ULTRAVIOLET AND CHARGED PARTICLE IRRADIATION OF PROPOSED SOLAR CELL COVERSIDE MATERIALS AND CONDUCTIVE COATINGS FOR THE HELIOS SPACECRAFT

J. FRY
C. A. NICOLETTA

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND
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ABSTRACT

Coverslide materials consisting of Corning 7940 fused silica, multi-layers of titanium and manganese oxides (blue reflector), and indium oxide (conductive-coating) were exposed to 16 UVSC up to 800 EUVSH in vacuum. Slight changes in optical transmittance and optical absorptance were found in the (200-360) mμ regions of the fused silica and conductive coating respectively. Exposure to 4 KeV protons and 4.5 KeV electrons in vacuum, produced decreases of several percent in transmittance, (200-360) mμ region in the fused silicas after total fluxes ≥ 10^{14} particles/cm^2. Sheet resistance of the conductive coating increased above 1.0 kΩ/square after a total flux ≥ 10^{14} particles/cm^2.

Solar cells with coverglasses utilizing the indium oxide conductive coating were exposed to 1 Mev electrons and 1 Mev protons in air and in vacuum. Total fluxes ranged from 10^{11} particles/cm^2 to 10^{15} particle/cm^2. There was no appreciable degradation in the resistance of the conductive coating during or after these tests.
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ULTRAVIOLET AND CHARGED PARTICLE IRRADIATION OF PROPOSED SOLAR CELL COVERSLEEVE MATERIALS AND CONDUCTIVE COATINGS FOR THE HELIOS SPACECRAFT

I. Introduction

In essence this was a testing or scoping study of the solar cell coverslide material's resistance to ultraviolet and charged particle radiation seen by the Helios spacecraft.

The Helios project is a joint U.S.-West German effort to put a satellite in an eccentric solar orbit which will approach to within 0.3 A.U. of the sun. The first launch is tentatively scheduled for mid 1974. The package is composed of seven German and three U.S. experiments. Some of the experimental objectives are: Measurement of the solar wind velocity, mapping of the interplanetary magnetic field, measurement of plasma and radio waves, and determining the masses and energies of interplanetary dust.

The spacecraft is essentially spool-shaped, with the experiments and electronics housed in the middle cylindrical section. Due to the proximity of the spacecraft to the sun, charge buildup on an essentially non-conductive surface would cause electric fields outside the spacecraft, which would severely affect the sensitive instrumentation on board. It is therefore essential that the spacecraft have an equipotential or conducting surface. Indium oxide was chosen as a suitable coating for the outer surfaces of the solar cell coverslides in that it allows good transmittance and also suitable conductance to match the rest of the spacecraft's metallic skin. It remained to test the materials resistance to radiation comparable to that seen in the spacecraft's orbit, which led to the test plan that follows.

II. Test Description

The irradiation of the coverslides and solar cells/cover slides was divided into three phases:

1. A scoping study to give preliminary results and therefore indications of the scope of the materials resistance to ultraviolet, low energy and high energy charged particle irradiation.
2. Extension of (1) to include higher energy particles (200-300) KeV, with the same total fluxes, and also to determine temperature effects.

3. To determine specific values of energy, total flux of the predominant degradation species, along with an array of temperatures to obtain some correlation of energy, total flux and temperature on the degradation of the material.

Phases (2) and (3), it can be seen were dependent on the results of (1) which is the subject of this report.

Measurements and Samples

The following parameters were measured before and after irradiation. The instrument and its accuracy is also given.

- $\% T$ Optical Transmittance $(0.2 - 3.4) \mu$ Beckman Model DK-1A spectrophotometer, $\pm 2.0\%$
- $\% a$, Optical Absorptance $(0.2 - 2.5) \mu$ Beckman Model DK-2A spectrophotometer and integrating sphere, $\pm 2.0\%$
- $\varepsilon_n$, Normal emittance, Gier-Dunkle emissometer, $\pm 4.0\%$
- $R_s$, Sheet Resistance, Cambridge Four Point Probe, $\pm 2.0\%$
- Resistance of the coating on the solar cell/coverglass module, General Radio Resistance Bridge, Model GR 1650 A, $\pm 1\%$

The above measurements took several days to complete after each irradiation.

