Contract NAS5-99236

Development of Electrostatically Clean Solar Array Panels

Final Report

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Prepared by:
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For:
NASA / Goddard Space Flight Center
Introduction

Background

Certain missions require electrostatically clean solar array (ECSA) panels to establish a favorable environment for the operation of key scientific instruments. Current technology solar arrays have exposed electrical circuitry that interacts with the ambient plasma. This interaction affects the floating potential and particle trajectories surrounding the spacecraft, and so may influence scientific mission readings. Solar arrays with exposed conductors can both introduce and absorb current from the surrounding environment, and affect the shape of the plasma sheath that typically surrounds a solar array in earth orbit.

The exposed circuitry of a solar array comprises primarily the solar cell interconnects and cell edges, although cell string terminations, panel diodes and terminal boards can also provide sites for electrostatic field interactions. Typical solar cell arrays use individual cell/coverglass assemblies that have spacing between the cell/cover assemblies for electrical and thermomechanical reasons. If the covers use a conductive coating, the covers must be electrically connected to each other and to the array structure to establish a ground plane. Even so, spaces between the coverglasses still expose interconnects to interact with the ambient environment. A large number of these spaces exist on a typical solar panel because of the relatively small size of cell/coverglass assemblies.

An electrostatically clean solar panel needs a method for covering these inter-cell and edge areas so as to create a contiguous ground plane on the front side and edges. This would enable a panel that surrounds the solar cells with a grounded shield, since electrical conductivity is already achieved on the array backside. The approach needs to minimize thermal mismatch stresses, use materials and processes that are qualified by similarity to existing techniques on solar panels, and minimize cost and complexity. Reliable electrical continuity of the grounded shield and insulation of the shield from the photovoltaic electrical circuit is critical.

Objective

The objectives of this program are to design, develop and demonstrate:

- an ECSA panel with continuous grounded shield surrounding the photovoltaic circuit, which uses Standard Power Modules (SPM’s are multiple cells under a single conductively-coated coverglass),
- a Front Side Aperture (FSA) shield component that covers the areas between SPM’s and around the edges, uses space qualified materials, is compatible with established panel technology and manufacturing approaches, and is simple and low-cost, and
- an electrical bond between the coverglasses and the FSA shield that provides electrical continuity for the panel front and back sides, and insulation to assure electrical isolation between the FSA shield and the power circuit.

Approach

To accomplish the program objectives we set up a program team using expertise from COI, Maxwell Technologies, Inc., (MTI) and Tecstar. COI is to apply our knowledge in solar panel substrates and structures and electronic packaging techniques to create a grounded structure with appropriate shielding and grounding qualities. MTI is to apply its experience and knowledge in analysis electrostatic cleanliness criteria by performing simple calculations and establishing test and verification criteria. Tecstar is applying its solar cell array manufacturing technology and SPM design to create the basic panel photovoltaic circuit, suitable to modification into a shielded design.
The program approach includes the following elements:

- COI completes the basic design of an FSA that meets mass and manufacturability requirements.
- MTI analyzes the COI pre-design for its performance in maintaining low electrical potentials near the panel, and to establish criteria for surface resistance that will result in meeting the surface potential requirements of the program.
- Tecstar populates and flash tests the two protoflight coupons using substrates supplied by COI.
- COI fabricates and assembles the FSA onto the populated coupons, and exposes the coupons to thermal cycling environment. Electrical testing of the coupons before and after thermal cycling leads to an evaluation of design alternatives, and choice of the best design.
- COI and Tecstar fabricate and protoflight panel, and expose it to acoustic and thermal cycling regimes to qualify the performance and durability of the chosen design approach.

**ECSA Panel Design & Analysis**

**ECSA Panel Design**

The basic geometry of the ECSA Panel, shown in Figure 1 uses SPM’s each with an ITO coated coverglasses, and a Front-side Aperture Shield (FSA) to establish a contiguous ground plane on the panel front side surface.

![Figure 1. Basic Geometry of an ECSA Panel Using a Front Side Aperture Grid Shield](image)

COI developed the design for the qualification panel coupons using two different FSA bonding approaches and four different FSA-to-coverglass interconnecting schemes, one for each SPM aperture. The design of the FSA for the qualification coupons is shown in Figure 2.
The two approaches used for bonding the FSA to the coverglasses are a compliant RTV bond, and a film adhesive with an imbedded copper mesh. The interconnects shown on the three apertures are connected to the coverglasses with conductive adhesive, using McGann Nusil CV2-2646 silver-filled silicone adhesive. The fourth aperture, which is shown as blank, uses beryllium copper contact fingers, electrically and mechanically bonded to the FSA, and spring-contacted to the coverglass. This mechanical contact approach is derived from EMI shielding gaskets used in electronic packaging applications. The circular features on the corners of the FSA are for tooling pins to register the FSA against the SPM's during assembly of the qualification coupons. A similar set of registration features will be used on the full-scale prototype panel coupon.

![Figure 2. Layout of the Frontside Aperture Shield for the Qual Coupons.](image)

**ECSA Panel Analysis**

**Structural Analysis**

A top-level structural analysis was performed on the ECSA panel design to examine the stresses on the components of the panel associated with the modifications needed for electrostatic cleanliness. The panel materials considered in the analysis were glass, silicone adhesive and T300 composite 0.15mm, 0.1mm and 0.5mm thick respectively. A finite element model was constructed representing four cells and constrained at each of the four edges. Each edge is free to slide in plane, but constrained out of plane. The panel was analyzed using the two worst-case thermal load cases – cold soaking to -180C, and hot soaking to +90C. These analyses considered the stress-free condition to be at an ambient room temperature of 21C. The resulting stresses were compared with the known ultimate
capabilities of each material. This comparison showed large positive margins in all cases. Maximum deflections of the panel were 1.0mm under the +90C soak and 3.0mm while subjected to the -180C cold soak.

Of particular interest for maintaining the integrity of this design is the ability of the silicone adhesive to accommodate differential CTE stress. The maximum principal stress imposed on the adhesive was 70 psi. This compares with the specified tensile strength of the NuSil CV2-2506-6 at 350 psi.

**Electrostatic Analysis**

MTI performed electrostatic analysis of the ECSA design, focusing on exposed voltage established near the panels by the photovoltaic circuit, and the potentials established on the panels due to the charged particle environment. Detailed results for the MTI analysis are provided as Appendix 1.

MTI looked at the ECSA design to determine the voltages that might be incurred near the panel if the FSA does not seal the edges of the SPM’s. A gap height of 20mil (0.5mm) was used as a typical value achievable between the FSA and the SPM if a continuous bond to the edges of the coverglass was not used. The results showed that a small voltage is established near the gap area (<0.9V), but that this voltage dissipates rapidly with distance away from the gap, and is in fact <1mV at a distance greater than 1mm from the panel surface.

MTI’s analysis of maintaining equipotential on the ECSA panel surface looked at different ITO thicknesses and resulting resistance, and determined the maximum voltage that could be established on the coverglass under exposure to the charged particle environment. Initially, the environmental requirements were reviewed and found to be overstated by an order of magnitude. This is because it is the ram ion current, rather than the electron current that will result in charging of the panel surface. Since the ion current density is 0.1\( \mu \text{A/cm}^2 \) rather than the 1\( \mu \text{A/cm}^2 \) specified in the requirements. As a result, NASA agreed to modify the requirements to reflect the expected environmental interaction. The results of this analysis showed that an ITO coating with a resistivity of 3x10E+4 \( \Omega/\text{square} \) or less would be needed to establish a potential of <0.1V. This coating would be about 150A thick.

MTI also performed analysis to determine what the test criteria should be for establishing that sufficient conductivity had been achieved within the ITO coating and from the coating to the FSA grounded structure. This analysis considered various geometric configurations shown in Figure 2, and concluded that a measurement of less than 100kohms from the center of the coverglass to the structure would be sufficient to maintain the 0.1V requirement under space conditions. The analysis also showed that the results would be relatively independent of the size of the probe used to pick up the conduction path at the center of the coverglass.

**Qualification Coupons**

**Qualification Coupon Fabrication**

Having established the basic design of the qualification coupons, we sought to develop the manufacturing technology on some dummy test hardware to prove out the fabrication process without risking the populated panels. Three man-tech coupons were built to show the ability to position and bond the FSA while limiting the unwanted exposure of adhesive. The man-tech coupons used three different FSA bonding techniques - RTV CV2566 silicone adhesive, a similar silicone provided in a beta-staged pre-form, and a film adhesive with embedded copper mesh. Dummy coverglasses were fashioned from ordinary plate glass and mounted onto a typical solar panel substrate. The man-tech coupons showed the ability to bond the FSA using all three adhesive systems, although the liquid RTV system was the hardest to
maintain cleanliness. We chose to use the RTV pre-form (Coupon#002) and the film adhesive approach (Coupons#001) for the qualification coupons.

Two qualification coupons were fabricated. Each used four SPM's, where each SPM used two solar cells and a single coverglass. Redundant wiring was soldered to the solar cell interconnect pads at the edge of the panel, requiring that some of the FSA be trimmed away to prevent mechanical interference. One of the two qualification coupons is shown in Figure 3.

![Figure 3. Qualification coupon using four coverglass interconnect approaches](image)

**Qualification Coupon Tests**

Electrical I-V and resistance tests were performed on the qualification coupons prior to thermal cycling. Table 1 shows the values that were achieved on the two qualification coupons. Resistance readings were difficult to measure because an anti-reflection coating exists on top of the ITO coating on the coverglass. We had to scratch through the AR coating to get a reading. Conductive pads could also be used, but required some pressure to be applied in order to get consistent readings.

<table>
<thead>
<tr>
<th>Interconnect type</th>
<th>Qual coupon #1</th>
<th>Qual coupon #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slant</td>
<td>10</td>
<td>33</td>
</tr>
<tr>
<td>Serpentine</td>
<td>93</td>
<td>98</td>
</tr>
<tr>
<td>Diamond</td>
<td>5</td>
<td>23</td>
</tr>
<tr>
<td>Be-Cu Contact Finger</td>
<td>8</td>
<td>27</td>
</tr>
</tbody>
</table>

*Table 1. Resistance values (in kilo-ohms) measured on the qualification coupons prior to thermal cycling.*

Electrical measurements taken on the qualification coupons before and after bonding of the FSA showed an efficiency reduction of about 4% on S/N 001 and 6% on S/N 002. Resistance
from the PV circuit to the structure was open on both coupons initially. Because a couple of the interconnects on coupon #002 had poor fillets on the conductive adhesive bond, we touched them up prior to thermal cycling by adding additional adhesive. Unfortunately, some squeeze-out into the solar cell area caused a resistive short from the structure to the solar cell string, initially measured at >1MΩ.

The coupons were thermal cycled from -180°C to 35°C for 200 cycles, and re-measured, then thermal cycled from -90 to 90°C for 1000 cycles and re-measured. The results of these measurements are shown in Tables 2 and 3. After the initial 200 cycles, it was observed that the film adhesive bond between the FSA and the SPM for coupon #001 failed almost completely, lifting the FSA away from the surface, and pulling up the serpentine interconnects with it. As a result, no conductivity reading is seen for the serpentine or Be-Cu contact finger for coupon #001 after thermal cycling. Some separation of the bond-line around the area of the beryllium contact finger on Coupon #002 was also observed. In addition, the shunting resistance in Coupon #002 had decreased to <300ohms.

Table 2. Resistance values (in kΩ) measured on the qualification coupons after 200 cycles from -180 to 35°C.

<table>
<thead>
<tr>
<th>Interconnect type</th>
<th>Qual coupon #1</th>
<th>Qual coupon #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slant</td>
<td>20</td>
<td>12</td>
</tr>
<tr>
<td>Serpentine</td>
<td>open</td>
<td>26</td>
</tr>
<tr>
<td>Diamond</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Be-Cu Contact Finger</td>
<td>open</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 3. Resistance values (in kΩ) measured on the qualification coupons after 1,000 cycles from -90 to 90°C.

<table>
<thead>
<tr>
<th>Interconnect type</th>
<th>Qual coupon #1</th>
<th>Qual coupon #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slant</td>
<td>31</td>
<td>50</td>
</tr>
<tr>
<td>Serpentine</td>
<td>open</td>
<td>97</td>
</tr>
<tr>
<td>Diamond</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>Be-Cu Contact Finger</td>
<td>open</td>
<td>52</td>
</tr>
</tbody>
</table>

Qualification Coupon Analysis

Qualification coupon #002 represents a design that appears to have the ability to meet all program requirements. The RTV pre-form bond appears to be solid after thermal cycling, and the conductive adhesive also maintained bond integrity. Although all four interconnect approaches appear to work, the diamond interconnect configuration gave consistently lower resistances. The effectiveness of the diamond interconnect configuration may be due to maximizing continuous fibers within the interconnect. Also contributing may be the dual conductive path from the contact point of the coverglass, through the two legs of the diamond, to the FSA body structure.

