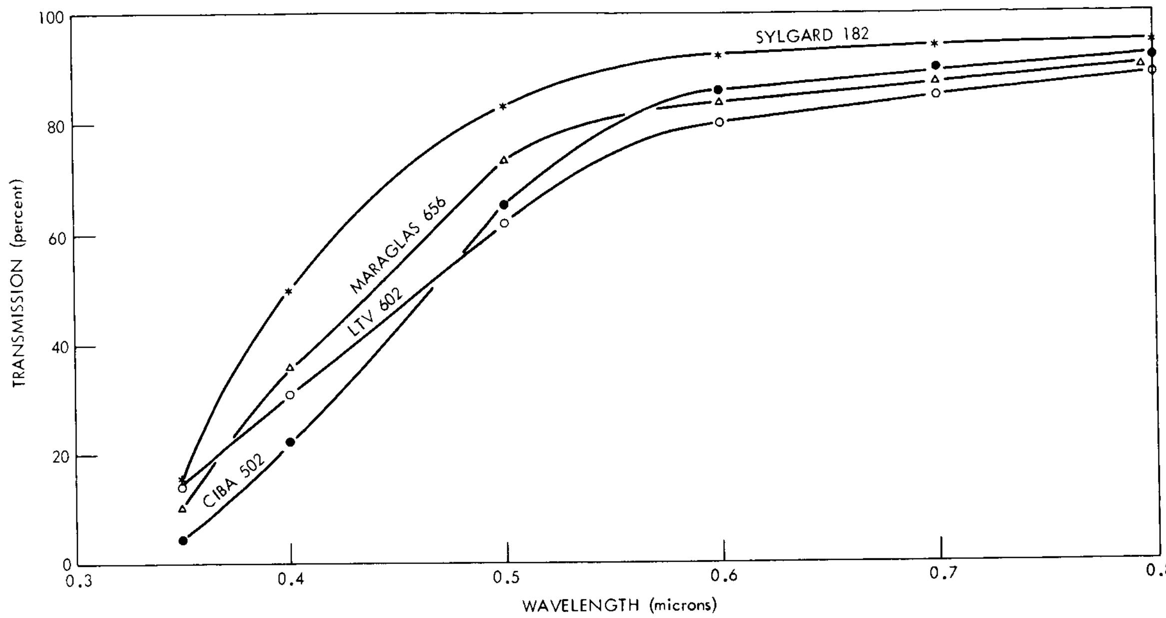

Figure 5—Transmission of Adhesives After 300 Hours of Exposure to Ultra-Violet

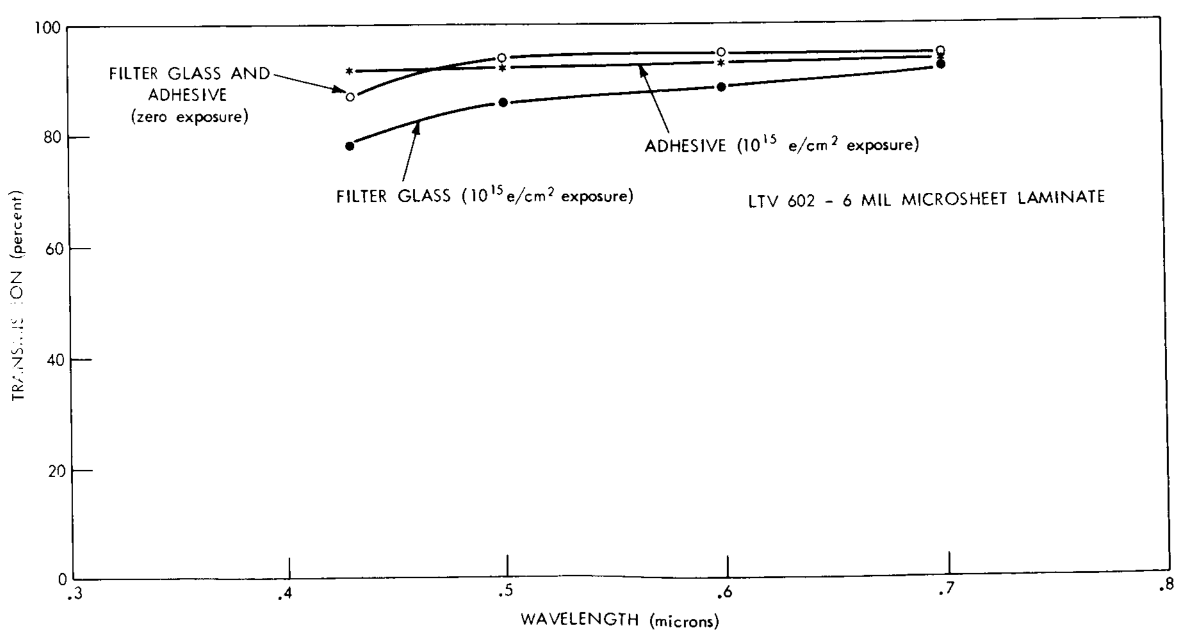