A number of coverslide samples were obtained from Optical Coatings Laboratory, Inc., Santa Rosa, California. The samples were all the same size, 25.4 mm by 21.5 mm and about 0.15 mm thick. The coverslides were divided into three groups.

1. Type A consisting only of the Corning 7940 fused silica substrate.

2. Type B consisting of the Corning 7940 substrate with a blue reflector coating on one side. The coating consists of multi-layers of titanium and manganese oxides to a thickness of about 8000 Å.
3. Type C consisting of the Corning 7940 substrate with the blue reflector coating (8000 Å) on the backside and the conductive coating (indium oxide, 1000 Å thick) on the front side.

AEG Telefunken supplied a solar cell/coverglass module. This module consisted of two strings of six cover glasses and two strings of six solar cells/cover glasses, all with a conductive coating. Each string was connected in series. The cover glasses with conductive coating were supplied to AEG Telefunken by OCLI and bounded to the solar cell by AEG.

Ultraviolet Irradiation and Results

The ultraviolet exposure was carried out in vacuum using a General Electric A H-6 mercury arc lamp. The lamp was positioned to supply 16 ultraviolet solar constants. The exposure was run for several days to obtain a total of 800 Equivalent Ultraviolet Sun Hours (EUVSH). Temperature of the sample holder was monitored throughout the test and was found to be 145°C ±10%. This is well below the critical 180°C specified by OCLI as causing possible degradation of the indium oxide coating. Figures 1-12 give the percentage transmittance vs. wavelength, while figures 13-24 give percentage transmittance vs. wavelength plus reflectance, from which absorptance is obtained, (1 - T + R = A).

The type B and C samples did not transmit at all in the near ultraviolet region (200-360) mµ, due to the blue reflector coating on both these types which cuts-off at ~415 mµ. See figure 5. This is a transmittance curve for Type B, Type C is similar. A decrease of several percent in transmittance was observed in the near ultraviolet region for Type A samples. See Figure 7. This was found comparable to that observed for Corning 7940 in recent studies of Optical Materials for the Earth Radiation Budget aboard NIMBUS (Reference 1).

A decrease of several percent in absorptance was noted for Type B from (200 to 360) mµ. See Figure 16. Type C exhibited an increase in absorptance over the same region as seen in Figure 22.

Type A material, fused silica, shows an increase in absorptance over the same region, although to a lesser extent. See Figure 19. Comparing Figures 16 and 22, some absorptance can be attributed to the conductive coating. No significant changes were observed for absorptance in the visible and near infra-red regions.

Normal emittance measurements at room temperature showed no changes from the initial values which were: Type A 0.80, Type B 0.79, Type C 0.79.
Sheet resistance for the Type C samples decreased slightly from about 0.9 kΩ/square to about 0.8 kΩ/square.

Scanning electron microscope studies of the samples at 400 X, 2000 X, and 4000 X showed no changes.

**Charged Particle Irradiation of Individual Coverglasses and Results**

The second part of this scoping phase involved charged particle irradiation at low energies. Specifically these were 4.0 KeV protons and 4.5 KeV electrons to fluences of $10^{12}$, $10^{14}$, and $10^{16}$ particles/cm$^2$. All samples were exposed in vacuum at approximately $10^{-6}$ torr. A 300 KeV Texas Nuclear accelerator was used for the two lower fluences, and an ORTEC RF source supplied the radiation for the $10^{16}$ particle/cm$^2$ run.