The use of a film adhesive with an imbedded copper-mesh does not provide sufficient bond strength to maintain mechanical connection in a thermal cycling environment. There may be several contributing causes to this, including the stiffness of the film adhesive, its relatively high CTE, stress applied by the beryllium-copper contact finger which may have increased with temperature, and possibly the bond-ability of the AR coating surface.

Given the successful measurement of the key parameter of coverglass conductivity to structure on Coupon #002, especially for the diamond interconnect geometry, we recommended that the protoflight panel use that design exclusively.
Prototype Panel

Based on the results of the qualification coupons, a prototype panel was fabricated that incorporated the diamond coverglass interconnect approach on a larger scale. The prototype panel used a total of 48 Standard Power Modules (SPM), with each SPM comprising two solar cells, a series interconnect between the cells, as a single coverglass covering both cells.

The layout of the solar cells was coordinated with Tecstar to allow appropriate spacing between each SPM, based on achieving a minimum structural bond-line width between the FSA edges and the coverglasses of 0.75mm (0.030”). A section of this layout pattern is shown in the drawing of Figure 4. Tecstar assembled the SPM’s, interconnected them to form 4 series connected strings of 12 SPM’s (i.e., 24 cells) each, and laid them down onto the COI supplied substrate to the pattern described by the layout drawing.

![Prototype Panel Diagram](image)

Figure 4. Cell layout drawing used to provide appropriate spacing for the FSA.

We then completed the assembly of the ECSA panel, using a single-piece FSA fabricated from T300 graphite fiber reinforced composite fabric, along with some Z-clips to close out the edges of the FSA to the edges of the substrate. As with the qualification coupons, this provided a complete and continuous grounded enclosure for the active solar cell components. Finally, we used conductive adhesive to bond the diamond interconnects to the coverglasses. The resulting panel is shown in the photographs of Figure 5. A listing of the parts and materials used in constructing this prototype panel is provided as Appendix 2.
Figure 5. Completed prototype ECSA panel.
The overall size of the prototype panel, including the extra edge area (edge distances were not optimized) is 0.532 X 0.585m. Its mass properties are shown in Table 4.

Table 4. Mass properties of the prototype panel.

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>711g</td>
</tr>
<tr>
<td>Panel without EC components (FSA, edge clips, and structural and conductive adhesives)</td>
<td>1055g</td>
</tr>
<tr>
<td>Completed prototype panel</td>
<td>1118g</td>
</tr>
</tbody>
</table>

Based on these mass properties, we observe that the components needed to provide electrostatic cleanliness add approximately 6% to the mass of a typical high performance solar panel. This does not include any mass added as a result of extra spacing between the solar cells needed to accommodate the FSA.

Prototype Panel Functional Tests and Environmental Exposures

The prototype panel was put through a set of functional tests and environmental exposures in the following order:

- Functional / Electrical testing
- Acoustic Testing
- Functional / Electrical Testing
- Thermal Cycling
- Functional / Electrical Testing

Each functional test included panel photovoltaic performance and electrical isolation and grounding. Functional testing was performed prior to and subsequent to each environmental exposure.

The photovoltaic performance testing was performed at Tecstar evaluated by taking I-V curves at room temperature and at 70C. 70C data was taken in a hot-box with Lexan window, with compensation for window transmission loss accomplished by using a reference calibrated solar cell. For the discussion in this section, we present the summary of the room temperature data, but complete data sets are provided in Appendix 3. No unusual effects were observed in the 70C data either before or after environmental exposures.
Electrical isolation and grounding performed at COI, i.e. isolation between the photovoltaic circuit and the panel ground/structure, resistance between each coverglass and ground. The test setup is illustrated in Figure 6. All isolation measurements were made with photovoltaic circuit leads shorted to each other to prevent the possibility of electrical damage.

Initial photovoltaic electrical testing of the prototype panel prior to application of the FSA component is summarized in Table 6. The results summarize the performance with all four circuits tied together in parallel. Although this was not a required measurement for this program, we wanted to understand how aperture blockage by the FSA affected the panel output.

The panel performance after final assembly, prior to acoustic testing is summarized in Table 7. From these results, we can see a current decrease of 7% with an equivalent decrease in efficiency performance. A slight drop in fill factor can be attributed to small additional mismatch in maximum power current between the various cells resulting from differences in blockage by the FSA and its associated bonds. The panel was also tested electrically for circuit isolation from ground and resistance from each coverglass to the panel substrate. The results of these tests are summarized in Table 8.

Table 6. Photovoltaic performance of the prototype panel at room temperature prior to application of modifications for electrostatic cleanliness.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voc</td>
<td>58.78V</td>
</tr>
<tr>
<td>Isc</td>
<td>1.49A</td>
</tr>
<tr>
<td>Pmax</td>
<td>69.42W</td>
</tr>
<tr>
<td>Vmp</td>
<td>49.37V</td>
</tr>
<tr>
<td>Imp</td>
<td>1.41A</td>
</tr>
<tr>
<td>FF</td>
<td>79.1%</td>
</tr>
<tr>
<td>Efficiency</td>
<td>21.98%</td>
</tr>
</tbody>
</table>
Table 7. Baseline photovoltaic performance of the assembled prototype panel at room temperature shows a 7% decrease in current compared to a bare panel resulting from the expected FSA blockage.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voc</td>
<td>58.61V</td>
</tr>
<tr>
<td>Isc</td>
<td>1.40A</td>
</tr>
<tr>
<td>Pmax</td>
<td>64.33W</td>
</tr>
<tr>
<td>Vmp</td>
<td>49.26V</td>
</tr>
<tr>
<td>Imp</td>
<td>1.31A</td>
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<tr>
<td>FF</td>
<td>78.2%</td>
</tr>
<tr>
<td>Efficiency</td>
<td>20.37%</td>
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</tbody>
</table>

Table 8. Results of electrical continuity and isolation tests for the prototype panel pre-environmental exposure.

<table>
<thead>
<tr>
<th>Resistance (kohm) from coverglass to panel ground</th>
<th>12</th>
<th>140</th>
<th>3</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>OC</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>5</td>
<td>3</td>
<td>6</td>
<td>5</td>
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</tr>
<tr>
<td>2</td>
<td>6</td>
<td>15</td>
<td>2</td>
<td>10</td>
<td>5</td>
<td>OC</td>
<td>OC</td>
<td></td>
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<td>6</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>2</td>
<td>8</td>
<td>4</td>
<td>2</td>
<td>6</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>14</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

| Circuit Isolation | OC | OC | OC | OC |

Acoustic testing was performed at Wyle Laboratories to the environment specified in the Statement of Work and Specification for the Development of Electrostatically Clean Solar Panels. The panel was placed in a net and exposed to an acoustic environment exceeding 142.5dB for a period of 60 seconds. The Wyle test report is included as Appendix 4.

After this exposure, panel photovoltaic and electrical measurements were completed. These results, as exhibited in Tables 9 and 10, indicate no change in photovoltaic performance (<1% variation in all parameters), but some increase in the number of coverglasses that exceed the maximum resistance requirement. After acoustic testing the number of coverglasses that did not have a resistance to ground of less than 100kohm was 11 compared to 4 out of 48 prior to acoustic testing. Visual inspection of the bonds did not indicate any obvious cause for this loss of continuity.
Table 9. Photovoltaic performance of the prototype panel at room temperature after acoustic.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voc</td>
<td>58.66V</td>
</tr>
<tr>
<td>Isc</td>
<td>1.40A</td>
</tr>
<tr>
<td>Pmax</td>
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</tr>
<tr>
<td>Vmp</td>
<td>49.31V</td>
</tr>
<tr>
<td>Imp</td>
<td>1.31A</td>
</tr>
<tr>
<td>FF</td>
<td>78.9%</td>
</tr>
<tr>
<td>Efficiency</td>
<td>20.51%</td>
</tr>
</tbody>
</table>

Table 10. Results of electrical continuity and isolation testing for the prototype panel after acoustic test.

<table>
<thead>
<tr>
<th>Resistance (kohm) from coverglass to panel ground</th>
<th>Circuit Isolation</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 OC 3 2 3 6 OC OC</td>
<td>OC</td>
</tr>
<tr>
<td>4 13 3 2 22 2 OC OC</td>
<td>OC</td>
</tr>
<tr>
<td>2 22 27 2 28 OC OC OC</td>
<td>OC</td>
</tr>
<tr>
<td>17 250 5 3 5 OC OC OC</td>
<td>OC</td>
</tr>
<tr>
<td>2 2 1 6 11 10 4 33 OC OC OC</td>
<td>OC</td>
</tr>
<tr>
<td>2 2 5 4 2 9 OC OC</td>
<td>OC</td>
</tr>
</tbody>
</table>

Following this evaluation, the prototype panel was bagged and placed in a thermal cycle chamber, and exposed to thermal cycle environments of 200 cycles from -180 to 35°C followed by 1000 cycles from -90 to 90°C. Test tolerances for each thermal cycle environment limits were +/-5°C.

Inspection of the panel after thermal cycling showed no observable physical effects. There was no warping of the panel or the FSA, and all structural bonds appeared intact. The results of photovoltaic and electrical testing are provided in Tables 11 and 12. Photovoltaic testing showed no change in performance (<1% difference in all values). Electrical isolation was still good, but continuity testing did indicate 8 additional failures of coverglass-to-FSA bonds. A total of 19 out of 48 coverglasses did not meet the continuity requirement after all environmental exposures. A failure analysis was performed on the coverglass continuity and is described in the next section.
Table 11. Photovoltaic performance of the prototype panel at room temperature after thermal cycling in simulated LEO and GEO environments.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voc</td>
<td>58.66V</td>
</tr>
<tr>
<td>Isc</td>
<td>1.40A</td>
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<tr>
<td>Pmax</td>
<td>64.57W</td>
</tr>
<tr>
<td>Vmp</td>
<td>49.29V</td>
</tr>
<tr>
<td>Imp</td>
<td>1.31A</td>
</tr>
<tr>
<td>FF</td>
<td>78.9%</td>
</tr>
<tr>
<td>Efficiency</td>
<td>20.45%</td>
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</tbody>
</table>

Table 12. Results of electrical continuity testing for the prototype panel after thermal cycling exposure.

<table>
<thead>
<tr>
<th>Resistance (kohm) from coverglass to panel ground</th>
<th>OC</th>
<th>OC</th>
<th>OC</th>
<th>39</th>
<th>12</th>
<th>74</th>
<th>OC</th>
<th>OC</th>
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</thead>
<tbody>
<tr>
<td>620</td>
<td>500</td>
<td>46</td>
<td>6</td>
<td>330</td>
<td>8</td>
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</tr>
<tr>
<td>76</td>
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<td>800</td>
<td>9</td>
<td>OC</td>
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<tr>
<td>61</td>
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<td>16</td>
<td>OC</td>
<td>60</td>
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</tbody>
</table>

Circuit Isolation

<table>
<thead>
<tr>
<th>OC</th>
<th>OC</th>
<th>OC</th>
</tr>
</thead>
</table>

Prototype Panel Evaluation and Failure Analysis

The prototype panel was evaluated to determine its ability to meet the requirements of this program. The photovoltaic performance, electrical continuity, and visual inspection of the panel before and after environmental exposures demonstrated the following key attributes:

- A composite FSA can be used as an electrostatic shield with a small performance and cost penalty, and is structurally robust in acoustic and thermal cycling environment.

- Beyond the shadowing of solar cells from the FSA, the performance of the solar panel, and its response to acoustic and thermal cycling environment, is not impacted by addition of electrostatically clean features.

- A continuous grounded enclosure that would result in less than 0.1V of potential between any two points on a solar panel can be assembled using ITO coated coverglasses, the FSA and conductive adhesive providing a connection between the two through a stress-relieved interconnect.

The ability to maintain grounding continuity to the SPM's after environmental exposure was not demonstrated because of failure of the conductively bonded joints. The direct cause of the failure was loss of adhesion at the interface between the glass and the conductive adhesive.
which we determined by measuring resistances across the FSA, and between the coverglasses and the FSA on the failed SPM's.

We performed a failure analysis to determine the root cause of the loss of bond adhesion to the coverglasses, using the “fish-bone” failure analysis technique. The fishbone approach correlates observations from inspection and non-destructive testing to possible failure modes. It is especially useful when multiple causes may be involved, and limited diagnostic test data are available.

The root cause fishbone for the bond adhesion failure is shown in Figure 7. Additional diagnostics were performed to support the fishbone analysis – measurement of surface resistance within each coverglass, evaluation of conductive adhesive bond size and fillet shape, and evaluation of position of the failures. The results are summarized in Table 12, and the plot of the coverglass resistances as a function of position shown in Figure 8. The analysis of the likelihood of root cause based on the possibilities presented in the fishbone diagram is provided in Table 13.
Figure 7. Root cause failure analysis fishbone diagram

Table 12. Additional NDE performed for fishbone evaluation. Failed bonds are shaded.

