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

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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.

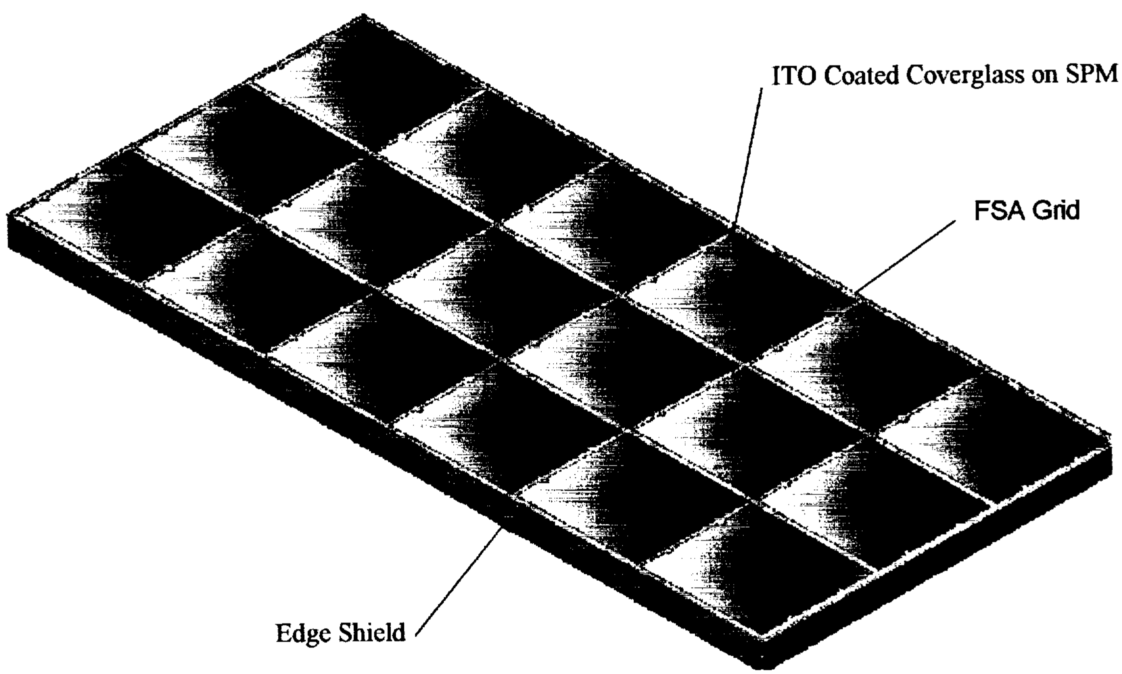


Figure 1. Basic Geometry of an ECSA Panel Using a Front Side Aperture Grid Shield

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.

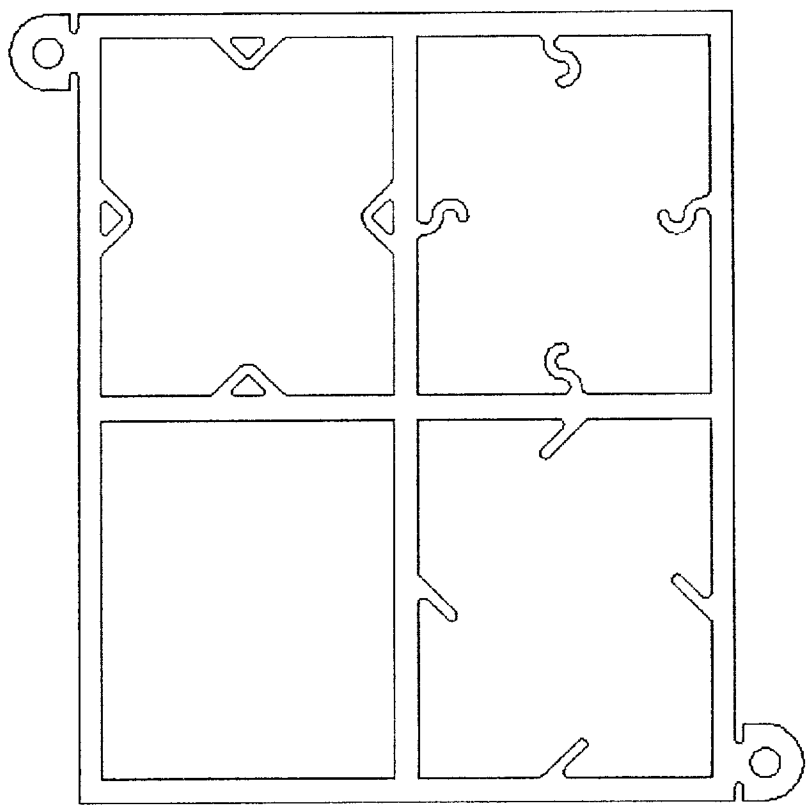


Figure 2. Layout of the Frontside Aperture Shield for the Qual Coupons.

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 20mils (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 $0.1\mu A/cm^2$ rather than the $1\mu A/cm^2$ 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 Ω/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.

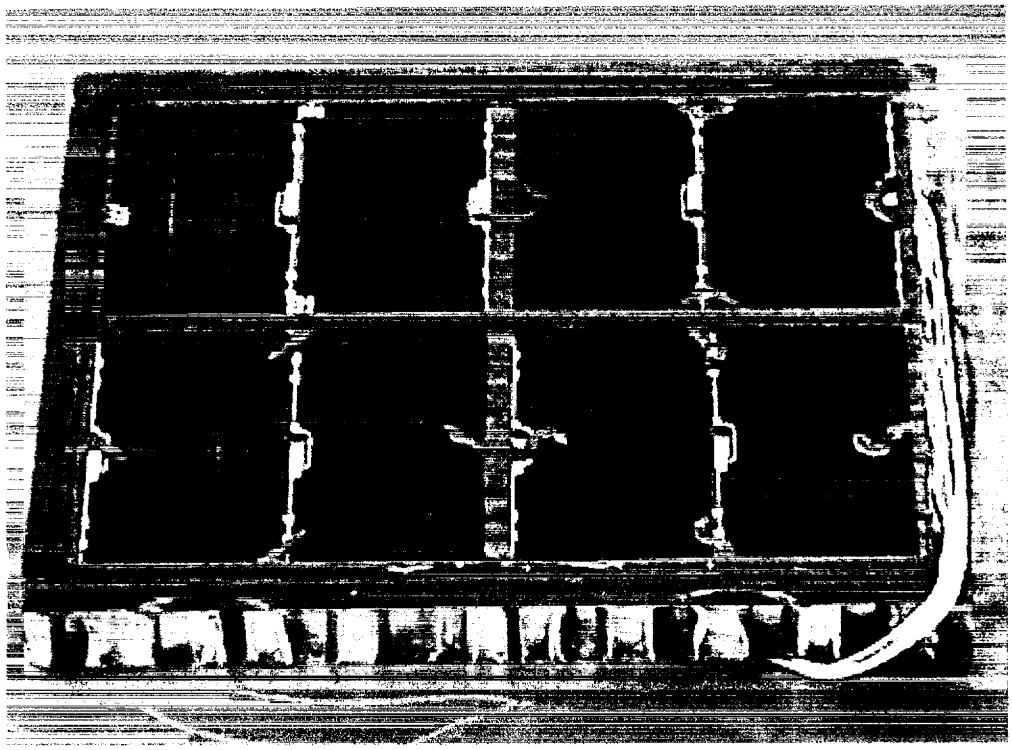


Figure 3. Qualification coupon using four coverglass interconnect approaches

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

Interconnect type	Qual coupon #1	Qual coupon #2
Slant	10	33
Serpentine	93	98
Diamond	5	23
Be-Cu Contact Finger	8	27

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 –180C to 35C for 200 cycles, and re-measured, then thermal cycled from –90 to 90C 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 35C.

Interconnect type	Qual coupon #1	Qual coupon #2
Slant	20	12
Serpentine	open	26
Diamond	6	7
Be-Cu Contact Finger	open	8

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

Interconnect type	Qual coupon #1	Qual coupon #2
Slant	31	50
Serpentine	open	97
Diamond	50	20
Be-Cu Contact Finger	open	52

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.

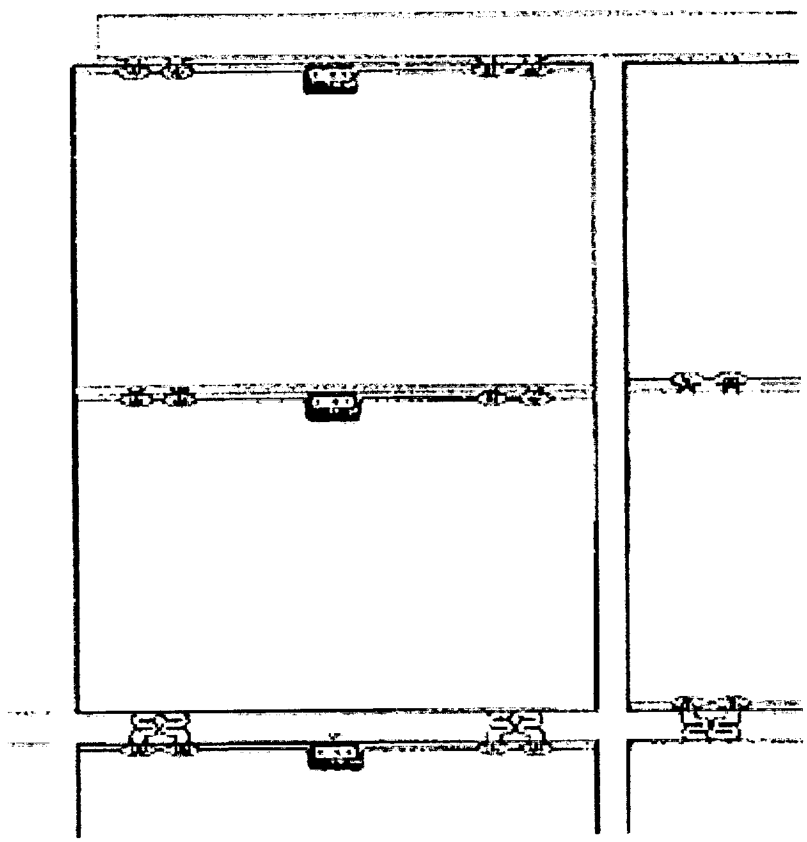


Figure 4. Cell layout drawing used to provide appropriate spacing for the FSA.

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.

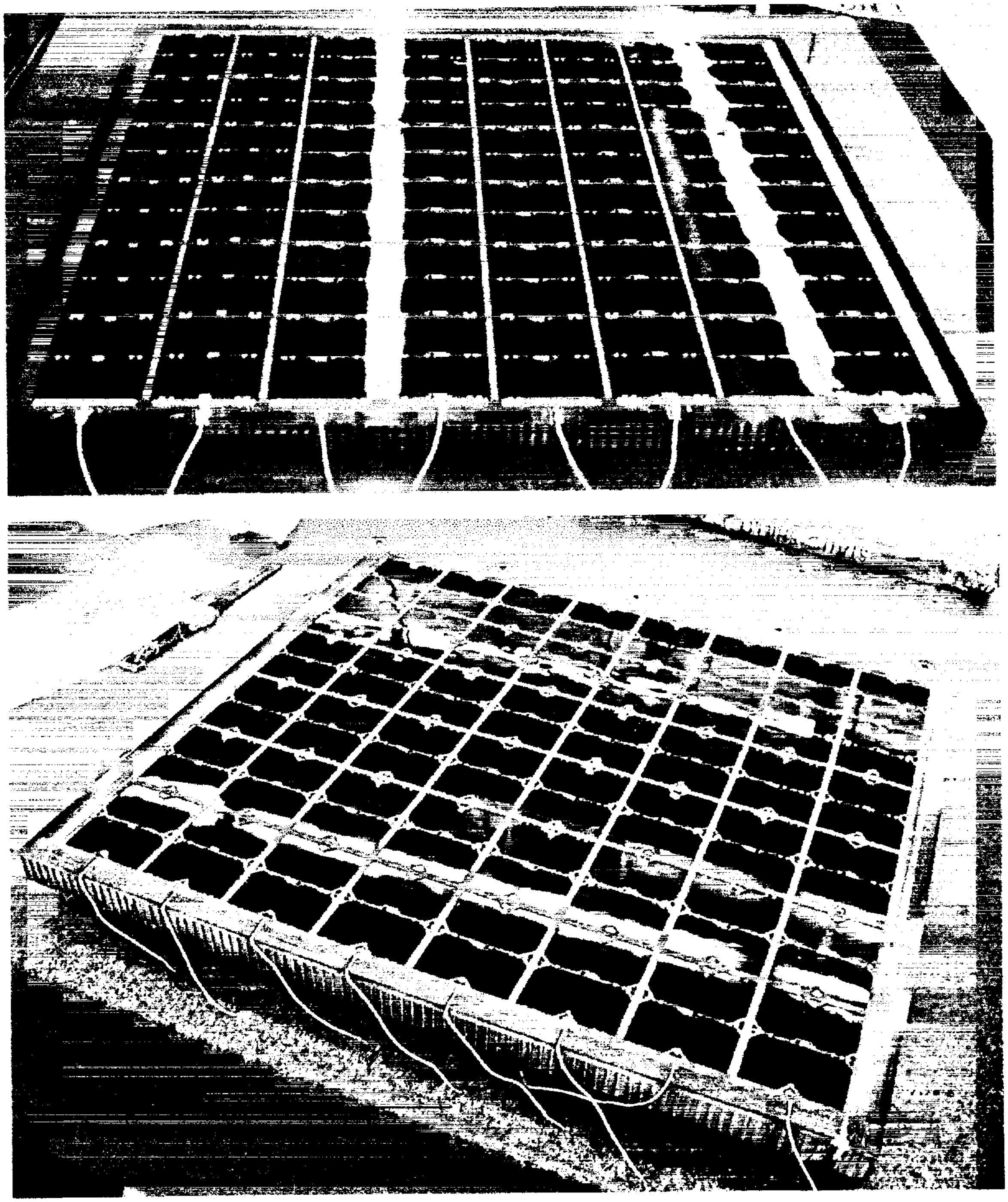


Figure 5. Completed prototype ECSA panel.

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.

Component	Mass
Substrate	711g
Panel without EC components (FSA, edge clips, and structural and conductive adhesives)	1055g
Completed prototype panel	1118g

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.

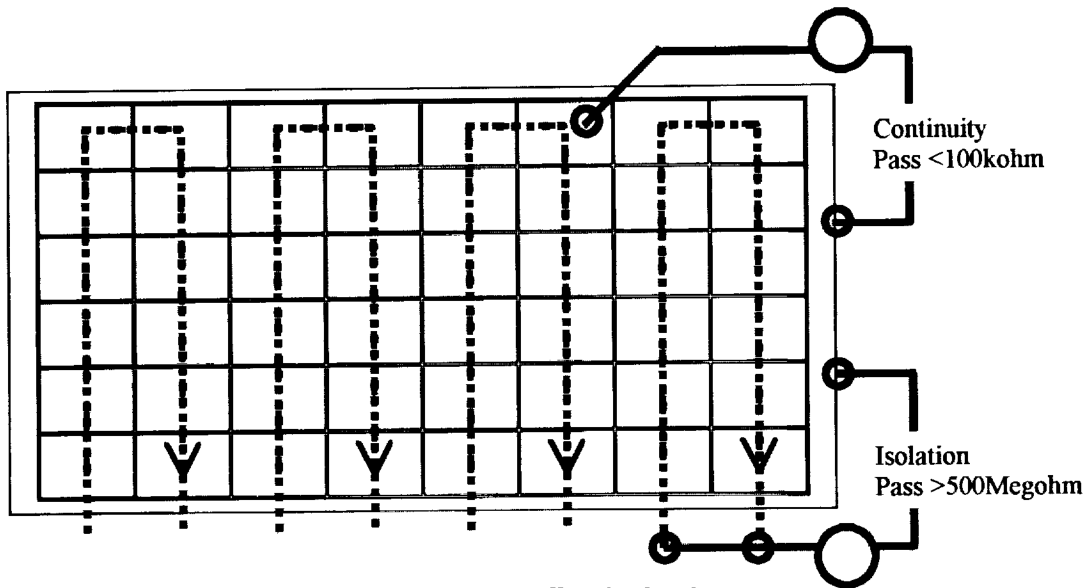


Figure 6. Electrical isolation/grounding test setups

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.

Parameter	**Value**
Voc	58.78V
Isc	1.49A
Pmax	69.42W
Vmp	49.37V
Imp	1.41A
FF	79.1%
Efficiency	21.98%

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.

Parameter	Value
Voc	58.61V
Isc	1.40A
Pmax	64.33W
Vmp	49.26V
Imp	1.31A
FF	78.2%
Efficiency	20.37%

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

Resistance (kohm) from coverglass to panel ground	12	140	3	2	3	4	OC	50
	5	5	3	2	5	3	6	5
	2	6	15	2	10	5	OC	OC
	7	6	4	5	3	3	5	16
	7	2	2	8	4	2	6	22
	3	4	4	3	2	4	14	4
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.

Parameter	Value
Voc	58.66V
Isc	1.40A
Pmax	64.78W
Vmp	49.31V
Imp	1.31A
FF	78.9%
Efficiency	20.51%

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

Resistance (kohm) from coverglass to panel ground	24	OC	3	2	3	6	OC	OC
	4	13	3	2	22	2	13	7
	2	22	27	2	28	OC	OC	OC
	17	250	5	3	5	OC	OC	OC
	2	2	1	6	11	10	4	33
	2	2	5	4	2	9	OC	3
Circuit Isolation	OC		OC		OC		OC	

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 35C followed by 1000 cycles from –90 to 90C. Test tolerances for each thermal cycle environment limits were +/-5C.

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.

Parameter	Value
Voc	58.66V
Isc	1.40A
Pmax	64.57W
Vmp	49.29V
Imp	1.31A
FF	78.9%
Efficiency	20.45%

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

Resistance (kohm) from coverglass to panel ground	OC	OC	OC	39	12	74	OC	OC
	620	500	46	6	330	8	32	35
	76	18	800	9	OC	OC	OC	OC
	61	1500	11	14	15	OC	OC	OC
	22	9	4	10	6	11	10	37
	5	9	OC	17	6	16	OC	60
Circuit Isolation	OC		OC		OC		OC	

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.

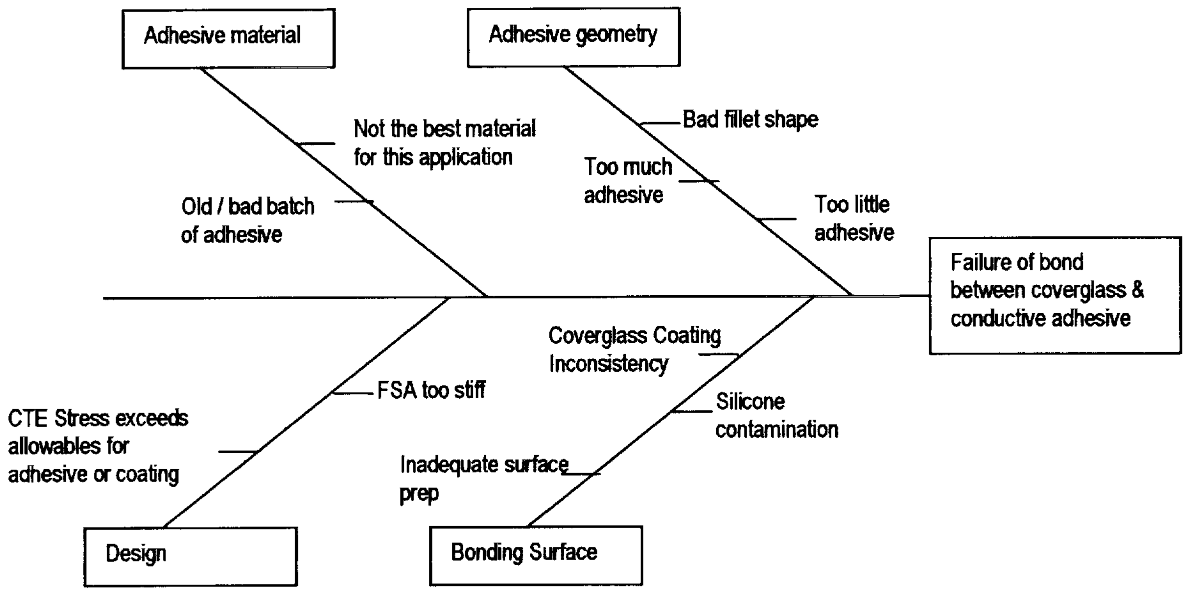


Figure 7. Root cause failure analysis fishbone diagram

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

Resistance (kohm) from coverglass to panel ground	OC HCR, Lg	OC HCR	OC	39	12	74	OC	OC HCR
	620 Lg	500 HCR, Lg	46	6	330 HCR, Lg	8	32 Lg	35 Lg
	76	18 HCR, Lg	800 Lg	9	OC HCR, Lg	OC	OC	OC
	61	1500 HCR, Sm	11 HCR	14	15	OC HCR	OC	OC Sm
	22	9	4	10 HCR	6	11 HCR, Lg	10 Sm	37 Sm
	5	9 Sm	OC Sm	17	6	16	OC Sm	60 Sm
Circuit Isolation	OC		OC		OC		OC	

Key:
HCR=high coating surface resistance
Sm=small adhesive bond
Lg=large adhesive bond

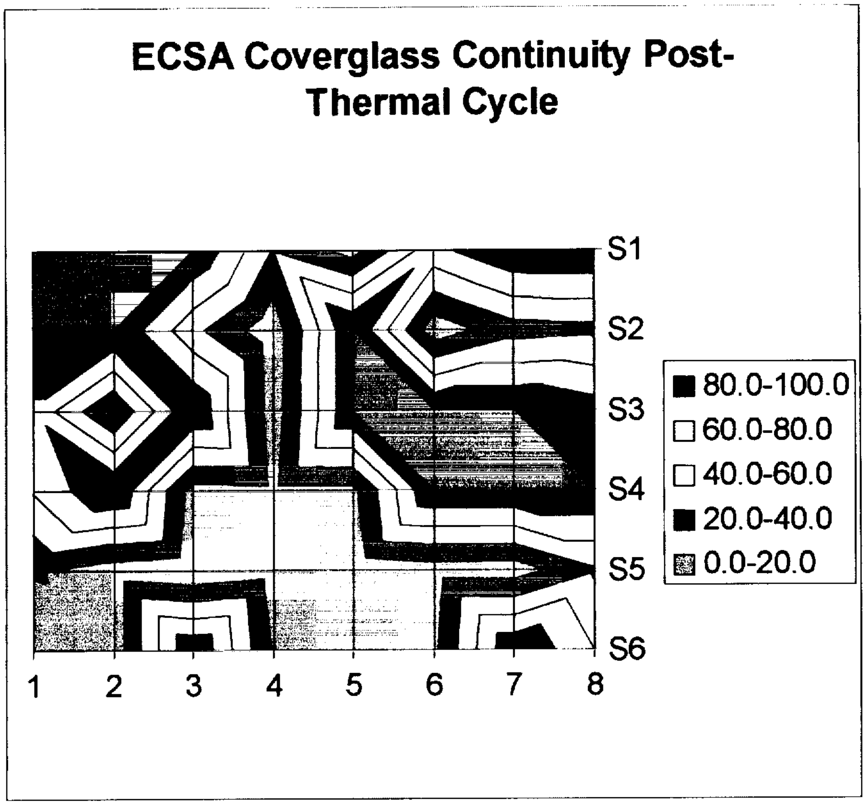


Figure 8. Correlation between areas of marginal and failed continuity with position on the panel.