As in the case of the ultraviolet tests, the same before and after measurements were made. Figures 25-66 give percent transmittance, and figures 67-95 give % (transmittance + reflectance). No significant losses in transmittance occurred except for the Type A samples after $10^{16}$ electrons/cm$^2$ at 4.5 KeV. (See Figure 64.)

No changes at all were observed in the normal emittance and absorptance measurements.

In the sheet resistance, changes did occur. Table 1 gives the values before and after radiation.

<table>
<thead>
<tr>
<th></th>
<th>4 KeV Protons</th>
<th>4.5 KeV Electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10$^{12}$</td>
<td>10$^{14}$</td>
</tr>
<tr>
<td>$\Phi$ particles/cm$^2$</td>
<td>m</td>
<td>m</td>
</tr>
<tr>
<td>$R_\parallel$ kΩ/square</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>$R_\parallel$ kΩ/square</td>
<td>1.1</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Note that a large jump in the sheet resistance occurs due to the $10^{16}$ electrons/cm$^2$ exposure. The value of 3.6 kΩ/square is still well under the 20 kΩ/square limitation placed on the indium oxide coating.
Two strings, one with solar cells and cover glasses and one with cover glasses only, were shielded and used as a control. The other two strings were irradiated under the following conditions:

1. 1 MeV electrons in air, $10^{11} \text{ e/cm}^2$ to $10^{15} \text{ e/cm}^2$. Sample removed from machine for each resistance measurement.

2. 1 MeV protons in vacuum, $10^{11} \text{ p/cm}^2$ to $10^{15} \text{ p/cm}^2$. Samples removed from machine for each resistance measurement.

3. 1 MeV electrons in vacuum, $10^{12} \text{ e/cm}^2$ to $10^{15} \text{ e/cm}^2$. Samples removed from machine for each resistance measurement.

4. 1 MeV electrons in vacuum, $10^{11} \text{ e/cm}^2$ to $10^{15} \text{ e/cm}^2$. Resistance measured simultaneously with irradiation.

5. 1 MeV protons in vacuum, $10^{11} \text{ p/cm}^2$ to $10^{15} \text{ p/cm}^2$. Resistance measured simultaneously with irradiation.

Tables 2 and 3 give a summary of the data obtained before and during the irradiation. Figures 96, 97 and 98 show plots of the data against particles/cm$^2$. There was no appreciable degradation of the conductive coating during or after any of the tests.

III. Summary and Conclusions

Table 4 gives a summary of changes that occurred due to the ultraviolet and charged particle irradiations.

Essentially no significant changes occur due to radiation which would prohibit use of the conductive coating, blue reflector and Corning 7940 fused silica substrate combined to form a suitable solar cell coverslip. The increase in sheet resistance due to the charged particle irradiation appears to be dependent on the fluence acquired. A high enough accumulation of charged particle radiation produces enough defect structure in the coating to cause resistivity changes. From comparison calculations for germanium taken from tables (Reference 2), the electrons most probably penetrate the conductive coating while the protons do not. Even though all their energy is not expended in the conductive coating, the electrons account for a somewhat greater change in the sheet resistance than do the protons.
Table 2
AEG Telefunken Conductive Coating Irradiation Test