<table>
<thead>
<tr>
<th>Resistance (ohm) from coverglass to panel ground</th>
<th>OC</th>
<th>HCR, Lg</th>
<th>OC</th>
<th>HCR, Lg</th>
<th>OC</th>
<th>39</th>
<th>12</th>
<th>74</th>
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<th>OC HCR</th>
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<td>Lg</td>
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<td>OC</td>
<td>9</td>
<td>HCR, Lg</td>
<td>OC</td>
<td>OC</td>
<td>OC</td>
<td>OC</td>
<td></td>
<td></td>
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</tr>
<tr>
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<td>OC</td>
<td>14</td>
<td>15</td>
<td>OC HCR</td>
<td>OC</td>
<td>OC</td>
<td>Sm</td>
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<tr>
<td>22 9 4 HCR</td>
<td>OC</td>
<td>10</td>
<td>HCR</td>
<td>6</td>
<td>11</td>
<td>HCR, Lg</td>
<td>10</td>
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<td>37</td>
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<tr>
<td>5 9 Sm</td>
<td>OC</td>
<td>17</td>
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<td>Circuit Isolation</td>
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<td>OC</td>
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</tbody>
</table>

**Key:**

- HCR = high coating surface resistance
- Sm = small adhesive bond
- Lg = large adhesive bond
Figure 8. Correlation between areas of marginal and failed continuity with position on the panel.

Table 13. Root cause analysis based on fishbone diagram.

<table>
<thead>
<tr>
<th>Category</th>
<th>Possible Cause</th>
<th>Likelihood</th>
<th>Rationale</th>
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<tbody>
<tr>
<td>Adhesive Material</td>
<td>Not the best material for this application</td>
<td>Very Unlikely</td>
<td>This material qualified for flight coverglass ESD bond</td>
</tr>
<tr>
<td></td>
<td>Old/bad batch of material</td>
<td>Unlikely</td>
<td>Material controlled to R&amp;D standards</td>
</tr>
<tr>
<td>Adhesive Geometry</td>
<td>Too little adhesive</td>
<td>Possible Contributor</td>
<td>Some correlation</td>
</tr>
<tr>
<td></td>
<td>Too much adhesive</td>
<td>Possible Contributor</td>
<td>Some correlation</td>
</tr>
<tr>
<td></td>
<td>Bad fillet shape</td>
<td>Possible Contributor</td>
<td>Some evidence</td>
</tr>
<tr>
<td>Design</td>
<td>CTE stresses exceeds allowable</td>
<td>Unlikely</td>
<td>Based on stress analysis results</td>
</tr>
<tr>
<td></td>
<td>FSA too stiff</td>
<td>Unlikely</td>
<td>Based on material selection and stress analysis</td>
</tr>
<tr>
<td>Bonding Surface</td>
<td>Coverglass coating inconsistency</td>
<td>Possible Contributor</td>
<td>Correlation between inconsistent coverglass surface resistance</td>
</tr>
<tr>
<td></td>
<td>Inadequate surface prep</td>
<td>Likely Contributor</td>
<td>Minimal prep was used to prevent coating erosion</td>
</tr>
<tr>
<td></td>
<td>Silicone or other contamination</td>
<td>Likely Contributor</td>
<td>Grouping of failures and higher bond resistance areas</td>
</tr>
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</table>

Based on the analysis summarized in Table 13, the most likely root cause appears to be a combination of contamination and inadequate surface preparation. We had discussions with OCLI and Tecstar about how silicone squeeze-out is cleaned during the lay-down process, the potential for silicone contamination on the glass surface, and how we should have prepared the surfaces for bonding. The conclusion of this discussion is that there was a high likelihood of some level of silicone contamination on the coverglasses, which should have been removed by cleaning the surface prior to adhesive application.

The grouping of failures is further evidence of local area contamination, and the differences in coverglass surface resistance may be evidence of either contamination or inconsistent coating thickness. Our lack of experience in bonding to coated glass surfaces led us to be overly cautious in preparing the glass surface. The coverglass coating, comprising ITO with MgF AR overcoat is more durable than we had assumed, and should be cleaned thoroughly with...
acetone and alcohol prior to applying the conductive adhesive. The structural analysis, which indicates a relatively low load on the conductive bond joint, and the extensive heritage around bonding grounding wires to coverglasses using this adhesive, make the risk of the corrective action for this developmental failure low. Implementation of this corrective action and demonstration of its effectiveness can be accomplished as part of the initial ECSA flight application qualification.

Conclusions and Recommendations

This development program has developed a design with the ability to meet the stated requirements of this program. The following technical goals and requirements, taken from the program Statement of Work and Specification, were demonstrated by analysis or tests on the prototype panel:

- Demonstrated the ability to establish equi-potential solar array surface (<100mV) by bonding the FSA to conductively coated coverglasses, establishing the method for maintaining that electrical continuity through the panel life-cycle, and through analysis of the panel geometry.

- Demonstrated the ability to prevent exposure of voltage produced by the solar cell, and panel insulators to the charged particle environment through encapsulation of inter-cell areas using a grounded conductive shield. This was shown by MMJ's analysis in this program to result in negligible electric potentials from being established even 1cm away from the panel. The FSA, which provides this function, was demonstrated for structural integrity in launch and space environments.

- Minimization of the number of parts used to achieve electrostatic cleanliness was achieved. The prototype panel used a single FSA and four edge clips, a total of five parts (plus two kinds of adhesive), which minimizes cost and complexity.

- Established small and consistent current and associated power reduction from incorporation of electrostatically clean components, at about 7%. We also established stability of solar panel performance in acoustic and thermal cycling environment with these components incorporated.

- Established that the mass penalty for achieving electrostatic cleanliness is small, on the order of 6%.

- The cost delta associated with achieving electrostatic cleanliness is small. For the prototype panel, the cost for fabricating the FSA and edge clips, and bonding these components structurally and electrically, added ~5% to the cost of the panel.

- The design of the prototype panel is compatible with any thickness coverglass, any type of solar cell, standard spacecraft outgassing requirements, and standard solar array materials and assembly processes. The design uses no magnetic parts.

The ECSA technology that was developed in this program has demonstrated the capability to meet all of the goals and requirements of this program, and should be qualified for flight on an intended application. In implementing a new solar panel technology, material characterization testing, the fabrication of Design Evaluation Test (DET) coupons and a qualification panel are often standard practice. In addition, it is advisable (and standard practice at COI) to establish allowables for bonded joints in a flight configuration for any structural bond, whenever new material and adhesive combinations are involved.
We recommend that a bonded joint characterization program be implemented as part of the solar panel qualification for the first mission to use this technology. The characterization would establish allowable ultimate tensile stress for a bond between graphite fiber reinforced composite and coated glass. Structural analysis can then use these allowables to establish the margin of safety for this adhesive bond joint. The use of DET coupons for thermal cycling and other environmental tests will demonstrate the corrective action to resolve any remaining questions regarding the robustness of the ECSA design. Finally, the implementation of the design on a full-scale qualification panel should remove any uncertainties associated with scale-up of the technology.

A further recommendation for implementation of this technology relates to rework and repair of individual solar cells. Typically such a process is necessary to account for cell cracking or other failures that can occur during array acceptance testing. We recommend that a remove and replace procedure be developed for ECSA panels that account for the removal and replacement of part of the FSA and edge clips, if necessary, as well as the solar cells. While we don’t anticipate this to be a major effort, since the FSA and edge clips are thin and can be readily cut and removed with a razor blade, it is nonetheless a process which would need to be worked out for the eventual application.

Finally, the performance of the ECSA components should be optimized as part of the engineering development and qualification of a flight panel design. The reduction of panel performance by shadowing and cell spacing can be minimized by reducing the width of the individual elements of the FSA, and by maximizing the size of each SPM. If the width of each member of the FSA were reduced from 0.51cm to 0.25cm, and the number of cells per SPM were increased from 2 to 4, this would reduce the degradation in packing factor from 7% to 2%, and the shadow factor from 7% to 4%. The net result would be a reduction in performance penalty for electrostatic cleanliness by more than half, to about 6%. This would also reduce the mass associated with the components used for electrostatic cleanliness while having a negligible impact on cost. By using a flight application to optimize and demonstrate this approach, these recommendations will bring a higher performance Electrostatically Clean Solar Array panel concept to a state of flight readiness.
Appendix 1 – Electrostatic Analysis of the ECSA Panel
Electrostatically Clean Array Current Collection in LEO

Ira Katz
Victoria Davis

September 3, 1998
Low Energy Electrons
Collected on Interconnects

- 20 mil gap, 20 mil FSA overhang, interconnect at top of coverglass
- Interconnect at 65 V; Grounded conducting surfaces at 0 V
# Floating potential of isolated solar array in eclipse

- **Edge to Ram**
- **Thermal ion current** = thermal electron current * exponential barrier

\[
e n \sqrt{\frac{e\theta}{2\pi m_i}} = e^{-\phi/\theta} e n \sqrt{\frac{e\theta}{2\pi m_e}}
\]

\[\phi = 5.14 \theta\]

- **Face to Ram**
- **Ram ion current** = thermal electron current * exponential barrier
- **\( \theta = 0.1 \text{ eV}, v_i = 7800 \text{ m/s} \)**

\[
e n v_i = e^{-\phi/\theta} e n \sqrt{\frac{e\theta}{2\pi m_e}}
\]

\[\phi = 1.91 \theta\]
Net current collected if spacecraft ground shifted by 0.1 V

\[
\text{Net Current} = \text{Area} \times \left( j_{\text{ion}} + \exp\left( \frac{(\phi_0 + \Delta\phi)}{\theta} \right) j_{\text{th}} + \eta j_{\text{th}} \right)
\]

\[
j_{\text{ion}} = -\exp\left( \frac{\phi_0}{\theta} \right) j_{\text{th}} \quad \text{Gap Current} = \text{Area} \times \eta j_{\text{th}}
\]

\[
\text{Net Current} = \text{Area} \times \left( \exp\left( \frac{\phi_0}{\theta} \right) \left( \exp\left( \frac{\Delta\phi}{\theta} \right) - 1 \right) + \eta \right) j_{\text{th}}
\]

- If potential is more negative, electron current is reduced to panel area
- Reduction of panel area (ground potential) electron current needed to balance electron current collected by cells through gaps
Current collection limited by barrier

- 20 mil gap, 20 mil FSA overhang, interconnect at top of coverglass
- Interconnect at 65 V; Grounded conducting surfaces at -0.291 V
- $\phi = 0$ at 3 mm underestimates barrier height
- Barrier width under 30 mil, height over -0.21 V
Barrier Height Linear Function of Interconnect Potential

- Almost Laplacian potentials
- Linear fits to several cell potentials

**Estimate of barrier height**

![Graph showing the relationship between barrier height and interconnect potential](image-url)
Upper Bound Estimate of Gap Current

\[ \text{Area} \times \eta < \sum \text{gaps} \times W_{\text{barrier}} \times L_{\text{gap}} \times \exp \left( \phi_{\text{barrier}} / \theta \right) \]

- Assume each cell generates 1.13 V
- ISM has 2 cells

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<th>Barrier (V)</th>
<th>Exponential</th>
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Calculation Shows 0.1V Greater than Necessary to Balance Cell Collection

\[
\text{Net Current} = N_{cg} \times L_{cg} \times W_{cg} \times \exp\left(\frac{\phi_o}{\theta}\right) \left(\exp\left(\Delta\phi/\theta\right) - 1\right) j_{th} \\
+ \sum_{\text{gaps}} W_{\text{barrier}} \times L_{\text{gap}} \times \exp\left(\frac{\phi_{\text{barrier}}}{\theta}\right) j_{th}
\]

\[
\text{Net Current} = 29 \times 0.06 \times 0.04 \times \exp\left(\frac{\phi_o}{\theta}\right) (-0.632) j_{th} \\
+ \sum_{\text{gaps}} 7.62 \times 10^{-4} \times 0.06 \times \exp\left(\frac{\phi_{\text{barrier}}}{\theta}\right) j_{th}
\]

**NOTE:** $j_{th} < 0$

Edge to Ram: Net Current $= -2.58 \times 10^{-4} j_{th} + 1.21 \times 10^{-5} j_{th} > 0$

Face to Ram: Net Current $= -6.51 \times 10^{-3} j_{th} + 2.51 \times 10^{-4} j_{th} > 0$
Conclusion

- Potential change on panels due to charged particle collection $< 0.1V$
- Margin greater than a factor of twenty
- LEO the most difficult environment, GEO current collection much smaller, and photo emission dominates
Verification of Maximum Surface Potential
By Measurement of Resistance in Laboratory

Victoria Davis
Ira Katz
October 15, 1999
Verification of Maximum Surface Potential
By Measurement of Resistance

- Purpose

Define a laboratory resistance measurement that will verify that the coverglass surface potential will not exceed 0.1V in a plasma with an ion current of 0.001Am⁻²

- Procedure

Perform calculations for the four coverglass grounding schemes to determine the coefficient relating maximum surface potential and surface resistivity of the ITO coating in an assumed 0.001Am⁻² plasma current

For each of the four grounding schemes, determine the resistance between a probe and ground for a fixed surface resistivity, but varying the probe size.