Table 13. Root cause analysis based on fishbone diagram.

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

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 qualificaiton.

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 MTI'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 an 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

Maxwell TECHNOLOGIES

Electrostatically Clean Array Current Collection in LEO

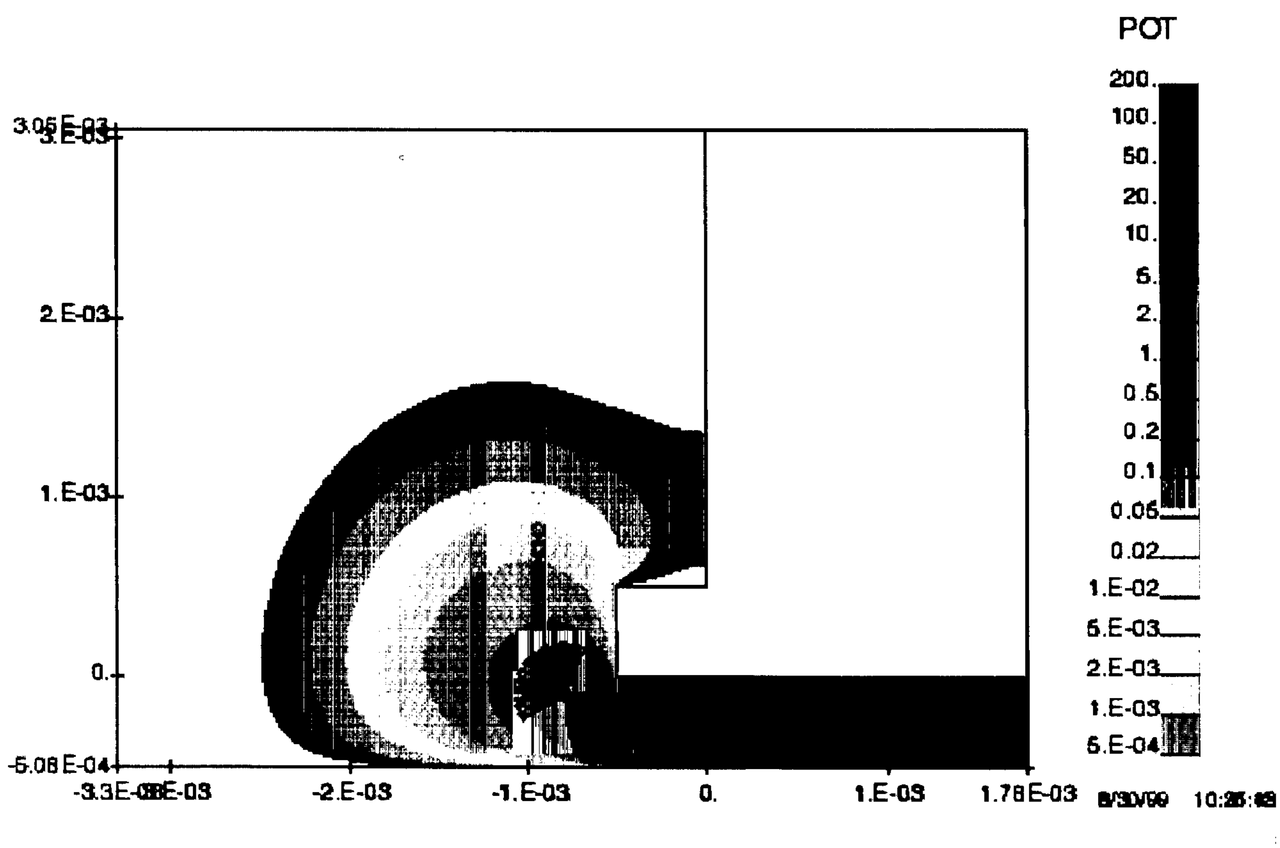
Ira Katz

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
- $\theta = 0.1$ eV, $v_i = 7800$ 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

$$\text{Net Current} = \text{Area} \times \left(j_{ion} + \exp\left((\phi_o + \Delta\phi)/\theta \right) j_{th} + \eta \, j_{th} \right)$$

$$j_{ion} = -\exp\left(\phi_o / \theta \right) j_{th} \qquad \text{Gap Current} = \text{Area} \times \eta \, j_{th}$$

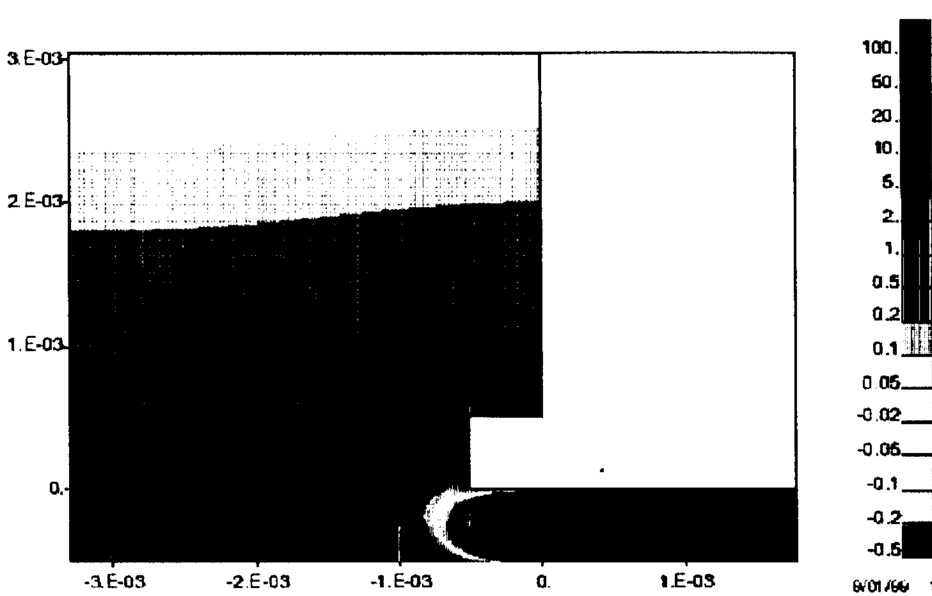
$$\text{Net Current} = \text{Area} \times \left(\exp\left(\phi_o / \theta \right) \left(\exp\left(\Delta\phi / \theta \right) - 1 \right) + \eta \right) j_{th}$$

- 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

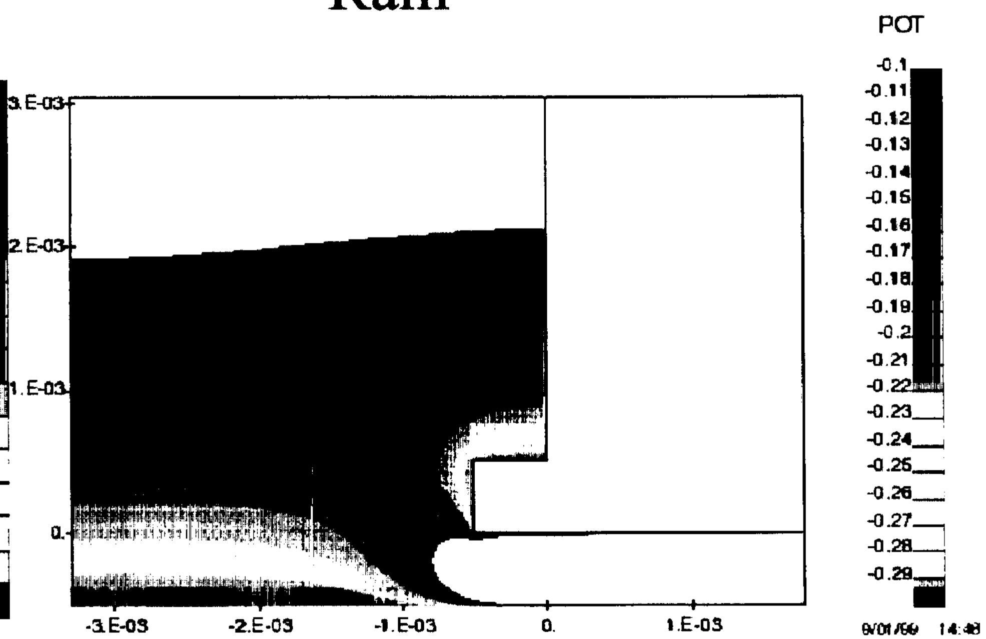
Current collection limited by barrier

- 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

Edge on

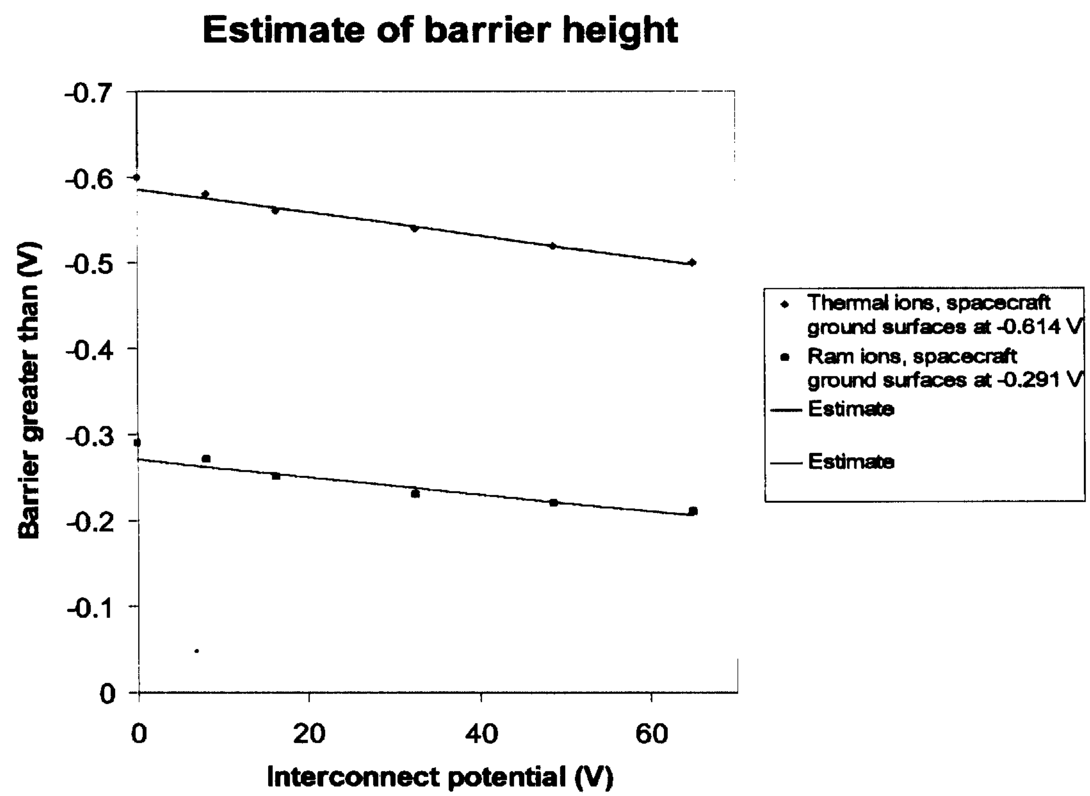


Ram



Barrier Height Linear Function of Interconnect Potential

- Almost Laplacian potentials
- Linear fits to several cell potentials



Upper Bound Estimate of Gap Current

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

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

Edge to Ram			Face to Ram		
Interconnect (V)	Barrier (V)	Exponential	Interconnect (V)	Barrier (V)	Exponential
-0.614	-0.587	0.00283	-0.291	-0.270	0.06701
1.646	-0.584	0.00292	1.969	-0.268	0.06854
3.906	-0.581	0.00301	4.229	-0.266	0.07010
6.166	-0.578	0.00310	6.489	-0.264	0.07170
8.426	-0.575	0.00319	8.749	-0.261	0.07333
10.686	-0.572	0.00329	11.009	-0.259	0.07500
12.946	-0.569	0.00340	13.269	-0.257	0.07671
15.206	-0.565	0.00350	15.529	-0.255	0.07846
17.466	-0.562	0.00361	17.789	-0.252	0.08025
19.726	-0.559	0.00372	20.049	-0.250	0.08208
21.986	-0.556	0.00384	22.309	-0.248	0.08395
24.246	-0.553	0.00395	24.569	-0.246	0.08586
26.506	-0.550	0.00408	26.829	-0.243	0.08782
28.766	-0.547	0.00420	29.089	-0.241	0.08982
31.026	-0.544	0.00433	31.349	-0.239	0.09187
33.286	-0.541	0.00447	33.609	-0.236	0.09396
35.546	-0.538	0.00461	35.869	-0.234	0.09610
37.806	-0.535	0.00475	38.129	-0.232	0.09829
40.066	-0.532	0.00490	40.389	-0.230	0.10053
42.326	-0.529	0.00505	42.649	-0.227	0.10282
44.586	-0.526	0.00520	44.909	-0.225	0.10516
46.846	-0.523	0.00536	47.169	-0.223	0.10756
49.106	-0.520	0.00553	49.429	-0.221	0.11001
51.366	-0.517	0.00570	51.689	-0.218	0.11252
53.626	-0.514	0.00588	53.949	-0.216	0.11508
55.886	-0.511	0.00606	56.209	-0.214	0.11771
58.146	-0.508	0.00625	58.469	-0.212	0.12039
60.406	-0.505	0.00644	60.729	-0.209	0.12313
62.666	-0.501	0.00664	62.989	-0.207	0.12594
64.926	-0.498	0.00685	65.249	-0.205	0.12881

Maxwell Technologies

Calculation Shows 0.1V Greater than Necessary to Balance Cell Collection

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

$$\text{Net Current} = 29 \times 0.06 \times 0.04 \times \exp(\phi_o/\theta)(-0.632)\, j_{th} + \sum_{\text{gaps}} 7.62 \times 10^{-4} \times 0.06 \times \exp(\phi_{\text{barrier}}/\theta)\, j_{th}$$

$\boxed{\text{NOTE: } j_{th} < 0}$

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

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

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

Maxwell TECHNOLOGIES

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 $0.001 Am^{-2}$

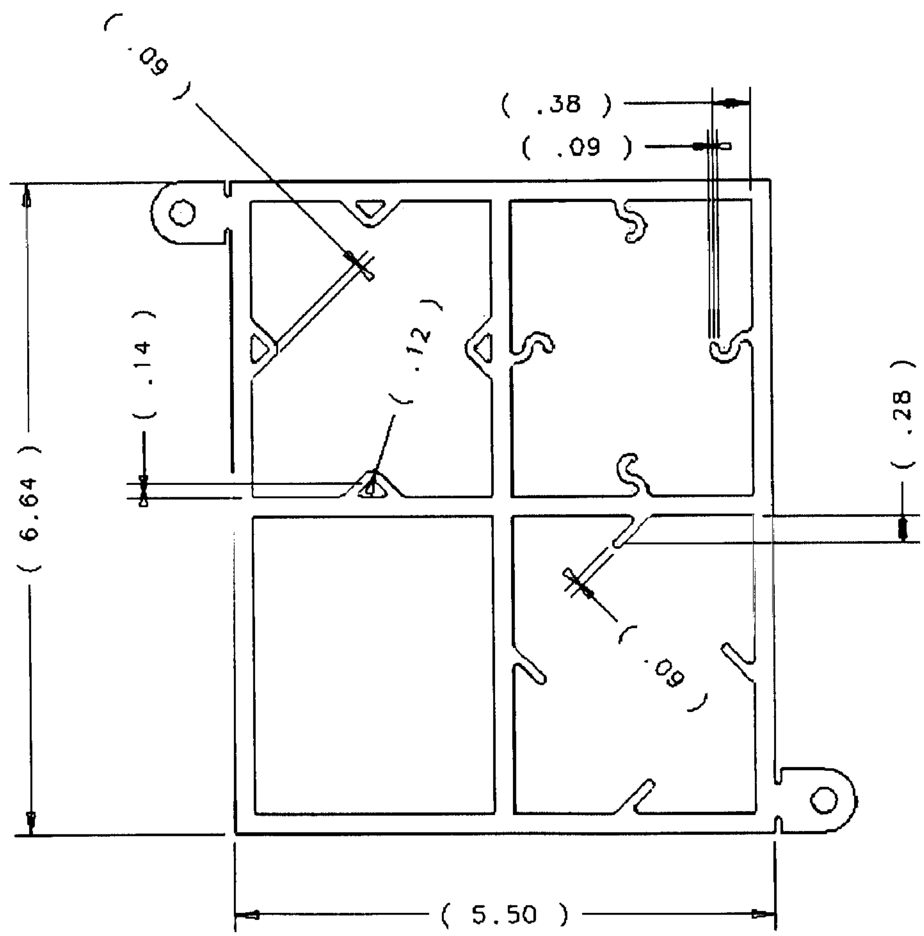
- Procedure

  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 $0.001 Am^{-2}$ 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 $0.001 Am^{-2}$ plasma

FSA Grid Configuration - Qual Coupons (provided by COI)



Space Requirement: $\phi_{max} < 0.1$ V for $j_{plasma} = 0.001 \mathrm{Am}^{-2}$

- Ion current density drives potential
- Divergence of the surface current is the plasma current

  $\nabla \bullet \mathbf{K} = j_{plasma}$
- Ohm's law

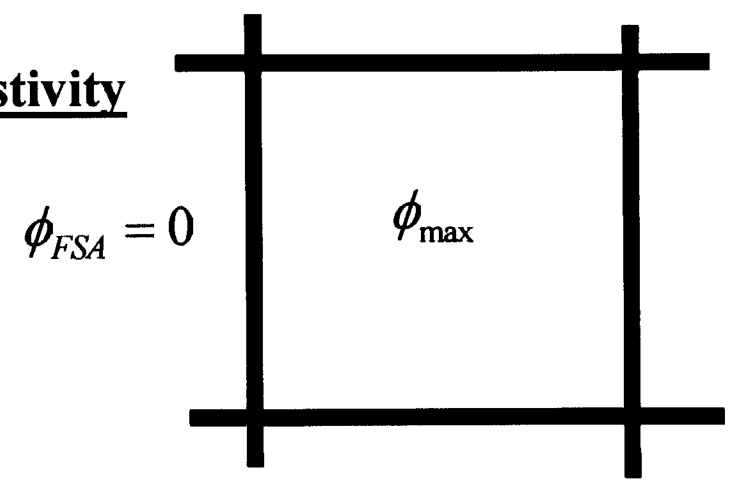
  $\mathbf{E} = \eta \mathbf{K}$
- **<u>Potential proportional to the resistivity</u>**