1 MeV Electrons in Air - 10/6/71 - 10/7/71

<table>
<thead>
<tr>
<th>String</th>
<th>Initial</th>
<th>$10^{11} \text{ e/cm}^2$</th>
<th>$10^{12} \text{ e/cm}^2$</th>
<th>$10^{13} \text{ e/cm}^2$</th>
<th>$10^{14} \text{ e/cm}^2$</th>
<th>**</th>
<th>**</th>
<th>$10^{15} \text{ e/cm}^2$</th>
<th>**</th>
<th>**</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>11.8</td>
<td>12.2</td>
<td>12.3</td>
<td>12.4</td>
<td>12.0</td>
<td>11.8</td>
<td>11.9</td>
<td>11.2</td>
<td>10.9</td>
<td>10.8</td>
</tr>
<tr>
<td>B</td>
<td>8.7</td>
<td>8.9</td>
<td>9.1</td>
<td>9.4</td>
<td>9.2</td>
<td>9.2</td>
<td>9.2</td>
<td>9.2</td>
<td>8.8</td>
<td>8.8</td>
</tr>
<tr>
<td>C (control)</td>
<td>12.8</td>
<td>12.8</td>
<td>12.8</td>
<td>12.8</td>
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<td>12.7</td>
</tr>
<tr>
<td>D (control)</td>
<td>8.3</td>
<td>8.3</td>
<td>8.3</td>
<td>8.3</td>
<td>8.3</td>
<td>8.3</td>
<td>8.3</td>
<td>8.2</td>
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<td>8.2</td>
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1 MeV Protons in Vacuum - 11/19/71

<table>
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<th>$10^{12} \text{ e/cm}^2$</th>
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<th>$10^{14} \text{ e/cm}^2$</th>
<th>**</th>
<th>**</th>
<th>$10^{15} \text{ e/cm}^2$</th>
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<th>**</th>
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<tbody>
<tr>
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<td>10.0</td>
<td>10.2</td>
<td>10.2</td>
<td>11.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>8.2</td>
<td>7.4</td>
<td>7.1</td>
<td>7.1</td>
<td>6.8</td>
<td>6.8</td>
<td>6.8</td>
<td>8.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C (control)</td>
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<td>10.8</td>
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<td>10.4</td>
<td>10.4</td>
<td>12.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D (control)</td>
<td>8.2</td>
<td>7.4</td>
<td>7.1</td>
<td>7.1</td>
<td>6.8</td>
<td>6.8</td>
<td>7.4</td>
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</table>

1 MeV Electrons in Vacuum - 11/22/71

<table>
<thead>
<tr>
<th>String</th>
<th>Initial</th>
<th>$10^{11} \text{ e/cm}^2$</th>
<th>$10^{12} \text{ e/cm}^2$</th>
<th>$10^{13} \text{ e/cm}^2$</th>
<th>$10^{14} \text{ e/cm}^2$</th>
<th>**</th>
<th>**</th>
<th>$10^{15} \text{ e/cm}^2$</th>
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<tbody>
<tr>
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<td>10.3</td>
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<td>10.4</td>
<td>10.4</td>
<td></td>
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</tr>
<tr>
<td>B</td>
<td>8.3</td>
<td>8.6</td>
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<td>8.5</td>
<td>8.5</td>
<td>8.5</td>
<td>8.5</td>
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<td></td>
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<tr>
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<tr>
<td>D (control)</td>
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<td>8.1</td>
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<td>8.0</td>
<td>8.0</td>
<td>7.6</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

* 2 hours after exposure
** 16 hours after exposure
### Table 3
AEG Telefunken Conductive Coating Irradiation Test

**Resistance in KΩ**

#### 1 MeV Electrons in Vacuum, Simultaneous Measurement
(12/21/71)

<table>
<thead>
<tr>
<th>String</th>
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<th>1.4×10^{14} e/cm²</th>
<th>2.7×10^{14} e/cm²</th>
<th>4×10^{14} e/cm²</th>
<th>5.4×10^{14} e/cm²</th>
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<th>9.5×10^{14} e/cm²</th>
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<th>10^{13} e/cm²</th>
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<td>9.6</td>
<td>9.6</td>
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<td>9.7</td>
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<td>13.4</td>
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</tr>
<tr>
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<td>8.7</td>
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<td>8.6</td>
<td>8.5</td>
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<td>8.5</td>
<td>8.5</td>
<td>8.5</td>
<td>8.7</td>
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</table>

(110 minutes to reach 1×10^{15} e/cm²)