Combine the results to find the maximum measured resistance which would control the potential in a 0.001Am⁻² plasma
FSA Grid Configuration - Qual Coupons
(provided by COI)
Space Requirement: $\phi_{\text{max}} < 0.1 \text{ V}$ for $j_{\text{plasma}} = 0.001 \text{Am}^{-2}$

- Ion current density drives potential
- Divergence of the surface current is the plasma current
  \[ \nabla \cdot K = j_{\text{plasma}} \]
- Ohm's law
  \[ E = \eta K \]
- **Potential proportional to the resistivity**
  \[ K = \frac{1}{\eta} E = -\frac{1}{\eta} \nabla \phi \]
  \[ \nabla \cdot \nabla \phi = -\eta j_{\text{plasma}} \]
  \[ \nabla^2 \phi = -\eta j_{\text{plasma}} \]
  \[ \phi_{\text{max}} \propto \eta \]

\[ \phi_{\text{FSA}} = 0 \]
\[ \phi_{\text{max}} \]
Solution in Cylindrical Symmetry

\[
- \frac{1}{r} \frac{d}{dr} \left( r \frac{d\phi}{dr} \right) = -\eta j_{\text{plasma}}
\]

\[
\phi(r) = \frac{-\eta j_{\text{plasma}}}{4} r^2 + D + F \ln r
\]

- Apply boundary conditions: \( \phi(R) = 0 \) and \( \phi(0) = 0.1 \text{ V} \ (R = 0.039 \text{ m}) \)

\[
\phi(r) = \frac{-\eta j_{\text{plasma}}}{4} r^2 + 0.1 \text{V}
\]

\[
\eta j_{\text{plasma}} = 260 \ \Omega^{-1} \text{Am}^{-2}
\]

- For \( j_{\text{plasma}} = 0.001 \ \text{Am}^{-2} \)

\[
\eta < 260 \ \text{k}\Omega^{-1}
\]
2-D Computations of Peak Potential

\[ \eta_j^{\text{plasma}} = 260 \, \Omega \, \text{m}^{-1} \, \text{Am}^{-2} \]
Grounded edges: \( \phi_{\text{max}} = 0.0880 \, \text{V} \)
8 0.5 cm tabs: \( \phi_{\text{max}} = 0.109 \, \text{V} \)
8 1 cm tabs: \( \phi_{\text{max}} = 0.0753 \, \text{V} \)
2-D Computations of Peak Potential

\[ \eta J_{\text{plasma}} = 260 \, \Omega \, \square^{-1} \, \text{Am}^{-2} \]

4 Triangular tabs: \( \phi_{\text{max}} = 0.126 \, \text{V} \)

4 0.635 cm tabs: \( \phi_{\text{max}} = 0.156 \, \text{V} \)

4 1 cm tabs: \( \phi_{\text{max}} = 0.121 \, \text{V} \)
Required Surface Resistivity

Required surface resistivity scales inversely with calculated potential

- Calculations:
  \[ \eta j_{\text{plasma}} = 260 \ \Omega \ \square^{-1} \ \text{Am}^{-2} \]
  \[ j_{\text{plasma}} = 10^{-3} \ \text{Am}^{-2} \]

- Grounded edges: \( \phi_{\text{max}} = 0.0880 \ \text{V} \)
  Required \( \eta < 295 \ \text{k}\Omega \ \square^{-1} \)

- Eight 0.5 cm tabs: \( \phi_{\text{max}} = 0.109 \ \text{V} \)
  Required \( \eta < 239 \ \text{k}\Omega \ \square^{-1} \)

- Four triangular tabs: \( \phi_{\text{max}} = 0.126 \ \text{V} \)
  Required \( \eta < 206 \ \text{k}\Omega \ \square^{-1} \)

- Eight 1 cm tabs: \( \phi_{\text{max}} = 0.0753 \ \text{V} \)
  Required \( \eta < 345 \ \text{k}\Omega \ \square^{-1} \)

- Four 0.635 cm tabs: \( \phi_{\text{max}} = 0.156 \ \text{V} \)
  Required \( \eta < 167 \ \text{k}\Omega \ \square^{-1} \)

- Four 1 cm tabs: \( \phi_{\text{max}} = 0.121 \ \text{V} \)
  Required \( \eta < 215 \ \text{k}\Omega \ \square^{-1} \)
Laboratory Confirmation of Resistivity

- Use previous equations
  \[ \nabla^2 \phi = -\eta j\text{plasma} \quad K = -\frac{1}{\eta} \nabla \phi \quad \phi_{FSA} = 0 \]

- Plasma current density is zero
  \[ \nabla^2 \phi = 0 \]

- Total probe current is the integral of the surface current
  \[ I_{\text{probe}} = \oint_{\text{probe}} K \, ds \]

- **Resistance proportional to resistivity**
  \[ I_{\text{probe}} = -\frac{1}{\eta} \oint_{\text{probe}} \nabla \phi \, ds \]
Solution for Cylindrical Symmetry

- \( \frac{1}{r} \frac{d}{dr} \left( r \frac{d\phi}{dr} \right) = 0 \)

- \( \phi(r) = D + F \ln r \)

- Apply boundary conditions: \( \phi(R) = 0 \) and \( \phi(r_0) = 1 \text{ V} (R = 0.039 \text{ m}) \)

- \( \phi(r) = 1 \text{V} \frac{\ln(r/R)}{\ln(r_0/R)} \)

- \( \eta I_{\text{probe}} = -\oint \frac{d\phi}{dr} dl = -2\pi r_0 \frac{d\phi}{dr}\bigg|^{r_0}_{r_0} \)

- \( \eta I_{\text{probe}} = \frac{-2\pi r_0 \times 1 \text{V} \left(\frac{1}{r_0}\right)}{\ln(r_0/R)} = \frac{-2\pi \times 1 \text{V}}{\ln(r_0/R)} \)

- Resistance \( = \frac{\phi_{\text{probe}}}{I_{\text{probe}}} = -\eta \frac{\ln(r_0/R)}{2\pi} \)

<table>
<thead>
<tr>
<th>( r_0 \text{ (m)} )</th>
<th>( \eta I_{\text{probe}} \text{ (V)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>4.6</td>
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<tr>
<td>0.001</td>
<td>1.7</td>
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<tr>
<td>0.0001</td>
<td>1.05</td>
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<tr>
<td>0.00001</td>
<td>0.76</td>
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</tbody>
</table>
2-D Computations
1 cm diameter test probe

\[ \phi_{\text{probe}} = 1 \]
Grounded edges: \( \eta I_{\text{probe}} = 3.15 \, \Omega \, \square^{-1} \, \text{A} \)
8 0.5 cm tabs: \( \eta I_{\text{probe}} = 2.97 \, \Omega \, \square^{-1} \, \text{A} \)
8 1 cm tabs: \( \eta I_{\text{probe}} = 3.31 \, \Omega \, \square^{-1} \, \text{A} \)
2-D Computations
1 cm diameter test probe

\[ \phi_{\text{probe}} = 1 \]

4 Triangular tabs: \( \eta I_{\text{probe}} = 2.97 \, \Omega \, \square^{-1} \, A \)
4 0.635 cm tabs: \( \eta I_{\text{probe}} = 2.82 \, \Omega \, \square^{-1} \, A \)
4 1 cm tabs: \( \eta I_{\text{probe}} = 3.23 \, \Omega \, \square^{-1} \, A \)
Required Resistance Measurements
1 cm diameter test probe

- **Grounded edges:**
  \[ \eta I_{\text{probe}} = 3.15 \, \Omega \, \text{cm}^{-1} \, \text{A} \]
  Required \( \eta < 295 \, \text{k\Omega} \, \text{cm}^{-1} \)
  \[ R = \frac{\phi_{\text{probe}}}{I_{\text{probe}}} < 94 \, \text{k\Omega} \]

- **Eight 0.5 cm tabs:**
  \[ \eta I_{\text{probe}} = 2.97 \, \Omega \, \text{cm}^{-1} \, \text{A} \]
  Required \( \eta < 239 \, \text{k\Omega} \, \text{cm}^{-1} \)
  \[ R = \frac{\phi_{\text{probe}}}{I_{\text{probe}}} < 80 \, \text{k\Omega} \]

- **Eight 1 cm tabs:**
  \[ \eta I_{\text{probe}} = 3.31 \, \Omega \, \text{cm}^{-1} \, \text{A} \]
  Required \( \eta < 345 \, \text{k\Omega} \, \text{cm}^{-1} \)
  \[ R = \frac{\phi_{\text{probe}}}{I_{\text{probe}}} < 104 \, \text{k\Omega} \]

- **Four triangular tabs:**
  \[ \eta I_{\text{probe}} = 2.97 \, \Omega \, \text{cm}^{-1} \, \text{A} \]
  Required \( \eta < 206 \, \text{k\Omega} \, \text{cm}^{-1} \)
  \[ R = \frac{\phi_{\text{probe}}}{I_{\text{probe}}} < 69 \, \text{k\Omega} \]

- **Four 0.635 cm tabs:**
  \[ \eta I_{\text{probe}} = 2.82 \, \Omega \, \text{cm}^{-1} \, \text{A} \]
  Required \( \eta < 167 \, \text{k\Omega} \, \text{cm}^{-1} \)
  \[ R = \frac{\phi_{\text{probe}}}{I_{\text{probe}}} < 59 \, \text{k\Omega} \]

- **Four 1 cm tabs:**
  \[ \eta I_{\text{probe}} = 3.23 \, \Omega \, \text{cm}^{-1} \, \text{A} \]
  Required \( \eta < 215 \, \text{k\Omega} \, \text{cm}^{-1} \)
  \[ R = \frac{\phi_{\text{probe}}}{I_{\text{probe}}} < 67 \, \text{k\Omega} \]
Required Resistance Measurements
0.1 cm diameter test probe

- Grounded edges:
  \[ \eta I_{\text{probe}} = 1.496 \, \Omega \, \Box^{-1} \, \text{A} \]
  Required \( \eta < 295 \, \text{k\Omega} \, \Box^{-1} \)
  \( R = \phi_{\text{probe}} / I_{\text{probe}} < 197 \, \text{k\Omega} \)

- Four triangular tabs:
  \[ \eta I_{\text{probe}} = 1.454 \, \Omega \, \Box^{-1} \, \text{A} \]
  Required \( \eta < 206 \, \text{k\Omega} \, \Box^{-1} \)
  \( R = \phi_{\text{probe}} / I_{\text{probe}} < 142 \, \text{k\Omega} \)

- Eight 0.5 cm tabs:
  \[ \eta I_{\text{probe}} = 1.454 \, \Omega \, \Box^{-1} \, \text{A} \]
  Required \( \eta < 239 \, \text{k\Omega} \, \Box^{-1} \)
  \( R = \phi_{\text{probe}} / I_{\text{probe}} < 164 \, \text{k\Omega} \)

- Four 0.635 cm tabs:
  \[ \eta I_{\text{probe}} = 1.418 \, \Omega \, \Box^{-1} \, \text{A} \]
  Required \( \eta < 167 \, \text{k\Omega} \, \Box^{-1} \)
  \( R = \phi_{\text{probe}} / I_{\text{probe}} < 118 \, \text{k\Omega} \)

- Eight 1 cm tabs:
  \[ \eta I_{\text{probe}} = 1.531 \, \Omega \, \Box^{-1} \, \text{A} \]
  Required \( \eta < 345 \, \text{k\Omega} \, \Box^{-1} \)
  \( R = \phi_{\text{probe}} / I_{\text{probe}} < 225 \, \text{k\Omega} \)

- Four 1 cm tabs:
  \[ \eta I_{\text{probe}} = 1.515 \, \Omega \, \Box^{-1} \, \text{A} \]
  Required \( \eta < 215 \, \text{k\Omega} \, \Box^{-1} \)
  \( R = \phi_{\text{probe}} / I_{\text{probe}} < 142 \, \text{k\Omega} \)
Verification of Maximum Surface Potential
By Measurement of Resistance in Laboratory

- Results insensitive to the ITO grounding geometry
- Required surface resistivity
  \[ \eta \sim 200 \text{ k}\Omega \text{ \square}^{-1} \]
- Measured resistance
  \[ R \sim 100 \text{ k}\Omega \]
Potentials for Analytic Results

Cylindrical Symmetry Result (for phimax=0.1 V)
Preliminary Electrostatic Analysis of Electrostatically Clean Solar Panels

Ira Katz
Victoria Davis

August 26, 1999
Preliminary Electrostatic Analysis of Electrostatically Clean Solar Panels