  $\mathbf{K} = \frac{1}{\eta}\mathbf{E} = -\frac{1}{\eta}\nabla\phi$

  $\nabla \bullet \nabla\phi = -\eta\, j_{plasma}$

  $\nabla^2\phi = -\eta\, j_{plasma}$

  $\phi_{max} \propto \eta$



Solution in Cylindrical Symmetry

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

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

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

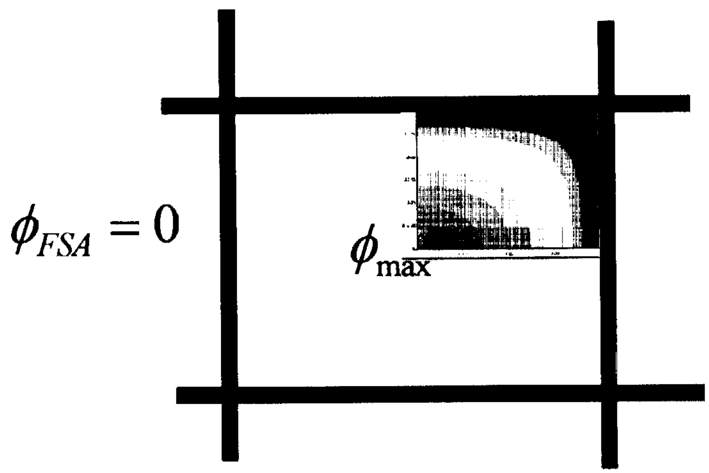
$$\phi(r) = \frac{-\eta j_{plasma}}{4} r^2 + 0.1V$$

$$\eta j_{plasma} = 260\ \Omega\square^{-1}\,Am^{-2}$$

- For $j_{plasma} = 0.001\ Am^{-2}$

$$\eta < 260\ k\Omega\square^{-1}$$

2-D Computations of Peak Potential

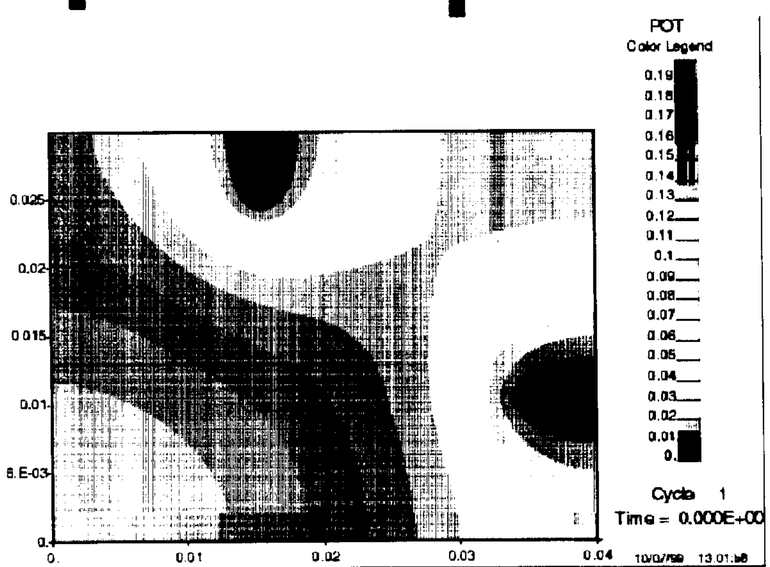


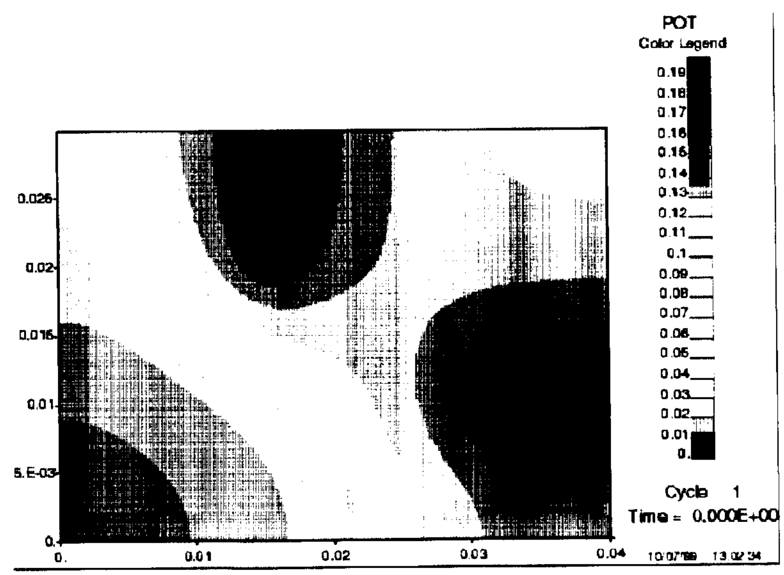
$\eta j_{plasma} = 260\ \Omega\ \square^{-1}\ \mathrm{Am}^{-2}$

Grounded edges: $\phi_{max} = 0.0880$ V

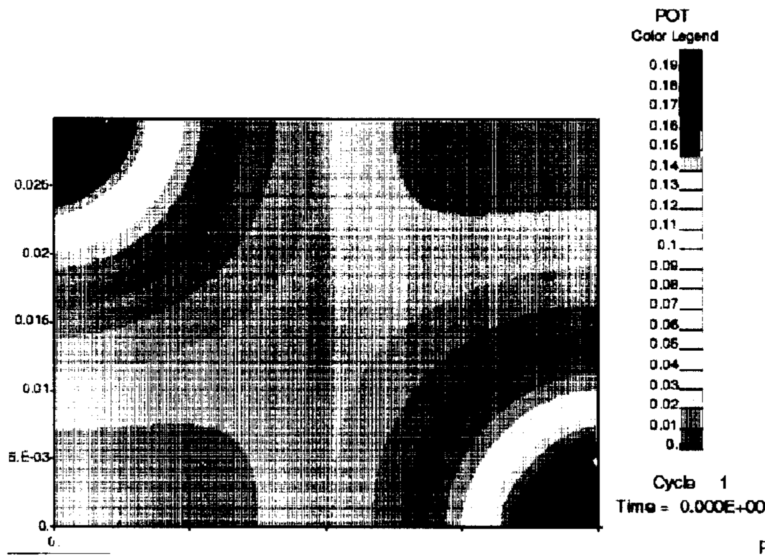
8 0.5 cm tabs: $\phi_{max} = 0.109$ V

8 1 cm tabs: $\phi_{max} = 0.0753$ V





2-D Computations of Peak Potential

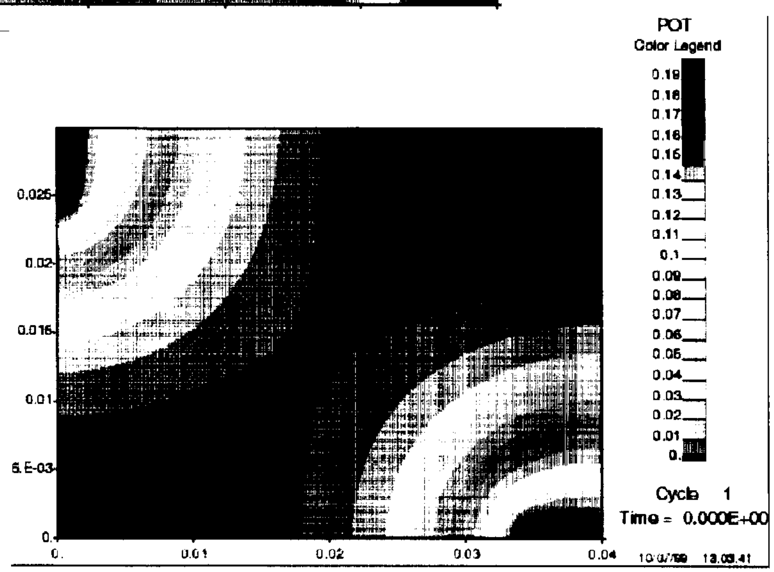


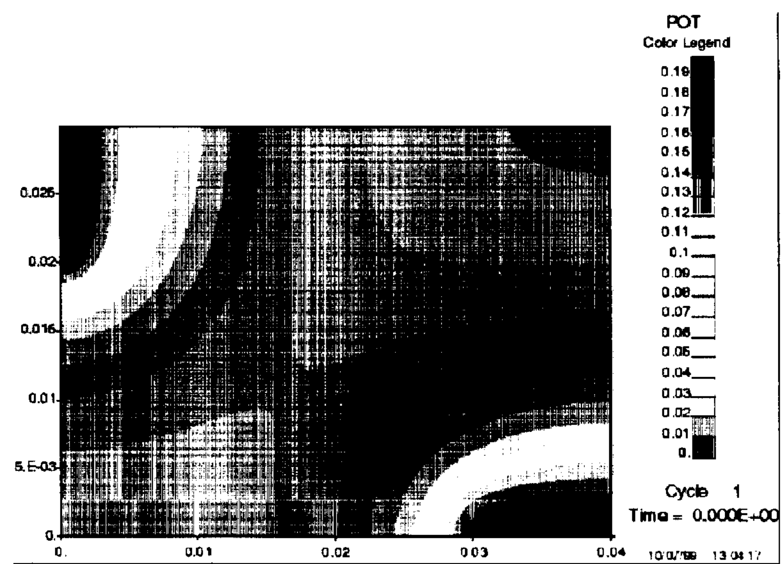
$\eta j_{plasma} = 260\ \Omega\ \square^{-1}\ Am^{-2}$

4 Triangular tabs: $\phi_{max} = 0.126$ V

4 0.635 cm tabs: $\phi_{max} = 0.156$ V

4 1 cm tabs: $\phi_{max} = 0.121$ V





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Required Surface Resistivity

Required surface resistivity scales inversely with calculated potential

- Calculations:

  $$\eta j_{plasma} = 260\ \Omega\ \square^{-1}\ \mathrm{Am}^{-2}$$
  $$j_{plasma} = 10^{-3}\ \mathrm{Am}^{-2}$$

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

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

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

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

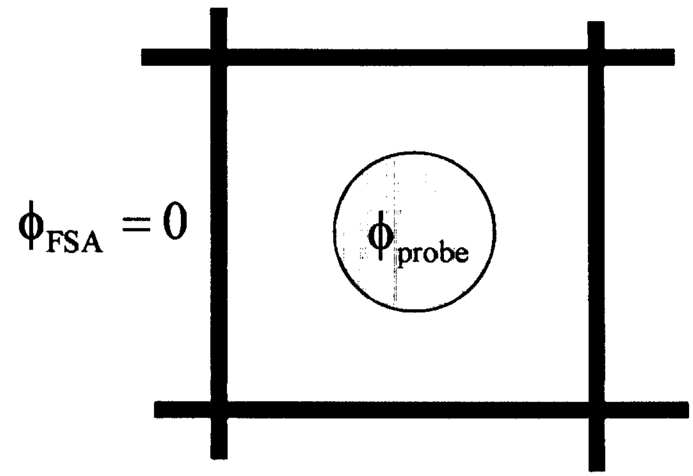
- Four 0.635 cm tabs: $\phi_{max} = 0.156$ V
  Required $\eta < 167\ \mathrm{k}\Omega\ \square^{-1}$

- Four 1 cm tabs: $\phi_{max} = 0.121$ V
  Required $\eta < 215\ \mathrm{k}\Omega\ \square^{-1}$

Laboratory Confirmation of Resistivity

- Use previous equations

$$\nabla^2 \phi = -\eta \, j_{plasma} \qquad \mathbf{K} = -\frac{1}{\eta} \nabla \phi$$



- Plasma current density is zero

$$\nabla^2 \phi = 0$$

- Total probe current is the integral of the surface current

$$I_{probe} = \oint_{probe} K \, ds$$

- **<u>Resistance proportional to resistivity</u>**

$$I_{probe} = -\frac{1}{\eta} \oint_{probe} \nabla \phi \; ds$$

Maxwell TECHNOLOGIES

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 $\phi(r_o) = 1$ V ($R = 0.039$ m)

- $$\phi(r)=1V\frac{\ln(r/R)}{\ln(r_o/R)}$$

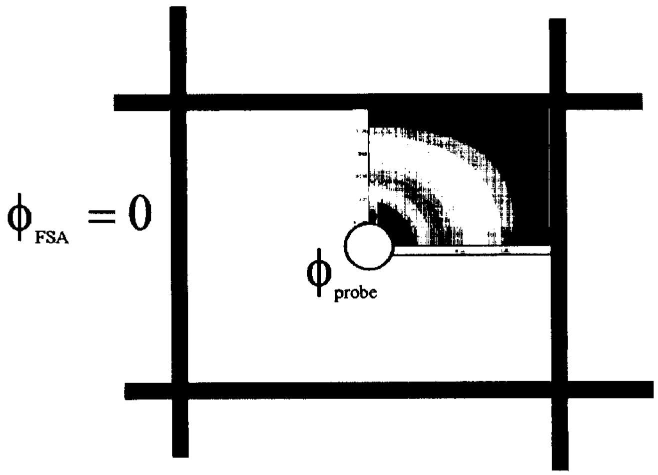
- $$\eta I_{probe}=-\oint\frac{d\phi}{dr}dl=-2\pi r_o\left.\frac{d\phi}{dr}\right|_{r_o}$$

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

r_o (m)	ηI_{probe} (V)
0.01	4.6
0.001	1.7
0.0001	1.05
0.00001	0.76

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

2-D Computations
1 cm diameter test probe

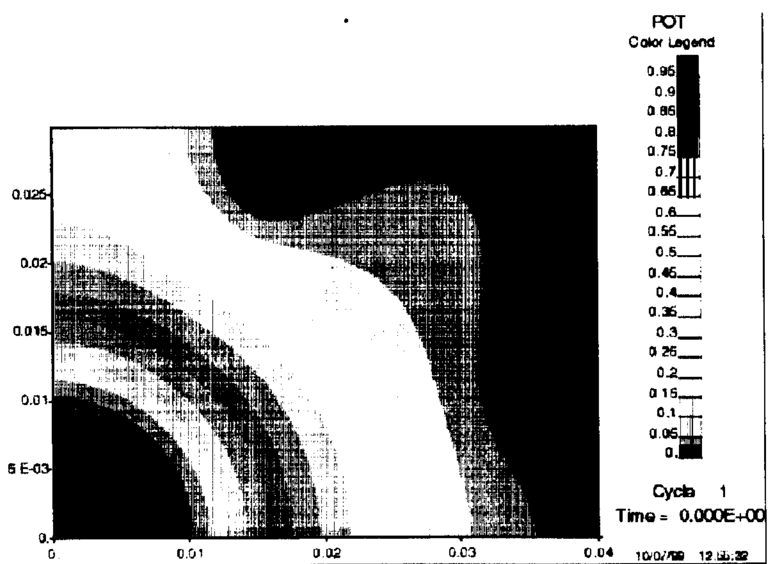


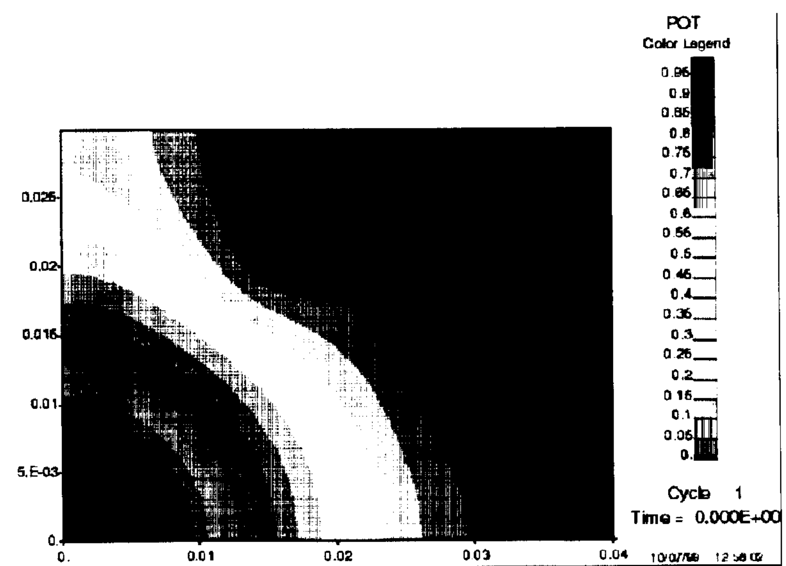
$\phi_{probe} = 1$

Grounded edges: $\eta I_{probe} = 3.15\ \Omega\ \square^{-1}$ A

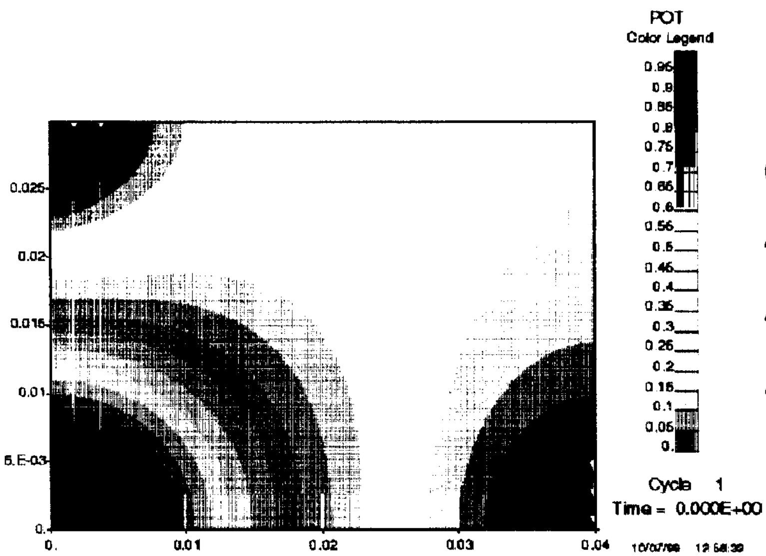
8 0.5 cm tabs: $\eta I_{probe} = 2.97\ \Omega\ \square^{-1}$ A

8 1 cm tabs: $\eta I_{probe} = 3.31\ \Omega\ \square^{-1}$ A





2-D Computations
1 cm diameter test probe

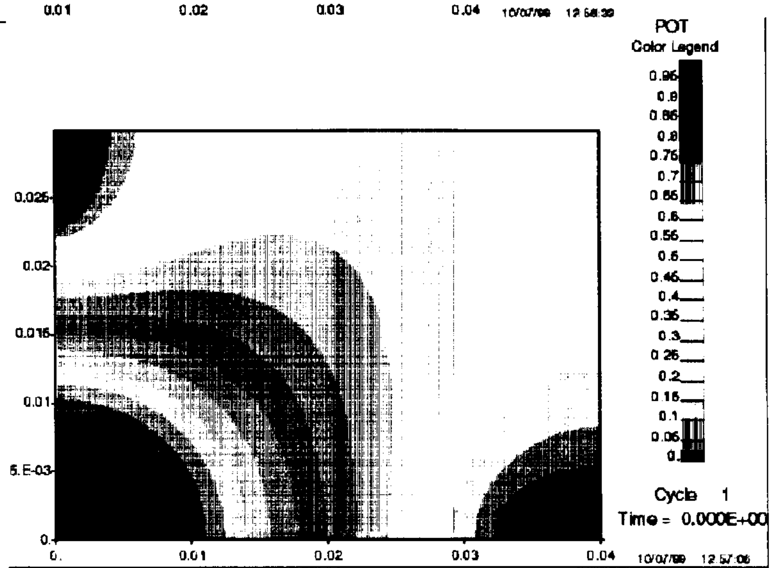


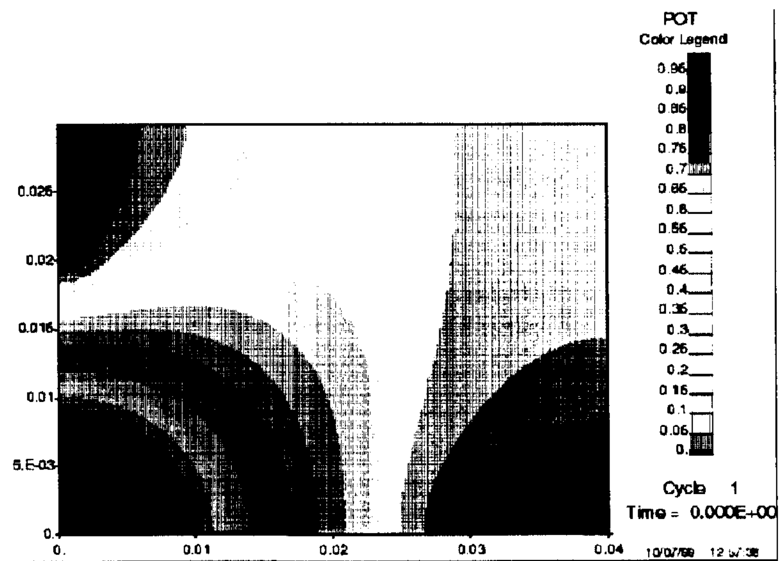
$\phi_{probe} = 1$

4 Triangular tabs: $\eta I_{probe} = 2.97\ \Omega\ \Box^{-1}\ A$

4 0.635 cm tabs: $\eta I_{probe} = 2.82\ \Omega\ \Box^{-1}\ A$

4 1 cm tabs: $\eta I_{probe} = 3.23\ \Omega\ \Box^{-1}\ A$





Required Resistance Measurements
1 cm diameter test probe

- Grounded edges:
  $\eta I_{probe} = 3.15\ \Omega\ \square^{-1}\ A$
  Required $\eta < 295\ k\Omega\ \square^{-1}$
  $R = \phi_{probe}/I_{probe} < 94\ k\Omega$