#### 1 MeV Protons in Vacuum Simultaneous Measurement
(2/25/72)

<table>
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<tr>
<th>String</th>
<th>Initial</th>
<th>10^{12} p/cm²</th>
<th>10^{13} p/cm²</th>
<th>10^{14} p/cm²</th>
<th>2.5×10^{14} p/cm²</th>
<th>5×10^{14} p/cm²</th>
<th>7.5×10^{14} p/cm²</th>
<th>10^{15} p/cm²</th>
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<tr>
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<td>10.5</td>
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<td>9.8</td>
<td>9.8</td>
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<td>7.1</td>
<td>7.1</td>
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</table>

(167 minutes to reach 1×10^{15} p/cm²)
<table>
<thead>
<tr>
<th>Measurements</th>
<th>U.V.</th>
<th>Protons</th>
<th>Electrons</th>
</tr>
</thead>
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<tr>
<td></td>
<td>800 EYVSH</td>
<td>$10^{12}$ p/cm²</td>
<td>$10^{14}$ p/cm²</td>
</tr>
<tr>
<td>$\phi_T$</td>
<td>Decrease in fused silica (200–360) m/μ</td>
<td>Slight decrease in fused silica (200–360) m/μ</td>
<td>Slight decrease in fused silica (200–360) m/μ</td>
</tr>
<tr>
<td>$% \alpha$</td>
<td>Slight increase in conductive coating (200–360) m/μ</td>
<td>No change</td>
<td>No change</td>
</tr>
<tr>
<td>$\eta$</td>
<td>No change</td>
<td>No change</td>
<td>No change</td>
</tr>
<tr>
<td>$R_{\eta}$</td>
<td>Slight decrease in conductive coating</td>
<td>Slight increase in conductive coating</td>
<td>Slight increase in conductive coating</td>
</tr>
</tbody>
</table>
Due to the favorable results obtained in this first Phase of the coverslip and module tests, phases two and three will not have to be considered.

IV. Acknowledgements

Thanks for irradiation of the samples go to Jules Hirschfield, Arthur Dufault, John Stuart and Ronald Hunkeler. John Henninger, Walter Viehmann and Jane Jellison conducted various measurements on the samples.

V. References


Figure 1.

Helios Sample 0
Corning 7940 Fused Silica

- Initial
- After Irradiation of 800 EUVSH Type A

% T

Wavelength (µm)
Figure 2.
Figure 3.

HELIOS SAMPLE 0
CORNING 7940 FUSED SILICA

INITIAL

AFTER IRRADIATION
OF 800 EUVSH
TYPE A
HELIOS SAMPLE Y
CORNING 7940 FUSED SILICA
+
BLUE REFLECTOR
---
INITIAL
---
AFTER IRRADIATION
OF 800 EUV SH TYPE B

Figure 4.
Figure 5.
Figure 6.
Figure 7.

HELIOS SAMPLE U
CORNING 7940 FUSED SILICA

--- INITIAL ---

--- AFTER IRRADIATION OF 800 EUVSH TYPE A ---
Figure 8.

- HELIOS SAMPLE U
- CORNING 7940 FUSED SILICA
- INITIAL
- AFTER IRRADIATION OF 800 EUVSH TYPE A
Figure 10. 

HELIOS SAMPLE A 
CORNING 7940 
+ 
BLUE REFLECTOR 
+ 
CONDUCTIVE COATING 

INITIAL 

AFTER IRRADIATION 
OF 800 EUVSH 
TYPE C 

0 TRANSMITTANCE 

WAVELENGTH (mμ)
Figure 14.

HELIOS SAMPLE 0
CORNING 7940 FUSED SILICA

- INITIAL
- AFTER IRRADIATION
OF 800 EUVSH
TYPE A
Figure 15.

- Helios Sample O
- Corning 7940 Fused Silica

Initial

After Irradiation of 800 EUVSH Type A
Figure 16.

- **Y = 50 HRS. UV 16 SUNS**
- **INITIAL RUN**
- **10-8-71 50 HRS. UV 16 SUNS**

**HELIOS SAMPLE Y**
**CORNING 7940 + BLUE REFLECTOR**
- **INITIAL**
- **AFTER IRRADIATION OF 800 EUVSH TYPE B**
Figure 17.