- Review of requirements & critical parameters
- Analysis of ITO coating potentials
- Front Side Aperture potential shielding calculations
- Summary of design issues
Review of GSFC Requirements

- Regardless of size no more than 100 millivolt potential difference
  0.1 V not including $\mathbf{v} \times \mathbf{B}$
- Environment current density of one microampere per square centimeter
  $10^{-2}$ A/m² electron current
- Not expose cell voltage to charged particle environment
  0.1 V max potential
  particle currents << thermal current to array
  (more than one order of magnitude)
- No insulators, front or rear
  voltage drop < 0.1 V
- Connection to the spacecraft
Data for Electrostatic Calculations

- SPM + FSA in plane dimensions
- Cross section through cell stack and FSA
  min and max of all dimensions
  materials
  ITO ~ 100 kΩ/square

\[ \begin{align*}
A &= 0.200 \pm 0.010 \\
B &= 0.020 \pm 0.002 \\
C &= 0.030 +0/-0.010 \\
D &= 0.000 +0.020/-0 \\
E &= 0.010 +0.005/-0.000 \\
F &= 0.063 +0.015/-0.000 \text{(?)} \\
G &= 0.0060 +0.0009/-0.000 \\
H &= 0.160 +/- \\
I &= 0.007 \text{ to } 0.010 \\
J &= 0.002 \text{ to } 0.003
\end{align*} \]

*We assume F = 0.0063*
Potential Drop Across ITO Coated Coverglass

- Two cases
  - small tabs (1mm radius)
  - grounded edges
- Computational approach
  - apply $10^{-2}$ A/m² to surface
  - calculate ohmic drop
  - 1 mm radius tab - find maximum radius of collection edges
    - assume SPM a 4 cm radius circle
    - find potential required to collect 48 μA
- Results
  - For tabs ITO resistivity required to be less than $\sim 2000$ Ω/square
  - For full edge contact, resistivity required to be less than $\sim 2000$ Ω/square
Potential Drop and Current Collection From a Tab on ITO Coated Coverglass

- Ohm’s Law
- Tab of radius $R_o$ collects $I_o$
- Integrate electric field to get potential
- Determine maximum collecting radius
- Resistance = Current/voltage

\[
E = \eta K
\]

\[
I(r) = I_0 - j \pi (r^2 - R_o^2)
\]

\[
K(r) = \frac{I(r)}{2 \pi r}
\]

\[
\varphi(R) = - \int_{R_o}^{R} E(r) \, dr
\]

\[
= - \int_{R_o}^{R} \eta K(r) \, dr
\]

\[
K(R) = 0 = \left( \frac{I_0}{2 \pi} + j \frac{R_o^2}{2} \right) \left( \frac{1}{R} - \frac{j}{2} \right)
\]

\[
\varphi(R) = -\frac{\eta}{4} \left( \frac{I_0}{\pi} + j R_o^2 \right) \ln \left( \frac{\pi j}{R_o^2} \right) - \frac{\eta I_0}{4 \pi}
\]
- Nominal ITO coating
  10^5 Ω/square
  ~ 50 Å

<table>
<thead>
<tr>
<th>I (A)</th>
<th>Vmax</th>
<th>Res. eff</th>
<th>rmax (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0E-05</td>
<td>0.4</td>
<td>3.8E+04</td>
<td>0.018</td>
</tr>
<tr>
<td>2.0E-05</td>
<td>0.9</td>
<td>4.4E+04</td>
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</tr>
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<td>3.0E-05</td>
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<td>5.1E+04</td>
<td>0.040</td>
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<td>7.0E-05</td>
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<td>4.4</td>
<td>5.4E+04</td>
<td>0.050</td>
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<td>9.0E-05</td>
<td>5.0</td>
<td>5.5E+04</td>
<td>0.054</td>
</tr>
<tr>
<td>1.0E-04</td>
<td>5.6</td>
<td>5.6E+04</td>
<td>0.056</td>
</tr>
</tbody>
</table>

- Increased ITO conductivity
  1000 Ω/square
  ~ 100 times the thickness
  ~ 0.5 micron (5000 Å)
Current Collection by Edge Grounded
ITO Coated Coverglass

- ITO coated disk grounded at edge
- Integration from outside in
- Calculation of conducted currents
  - Ohm's Law
  - Circle of \( R_o \) collects \( I_o \)
  - Integrate electric field to get potential
  - Determine maximum current
  - Resistance = Current/voltage

\[
E = \eta \ K
\]
\[
I(r) = I_0 - j\pi (R_o^2 - r^2)
\]
\[
K(r) = \frac{I(r)}{2\pi r}
\]
\[
\varphi(R) = -\int_{R_0}^{R} E(r) \, dr = -\int_{R_0}^{R} \eta \ K(r) \, dr
\]
\[
\varphi(R) = -\frac{\eta}{2\pi} \left\{ \left( I_0 - j\pi R_0^2 \right) \ln\left( \frac{R}{R_0} \right) + \frac{j\pi}{2} \left( R^2 - R_0^2 \right) \right\}
\]
\[
I(R') = 0 = I_0 - j\pi R_0^2 + j\pi R'^2
\]
\[
\Rightarrow \frac{I_0}{j\pi} + R_0^2 = R'^2
\]
\[
\varphi(R') = -\frac{\eta}{4\pi} \left\{ \frac{\left( I_0 - j\pi R_0^2 \right)}{2} \ln \left( I - \frac{I_0}{R_0^2 j\pi} \right) - I_0 \right\}
\]
ITO Grounded Edge Results

- Nominal ITO coating
  coating
  $10^5 \ \Omega$/square
  $\sim 50$ Å thick
  effective radius radius 0.04 m
  current density $10^{-2}$ A/m$^2$
  potential 0.3 V difference from edge to center

- Required ITO coating
  coating
  $3 \times 10^4 \ \Omega$/square
  $\sim 150$ Å thick
  effective radius 0.04 m
  current density $10^{-2}$ A/m$^2$
  potential 0.1 V
Electrostatic Field Calculations

- Potential “leaks out” through gap between coverglass and FSA
- Computer model
  - 2D XY geometry
  - Solves Poisson’s equation
  - Currents have not yet been calculated
- Results sensitive to
  - gap height
  - FSA overhang
  - Interconnect geometry
    - no interconnect
    - Interconnect at below coverglass
    - Interconnect at coverglass

All Calculations Performed With Worst Case Gap Height!
Computational Grid

- Cross section through FSA - cell stack
- Resolution down to 2 mil
- Mirror plane boundary between SPM’s

Symmetry plane

Coverglass

Solar cell

Two interconnect locations
Validation of Numerical Technique

- Analytical solution for potential between two zero potential plates with a cosine potential at one end

$$\phi(x, y) = \exp(-\pi x) \sin(\pi y)$$

- Numerical solution has required accuracy
- Exposed potentials of 0.0069 V and 0.030 V.

30 mil FSA overhang  
20 mil FSA overhang
30 mil FSA overhang

- Exposed potentials of 0.098 V and 0.175 V.

Interconnect at bottom of coverglass

Interconnect at top of coverglass
- Exposed potentials of 0.489 V and 0.875 V.

Interconnect at bottom of coverglass  
Interconnect at top of coverglass
Summary of Preliminary Results

- ITO resistivity
  Question about requirement: Why electron and not ram ion current density?
  \(10^{-2} \text{ A/m}^2\) electron current
  \(10^{-3} \text{ A/m}^2\) ram ion current
  S/C with these solar array panels, only tiny net currents would be collected
  present ITO would meet 0.1 V requirement
  grounding with tabs would be adequate

- Solar array potential exposure to environment
  design meets requirements on edges without interconnects
  more work needed for worst case gap height
  \textbf{COMBINED WITH:} worst case interconnect height
  worst case overhang

- Particle collection expected to be negligible
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  0.1 V not including $v \times B$
- Environment current density of one microampere per square centimeter
  $10^{-2}$ A/m$^2$ electron current
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  0.1 V max potential
  particle currents $<<$ thermal current to array
  (more than one order of magnitude)
- No insulators, front or rear
  voltage drop $< 0.1$ V
- Connection to the spacecraft
Data for Electrostatic Calculations

- SPM + FSA in plane dimensions
- Cross section through cell stack and FSA
  min and max of all dimensions
  materials
  ITO \sim 100 \text{ K}\Omega/\text{square}

\begin{align*}
A &= 0.200 \pm 0.010 \\
B &= 0.020 \pm 0.002 \\
C &= 0.030 +0/-0.010 \\
D &= 0.000 +0.020/-0 \\
E &= 0.010 +0.005/-0.000 \\
F &= 0.063 +0.015/-0.000(?) \\
G &= 0.0060 +0.0009/-0.000 \\
H &= 0.160 +/-?
\end{align*}

We assume \( F = 0.0063 \)
Potential Drop Across ITO Coated Coverglass

- Two cases
  - small tabs (1mm radius)
  - grounded edges
- Computational approach
  - apply $10^{-2}$ A/m$^2$ to surface
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  - 1 mm radius tab - find maximum radius of collection edges
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  - For tabs ITO resistivity required to be less than $\sim 2000 \ \Omega$/square
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Potential Drop and Current Collection From a Tab on ITO Coated Coverglass

- Ohm's Law
- Tab of radius \( R_o \) collects \( I_o \)
- Integrate electric field to get potential
- Determine maximum collecting radius
- Resistance = Current/voltage

\[
E = \eta \ K
\]

\[
I(r) = I_o - j \pi (r^2 - R_o^2)
\]

\[
K(r) = \frac{I(r)}{2 \pi r}
\]

\[
\varphi(R) = -\int_{R_o}^{R} E(r) \, dr
\]

\[
= -\int_{R_o}^{R} \eta \ K(r) \, dr
\]

\[
K(R) = 0 = \left( \frac{I_o}{2 \pi} + \frac{j R_0^2}{2} \right) \frac{1}{R} - \frac{j}{2} R
\]

\[
\varphi(R) = -\frac{\eta}{4} \left( \frac{I_o}{\pi} + j R_0^2 \right) \ln \left( \frac{I_o + R_0^2}{R^2} \right) - \eta \frac{I_o}{4 \pi}
\]
ITO Tab Current Collection

- Nominal ITO coating
  $10^5 \, \Omega/$square
  $\sim 50 \, \AA$

- Increased ITO conductivity
  $1000 \, \Omega/$square
  $\sim 100$ times the thickness
  $\sim 0.5$ micron (5000 $\AA$)
Current Collection by Edge Grounded ITO Coated Coverglass

- ITO coated disk grounded at edge
- Integration from outside in
- Calculation of conducted currents
  - Ohm's Law
  - Circle of $R_0$ collects $I_0$
  - Integrate electric field to get potential
  - Determine maximum current
  - Resistance = Current/voltage

\[ E = \eta K \]

\[ I(r) = I_0 - j\pi (R_0^2 - r^2) \]

\[ K(r) = \frac{I(r)}{2\pi r} \]

\[ \varphi(R) = -\int_{R_0}^{R} E(r) \, dr = -\int_{R_0}^{R} \eta K(r) \, dr \]

\[ \varphi(R) = -\frac{\eta}{2\pi} \left( (I_0 - j\pi R_0^2) \ln\left(\frac{R}{R_0}\right) + \frac{j\pi}{2} \left( R^2 - R_0^2 \right) \right) \]

\[ I(R') = 0 = I_0 - j\pi R_0^2 + j\pi R'^2 \]

\[ \Rightarrow -\frac{I_0}{j\pi} + R_0^2 = R'^2 \]

\[ \varphi(R') = -\frac{\eta}{4\pi} \left( \frac{(I_0 - j\pi R_0^2)}{2} \ln\left(1 - \frac{I_0}{R_0^2 j\pi}\right) - I_0 \right) \]
ITO Grounded Edge Results

- Nominal ITO coating
  - coating
  - $10^5 \ \Omega$/square
  - ~ 50 Å thick
  - effective radius radius 0.04 m
  - current density $10^{-2}$ A/m$^2$
  - potential 0.3 V difference from edge to center

- Required ITO coating
  - coating
  - $3 \times 10^4 \ \Omega$/square
  - ~ 150 Å thick
  - effective radius 0.04 m
  - current density $10^{-2}$ A/m$^2$
  - potential 0.1 V
Electrostatic Field Calculations

- Potential "leaks out" through gap between coverglass and FSA
- Computer model
  - 2D XY geometry
  - Solves Poisson's equation
  - Currents have not yet been calculated
- Results sensitive to
  - gap height
  - FSA overhang
  - interconnect geometry
    - no interconnect
    - interconnect at below coverglass
    - interconnect at coverglass

All Calculations Performed With Worst Case Gap Height!
Computational Grid

- Cross section through FSA - cell stack
- Resolution down to 2 mil
- Mirror plane boundary between SPM’s

Symmetry plane

Coverglass 4 mil 20 mil 30 mil 70 mil Two interconnect locations
Validation of Numerical Technique

- Analytical solution for potential between two zero potential plates with a cosine potential at one end

\[ \phi(x, y) = \exp(-\pi x) \sin(\pi y) \]

- Numerical solution has required accuracy
- Exposed potentials of 0.0069 V and 0.030 V.