- Eight 0.5 cm tabs:
  $\eta I_{probe} = 2.97\ \Omega\ \square^{-1}\ A$
  Required $\eta < 239\ k\Omega\ \square^{-1}$
  $R = \phi_{probe}/I_{probe} < 80\ k\Omega$

- Eight 1 cm tabs:
  $\eta I_{probe} = 3.31\ \Omega\ \square^{-1}\ A$
  Required $\eta < 345\ k\Omega\ \square^{-1}$
  $R = \phi_{probe}/I_{probe} < 104\ k\Omega$

- Four triangular tabs:
  $\eta I_{probe} = 2.97\ \Omega\ \square^{-1}\ A$
  Required $\eta < 206\ k\Omega\ \square^{-1}$
  $R = \phi_{probe}/I_{probe} < 69\ k\Omega$

- Four 0.635 cm tabs:
  $\eta I_{probe} = 2.82\ \Omega\ \square^{-1}\ A$
  Required $\eta < 167\ k\Omega\ \square^{-1}$
  $R = \phi_{probe}/I_{probe} < 59\ k\Omega$

- Four 1 cm tabs:
  $\eta I_{probe} = 3.23\ \Omega\ \square^{-1}\ A$
  Required $\eta < 215\ k\Omega\ \square^{-1}$
  $R = \phi_{probe}/I_{probe} < 67\ k\Omega$

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Required Resistance Measurements
0.1 cm diameter test probe

- Grounded edges:
  $\eta I_{probe} = 1.496\ \Omega\ \square^{-1}\ A$
  Required $\eta < 295\ k\Omega\ \square^{-1}$
  $R = \phi_{probe}/I_{probe} < 197\ k\Omega$

- Eight 0.5 cm tabs:
  $\eta I_{probe} = 1.454\ \Omega\ \square^{-1}\ A$
  Required $\eta < 239\ k\Omega\ \square^{-1}$
  $R = \phi_{probe}/I_{probe} < 164\ k\Omega$

- Eight 1 cm tabs:
  $\eta I_{probe} = 1.531\ \Omega\ \square^{-1}\ A$
  Required $\eta < 345\ k\Omega\ \square^{-1}$
  $R = \phi_{probe}/I_{probe} < 225\ k\Omega$

- Four triangular tabs:
  $\eta I_{probe} = 1.454\ \Omega\ \square^{-1}\ A$
  Required $\eta < 206\ k\Omega\ \square^{-1}$
  $R = \phi_{probe}/I_{probe} < 142\ k\Omega$

- Four 0.635 cm tabs:
  $\eta I_{probe} = 1.418\ \Omega\ \square^{-1}\ A$
  Required $\eta < 167\ k\Omega\ \square^{-1}$
  $R = \phi_{probe}/I_{probe} < 118\ k\Omega$

- Four 1 cm tabs:
  $\eta I_{probe} = 1.515\ \Omega\ \square^{-1}\ A$
  Required $\eta < 215\ k\Omega\ \square^{-1}$
  $R = \phi_{probe}/I_{probe} < 142\ k\Omega$

Maxwell Technologies

Verification of Maximum Surface Potential By Measurement of Resistance in Laboratory

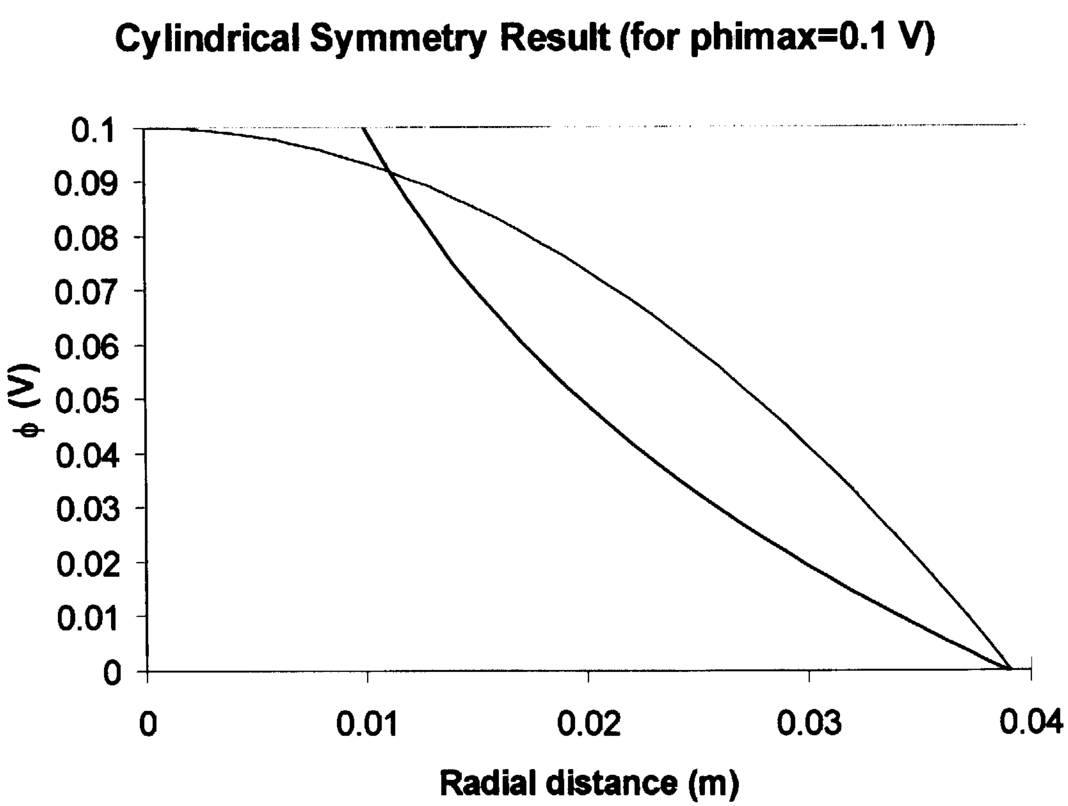
- Results insensitive to the ITO grounding geometry
- Required surface resistivity

  $$\eta \sim 200\ \mathrm{k}\Omega\ \square^{-1}$$

- Measured resistance

  $$R \sim 100\ \mathrm{k}\Omega$$

Potentials for Analytic Results



Maxwell TECHNOLOGIES

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

Maxwell TECHNOLOGIES

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/m^2 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

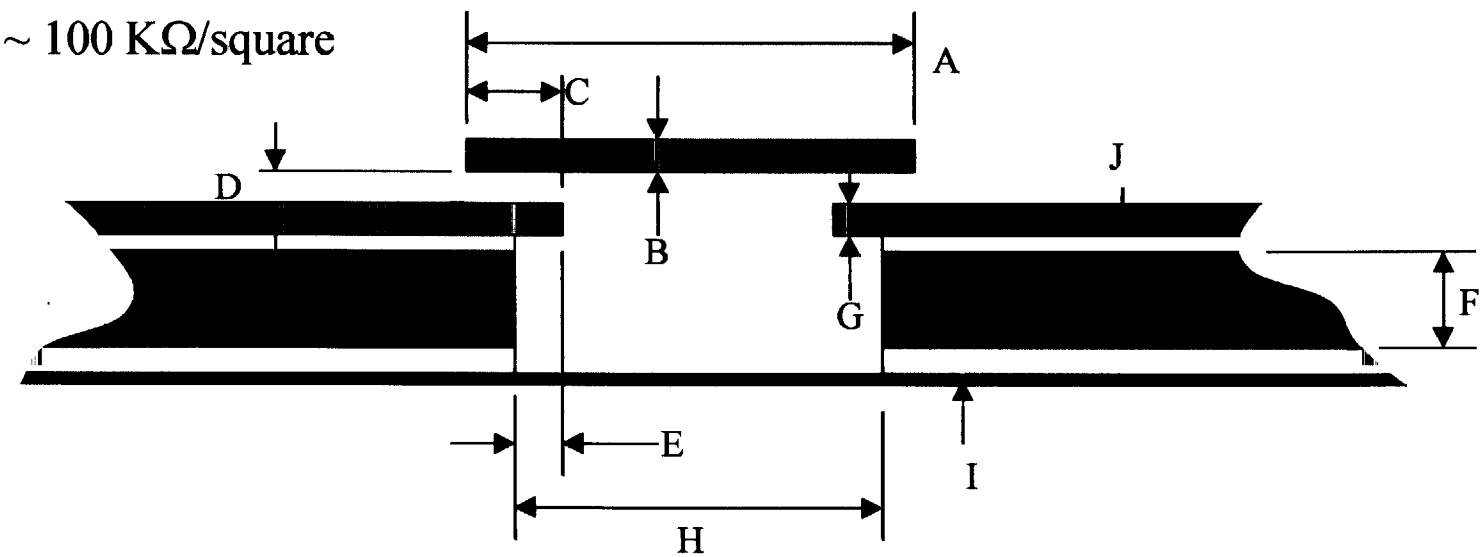
Data for Electrostatic Calculations

- SPM + FSA in plane dimensions
- Cross section through cell stack and FSA

  min and max of all dimensions

  materials

  ITO ~ 100 KΩ/square



A = 0.200 +/- .010
B = 0.020 +/- .002
C = 0.030 +0/-0.010
D = 0.000 +0.020/-0

E = 0.010 +.005/-.000
F = 0.063 +.015/-.000(?)
G = 0.0060 +.0009/-.000
H = 0.160 +/-?

I = 0.007 to 0.010
J = 0.002 to 0.003

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
  - 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 ~ 2000 Ω/square
  - For full edge contact, resistivity required to be less than ~ 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
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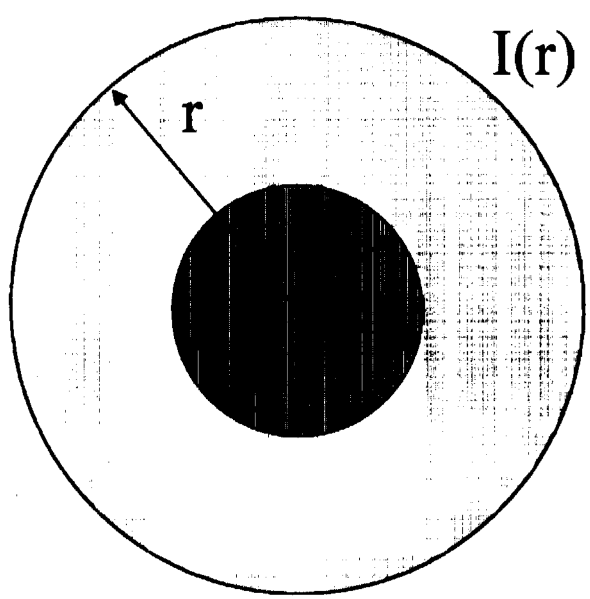

$$E = \eta K$$

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Maxwell TECHNOLOGIES

ITO Tab Current Collection

- Nominal ITO coating

  10^5 Ω/square

  ~ 50 Å

R tab	1.00E-03	m	
j	1.00E-02	A/m2	
eta	1.00E+05	ohm/sq	
I (A)	Vmax	Res eff	r max (m)
1.0E-05	0.4	3.8E+04	0.018
2.0E-05	0.9	4.4E+04	0.025
3.0E-05	1.4	4.7E+04	0.031
4.0E-05	2.0	4.9E+04	0.036
5.0E-05	2.5	5.1E+04	0.040
6.0E-05	3.1	5.2E+04	0.044
7.0E-05	3.7	5.3E+04	0.047
8.0E-05	4.4	5.4E+04	0.050
9.0E-05	5.0	5.5E+04	0.054
1.0E-04	5.6	5.6E+04	0.056

- Increased ITO conductivity

  1000 Ω/square

  ~100 times the thickness

  ~ 0.5 micron (5000 Å)

R tab	1.00E-03	m	
j	1.00E-02	A/m2	
eta	1.00E+03	ohm/sq	
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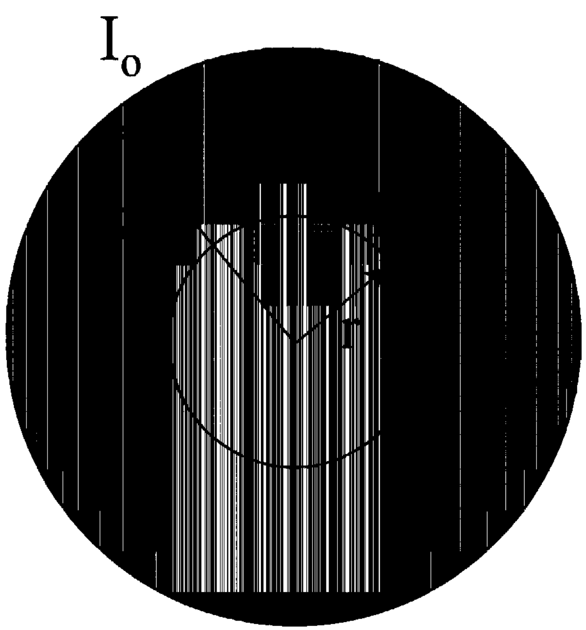
Current Collection by Edge Grounded ITO Coated Coverglass

- 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



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

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$$\varphi(R') = -\frac{\eta}{4\pi}\left\{\frac{\left(I_0 - j\pi R_0^2\right)}{2} ln\left(1 - \frac{I_0}{R_0^2 j\pi}\right) - I_0\right\}$$

Maxwell TECHNOLOGIES

ITO Grounded Edge Results

- Nominal ITO coating
  - coating
    - 10^5 Ω/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
    - $3x10^4$ Ω/square
    - ~ 150 Å thick
  - effective radius 0.04 m
  - current density 10^{-2} A/m^2
  - potential 0.1 V

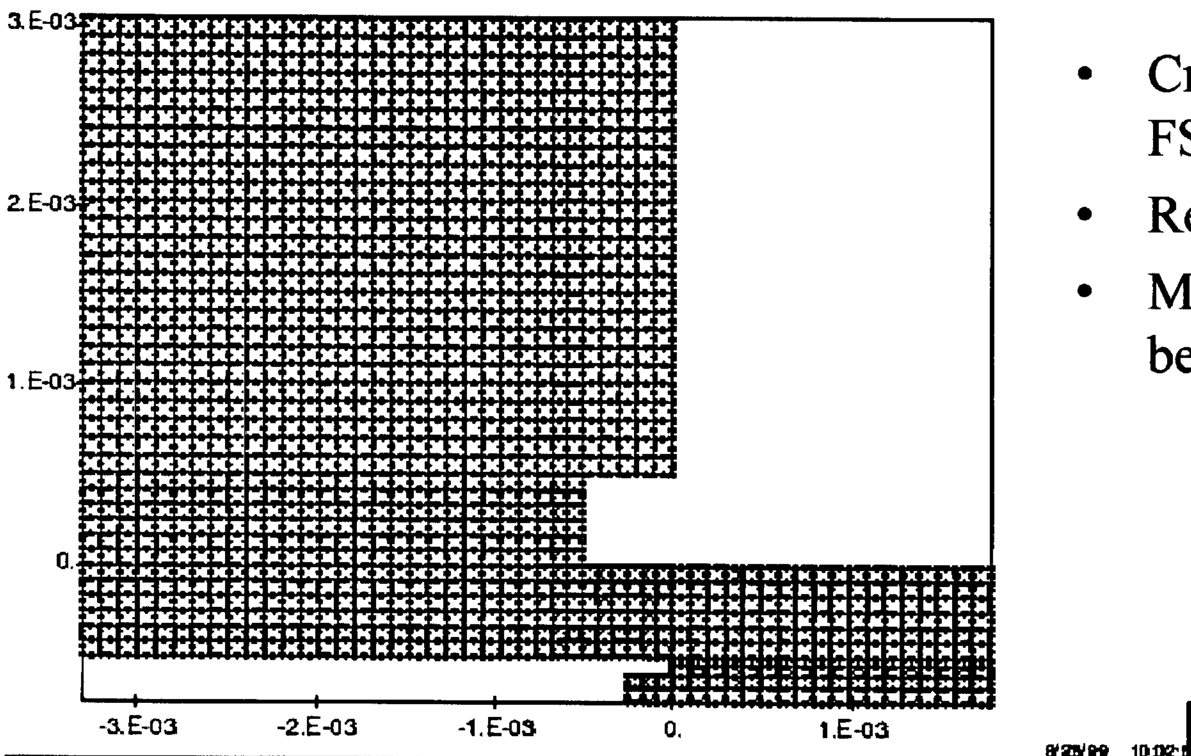
Maxwell TECHNOLOGIES

Electrostatic Field Calculations

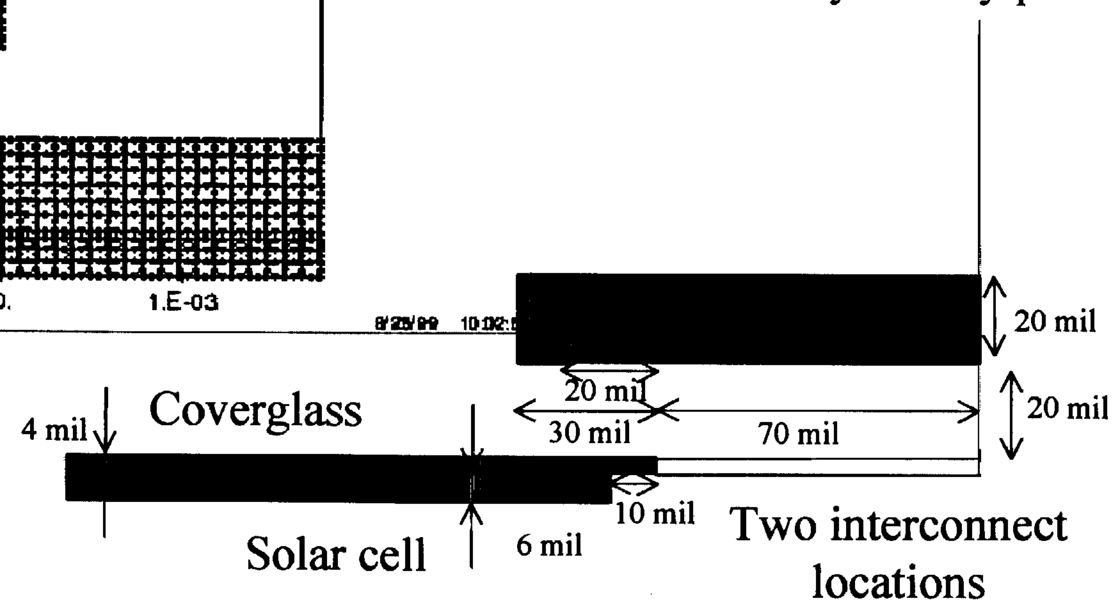
- Potential "leaks out" through gap between coverglass and FSA
- Computer model
    - 2D XY geometry
    - Solves Poisson's equation
    - Currents have not yet been calculated
- Results sensitive to
    - gap height
    - FSA overhang
    - interconnect geometry
        - no interconnect
        - interconnect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