HELIOS SAMPLE Y
CORNING 7940 + BLUE REFLECTOR
TYPE B

WAVELENGTH (μm)

% T + R

AFTER 50 HRS. UV 16 SUNS OR 800 EUVSH

INITIAL
Figure 18.
Figure 19.
Figure 20.
Figure 21.
Figure 22.
Figure 23.
Figure 24.

HELIOS SAMPLE A
CORNING 7940
+
BLUE REFLECTOR
+
CONDUCTIVE COATING

INITIAL

AFTER IRRADIATION
OF 800 EUVSH
TYPE C

% T + R

WAVELENGTH (µm)
SAMPLE B (c.c.)
4 Kev
$10^{12}$ P/cm²
--- INITIAL
--- AFTER IRRAD.

Figure 25.
Figure 26.

SAMPLE B (c.c.)
4 KeV
$10^{12}$ P/cm$^2$

- - - INITIAL
--- AFTER IRRAD.
Figure 27.
Figure 28.

SAMPLE E (c.c.)
4 KeV
$10^{16}$ P/cm$^2$

---

INITIAL
AFTER IRRAD.
Figure 29:

SAMPLE F (c.c.)
4 KeV
$10^{16}$ P/cm$^2$

- --- INITIAL
- --- AFTER IRRAD.
SAMPLE F (c.c.)
4 KeV
$10^{16}$ P/cm$^2$
- - - INITIAL
- - - AFTER IRRAD.

Figure 30.
Figure 32.

SAMPLE X (b.r.)
4 KeV
$10^{12}$ P/cm$^2$

--- INITIAL
--- AFTER IRRAD.
Figure 33.

SAMPLE V (b.r.)
4 KeV
$10^{14}$ P/cm²

--- INITIAL
--- AFTER IRRAD.
Figure 34.

SAMPLE V (b.r.)
4 KeV
$10^{14}$ p/cm$^2$

--- INITIAL
--- AFTER IRRAD.

% T

$\lambda$ ($\mu$)

0.7 1.0 1.5 2.0 2.5 3.0 3.4
SAMPLE BB (b.r.)
4 KeV
$10^{16}$ P/cm$^2$
--- INITIAL
--- AFTER IRRAD.

Figure 35.
Figure 37.
Figure 3R.

SAMPLE Q (clear f.s.)
4 KeV
$10^{12}$ P/cm²

--- INITIAL
--- AFTER IRRAD.
SAMPLE Q (clear f.s.)
4 KeV
$10^{12}$ P/cm²

--- INITIAL
--- AFTER IRRAD.

Figure 39.
Figure 40.

SAMPLE P (clear)
4 KeV
$10^{14}$ P/cm$^2$

--- INITIAL
--- AFTER IRRAD.
SAMPLE P (clear)
4 KeV
$10^{14}$ P/cm$^2$
--- INITIAL
--- AFTER IRRAD.

Figure 41.
Figure 42.

SAMPLE P (clear)
4 KeV P
$10^{14}$ P/cm$^2$

--- INITIAL
--- AFTER IRRAD.
SAMPLE R (clear)
4 KeV
$10^{16}$ P/cm$^2$

- INITIAL
- AFTER IRRAD.

Figure 43.
Figure 44.

SAMPLE R (clear)
4 KeV
$10^{16}$ P/cm$^2$
--- INITIAL
--- AFTER IRRAD.
SAMPLE G (c.c.)
4.5 KeV
$10^{15}$ e/cm²

--- INITIAL
--- AFTER IRRAD.

Figure 46.
SAMPLE G (c.c.)
4.5 KeV
$10^{12}$ e/cm$^2$

--- INITIAL
--- AFTER IRRAD.