30 mil FSA overhang

20 mil FSA overhang
30 mil FSA overhang

- Exposed potentials of 0.098 V and 0.175 V.

Interconnect at bottom of coverglass  
Interconnect at top of coverglass
20 mil FSA overhang

- Exposed potentials of 0.489 V and 0.875 V.

Interconnect at bottom of coverglass

Interconnect at top of coverglass
Summary of Preliminary Results

- ITO resistivity
  Question about requirement: Why electron and not ram ion current density?
  \[ 10^{-2} \text{ A/m}^2 \text{ electron current} \]
  \[ 10^{-3} \text{ A/m}^2 \text{ ram ion current} \]
  S/C with these solar array panels, only tiny net currents would be collected
  present ITO would meet 0.1 V requirement
  grounding with tabs would be adequate

- Solar array potential exposure to environment
  design meets requirements on edges without interconnects
  more work needed for worst case gap height

  COMBINED WITH: worst case interconnect height
  worst case overhang

- Particle collection expected to be negligible
Appendix 2 – Parts and Materials Used In Construction of The Prototype Panel

Substrate:
Faceskins - M55J/950-1, .0025” CPT, 5 plies (90,45,0,-45,90), FV=61%, RC=38%
Aluminum Honeycomb Core - CR3-5056 .0015” foil, 1/4” cell, 3.4 pcf
Film Adhesive - Reticulated FM73U, .030pcf
Insulator - Kapton, .002” FPC

Solar Cell Blanket:
Solar Cells – Tecstar Dual-Bandgap High Efficiency Solar Cell
Coverglass – OCLI ITO and AR-Coated CMG
Laydown Adhesive – Nusil CV-2566
Coverglass Adhesive – DC93-500

Electrostatically Clean Components
FSA Aperture Grid – T300/RS-3 Composite fabric laminate
FSA Edge Clips – T300/RS-3 composite fabric laminate
FSA structural adhesive – NuSil CV-2506-6, B-staged silicone sheet adhesive
FSA conductive adhesive – NuSil CV-2-2646, Silver filled silicone paste adhesive
Appendix 3 – Photovoltaic Performance of the ECSA Prototype Panel
ESCA PROTOFLIGHT PANEL
QUAL COUPON
STRING:A (Tech2 cell)

Test date: 01/06/2000

PARAMETERS

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<thead>
<tr>
<th>Calibration Standard:</th>
<th>512-98</th>
</tr>
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<tbody>
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<td>No. of Series Cells:</td>
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</tr>
<tr>
<td>No. of Parallel Cells:</td>
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</tr>
<tr>
<td>Area per Cell:</td>
<td>24.312 cm²</td>
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<tr>
<td>Target Temperature:</td>
<td>28 °C</td>
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DATA CORRECTED TO 28°C

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DATA CORRECTED TO TARGET TEMPERATURE

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QUAL COUPON
STRING:B

Test date: 01/06/2000

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ESCA
QUAL COUPON
STRING:C

PARAMETERS

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No. of Series Cells: 24
No. of Parallel Cells: 1
Area per Cell: 24.312 cm²
Target Temperature: 28 °C
Voltage Temp Coef.: -0.24 % VOC / °C

DATA CORRECTED TO 28°C

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<td>0.342</td>
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<td>49.291</td>
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DATA CORRECTED TO TARGET TEMPERATURE

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RESULTS

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ESCA
QUAL COUPON
STRING:D

Test date: 01/06/2000

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DATA CORRECTED TO 28°C

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DATA CORRECTED TO 28°C

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DATA CORRECTED TO TARGET TEMPERATURE

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RESULTS

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| PMAX:   | 69.420 W |
| VMAX:   | 49.374 V |
| IMAX:   | 1.406 A  |
| FF:     | 79.094 % |
| Eff:    | 21.983 % |
ESCA QUAL COUPON
STRING: A (Tech2 cell)
POST-CUSTOMER MODIFICATION

Test date: 01/27/2000

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DATA CORRECTED TO 28°C

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DATA CORRECTED TO TARGET TEMPERATURE

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RESULTS

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<th>Eff</th>
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<td>16.264 W</td>
<td>51.633 V</td>
<td>0.315 A</td>
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<td>20.602 %</td>
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ESCA
QUAL COUPON
STRING:B
POST-CUSTOMER MODIFICATION

Test date: 01/27/2000

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<td>Target Temperature:</td>
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<td>Voltage Temp Coef.:</td>
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<td>FF: 76.395 %</td>
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QUAL COUPON
STRING:C
POST-CUSTOMER MODIFICATION

Test date: 01/27/2000

PARAMETERS
Calibration Standard: 512-98
No. of Series Cells: 24
No. of Parallel Cells: 1
Area per Cell: 24.312 cm²
Target Temperature: 28 °C
Voltage Temp Coef.: -0.24 %VOC / °C

DATA CORRECTED TO 28°C

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DATA CORRECTED TO TARGET TEMPERATURE

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RESULTS

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ESCA
QUAL COUPON
STRING:D
POST-CUSTOMER MODIFICATION

Test date: 01/27/2000

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<td>No. of Parallel Cells:</td>
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DATA CORRECTED TO 28°C

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DATA CORRECTED TO TARGET TEMPERATURE

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RESULTS

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ESCA
QUAL COUPON
POST-CUSTOMER MODIFICATION
FULL PANEL

Test date: 01/27/2000

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DATA CORRECTED TO 28°C

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DATA CORRECTED TO TARGET TEMPERATURE

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RESULTS

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ESCA
PRE-HOT FLASH TEST INSIDE THE HOT BOX WITH COVER @ 28°C
QUAL COUPON
POST-CUSTOMER MODIFICATION
CKT:A

Test date: 01/27/2000

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DATA CORRECTED TO 28°C

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<th>POWER</th>
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<tr>
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<tr>
<td>FF</td>
<td>79.5415 %</td>
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<tr>
<td>Eff</td>
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ESCA
PRE-HOT FLASH TEST INSIDE THE HOT BOX WITH COVER @ 28°C
QUAL COUPON
POST-CUSTOMER MODIFICATION
CKT:B

Test date: 01/27/2000

PARAMETERS

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<td>No. of Parallel Cells:</td>
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</tr>
<tr>
<td>Area per Cell:</td>
<td>24.312 cm²</td>
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<tr>
<td>Target Temperature:</td>
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<td>Voltage Temp Coef.:</td>
<td>-0.24 %VOC / °C</td>
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DATA CORRECTED TO 28°C

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DATA CORRECTED TO TARGET TEMPERATURE

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<th>POWER</th>
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<tr>
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<td>10.8290</td>
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RESULTS

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<tr>
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ESCA
PRE-HOT FLASH TEST INSIDE THE HOT BOX WITH COVER @ 28°C
QUAL COUPON
POST-CUSTOMER MODIFICATION
CKT:C

Test date: 01/27/2000

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<td>No. of Series Cells:</td>
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<td>No. of Parallel Cells:</td>
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<td>Target Temperature:</td>
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<tr>
<td>Voltage Temp Coef.:</td>
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ESCA
PRE-HOT FLASH TEST INSIDE THE HOT BOX WITH COVER @ 28°C
QUAL COUPON
POST-CUSTOMER MODIFICATION
CKT:D

Test date: 01/27/2000

PARAMETERS
Calibration Standard: 512-98
No. of Series Cells: 24
No. of Parallel Cells: 1
Area per Cell: 24.312 cm²
Target Temperature: 28 °C
Voltage Temp Coef.: -0.24 %VOC / °C

DATA CORRECTED TO 28°C

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DATA CORRECTED TO TARGET TEMPERATURE

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RESULTS

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ESCA
HOT-FLASH TEST
QUAL COUPON
CKT:A

Test date: 01/27/2000

PARAMETERS

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<td>No. of Parallel Cells:</td>
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</tr>
<tr>
<td>Area per Cell:</td>
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<tr>
<td>Target Temperature:</td>
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<tr>
<td>Voltage Temp Coef.</td>
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<td>Current Temp Coef.</td>
<td>17.1 μA/cm²°C</td>
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TEST TEMPERATURE

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<th>POWER</th>
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DATA CORRECTED TO TARGET TEMPERATURE

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<td>FF:</td>
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<td>Eff:</td>
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ESCA
HOT-FLASH TEST
QUAL COUPON
CKT:B

Test date: 01/27/2000

PARAMETERS
Calibration Standard: 512-98
No. of Series Cells: 24
No. of Parallel Cells: 1
Area per Cell: 24.312 cm²
Target Temperature: 70 °C
Voltage Temp Coef.: -0.24 %VOC / °C
Current Temp Coef.: 17.1 µA/cm²/°C

<table>
<thead>
<tr>
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<tbody>
<tr>
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DATA CORRECTED TO TARGET TEMPERATURE

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<td>FF: 81.5190 %</td>
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ESCA
HOT-FLASH TEST
QUAL COUPON
CKT:C

Test date: 01/27/2000

| PARAMETERS |
|-------------------|----------------|
| Calibration Standard: | 512.98 |
| No. of Series Cells: | 24 |
| No. of Parallel Cells: | 1 |
| Area per Cell: | 24.312 cm² |
| Target Temperature: | 70 °C |
| Voltage Temp Coef.: | -0.24 %VOC/°C |
| Current Temp Coef.: | 17.1 μA/cm²/°C |

<table>
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<tbody>
<tr>
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| RESULTS |
|-------------------|----------------|
| VOC: | 53.2890 V |
| ISC: | 0.2707 A |
| PMAX: | 11.2964 W |
| VMAX: | 44.7560 V |
| IMAX: | 0.2524 A |
| FF: | 78.3096 % |
| Eff: | 14.3091 % |
ESCA
HOT-FLASH TEST
QUAL COUPON
CKT:D

Test date: 01/27/2000

PARAMETERS

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<tr>
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<td>Target Temperature:</td>
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<tr>
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<tr>
<td>Current Temp Coef:</td>
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TEST TEMPERATURE

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DATA CORRECTED TO TARGET TEMPERATURE

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<tr>
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ESCA
HOT-FLASH TEST
CKT:A @ 70°C
Adjustment made for the lost of the lexan glass
Voltage Ratio: 1.007 Current Ratio: 1.32

Test date: 01/27/2000

PARAMETERS
Calibration Standard: 512.98
No. of Series Cells: 24
No. of Parallel Cells: 1
Area per Cell: 24.312 cm²
Target Temperature: 70 °C
Voltage Temp Coef.: -0.24 %VOC/°C
Current Temp Coef.: 17.1 uA/cm²/°C

TEST TEMPERATURE

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DATA CORRECTED TO TARGET TEMPERATURE

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RESULTS

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<tr>
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ESCA
HOT-FLASH TEST
CKT:B @ 70°C
Adjustment made for the lost of the lexan glass
Voltage Ratio: 1.005 Current Ratio: 1.32

Test date: 01/27/2000

PARAMETERS

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<tr>
<td>Voltage Temp Coef.:</td>
<td>-0.24 %/°C</td>
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<td>Current Temp Coef.:</td>
<td>17.1 uA/cm²°C</td>
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TEST TEMPERATURE

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DATA CORRECTED TO
TARGET TEMPERATURE

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RESULTS

| VOC  | 53.540 V |
| ISCE | 0.359 A  |
| PMAX | 15.670 W |
| VMAX | 46.592 V |
| IMAX | 0.336 A  |
| FF   | 81.519 % |
| Eff  | 19.850 % |
ESCA
HOT-FLASH TEST
CKT: C @ 70°C
Adjustment made for the loss of the lexan glass
Voltage Ratio: 1.009 Current Ratio: 1.32
Test date: 01/27/2000

PARAMETERS

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<tbody>
<tr>
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</tr>
<tr>
<td>Area per Cell:</td>
<td>24.312 cm²</td>
</tr>
<tr>
<td>Target Temperature:</td>
<td>70 °C</td>
</tr>
<tr>
<td>Voltage Temp Coef.:</td>
<td>-0.24 %VOC/°C</td>
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<tr>
<td>Current Temp Coef.:</td>
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DATA CORRECTED TO TARGET TEMPERATURE

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RESULTS

| VOC:     | 53.769 V |
| ISC:     | 0.357 A  |
| PMAX:    | 15.045 W |
| VMAX:    | 45.159 V |
| IMAX:    | 0.333 A  |
| FF:      | 78.310 % |
| Eff:     | 19.058 % |
ESCA
HOT-FLASH TEST

CKT:D @ 70°C
Adjustment made for the lost of the lexan glass
Voltage Ratio: 1.008  Current Ratio: 1.33

Test date: 01/27/2000

PARAMETERS

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<tr>
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TEST TEMPERATURE