Figure 6—Electron Irradiation Effects on Laminate Components

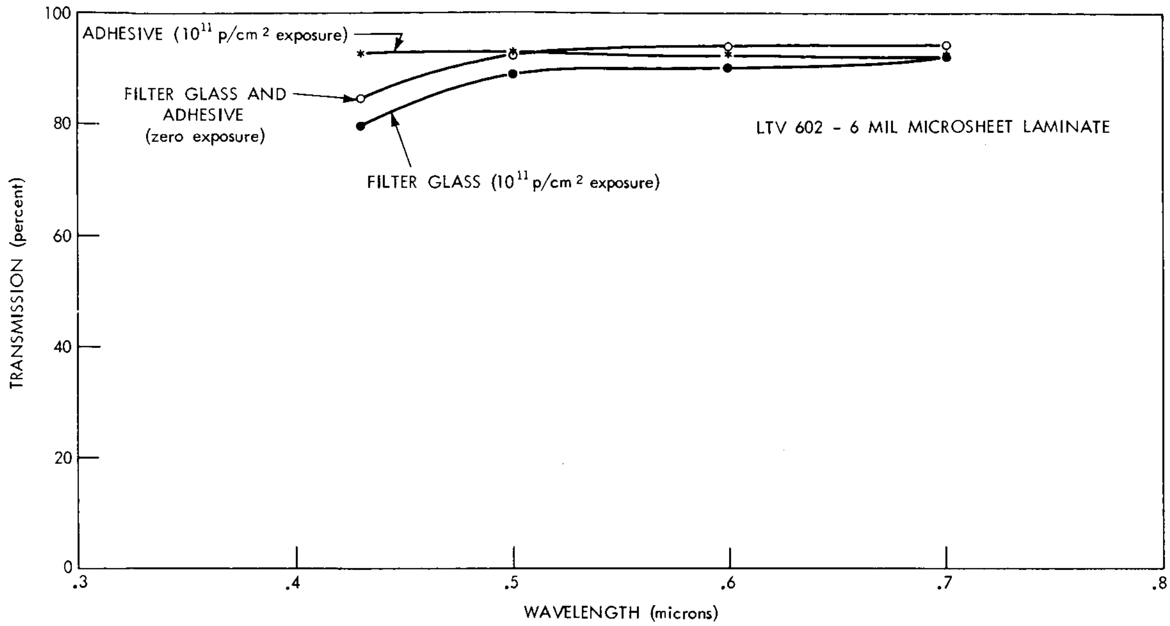

Figure 7—Proton Irradiation Effects on Laminate Components