<u>All</u> 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

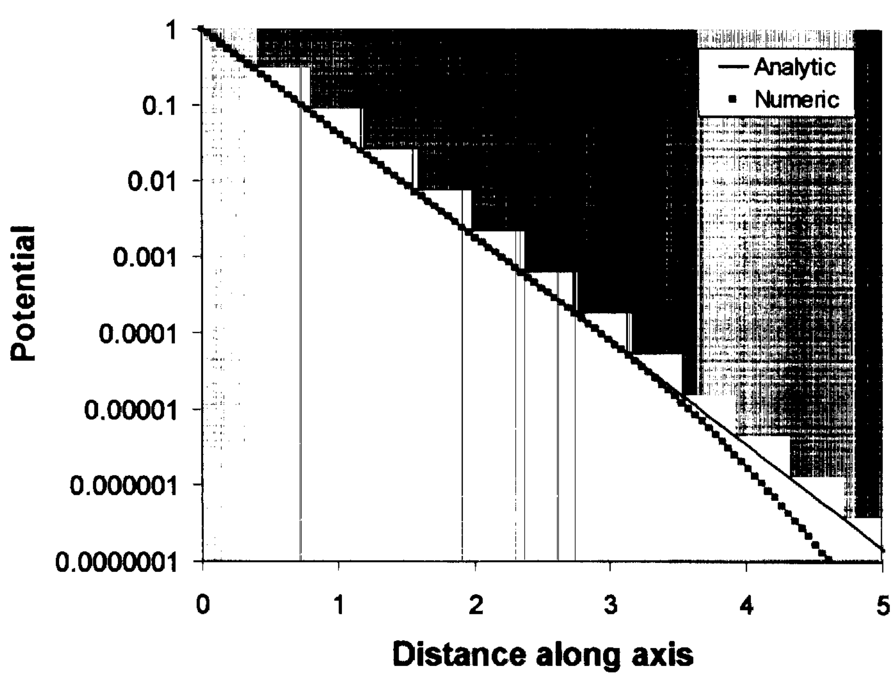


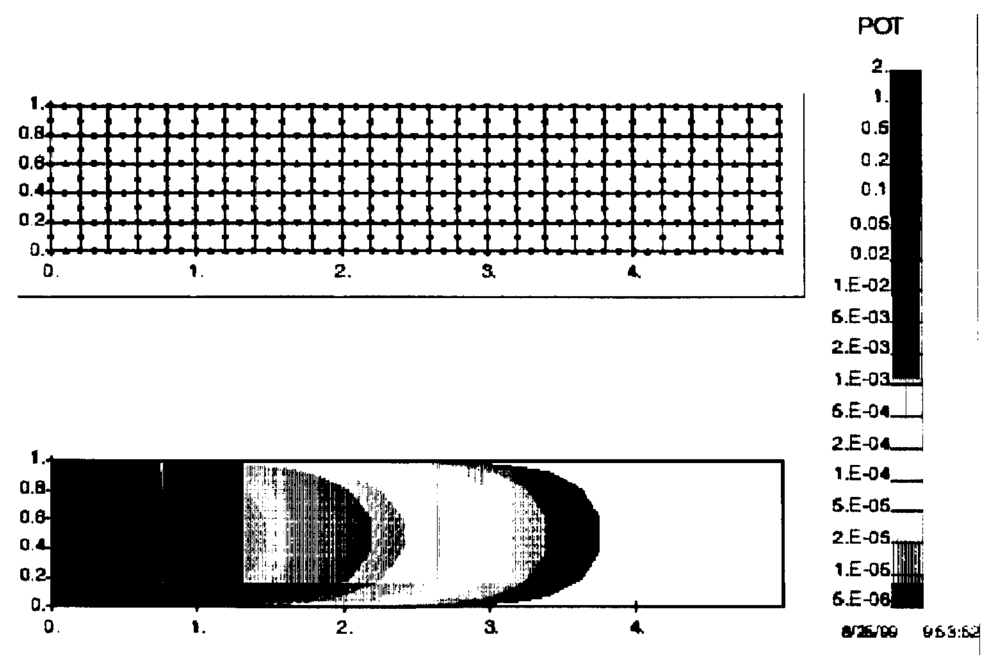
Validation of Numerical Technique

- 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





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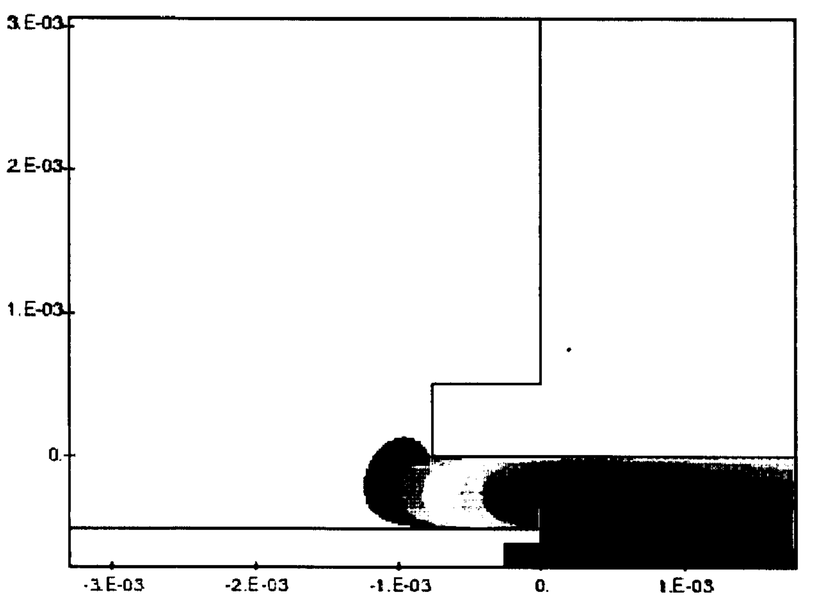
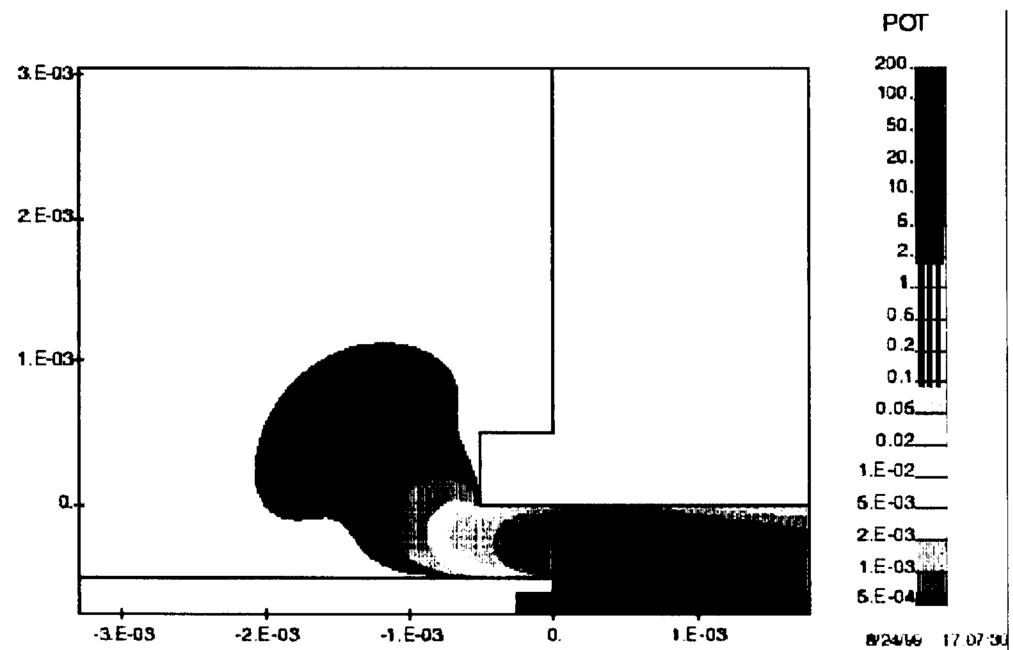


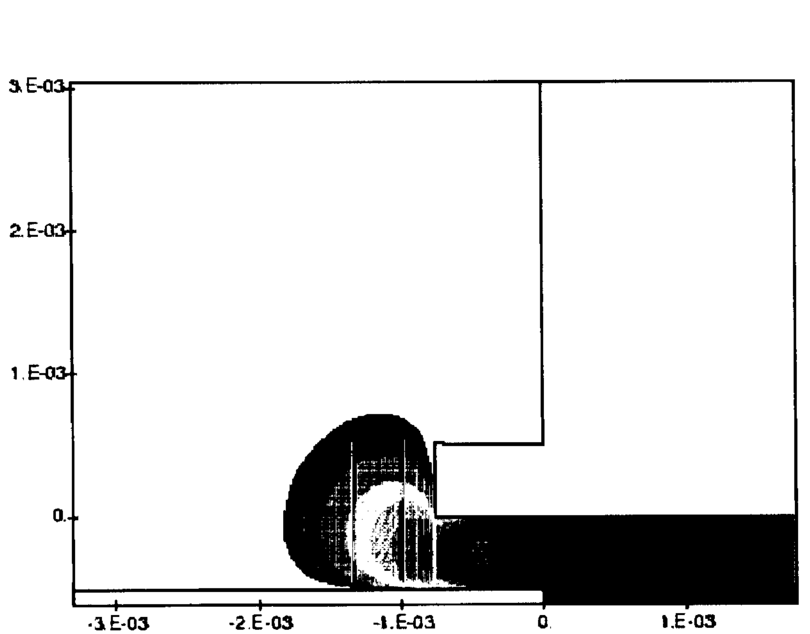
30 mil FSA overhang



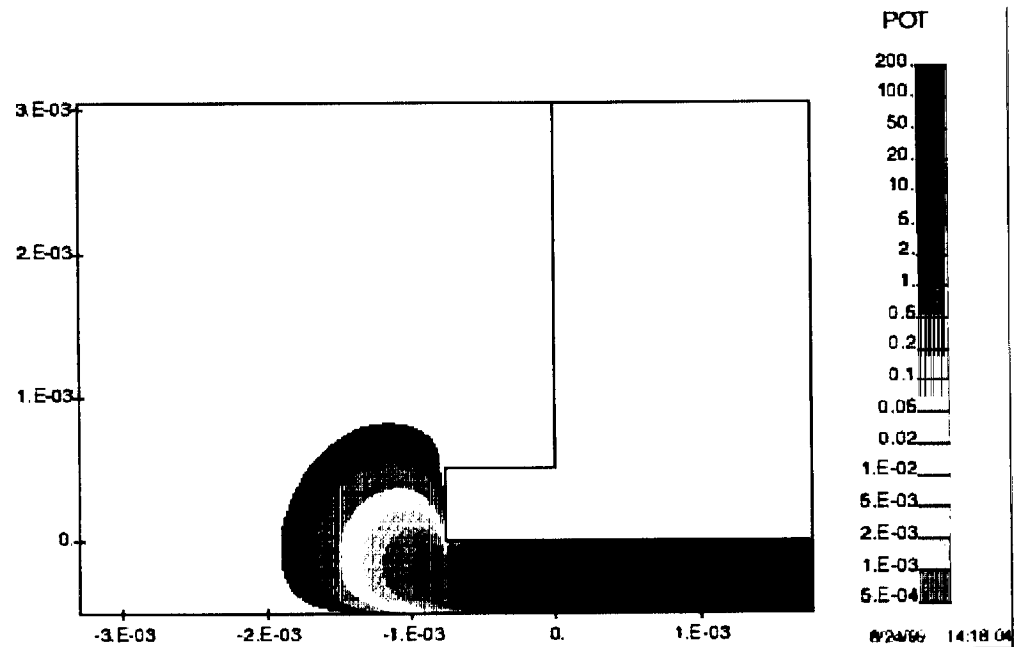
20 mil FSA overhang

30 mil FSA overhang

- Exposed potentials of 0.098 V and 0.175 V.



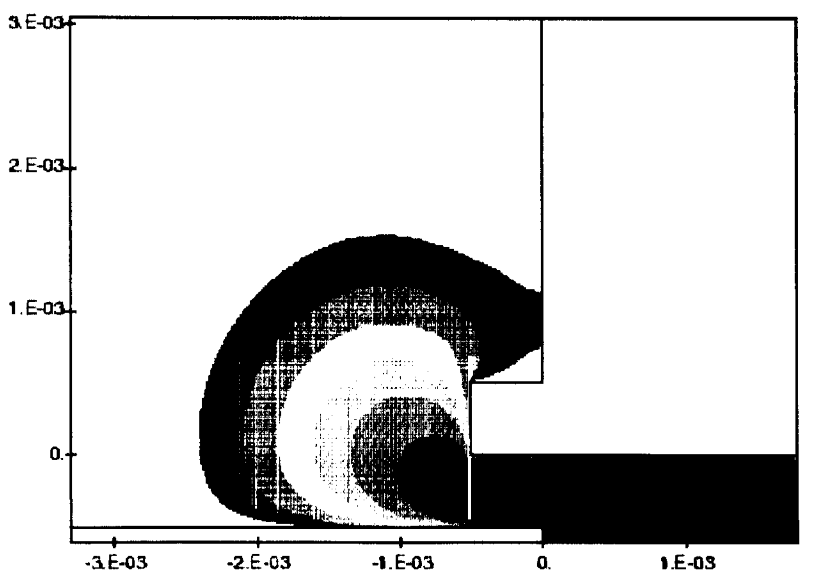
Interconnect at bottom of coverglass



Interconnect at top of coverglass

20 mil FSA overhang

- Exposed potentials of 0.489 V and 0.875 V.



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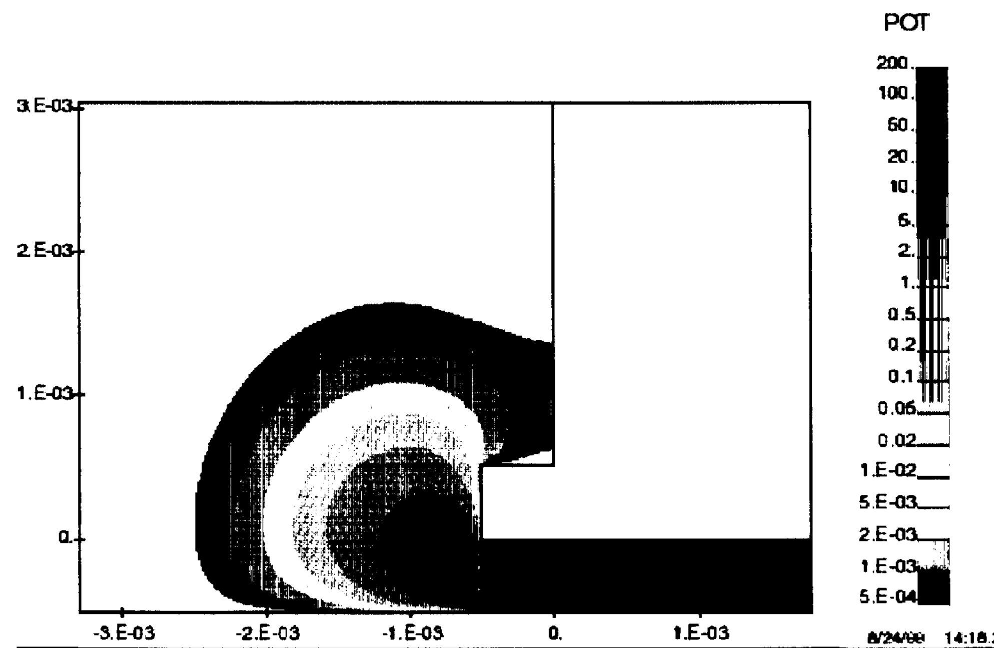


Interconnect at top of coverglass

Maxwell Technologies

Summary of Preliminary Results

- ITO resistivity
    - Question about requirement: Why electron and not ram ion current density?
        - 10^{-2} A/m^2 electron current
        - 10^{-3} 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
        - COMBINED WITH: worst case interconnect height
          worst case overhang
- Particle collection expected to be negligible

Maxwell Technologies

Preliminary Electrostatic Analysis of Electrostatically Clean Solar Panels

Ira Katz

Victoria Davis

August 26, 1999

Maxwell TECHNOLOGIES

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

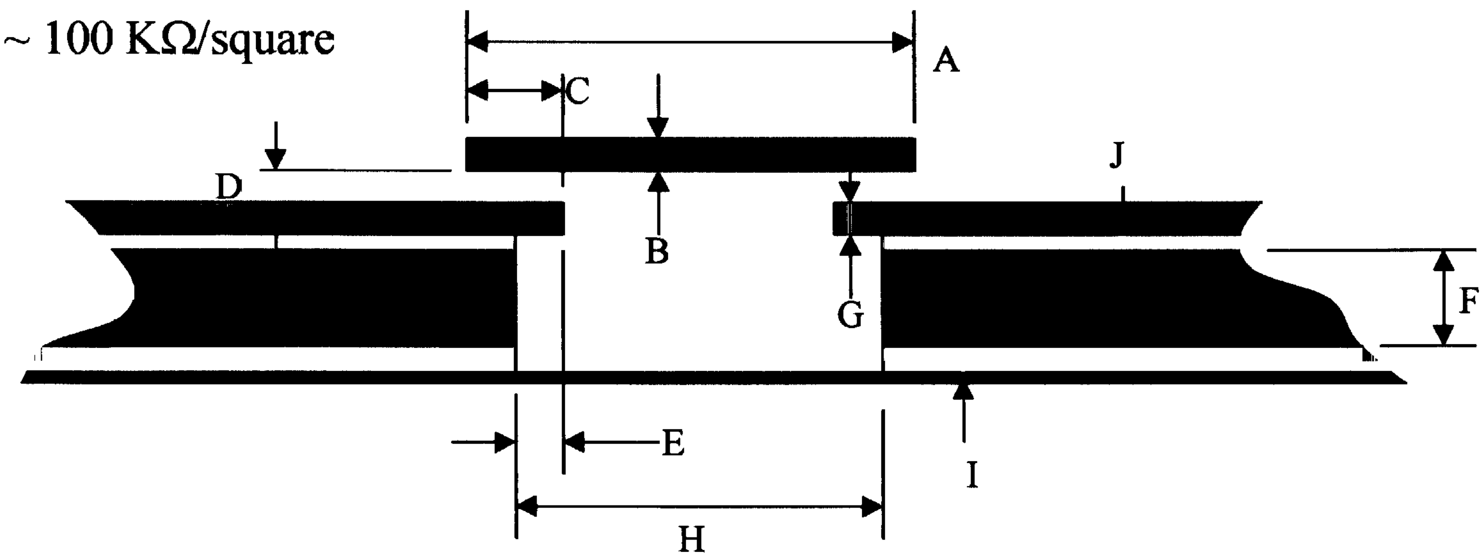
Maxwell TECHNOLOGIES

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/m^2 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



A = 0.200 +/- .010	E = 0.010 +.005/-.000	I = 0.007 to 0.010
B = 0.020 +/- .002	**F = 0.063 +.015/-.000(?)**	J = 0.002 to 0.003
C = 0.030 +0/-0.010	G = 0.0060 +.0009/-.000	
D = 0.000 +0.020/-0	H = 0.160 +/-?	

We assume F = 0.0063

Maxwell Technologies

Potential Drop Across ITO Coated Coverglass

- Two cases
  - small tabs (1mm radius)
  - grounded edges
- Computational approach
  - apply 10^{-2} A/m^2 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 ~ 2000 Ω/square
  - For full edge contact, resistivity required to be less than ~ 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
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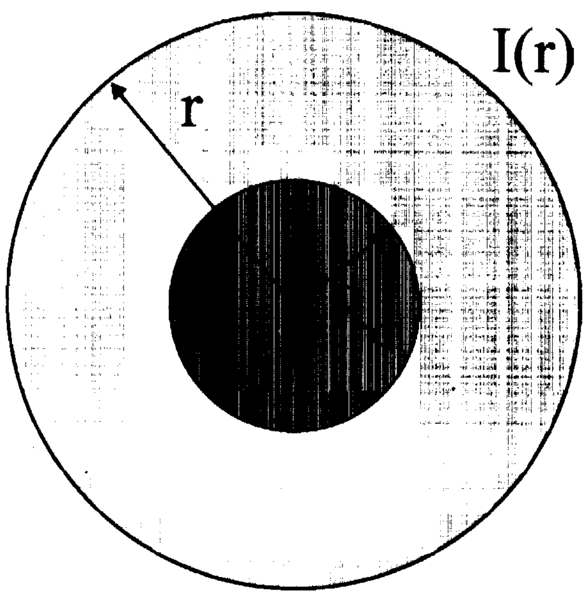

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Maxwell TECHNOLOGIES

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- Nominal ITO coating

  10^5 Ω/square

  ~ 50 Å

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Current Collection by Edge Grounded ITO Coated Coverglass

- ITO coated disk grounded at edge
- Integration from outside in
- Calculation of conducted currents
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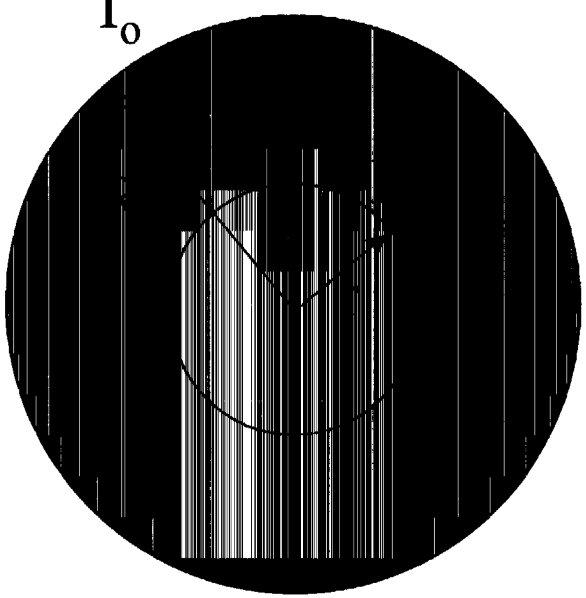
  - Determine maximum current
  - Resistance = Current/voltage

I_o



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ITO Grounded Edge Results

- Nominal ITO coating
  - coating
    - 10^5 Ω/square
    - ~ 50 Å thick
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  - current density 10^{-2} A/m^2
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    - $3x10^4$ Ω/square
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Maxwell TECHNOLOGIES

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- 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
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    - interconnect geometry
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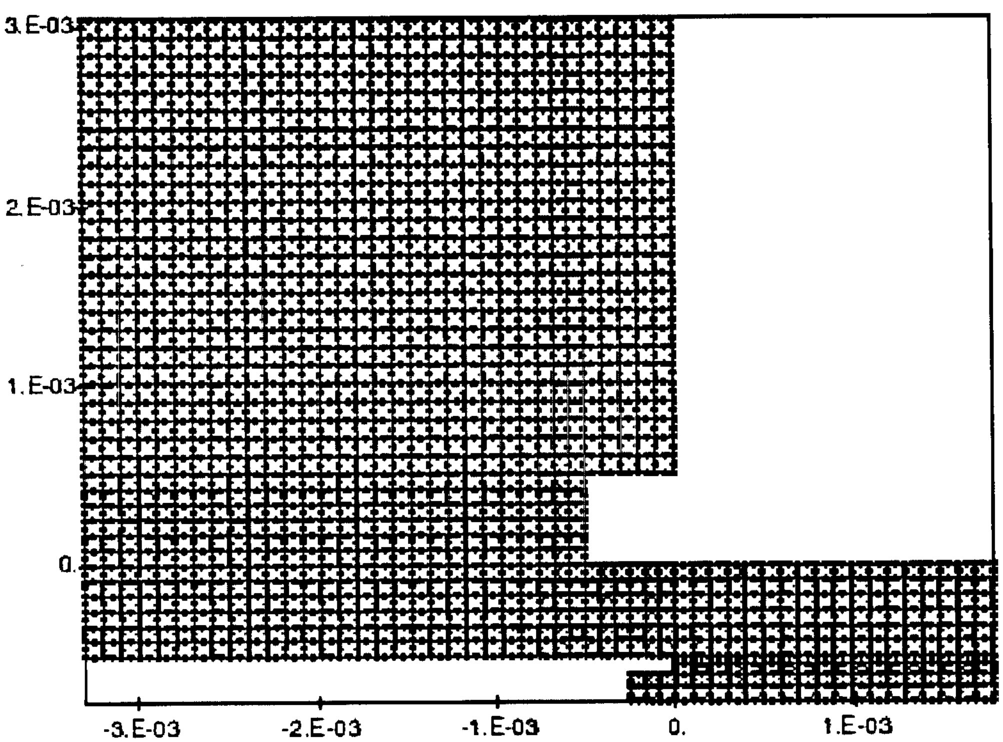
<u>All</u> Calculations Performed With Worst Case Gap Height!