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DATA CORRECTED TO TARGET TEMPERATURE

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RESULTS

<p>| | | |</p>
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<tr>
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<tbody>
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<td></td>
</tr>
<tr>
<td>ISC</td>
<td>0.360 A</td>
<td></td>
</tr>
<tr>
<td>PMAX</td>
<td>15.313 W</td>
<td></td>
</tr>
<tr>
<td>VMAX</td>
<td>44.904 V</td>
<td></td>
</tr>
<tr>
<td>IMAX</td>
<td>0.341 A</td>
<td></td>
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<tr>
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<tr>
<td>Eff</td>
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ESCA QUAL COUPON
STRING: A (Tech2 cell)
POST-ACOUSTIC TEST

PARAMETERS

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<td>No. of Parallel Cells:</td>
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</tr>
<tr>
<td>Area per Cell:</td>
<td>24.312 cm²</td>
</tr>
<tr>
<td>Target Temperature:</td>
<td>28 °C</td>
</tr>
<tr>
<td>Voltage Temp Coef.:</td>
<td>-0.24 %VOC / °C</td>
</tr>
</tbody>
</table>

DATA CORRECTED TO 28°C

<table>
<thead>
<tr>
<th>VOLTS</th>
<th>AMPS</th>
<th>POWER</th>
</tr>
</thead>
<tbody>
<tr>
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<td>-0.0001</td>
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<tr>
<td>55.2440</td>
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<tr>
<td>53.4430</td>
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</tr>
<tr>
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<tr>
<td>49.9230</td>
<td>0.3234</td>
<td>16.1451</td>
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RESULTS

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<th>PMAX</th>
<th>VMAX</th>
<th>IMAX</th>
<th>EFF</th>
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<tr>
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ESCA
QUAL COUPON
STRING:B
POST-ACOUSTIC TEST

Test date: 01/31/2000

PARAMETERS

| Calibration Standard: 512-98 |
| No. of Series Cells: 24 |
| No. of Parallel Cells: 1 |
| Area per Cell: 24.312 cm² |
| Target Temperature: 28 °C |
| Voltage Temp Coef.: -0.24 %VOC / °C |

DATA CORRECTED TO 28°C

<table>
<thead>
<tr>
<th>VOLTS</th>
<th>AMPS</th>
<th>POWER</th>
</tr>
</thead>
<tbody>
<tr>
<td>58.356</td>
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</tr>
<tr>
<td>54.285</td>
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<td>15.7531</td>
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<tr>
<td>50.796</td>
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<td>16.5849</td>
</tr>
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<td>49.034</td>
<td>0.3384</td>
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<td>0.3417</td>
<td>16.1604</td>
</tr>
<tr>
<td>44.925</td>
<td>0.3435</td>
<td>15.4317</td>
</tr>
<tr>
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<td>29.181</td>
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<td>10.1929</td>
</tr>
<tr>
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DATA CORRECTED TO TARGET TEMPERATURE

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<thead>
<tr>
<th>VOLTS</th>
<th>AMPS</th>
<th>POWER</th>
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</thead>
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RESULTS

| VOC: 58.356 V |
| ISC: 0.353 A |
| PMAX: 16.593 W |
| VMAX: 49.034 V |
| IMAX: 0.338 A |
| FF: 80.550% |
| ERT: 21.018% |
ESCA
QUAL COUPON
STRING:C
POST-AcouSTIC TEST

Test date: 01/31/2000

PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
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<td>Area per Cell:</td>
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<td>-0.24 %VOC / °C</td>
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DATA CORRECTED TO 28°C

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<th>Power</th>
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<td>49.146</td>
<td>0.3279</td>
<td>16.1150</td>
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<tr>
<td>47.362</td>
<td>0.3351</td>
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<td>45.059</td>
<td>0.3387</td>
<td>15.2815</td>
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<tr>
<td>42.109</td>
<td>0.3408</td>
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DATA CORRECTED TO TARGET TEMPERATURE

<table>
<thead>
<tr>
<th>Volts</th>
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<th>Power</th>
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RESULTS

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Voc</td>
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</tr>
<tr>
<td>Isc</td>
<td>0.350 A</td>
</tr>
<tr>
<td>Pmax</td>
<td>16.115 W</td>
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<tr>
<td>Vmax</td>
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<tr>
<td>Imax</td>
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<tr>
<td>FF</td>
<td>78.632 %</td>
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<tr>
<td>Ef</td>
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ESCA QUAL COUPON STRING:D POST-AcouSTIC TEST

Test date: 01/31/2000

PARAMETERS

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<td>No. of Parallel Cells</td>
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</tr>
<tr>
<td>Area per Cell</td>
<td>24.312 cm²</td>
</tr>
<tr>
<td>Target Temperature</td>
<td>28 °C</td>
</tr>
<tr>
<td>Voltage Temp Coef.</td>
<td>-0.24 %/°C</td>
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DATA CORRECTED TO 28°C

<table>
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<th>Volts</th>
<th>Amps</th>
<th>Power</th>
</tr>
</thead>
<tbody>
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<td>58.432</td>
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<td>49.115</td>
<td>0.3299</td>
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DATA CORRECTED TO TARGET TEMPERATURE

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<tr>
<th>Volts</th>
<th>Amps</th>
<th>Power</th>
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RESULTS

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<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>VOC</td>
<td>58.432 V</td>
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<tr>
<td>ISC</td>
<td>0.353 A</td>
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<tr>
<td>PMAX</td>
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<tr>
<td>VMAX</td>
<td>49.115 V</td>
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<tr>
<td>IMAX</td>
<td>0.330 A</td>
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<tr>
<td>FF</td>
<td>78.466 %</td>
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<tr>
<td>Eff</td>
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ESCA
QUAL COUPON
STRING:A (Tech2 cell)
POST-ENVIRONMENTAL

Test date: 05/01/2000

PARAMETERS

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<td>No. of Series Cells:</td>
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</tr>
<tr>
<td>No. of Parallel Cells:</td>
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</tr>
<tr>
<td>Area per Cell:</td>
<td>24.312 cm²</td>
</tr>
<tr>
<td>Target Temperature:</td>
<td>28 °C</td>
</tr>
<tr>
<td>Voltage Temp Coef.:</td>
<td>-0.24 VOC/°C</td>
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DATA CORRECTED TO 28°C

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RESULTS

VOC: 59.349 V
ISC: 0.346 A
PMAX: 16.348 W
VMAX: 51.636 V
IMAX: 0.317 A
FF: 79.611 %
Eff: 20.708 %
ESCA
QUAL COUPON
STRING:B
POST-ENVIRONMENTAL

Test date: 05/01/2000

<table>
<thead>
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<td>No. of Parallel Cells: 1</td>
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<td>Target Temperature: 28 °C</td>
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<tr>
<td>Voltage Temp Coef.: -0.24 %VOC / °C</td>
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<table>
<thead>
<tr>
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</thead>
<tbody>
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<td>VOLTS</td>
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<td>50.7820</td>
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<td>29.1680</td>
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<table>
<thead>
<tr>
<th>RESULTS</th>
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</thead>
<tbody>
<tr>
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<tr>
<td>ISC: 0.352 A</td>
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<tr>
<td>PMAX: 16.550 W</td>
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<td>VMAX: 50.782 V</td>
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<tr>
<td>FF: 80.652 %</td>
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<td>Eff: 20.964 %</td>
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ESCA
QUAL COUPON
STRING:C
POST-ENVIRONMENTAL TEST

Test date: 05/01/2000

PARAMETERS
Calibration Standard: 512-98
No. of Series Cells: 24
No. of Parallel Cells: 1
Area per Cell: 24.312 cm²
Target Temperature: 28 °C
Voltage Temp Coef.: -0.24 %VOC / °C

DATA CORRECTED TO 28°C

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DATA CORRECTED TO TARGET TEMPERATURE

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ESCA
QUAL COUPON
STRING:D
POST-ENVIRONMENTAL TEST

Test date: 05/01/2000

PARAMETERS
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No. of Series Cells: 24
No. of Parallel Cells: 1
Area per Cell: 24.312 cm^2
Target Temperature: 28 °C
Voltage Temp Coef.: -0.24 %VOC / °C

DATA CORRECTED TO 28°C

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DATA CORRECTED TO TARGET TEMPERATURE

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ESCA
QUAL COUPON
POST-AcouSTIC TEST
FULL PANEL

Test date: 01/31/2000

PARAMETERS

| Calibration Standard: | 612-98 |
| No. of Series Cells:  | 24     |
| No. of Parallel Cells:| 4      |
| Area per Cell:        | 24.312 cm²² |
| Target Temperature:   | 28 °C  |
| Voltage Temp Coef.:   | -0.24 %VOC / °C |

DATA CORRECTED TO 28°C

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DATA CORRECTED TO TARGET TEMPERATURE

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RESULTS

| VOC:      | 58.662  |
| ISC:      | 1.400   |
| PMAX:     | 64.777  |
| VMAX:     | 49.309  |
| IMAX:     | 1.314   |
| FF:       | 78.863  |
| EFF:      | 20.513  |
ESCA
QUAL COUPON
POST-ENVIRONMENTAL
FULL PANEL

Test date: 05/01/2000

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DATA CORRECTED TO 28°C

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VOC: 58.661 V
ISC: 1.395 A
PMAK: 64.566 W
VMAX: 49.291 V
IMAK: 1.310 A
FF: 78.890 %
Eff: 20.446 %
ESCA
PRE-HOT FLASH TEST INSIDE THE HOT BOX WITH COVER @ 28°C
QUAL COUPON
POST ENVIRONMENTAL TEST
CKT:A

Test date: 05/01/2000

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ESCA
PRE-HOT FLASH TEST INSIDE THE HOT BOX WITH COVER @ 28°C
QUAL COUPON
POST-ENVIRONMENTAL TEST
CKT:B

Test date: 05/01/2000

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DATA CORRECTED TO 28°C

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DATA CORRECTED TO TARGET TEMPERATURE

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ESCA
PRE-HOT FLASH TEST INSIDE THE HOT BOX WITH COVER @ 28°C
QUAL COUPON
POST-ENVIRONMENTAL TEST
CKT:C

Test date: 05/01/2000

PARAMETERS

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<tr>
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<td>No. of Parallel Cells:</td>
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<tr>
<td>Area per Cell:</td>
<td>24.312 cm²</td>
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<tr>
<td>Target Temperature:</td>
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</tr>
<tr>
<td>Voltage Temp Coef.:</td>
<td>-0.24 %VOC / ºC</td>
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DATA CORRECTED TO 28°C

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<td>12.2970</td>
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<td>0.2532</td>
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<td>0.2576</td>
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<td>0.2604</td>
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<td>0.2676</td>
<td>0.0000</td>
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DATA CORRECTED TO TARGET TEMPERATURE

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<th>POWER</th>
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<tbody>
<tr>
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<td>-0.0058</td>
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<td>53.9330</td>
<td>0.1919</td>
<td>10.3497</td>
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RESULTS

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<tr>
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ESCA
PRE-HOT FLASH TEST INSIDE THE HOT BOX WITH COVER @ 28°C
QUAL COUPON
POST-ENVIRONMENTAL TEST
CKT:D

Test date: 05/01/2000

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<tr>
<td>Voltage Temp Coef.:</td>
<td>-0.24 %VOC / °C</td>
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DATA CORRECTED TO 28°C

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DATA CORRECTED TO TARGET TEMPERATURE

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ESCA
HOT-FLASH TEST
QUAL COUPON
CKT:A
POST-ENVIRONMENTAL TEST

Test date: 05/01/2000

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<tr>
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<tr>
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<tr>
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TEST TEMPERATURE

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<td>0.2728</td>
<td>0.0214</td>
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DATA CORRECTED TO TARGET TEMPERATURE

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<thead>
<tr>
<th>Volts</th>
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<tr>
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RESULTS

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ESCA
HOT-FLASH TEST
QUAL COUPON
CKT:B
POST-ENVIRONMENTAL TEST

Test date: 05/01/2000

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<td>No. of Parallel Cells:</td>
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<tr>
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</tr>
<tr>
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<tr>
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<table>
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ESCA
HOT-FLASH TEST
QUAL COUPON
CKT:C
POST-ENVIRONMENTAL TEST

Test date: 05/01/2000

PARAMETERS
Calibration Standard: 512-98
No. of Series Cells: 24
No. of Parallel Cells: 1
Area per Cell: 24.312 cm^2
Target Temperature: 70 °C
Voltage Temp Coef.: -0.24 %/°C
Current Temp Coef.: 17.1 uA/cm^2/°C

TEST TEMPERATURE
70 °C

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DATA CORRECTED TO TARGET TEMPERATURE

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RESULTS

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ESCA
HOT-FLASH TEST
QUAL COUPON
CKT:D
POST-ENVIRONMENTAL TEST

Test date: 05/01/2000

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TEST TEMPERATURE

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DATA CORRECTED TO TARGET TEMPERATURE