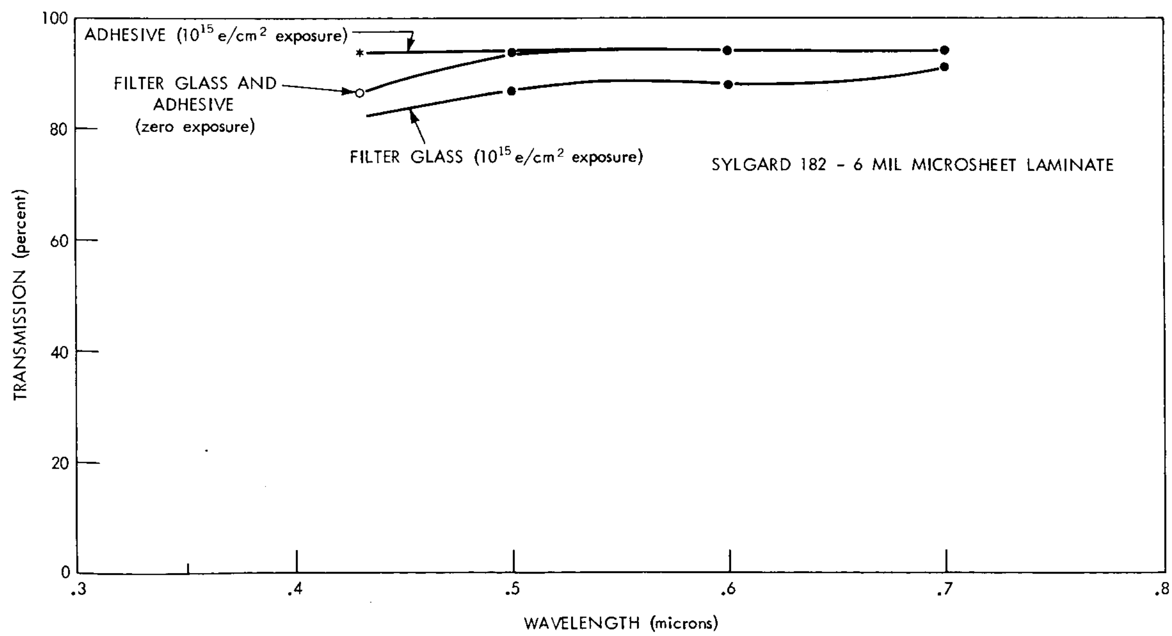

Figure 8—Electron Irradiation Effects on Laminate Components

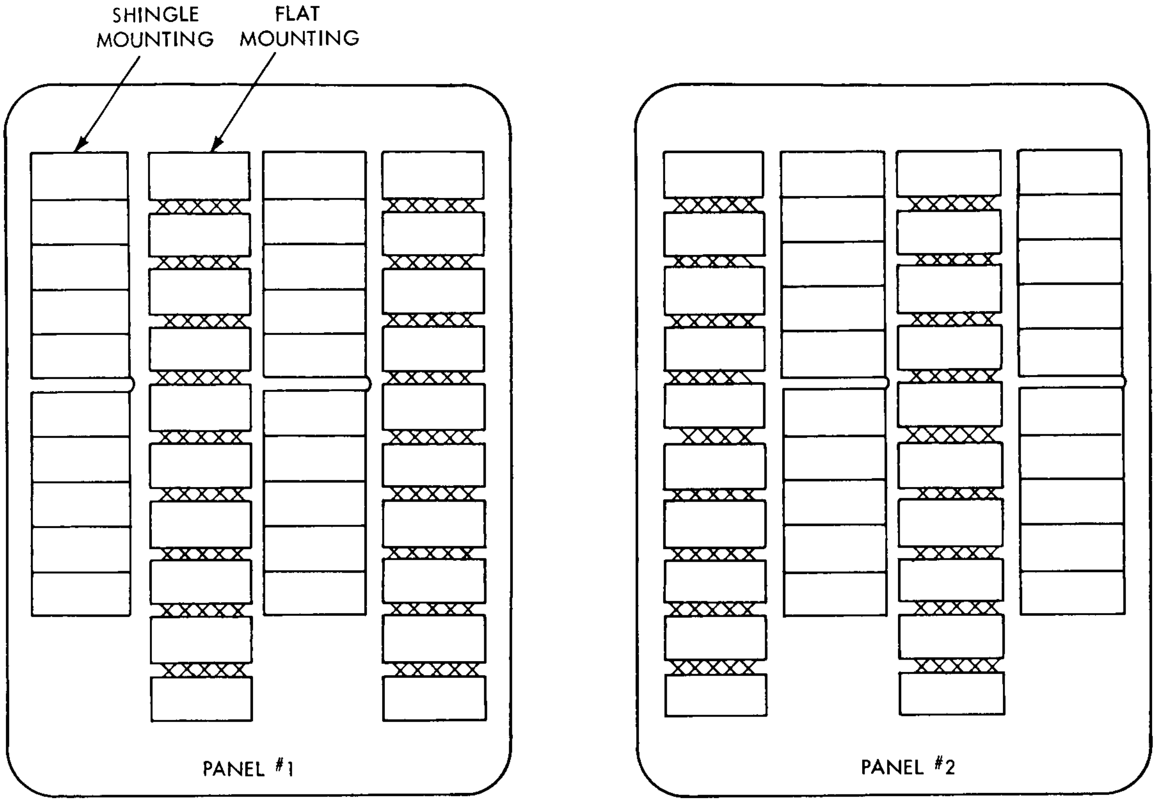

Figure 9—Solar Cell Panel Layout