Figure 47.
Sample I (c.c.)
4.5 KeV
$10^{14}$ e/cm$^2$

- INITIAL
- AFTER IRRAD.

Figure 48.
Figure 49.

SAMPLE I (c.c.)
4.5 keV
$10^{14}$ e/cm$^2$

- INITIAL
- AFTER IRRAD.
Figure 51.
Figure 52.
SAMPLE BB (b.r.)
4.5 KeV
$10^{12}$ e/cm²
--- INITIAL
--- AFTER IRRAD.

Figure 53.
Figure 54.

Sample Z (b.r.)
4.5 KeV
$10^{14}$ e/cm$^2$

- - - INITIAL
- - - AFTER IRRAD.
SAMPLE Z (b.r.)
4.5 KeV
$10^{14}$ e/cm$^2$
--- INITIAL
--- AFTER IRRAD.

Figure 55.
Figure 57.

SAMPLE Z (b.r.)
4.5 KeV
$10^{16}$ e/cm$^2$

--- INITIAL
--- AFTER IRRAD.
Figure 58.

SAMPLE S (clear f.s.)
4.5 KeV
$10^{12}$ e/cm$^2$

--- INITIAL
--- AFTER IRRAD.
SAMPLE S (clear f.s.)
4.5 FeV
$10^{12}$ e/cm$^2$

- - - INITIAL

- - - AFTER IRRAD.

Figure 59.
Figure 60.

SAMPLE S (clear f.s.)
4.5 KeV
$10^{12}$ e/cm$^2$

- - - - INITIAL
--- AFTER IRRAD.
SAMPLE T (clear)
4.5 KeV
$10^{14}$ e/cm$^2$

INITIAL
AFTER IRRAD.

Figure 61.
SAMPLE T (clear)
4.5 keV
$10^{14}$ e/cm²

--- INITIAL
--- AFTER IRRAD.

Figure 62.
Figure 63.

SAMPLE T (clear)
4.5 KeV
$10^{14}$ e/cm²

- --- INITIAL
- ---- AFTER IRRAD.
SAMPLE T (clear)
4.5 KeV
$10^{16}$ e/cm$^2$

INITIAL
AFTER IRRAD.

Figure 64.
Figure 65.

- SAMPLE T (clear)
- 4.5 KeV
- $10^{16}$ e/cm$^2$
- INITIAL
- AFTER IRRAD.
SAMPLE T (clear)
4.5 KeV
$10^{16}$ e/cm$^2$
--- INITIAL
--- AFTER IRRAD.

Figure 66.
SAMPLE H (c.c.)
4.5 KeV
$10^{12}$ e/cm$^2$
--- INITIAL
--- AFTER IRRAD.

Figure 67.
Figure 68.

% T + R

SAMPLE I (c.c.)
4.5 KeV
$10^{14}$ e/cm²

- - - - INITIAL
- - - - AFTER IRRAD.
Figure 69.

SAMPLE G (c.c)
4.5 KeV
$10^{16}$ e/cm$^2$

--- INITIAL
--- AFTER IRRAD.

% T + R

WAVELENGTH (m$\mu$)
SAMPLE H (c.c.)
4.5 KeV
$10^{16}$ e/cm²
--- INITIAL
--- AFTER IRRAD.

WAVELENGTH (µm)

Figure 70.
SAMPLE H (c.c.)
4.5 KeV
$10^{16}$ e/cm²

--- INITIAL
- - - - AFTER IRRAD.

Figure 71.
Figure 72.

SAMPLE BB (b.r.)
4.5 KeV
$10^{12}$ e/cm$^2$

--- INITIAL
--- AFTER IRRAD.
SAMPLE S (clear f.s.)
4.5 KeV
$10^{12}$ e/cm$^2$

- INITIAL
- AFTER IRRAD.

Figure 74.
SAMPLE T (clear f.s.)
4.5 KeV
$10^{14}$ e/cm$^2$
--- INITIAL
--- AFTER IRRAD.