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ESCA
HOT-FLASH TEST
CKT:A @ 70°C
Adjustment made for the lost of the lexan glass
Voltage Ratio: 1.007  Current Ratio: 1.30

Test date: 05/01/2000

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TEST TEMPERATURE

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DATA CORRECTED TO
TARGET TEMPERATURE

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ESCA
HOT-FLASH TEST
CKT:B @ 70°C
Adjustment made for the lost of the lexan glass
Voltage Ratio: 1.009 Current Ratio: 1.31

Test date: 05/01/2000

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<td>FF: 81.684 %</td>
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<td>Eff: 20.118 %</td>
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**ESCA**

**HOT-FLASH TEST**

**CKT:C @ 70°C**

Adjustment made for the lost of the lexan glass

Voltage Ratio: 1.009  Current Ratio: 1.30

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**TEST TEMPERATURE**

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**DATA CORRECTED TO TARGET TEMPERATURE**

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**RESULTS**

| VOC       | 53.803 V |
| ISC       | 0.357 A  |
| PMAX      | 15.237 W |
| VMAX      | 45.202 V |
| IMAX      | 0.337 A  |
| FF        | 79.276 % |
| EFF       | 19.301 % |
ESCA
HOT-FLASH TEST

CKT: D @ 70°C

Adjustment made for the lost of the lexan glass

Voltage Ratio: 1.009  Current Ratio: 1.32

Test date: 05/01/2000

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RESULTS

| VOC: 53.601 V |
| ISC: 0.363 A |
| PMAX: 15.356 W |
| VMAX: 45.038 V |
| IMAX: 0.341 A |
| FF: 78.950 % |
| Eff: 19.451 % |
REPORT ON ACOUSTIC NOISE TESTS OF ONE TEST PANEL FOR

STATE OF CALIFORNIA
COUNTY OF LOS ANGELES

C. GLARETAS, MNGR EL SEGUNDO ACOUSTICS, being duly sworn, deposes and says: That the information contained in this report is the result of complete and carefully conducted tests and is to the best of his knowledge true and correct in all respects.

SUBSCRIBED and sworn to before me the 7th day of FEB 2000

[Signature]

CERTIFICATE

PRAIRIE WITKAMP
Commission # 1234213
Notary Public - California
Los Angeles County

W-781

DEPARTMENT: Acoustics

TEST ENGINEER: F. E. Hermoso

TEST WITNESS: (Not Applicable)

DCAS-QAR VERIFICATION

QUALITY ASSURANCE: G. Montgomery
## TABLE OF CONTENTS

1.0 PURPOSE  
2.0 REFERENCES  
3.0 TEST CONDITIONS AND EQUIPMENT  
3.1 Ambient Conditions  
3.2 Instrumentation and Equipment  
4.0 SUMMARY

## LIST OF ATTACHMENTS

(Note: each Attachment can contain Data Sheets, data plots, Notices of Deviation, Equipment Lists, and other explanatory documentation)

ATTACHMENT "ACO–A" ACOUSTIC NOISE TEST

## LIST OF PHOTOGRAPHS

PHOTOGRAPH 1 ACOUSTIC NOISE TEST SETUP
1.0 PURPOSE
The purpose of this report is to present the procedures employed and the results obtained during Acoustic Noise Tests on one Test Panel.

2.0 REFERENCES
2.1 Composite Optics, Incorporated Purchase Order No. 55246.

3.0 TEST CONDITIONS AND EQUIPMENT
3.1 Ambient Conditions
Unless otherwise specified all tests were performed at a barometric pressure of between 710 and 815 mm of mercury absolute, a temperature of +75±10 °F and a relative humidity between 30 and 70%.

3.2 Instrumentation and Equipment
3.2.1 Measuring and test equipment, utilized in the performance of this contract, were calibrated in accordance with ANSI/NCSL Z540–1–1994 (supersedes MIL–STD–45662) by the Wyle Laboratories Standards Laboratory, or a commercial facility, utilizing reference standards (or interim standards) whose calibrations have been certified as being traceable to the National Institute of Standards and Technology. All reference standards, utilized in the above calibration system, are supported by certificates, reports or data sheets attesting to the date, accuracy and conditions under which the results furnished were obtained. All subordinate standards, and measuring and test equipment, are supported by like data when such information is essential to achieve the accuracy control required by the subject contract.

3.2.2 Wyle Laboratories attests that the commercial sources providing calibration services on the above referenced equipment, other than the National Institute of Standards and Technology, are in fact capable of performing the required services to the satisfaction of the Wyle Laboratories Quality Control Department. Certificates and reports of all calibrations performed are retained in the Wyle Laboratories Quality Control files and are available for inspection, upon request, by customer representatives.

3.2.3 The test equipment utilized during this program is listed in Attachment "ACO–A."
4.0 SUMMARY
The Test Panel was subjected to an Acoustic Noise Test according to Reference 2.1 and Reference 2.2, Table 1. Equalization tests were performed on the empty test chamber using four control microphones. The test setup is shown in Photograph 1. The specimen was subjected to the required acoustic spectrum at 142.5 dB for 60 seconds. The Test Panel completed the Acoustic Noise Test without apparent damage. Refer to Attachment "ACO–A" for specific details of the test setup, conditions during the test, and test results.
<table>
<thead>
<tr>
<th>1/3 OCTAVE BAND CENTER FREQUENCY (Hz)</th>
<th>MEASURED 1/3 OCTAVE BAND SOUND PRESSURE LEVELS (dB*)</th>
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<tbody>
<tr>
<td>31.5</td>
<td>122.5</td>
</tr>
<tr>
<td>40</td>
<td>124.7</td>
</tr>
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<td>50</td>
<td>129.0</td>
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<td>63</td>
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<td>125</td>
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<td>200</td>
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<tr>
<td>630</td>
<td>128.0</td>
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<tr>
<td>800</td>
<td>125.2</td>
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<tr>
<td>1000</td>
<td>123.1</td>
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<tr>
<td>1250</td>
<td>120.8</td>
</tr>
<tr>
<td>1600</td>
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<td>3150</td>
<td>113.9</td>
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<td>4000</td>
<td>113.5</td>
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<td>5000</td>
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<tr>
<td>6300</td>
<td>112.1</td>
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<tr>
<td>8000</td>
<td>112.3</td>
</tr>
<tr>
<td>10000</td>
<td>112.6</td>
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</table>

Allowable Overall SPL: 142.8

*dB-Ref.: 2.0 x 10^{-5} Pa
ATTACHMENT "ACO–A"

ACOUSTIC NOISE TEST
RECEIVING INSPECTION DATA SHEET

Customer: COMPOSITE OPTICS, INC.  
Job No.: 43899

Specimen: PANEL  
Date: 1-28-2000

No. of Specimens Received: 1

Record identification information exactly as it appears on the tag or specimen:
Manufacturer: Composite Optics, Inc.

P/N's: NA  
S/N's: NA

How Does identification information appear: (e.g. name plate, tag, painted, imprinted, etc)

Per Customer Direction

Examination: Visual, for evidence of damage, poor workmanship, or other defects, and completeness of identification

Inspection Results: There was not visible evidence of damage to the specimen(s) unless otherwise noted below.

Inspected By: F.E. Hermoso
Approved By: Costa Glaretas
Date: January 28, 2000

W614 QA Form Approval
## ACOUSTIC NOISE

**Customer**  
COMPOSITE OPTICS, INC.

**Specimen**  
PANEL

**Part No**  
NA

**S/N**  
NA

**Test By**  
F.E. HERMOSO

**Witness**  

**Date**  
1-28-2000

### EQUIPMENT

<table>
<thead>
<tr>
<th>EQUIPMENT</th>
<th>MANUFACTURER</th>
<th>MODEL NO.</th>
<th>RANGE</th>
<th>WYLE No.</th>
<th>CALIBRATION</th>
<th>ACCURACY</th>
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<tr>
<td>Modulator</td>
<td>Wyle</td>
<td>WAS 3000</td>
<td>10,000 Hz</td>
<td>S/N 014</td>
<td>N.A</td>
<td>N.A</td>
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<td>Acoustic Control System</td>
<td>Wyle</td>
<td>ACS</td>
<td>20 Hz to 10 kHz</td>
<td>W13866</td>
<td>System Cal. Prior to Use</td>
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<td>1/3 Octave Real Time Analyzer</td>
<td>Norwegian Electronics</td>
<td>830</td>
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<td>W9453</td>
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<td>±0.20 dB</td>
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<tr>
<td>1/3 Octave Spectrum</td>
<td>Norwegian Electronics</td>
<td>731</td>
<td>20 Hz to 20 kHz</td>
<td>W11063</td>
<td>System Cal. Prior to Use</td>
<td>±0.20 dB</td>
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<tr>
<td>Sound Level</td>
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<td>4230</td>
<td>94 dB @ 1000 Hz</td>
<td>W12103</td>
<td>7-22-99</td>
<td>±0.13 dB</td>
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<tr>
<td>Pistonphone (if Sound Level Calibrator is not used)</td>
<td>Brüel &amp; Kjaer</td>
<td>4228</td>
<td>124 dB @ 250 Hz</td>
<td>W12107</td>
<td>5-19-99</td>
<td>±0.10 dB</td>
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<td>Acoustic Microphone</td>
<td>PCB</td>
<td>106M55</td>
<td>90 to 190 dB</td>
<td>(NONE)</td>
<td>Prior to use Sound Level Calibrator</td>
<td>N.A</td>
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<tr>
<td>Power Amplifier</td>
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<td>600 Watts</td>
<td>W10354</td>
<td>N.A</td>
<td>N.A</td>
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<tr>
<td>Power Amplifier</td>
<td>Ling</td>
<td>8004/8008</td>
<td>4kVA</td>
<td>N.A</td>
<td>N.A</td>
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<td>FFT Analyser</td>
<td>Ono Sokki</td>
<td>CF-350</td>
<td>1Hz to 40KHz</td>
<td>W10788</td>
<td>System Cal. Prior to use</td>
<td>N.A</td>
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<tr>
<td>Tape Recorder</td>
<td>Teac</td>
<td>RX-832</td>
<td>32 Channels</td>
<td>W14047</td>
<td>System Cal Prior to use</td>
<td>N.A</td>
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W614 C Q.C. Approval
TEST RECORD DATA SHEET

TEST TITLE  ACOUSTIC NOISE

Customer  COMPOSITE OPTICS, INC.  Job No.  43899
Specimen  PANEL  Date Started  1-28-2000
Part No.  NA  Serial No.  NA  Date Comp  1-28-2000
Spec.  Facsimile Dated 5-28-99  Par.  Table 1  Photo  Yes  Amb. Temp.  75 ± 10 deg. F

PROCEDURE:

The Specimen was subjected to Acoustic Random Noise Testing in accordance with the above referenced specifications. Adjustment of sound pressure levels and spectrum shapes were accomplished prior to installing the Specimen in the High Intensity Reverberation Room. The specimen was suspended in the Reverberation Room by nylon net.

High intensity noise was then introduced into the chamber with an overall Sound Pressure Level (SPL) of 142.5dB. This condition was maintained for 60 Seconds.

RESULTS:

Qualification Test was completed with no apparent damage to the specimen. Measured acoustic noise data are shown on 1/n octave plots.

 Tested By  F.E. HERMOSO
W614A-82 QA Form  Approval  
Engineer  F.E. HERMOSO
WYLE LABORATORIES

ACOUSTIC TEST

COMPOSITE OPTICS, INC. 43899, PANEL

0 dB CONTROL MIC -4

JANUARY 28, 2000

OASPL: 142.5 dB
PHOTOGRAPH 1

ACOUSTIC NOISE TEST SETUP
PHOTOGRAPH 1
ACOUSTIC NOISE TEST SETUP
Certain missions require Electrostatically Clean Solar Array (ECSA) panels to establish a favorable environment for the operation of sensitive scientific instruments. The objective of this program was to demonstrate the feasibility of an ECSA panel that minimizes panel surface potential below 100mV in LEO and GEO charged particle environments, prevents exposure of solar cell voltage and panel insulating surfaces to the ambient environment, and provides an equipotential, grounded structure surrounding the entire panel. An ECSA panel design was developed that uses a Front Side Aperture-Shield (FSA) that covers all inter-cell areas with a single graphite composite laminate, composite edge clips for connecting the FSA to the panel substrate, and built-in tabs that interconnect the FSA to conductive coated coverglasses using a conductive adhesive. Analysis indicated the ability of the design to meet the ECSA requirements. Qualification coupons and a 0.5m X 0.5m prototype panel were fabricated and tested for photovoltaic performance and electrical grounding before and after exposure to acoustic and thermal cycling environments. The results show the feasibility of achieving electrostatic cleanliness with a small penalty in mass, photovoltaic performance and cost, with a design is structurally robust and compatible with a wide range of current solar panel technologies.