Computational Grid



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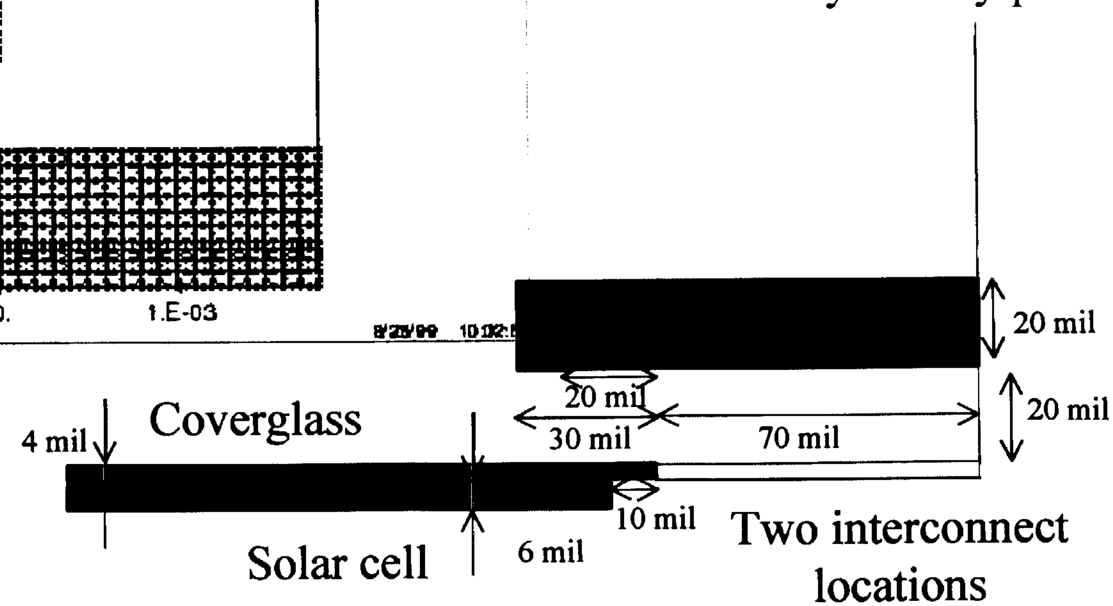

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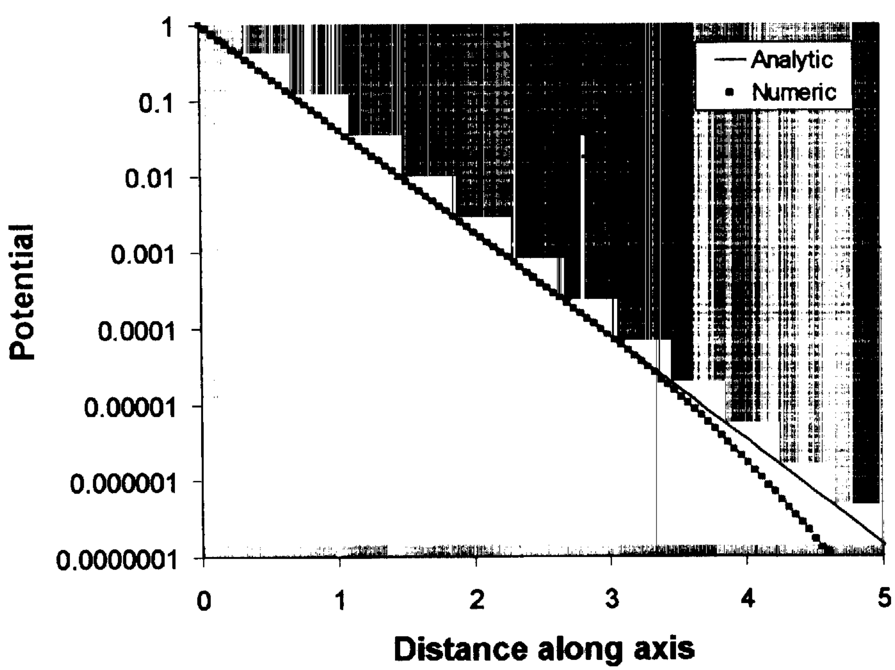

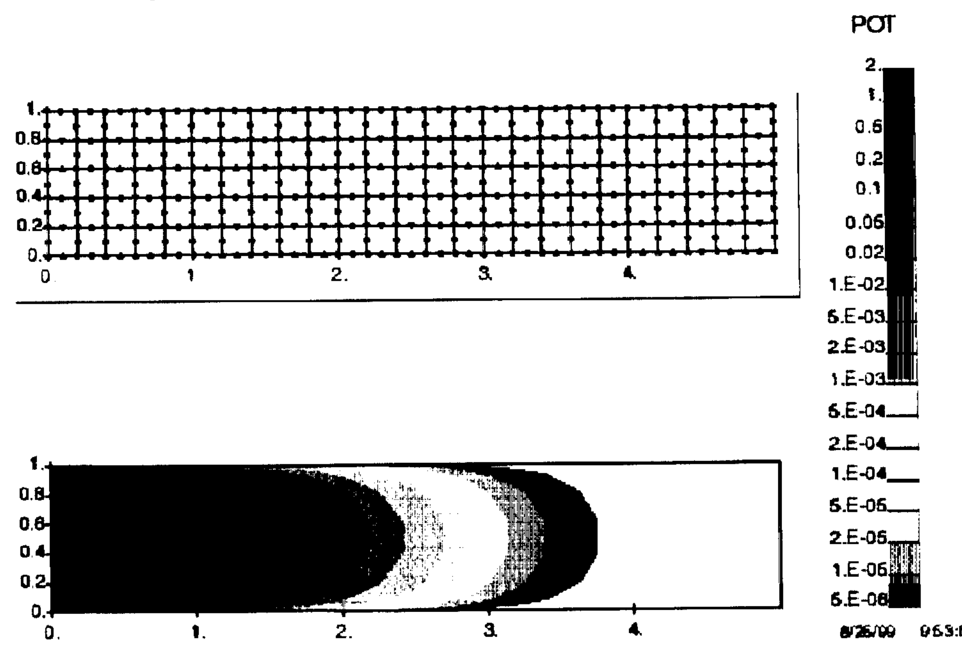

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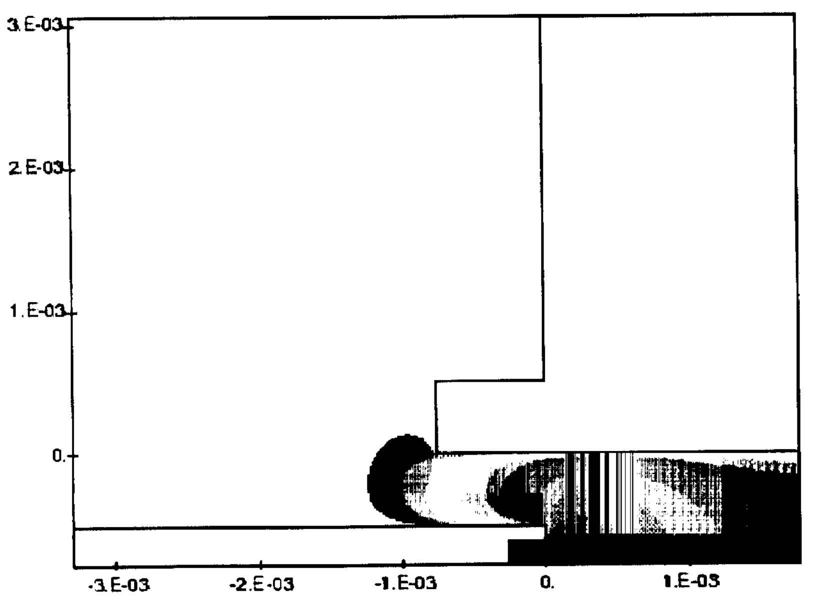
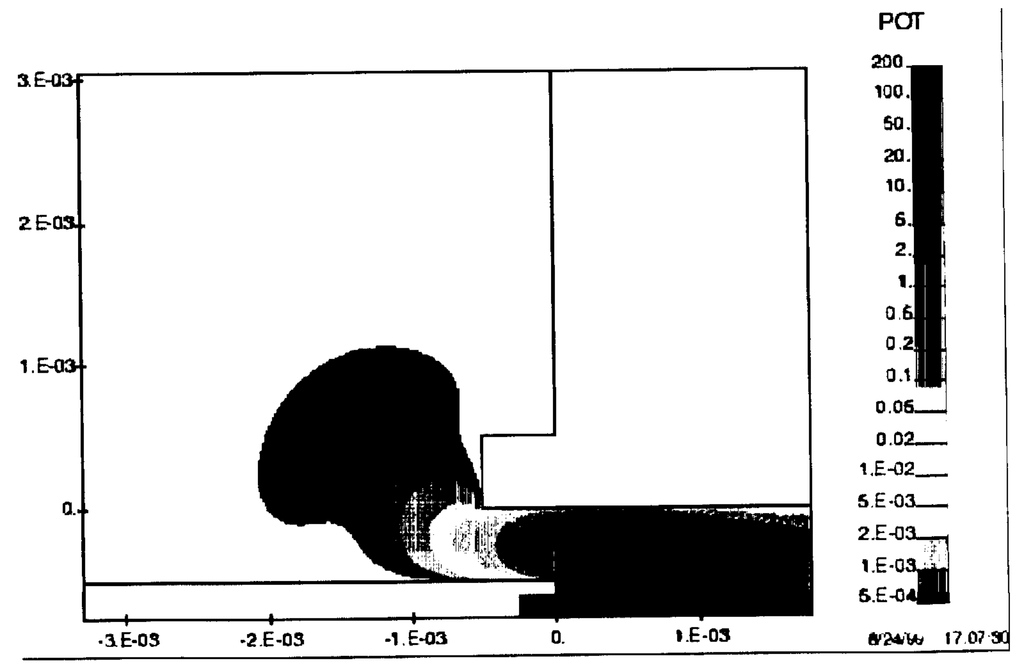


30 mil FSA overhang



20 mil FSA overhang

30 mil FSA overhang

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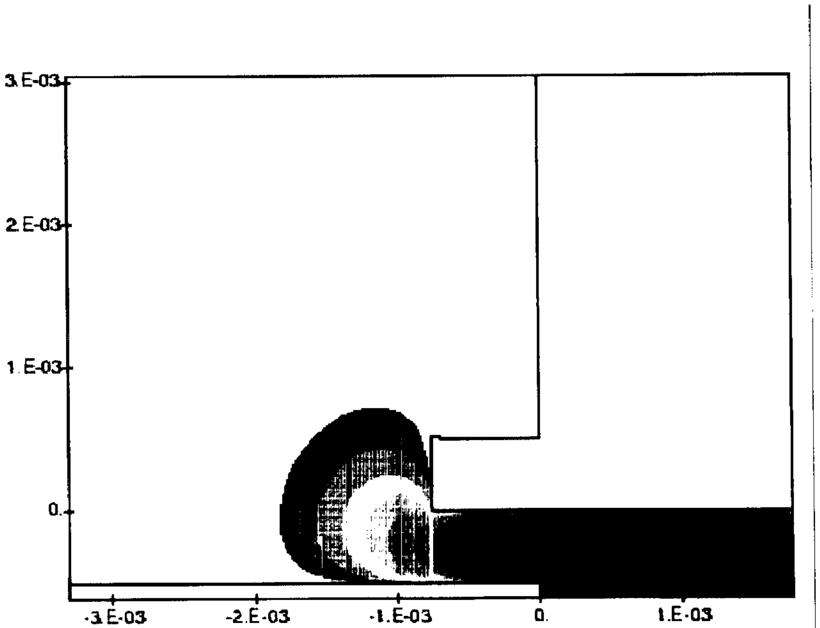
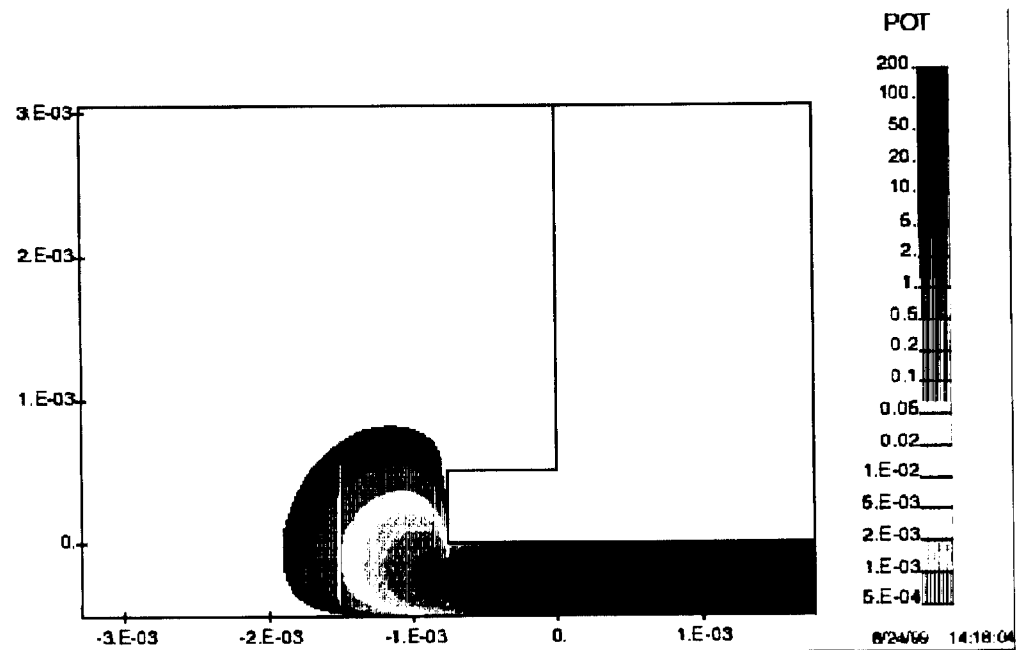


Interconnect at bottom of coverglass



Interconnect at top of coverglass

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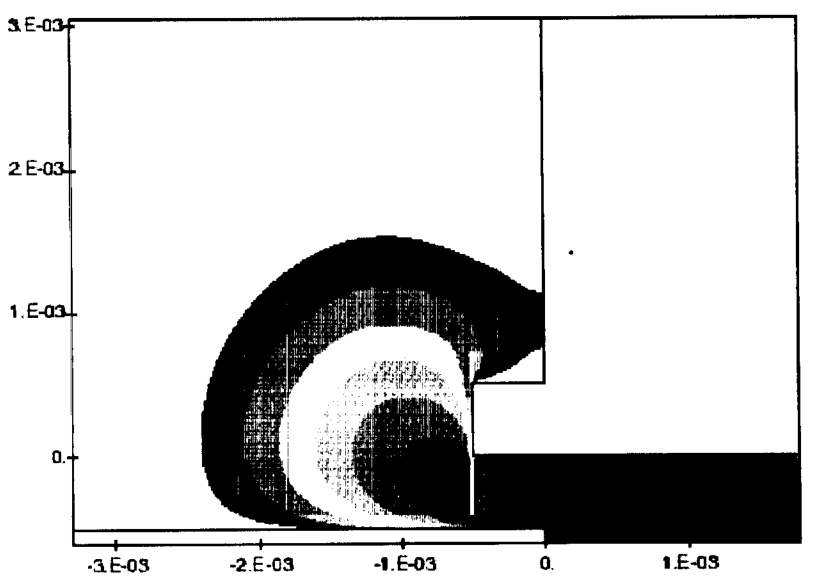
- Exposed potentials of 0.489 V and 0.875 V.