Figure 75.
SAMPLE T (clear)
4.5 KeV
$10^{14}$ e/cm$^2$

--- INITIAL
---- AFTER IRRAD.

WAVELENGTH (µm)

Figure 76.
Figure 77.

SAMPLE T (clear f.s.)
4.5 keV
$10^{16}$ e/cm$^2$
--- INITIAL
--- AFTER IRRAD.
Figure 79.

SAMPLE B (c.c.)
4 KeV
$10^{12} \text{H} / \text{cm}^2$

--- INITIAL
--- AFTER IRRAD.

WAVELENGTH (m$\mu$)
Figure 90.

SAMPLE B (c.c.)
4 KeV
$10^{12}$ H$^+$ cm$^{-2}$
--- INITIAL
--- AFTER IRRAD.
SAMPLE E (c.c.)
4 keV
10^{14} H⁺/cm²
--- INITIAL
--- AFTER IRRAD.

Figure 81.
Figure 82.

SAMPLE E (c.c.)
4 KeV
$10^{14}$ H$^+$/cm$^2$

- - - INITIAL

- - - AFTER IRRAD.

WAVELENGTH (m$\mu$)

% T + R
Figure 84.
Figure 84.

SAMPLE F (c.c.)
4 KeV
$10^{16}$ P/cm$^2$

--- INITIAL
--- AFTER IRRAD.
Figure 85.

SAMPLE F (c.c.)
4 keV
$10^{16}$ P/cm$^2$

- - - - INITIAL
- - - - AFTER IRRAD.
Figure 86.

SAMPLE X (b.r.)
4 KeV
$10^{12} \text{H/cm}^2$

INITIAL
AFTER IRRAD.
NO CHANGE FROM INITIAL RUN

SAMPLE X (b.r.)
4 KeV
$10^{12}$ H$^+$ cm$^{-2}$

- - - - INITIAL
- - - - AFTER IRRAD.

Figure 87.
Figure 88.

SAMPLE V (b.r.)
4 KeV
$10^{14} \text{H}^+ / \text{cm}^2$

- - - INITIAL
- - - AFTER IRRAD.
Figure 89.

NO CHANGE FROM INITIAL RUN

SAMPLE V (b.r.)
4 KeV
$10^{14}$ H$^+$cm$^{-2}$

- - - INITIAL
--- AFTER IRRAD.
SAMPLE Q (clear f.s.)
4 KeV
$10^{12}$ H⁺/cm²

- --- INITIAL
- - - - - AFTER IRRAD.

Figure 90.
NO CHANGE
FROM INITIAL RUN

WAVELENGTH (m\textmu )

% T + R

SAMPLE Q (clear f.s.)
4 keV
10^{12} \text{H}^+ / \text{cm}^2

INITIAL
AFTER IRRAD.

Figure 91.
Figure 92.

SAMPLE P (clear f.s.)
4 KeV
$10^{14}$ H$^+$ cm$^{-2}$

INITIAL
AFTER IRRAD.
No change from initial run

Sample P (clear f.s.)
4 KeV
$10^{14}$ H$^+$/cm$^2$

- Initial
- After Irrad.

Wavelength (m$\mu$)

Figure 93.
SAMPLE R (clear fused silica)
4 KeV
$10^{16}$ P/cm$^2$
--- INITIAL
--- AFTER IRRAD.

Figure 95.
1 MeV ELECTRONS IN AIR

Figure 96.
Figure 97.
SIMULTANEOUS IRRADIATION/MEASUREMENT

- STRING A COVER GLASS ONLY
- STRING B COVER GLASS/SOLAR CELL
- STRING C COVER GLASS ONLY - SHIELDED/CONTROL
- STRING D COVER GLASS/SOLAR CELL - SHIELDED/CONTROL

1 Mev ELECTRONS IN VACUUM
1 Mev PROTONS IN VACUUM

Figure 98.