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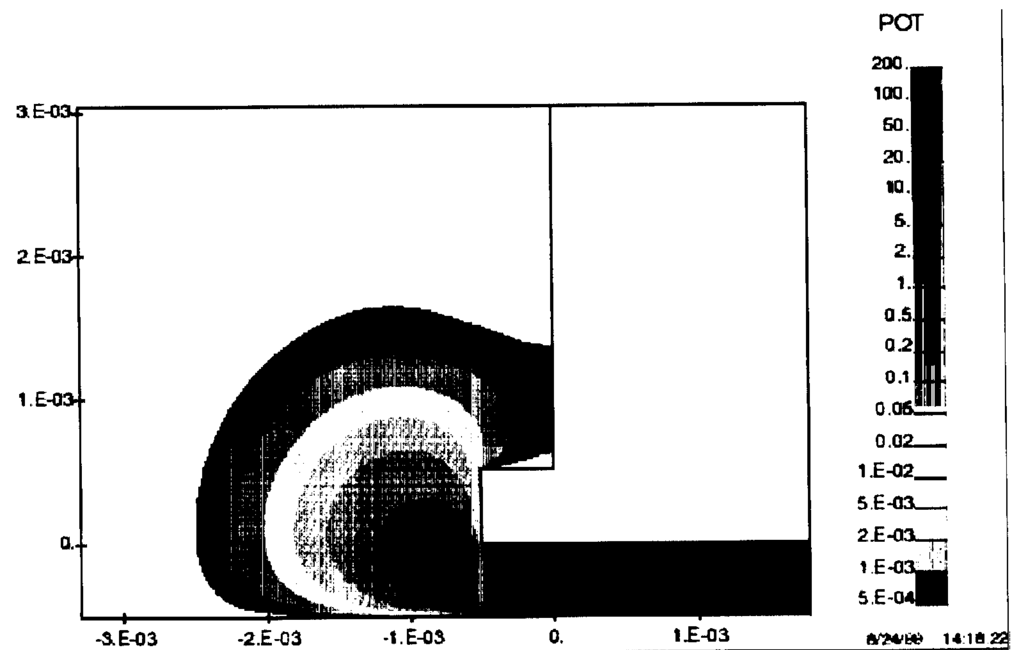

Interconnect at top of coverglass

Maxwell Technologies

Summary of Preliminary Results

- ITO resistivity
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    - 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
    - <u>COMBINED WITH:</u> 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

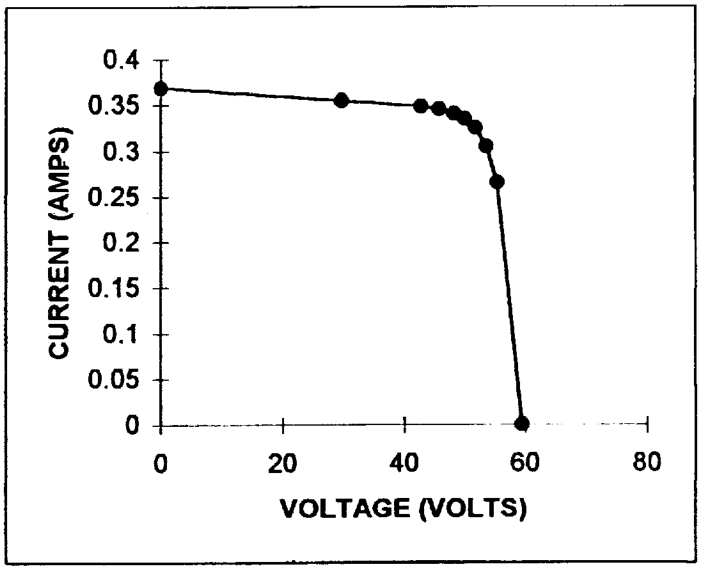
Appendix 3 – Photovoltaic Performance of the ECSA Prototype Panel

ESCA . PROTOFLIGHT PANEL
QUAL COUPON . BEFORE FSA
STRING:A (Tech2 cell)

Test date: 01/06/2000

PARAMETERS	
Calibration Standard:	512-98
No. of Series Cells:	24
No. of Parallel Cells:	1
Area per Cell :	24.312 cm^2
Target Temperature:	28 °C
Voltage Temp Coef.:	-0.24 %VOC / °C

DATA CORRECTED TO 28°C		
VOLTS	AMPS	POWER
59.4600	0.0000	0.0000
55.2960	0.2653	14.6700
53.5340	0.3047	16.3118
51.7360	0.3248	16.8039
49.9720	0.3347	16.7256
48.1580	0.3407	16.4074
45.7680	0.3452	15.7991
42.8180	0.3479	14.8964
29.7220	0.3542	10.5275
0.0000	0.3683	0.0000



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
59.46	0	0
55.296	0.2653	14.670029
53.534	0.3047	16.31181
51.736	0.3248	16.803853
49.972	0.3347	16.725628
48.158	0.3407	16.407431
45.768	0.3452	15.799114
42.818	0.3479	14.896382
29.722	0.3542	10.527532
0	0.3683	0

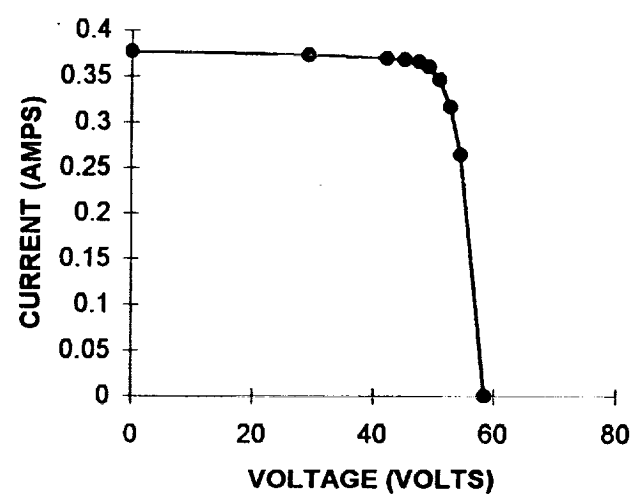
RESULTS		
VOC:	59.460	V
ISC :	0.368	A
PMAX :	16.804	W
VMAX :	51.736	V
IMAX :	0.325	A
FF :	76.733	%
Eff :	21.285	%

ESCA
QUAL COUPON
STRING:B

Test date: 01/06/2000

PARAMETERS	
Calibration Standard:	512-98
No. of Series Cells:	24
No. of Parallel Cells:	1
Area per Cell :	24.312 cm^2
Target Temperature:	28 °C
Voltage Temp Coef.:	-0.24 %VOC / °C

DATA CORRECTED TO 28°C		
VOLTS	AMPS	POWER
58.5230	0.0000	0.0000
54.4340	0.2639	14.3651
52.6720	0.3164	16.6654
50.9140	0.3463	17.6315
49.1520	0.3601	17.6996
47.4130	0.3653	17.3200
45.0640	0.3674	16.5565
42.1150	0.3690	15.5404
29.2660	0.3723	10.8957
0.0000	0.3765	0.0000



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
58.523	0	0
54.434	0.2639	14.365133
52.672	0.3164	16.665421
50.914	0.3463	17.631518
49.152	0.3601	17.699635
47.413	0.3653	17.319969
45.064	0.3674	16.556514
42.115	0.369	15.540435
29.266	0.3723	10.895732
0	0.3765	0

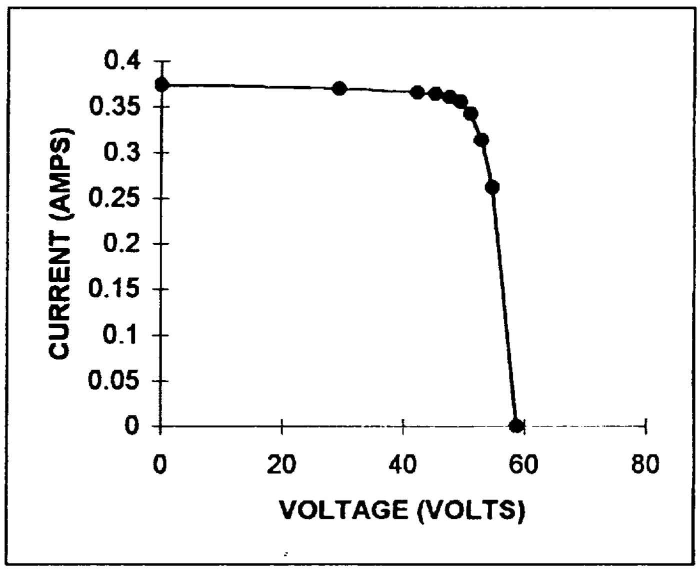
RESULTS		
VOC:	58.523	V
ISC :	0.377	A
PMAX :	17.700	W
VMAX :	49.152	V
IMAX :	0.360	A
FF :	80.329	%
Eff :	22.420	%

ESCA
QUAL COUPON
STRING:C

Test date: 01/06/2000

PARAMETERS	
Calibration Standard:	512-98
No. of Series Cells:	24
No. of Parallel Cells:	1
Area per Cell :	24.312 cm^2
Target Temperature:	28 °C
Voltage Temp Coef.:	-0.24 %VOC / °C

DATA CORRECTED TO 28°C		
VOLTS	AMPS	POWER
58.6860	0.0000	0.0000
54.5730	0.2617	14.2818
52.8110	0.3140	16.5827
51.0560	0.3426	17.4918
49.2910	0.3558	17.5377
47.5210	0.3610	17.1551
45.2040	0.3644	16.4723
42.2530	0.3659	15.4604
29.3300	0.3697	10.8433
0.0000	0.3740	0.0000



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
58.686	0	0
54.573	0.2617	14.281754
52.811	0.314	16.582654
51.056	0.3426	17.491786
49.291	0.3558	17.537738
47.521	0.361	17.155081
45.204	0.3644	16.472338
42.253	0.3659	15.460373
29.33	0.3697	10.843301
0	0.374	0

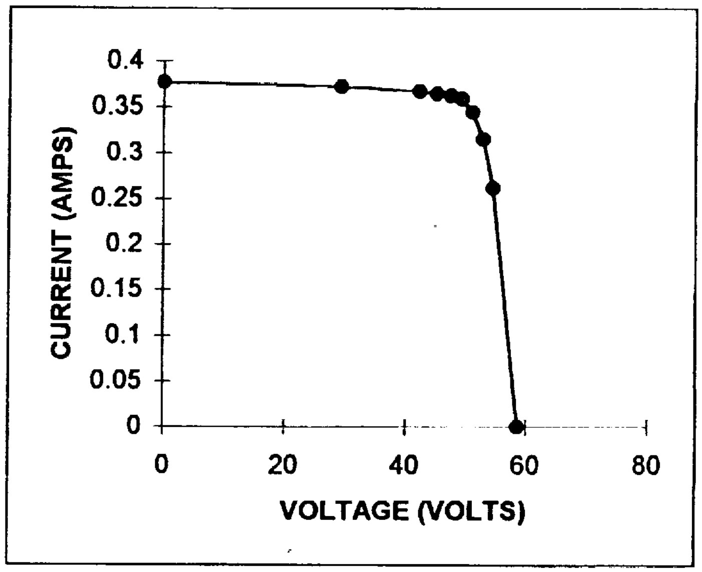
RESULTS		
VOC:	58.686	V
ISC :	0.374	A
PMAX :	17.538	W
VMAX :	49.291	V
IMAX :	0.356	A
FF :	79.904	%
Eff :	22.215	%

ESCA
QUAL COUPON
STRING:D

Test date: 01/06/2000

PARAMETERS	
Calibration Standard:	512-98
No. of Series Cells:	24
No. of Parallel Cells:	1
Area per Cell :	24.312 cm^2
Target Temperature:	28 °C
Voltage Temp Coef.:	-0.24 %VOC / °C

DATA CORRECTED TO 28°C		
VOLTS	AMPS	POWER
58.6220	0.0000	0.0000
54.5320	0.2621	14.2928
52.7680	0.3150	16.6219
51.0030	0.3444	17.5654
49.2430	0.3592	17.6881
47.4770	0.3627	17.2199
45.1190	0.3651	16.4729
42.2140	0.3672	15.5010
29.2830	0.3717	10.8845
0.0000	0.3770	0.0000



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
58.622	0	0
54.532	0.2621	14.292837
52.768	0.315	16.62192
51.003	0.3444	17.565433
49.243	0.3592	17.688086
47.477	0.3627	17.219908
45.119	0.3651	16.472947
42.214	0.3672	15.500981
29.283	0.3717	10.884491
0	0.377	0

RESULTS		
VOC:	58.622	V
ISC :	0.377	A
PMAX :	17.688	W
VMAX :	49.243	V
IMAX :	0.359	A
FF :	80.035	%
Eff :	22.405	%

ESCA

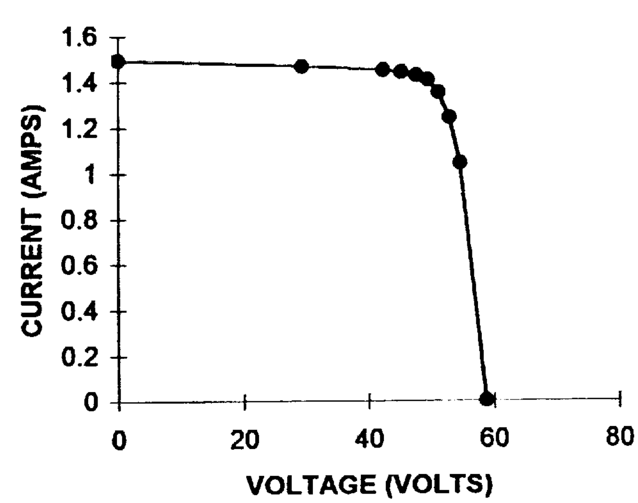
QUAL COUPON

FULL

Test date: 01/06/2000

PARAMETERS	
Calibration Standard:	512-98
No. of Series Cells:	24
No. of Parallel Cells:	4
Area per Cell :	24.312 cm^2
Target Temperature:	28 °C
Voltage Temp Coef.:	-0.24 %VOC / °C

DATA CORRECTED TO 28°C		
VOLTS	AMPS	POWER
58.7750	0.0000	0.0000
54.6570	1.0411	56.9034
52.8980	1.2409	65.6411
51.1280	1.3503	69.0381
49.3740	1.4060	69.4198
47.5980	1.4271	67.9271
45.2380	1.4400	65.1427
42.3100	1.4477	61.2522
29.3690	1.4651	43.0285
0.0000	1.4933	0.0000



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
58.775	0	0
54.657	1.0411	56.903403
52.898	1.2409	65.641128
51.128	1.3503	69.038138
49.374	1.406	69.419844
47.598	1.4271	67.927106
45.238	1.44	65.14272
42.31	1.4477	61.252187
29.369	1.4651	43.028522
0	1.4933	0

RESULTS		
VOC:	58.775	V
ISC :	1.493	A
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)

PROTOFLIGHT PANEL AFTER ESA

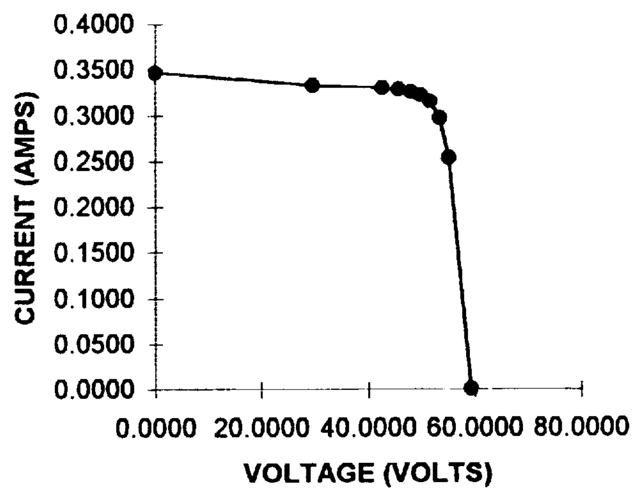
POST-CUSTOMER MODIFICATION

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 cm^2
Target Temperature:	28 °C
Voltage Temp Coef.:	-0.24 %VOC / °C

DATA CORRECTED TO 28°C

VOLTS	AMPS	POWER
59.3500	0.0004	0.0237
55.1970	0.2540	14.0200
53.4360	0.2969	15.8651
51.6330	0.3150	16.2644
49.8690	0.3218	16.0478
48.0670	0.3259	15.6650
45.7130	0.3285	15.0167
42.7210	0.3296	14.0808
29.6680	0.3326	9.8676
0.0100	0.3468	0.0035



DATA CORRECTED TO TARGET TEMPERATURE

VOLTS	AMPS	POWER
59.3500	0.0004	0.0237
55.1970	0.2540	14.0200
53.4360	0.2969	15.8651
51.6330	0.3150	16.2644
49.8690	0.3218	16.0478
48.0670	0.3259	15.6650
45.7130	0.3285	15.0167
42.7210	0.3296	14.0808
29.6680	0.3326	9.8676
0.0100	0.3468	0.0035

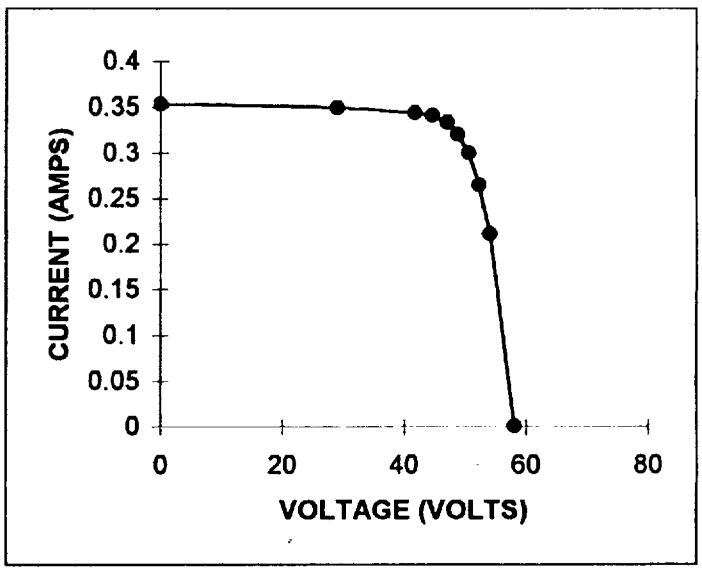
RESULTS		
VOC:	59.350	V
ISC :	0.347	A
PMAX :	16.264	W
VMAX :	51.633	V
IMAX :	0.315	A
FF :	79.020	%
Eff :	20.602	%

ESCA
QUAL COUPON
STRING:B
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 cm^2
Target Temperature:	28 °C
Voltage Temp Coef.:	-0.24 %VOC / °C

DATA CORRECTED TO 28°C		
VOLTS	AMPS	POWER
58.1290	0.0004	0.0233
54.0800	0.2109	11.4055
52.3130	0.2647	13.8473
50.5940	0.2993	15.1428
48.8280	0.3199	15.6201
47.0860	0.3333	15.6938
44.7400	0.3411	15.2608
41.8370	0.3438	14.3836
29.0600	0.3492	10.1478
0.0000	0.3534	0.0000



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
58.129	0.0004	0.0232516
54.08	0.2109	11.405472
52.313	0.2647	13.847251
50.594	0.2993	15.142784
48.828	0.3199	15.620077
47.086	0.3333	15.693764
44.74	0.3411	15.260814
41.837	0.3438	14.383561
29.06	0.3492	10.147752
0	0.3534	0

RESULTS		
VOC:	58.129	V
ISC :	0.353	A
PMAX :	15.694	W
VMAX :	47.086	V
IMAX :	0.333	A
FF :	76.395	%
Eff :	19.879	%

ESCA

QUAL COUPON

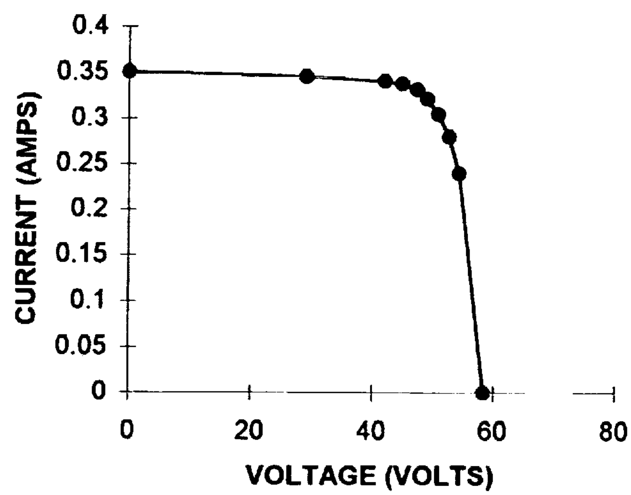
STRING:C

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 cm^2
Target Temperature:	28 °C
Voltage Temp Coef.:	-0.24 %VOC / °C

DATA CORRECTED TO 28°C		
VOLTS	AMPS	POWER
58.3840	0.0003	0.0175
54.2860	0.2403	13.0449
52.5630	0.2801	14.7229
50.8010	0.3046	15.4740
49.0350	0.3217	15.7746
47.3030	0.3322	15.7141
44.9530	0.3384	15.2121
42.0460	0.3410	14.3377
29.1890	0.3460	10.0994
0.0015	0.3512	0.0005



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
58.384	0.0003	0.0175152
54.286	0.2403	13.044926
52.563	0.2801	14.722896
50.801	0.3046	15.473985
49.035	0.3217	15.77456
47.303	0.3322	15.714057
44.953	0.3384	15.212095
42.046	0.341	14.337686
29.189	0.346	10.099394
0.0015	0.3512	0.0005268

RESULTS		
VOC:	58.384	V
ISC :	0.351	A
PMAX :	15.775	W
VMAX :	49.035	V
IMAX :	0.322	A
FF :	76.932	%
Eff : | 19.981 | % |

ESCA

QUAL COUPON

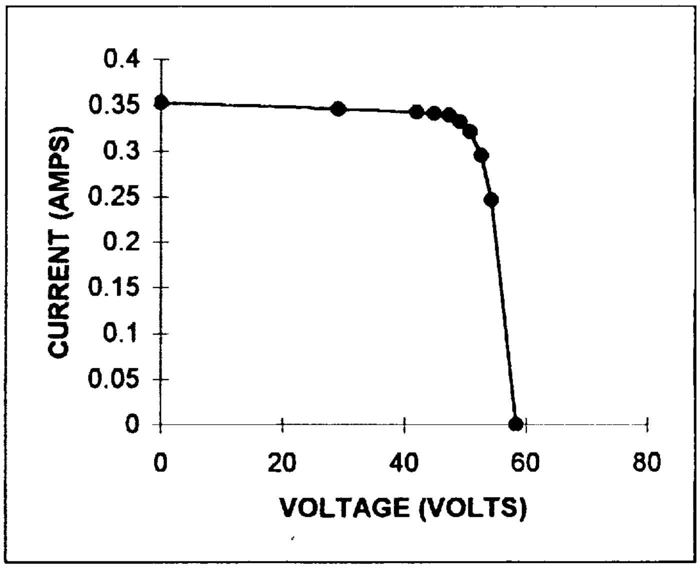
STRING:D

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 cm^2
Target Temperature:	28 °C
Voltage Temp Coef.:	-0.24 %VOC / °C

DATA CORRECTED TO 28°C		
VOLTS	AMPS	POWER
58.3800	0.0002	0.0117
54.3160	0.2464	13.3835
52.5500	0.2948	15.4917
50.7920	0.3207	16.2890
49.0690	0.3320	16.2909
47.2830	0.3388	16.0195
44.9380	0.3411	15.3284
42.0310	0.3423	14.3872
29.1820	0.3461	10.0999
0.0000	0.3530	0.0000



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
58.38	0.0002	0.011676
54.316	0.2464	13.383462
52.55	0.2948	15.49174
50.792	0.3207	16.288994
49.069	0.332	16.290908
47.283	0.3388	16.01948
44.938	0.3411	15.328352
42.031	0.3423	14.387211
29.182	0.3461	10.09989
0	0.353	0

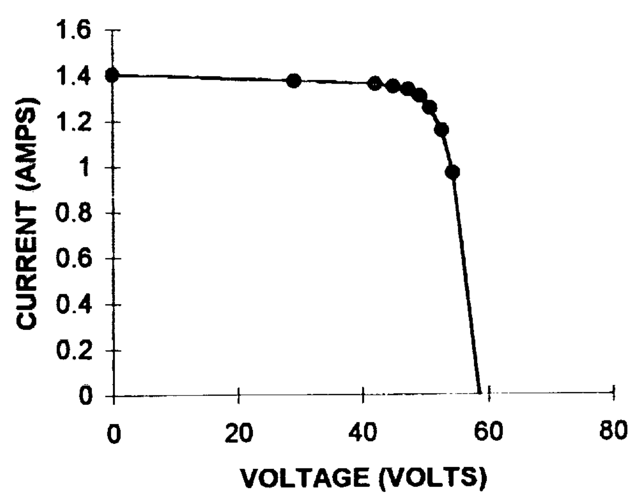
RESULTS		
VOC:	58.380	V
ISC :	0.353	A
PMAX :	16.291	W
VMAX :	49.069	V
IMAX :	0.332	A
FF :	79.051	%
Eff :	20.636	%

ESCA
QUAL COUPON
POST-CUSTOMER MODIFICATION
FULL PANEL

Test date: 01/27/2000

PARAMETERS	
Calibration Standard:	512-98
No. of Series Cells:	24
No. of Parallel Cells:	4
Area per Cell :	24.312 cm^2
Target Temperature:	28 °C
Voltage Temp Coef.:	-0.24 %VOC / °C

DATA CORRECTED TO 28°C		
VOLTS	AMPS	POWER
58.6080	-0.0015	-0.0879
54.5150	0.9694	52.8468
52.7520	1.1541	60.8811
50.9900	1.2530	63.8905
49.2620	1.3059	64.3312
47.5020	1.3325	63.2964
45.1360	1.3486	60.8704
42.2040	1.3575	57.2919
29.3030	1.3737	40.2535
0.0000	1.4035	0.0000



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
58.608	-0.0015	-0.087912
54.515	0.9694	52.846841
52.752	1.1541	60.881083
50.99	1.253	63.89047
49.262	1.3059	64.331246
47.502	1.3325	63.296415
45.136	1.3486	60.87041
42.204	1.3575	57.29193
29.303	1.3737	40.253531
0	1.4035	0

RESULTS		
VOC:	58.608	V
ISC :	1.404	A
PMAX :	64.331	W
VMAX :	49.262	V
IMAX :	1.306	A
FF :	78.208	%
Eff :	20.372	%

ESCA

PRE-HOT FLASH TEST INSIDE THE HOT BOX WITH COVER @ 28°C

QUAL COUPON

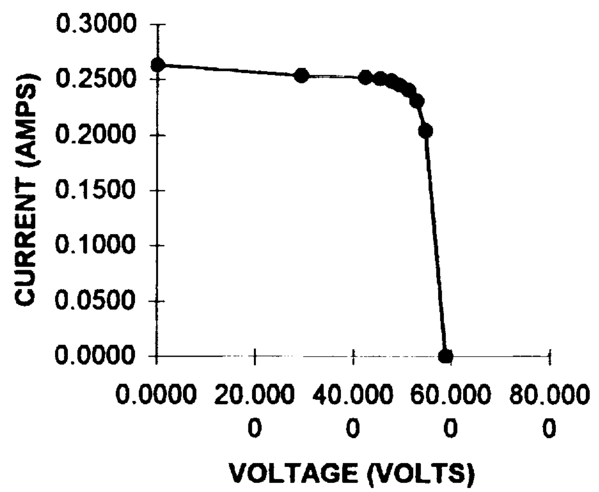
POST-CUSTOMER MODIFICATION

CKT:A

Test date: 01/27/2000

PARAMETERS	
Calibration Standard:	512-98
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		
VOLTS	AMPS	POWER
58.8790	0.0001	0.0059
54.7590	0.2040	11.1708
52.9950	0.2304	12.2100
51.2360	0.2404	12.3171
49.4710	0.2452	12.1303
47.7050	0.2484	11.8499
45.3480	0.2506	11.3642
42.4060	0.2517	10.6736
29.4300	0.2537	7.4664
0.0019	0.2630	0.0005



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
58.8790	0.0001	0.0059
54.7590	0.2040	11.1708
52.9950	0.2304	12.2100
51.2360	0.2404	12.3171
49.4710	0.2452	12.1303
47.7050	0.2484	11.8499
45.3480	0.2506	11.3642
42.4060	0.2517	10.6736
29.4300	0.2537	7.4664
0.0019	0.2630	0.0005

RESULTS		
VOC:	58.8790	V
ISC :	0.2630	A
PMAX :	12.3171	W
VMAX :	51.2360	V
IMAX :	0.2404	A
FF :	79.5415	%
Eff :	15.6020	%

ESCA

PRE-HOT FLASH TEST INSIDE THE HOT BOX WITH COVER @ 28°C

QUAL COUPON

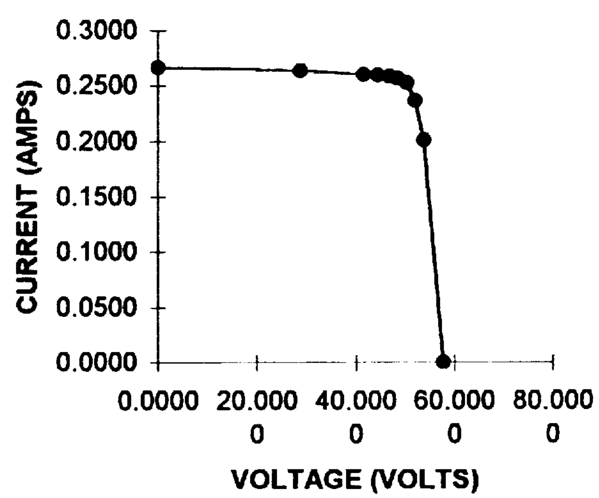
POST-CUSTOMER MODIFICATION

CKT:B

Test date: 01/27/2000

PARAMETERS	
Calibration Standard:	512-98
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		
VOLTS	AMPS	POWER
57.8140	0.0000	0.0000
53.7890	0.2012	10.8223
52.0560	0.2362	12.2956
50.2980	0.2524	12.6952
48.5560	0.2568	12.4692
46.8350	0.2582	12.0928
44.5190	0.2593	11.5438
41.6180	0.2602	10.8290
28.9220	0.2636	7.6238
0.0000	0.2664	0.0000



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
57.8140	0.0000	0.0000
53.7890	0.2012	10.8223
52.0560	0.2362	12.2956
50.2980	0.2524	12.6952
48.5560	0.2568	12.4692
46.8350	0.2582	12.0928
44.5190	0.2593	11.5438
41.6180	0.2602	10.8290
28.9220	0.2636	7.6238
0.0000	0.2664	0.0000

RESULTS		
VOC:	57.8140	V
ISC :	0.2664	A
PMAX :	12.6952	W
VMAX :	50.2980	V
IMAX :	0.2524	A
FF :	82.4276	%
Eff :	16.0809	%

ESCA

PRE-HOT FLASH TEST INSIDE THE HOT BOX WITH COVER @ 28°C

QUAL COUPON

POST-CUSTOMER MODIFICATION

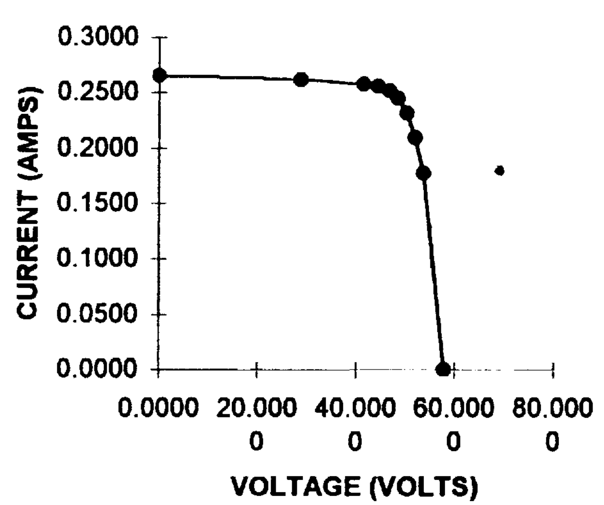
CKT:C

Test date: 01/27/2000

PARAMETERS	
Calibration Standard:	512-98
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

VOLTS	AMPS	POWER
57.8280	0.0000	0.0000
53.7860	0.1780	9.5739
52.0730	0.2098	10.9249
50.3070	0.2314	11.6410
48.5720	0.2448	11.8904
46.8490	0.2519	11.8013
44.5290	0.2560	11.3994
41.6290	0.2576	10.7236
28.8910	0.2619	7.5666
0.0150	0.2653	0.0040



DATA CORRECTED TO TARGET TEMPERATURE

VOLTS	AMPS	POWER
57.8280	0.0000	0.0000
53.7860	0.1780	9.5739
52.0730	0.2098	10.9249
50.3070	0.2314	11.6410
48.5720	0.2448	11.8904
46.8490	0.2519	11.8013
44.5290	0.2560	11.3994
41.6290	0.2576	10.7236
28.8910	0.2619	7.5666
0.0150	0.2653	0.0040

RESULTS		
VOC:	57.8280	V
ISC :	0.2653	A
PMAX :	11.8904	W
VMAX :	48.5720	V
IMAX :	0.2448	A
FF :	77.5036	%
Eff :	15.0615	%

ESCA

PRE-HOT FLASH TEST INSIDE THE HOT BOX WITH COVER @ 28°C

QUAL COUPON

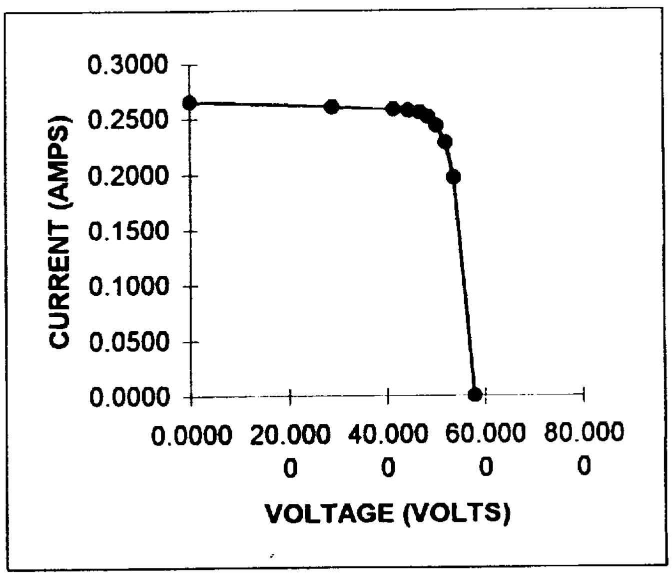
POST-CUSTOMER MODIFICATION

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 cm^2
Target Temperature:	28 °C
Voltage Temp Coef.:	-0.24 %VOC / °C

DATA CORRECTED TO 28°C		
VOLTS	**AMPS**	**POWER**
57.9140	0.0000	0.0000
53.8920	0.1970	10.6167
52.1220	0.2279	11.8786
50.3990	0.2430	12.2470
48.6650	0.2516	12.2441
46.9030	0.2553	11.9743
44.5860	0.2570	11.4586
41.6890	0.2582	10.7641
28.9490	0.2607	7.5470
0.0000	0.2652	0.0000



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	**AMPS**	**POWER**
57.9140	0.0000	0.0000
53.8920	0.1970	10.6167
52.1220	0.2279	11.8786
50.3990	0.2430	12.2470
48.6650	0.2516	12.2441
46.9030	0.2553	11.9743
44.5860	0.2570	11.4586
41.6890	0.2582	10.7641
28.9490	0.2607	7.5470
0.0000	0.2652	0.0000

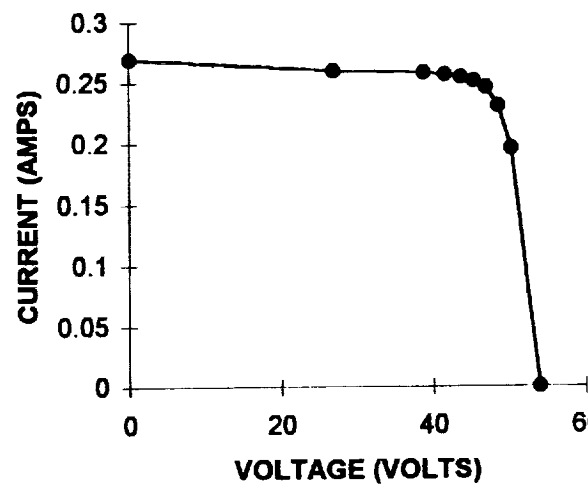
RESULTS		
VOC:	57.9140	V
ISC :	0.2652	A
PMAX :	12.2470	W
VMAX :	50.3990	V
IMAX :	0.2430	A
FF :	79.7391	%
Eff :	15.5131	%

ESCA
HOT-FLASH TEST
QUAL COUPON
CKT:A

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 cm^2
Target Temperature:	70 °C
Voltage Temp Coef.:	-0.24 %VOC / °C
Current Temp Coef:	17.1 uA/cm^2/°C

TEST TEMPERATURE 70 °C		
VOLTS	AMPS	POWER
53.9680	0.0000	0.0000
50.2120	0.1959	9.8365
48.5710	0.2305	11.1956
46.9570	0.2457	11.5373
45.3410	0.2514	11.3987
43.6980	0.2544	11.1168
41.5440	0.2566	10.6602
38.7990	0.2578	10.0024
26.9480	0.2596	6.9957
0.0781	0.2689	0.0210



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
53.968	0	0
50.212	0.1959	9.8365308
48.571	0.2305	11.195616
46.957	0.2457	11.537335
45.341	0.2514	11.398727
43.698	0.2544	11.116771
41.544	0.2566	10.66019
38.799	0.2578	10.002382
26.948	0.2596	6.9957008
0.0781	0.2689	0.0210011

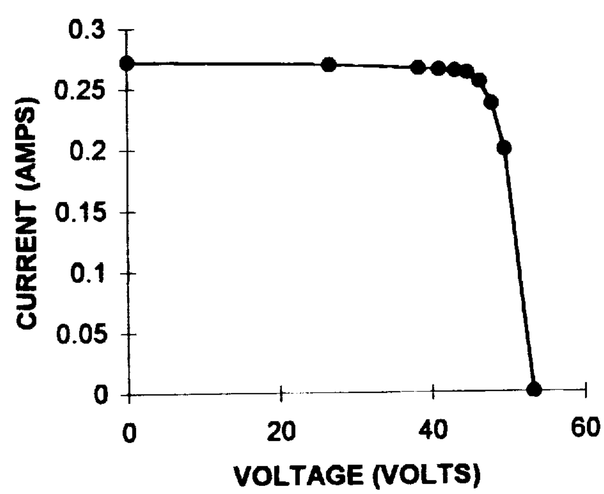
RESULTS		
VOC:	53.9680	V
ISC :	0.2689	A
PMAX :	11.5373	W
VMAX :	46.9570	V
IMAX :	0.2457	A
FF :	79.5021	%
Eff :	14.6142	%

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 cm^2
Target Temperature:	70 °C
Voltage Temp Coef.:	-0.24 %VOC / °C
Current Temp Coef:	17.1 uA/cm^2/°C

TEST TEMPERATURE 70 °C		
VOLTS	AMPS	POWER
53.2740	0.0000	0.0000
49.5360	0.1991	9.8626
47.9290	0.2366	11.3400
46.3600	0.2548	11.8125
44.7550	0.2620	11.7258
43.1450	0.2636	11.3730
41.0450	0.2647	10.8646
38.3490	0.2658	10.1932
26.6430	0.2692	7.1723
0.0791	0.2720	0.0215



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
53.274	0	0
49.536	0.1991	9.8626176
47.929	0.2366	11.340001
46.36	0.2548	11.812528
44.755	0.262	11.72581
43.145	0.2636	11.373022
41.045	0.2647	10.864612
38.349	0.2658	10.193164
26.643	0.2692	7.1722956
0.0791	0.272	0.0215152

RESULTS		
VOC:	53.2740	V
ISC :	0.2720	A
PMAX :	11.8125	W
VMAX :	46.3600	V
IMAX :	0.2548	A
FF :	81.5190	%
Eff :	14.9628	%

ESCA

HOT-FLASH TEST

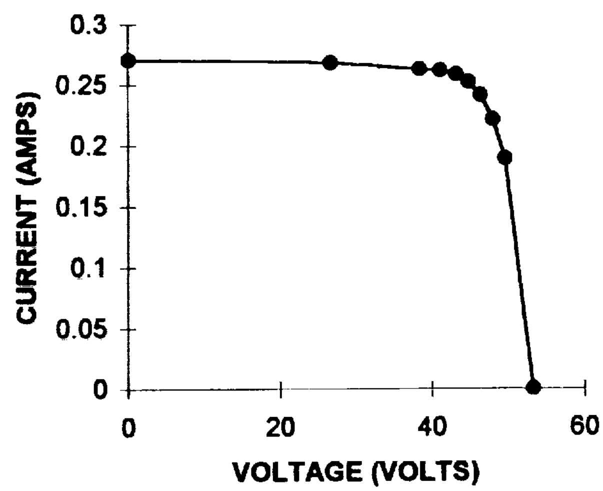
QUAL COUPON

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	cm^2
Target Temperature:	70	°C
Voltage Temp Coef.:	-0.24	%VOC / °C
Current Temp Coef:	17.1	uA/cm^2/°C

TEST TEMPERATURE 70 °C		
VOLTS	AMPS	POWER
53.2890	0.0000	0.0000
49.5790	0.1894	9.3903
47.9670	0.2210	10.6007
46.3600	0.2409	11.1681
44.7560	0.2524	11.2964
43.1440	0.2585	11.1527
41.0340	0.2617	10.7386
38.3420	0.2629	10.0801
26.6360	0.2677	7.1305
0.0892	0.2707	0.0241



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
53.289	0	0
49.579	0.1894	9.3902626
47.967	0.221	10.600707
46.36	0.2409	11.168124
44.756	0.2524	11.296414
43.144	0.2585	11.152724
41.034	0.2617	10.738598
38.342	0.2629	10.080112
26.636	0.2677	7.1304572
0.0892	0.2707	0.0241464

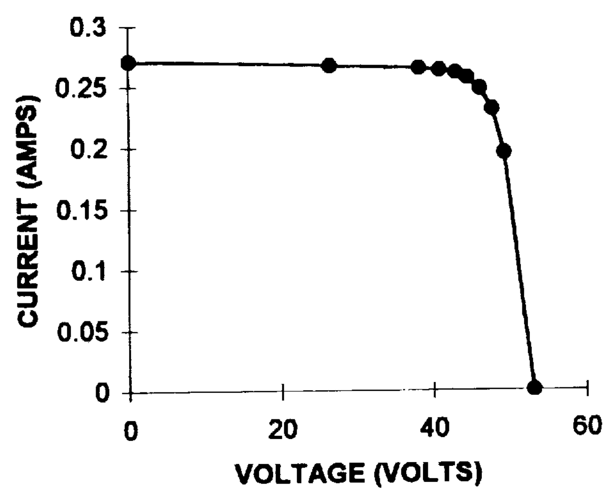
RESULTS		
VOC:	53.2890	V
ISC :	0.2707	A
PMAX :	11.2964	W
VMAX :	44.7560	V
IMAX :	0.2524	A
FF :	78.3096	%
Eff :	14.3091	%

ESCA
HOT-FLASH TEST
QUAL COUPON
CKT:D

Test date: 01/27/2000

PARAMETERS	
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 %VOC / °C
Current Temp Coef:	17.1 uA/cm^2/°C

TEST TEMPERATURE 70 °C		
VOLTS	**AMPS**	**POWER**
53.0750	0.0000	0.0000
49.3450	0.1949	9.6173
47.7790	0.2308	11.0274
46.1690	0.2473	11.4176
44.5480	0.2564	11.4221
42.9940	0.2605	11.1999
40.8650	0.2625	10.7271
38.1970	0.2641	10.0878
26.5100	0.2664	7.0623
0.0793	0.2708	0.0215



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	**AMPS**	**POWER**
53.075	0	0
49.345	0.1949	9.6173405
47.779	0.2308	11.027393
46.169	0.2473	11.417594
44.548	0.2564	11.422107
42.994	0.2605	11.199937
40.865	0.2625	10.727063
38.197	0.2641	10.087828
26.51	0.2664	7.062264
0.0793	0.2708	0.0214744

RESULTS		
VOC:	53.0750	V
ISC :	0.2708	A
PMAX :	11.4221	W
VMAX :	44.5480	V
IMAX :	0.2564	A
FF :	79.4708	%
Eff :	14.4683	%

ESCA

HOT-FLASH TEST

CKT:A @ 70°C

Adjustment made for the lost of the lexan glass

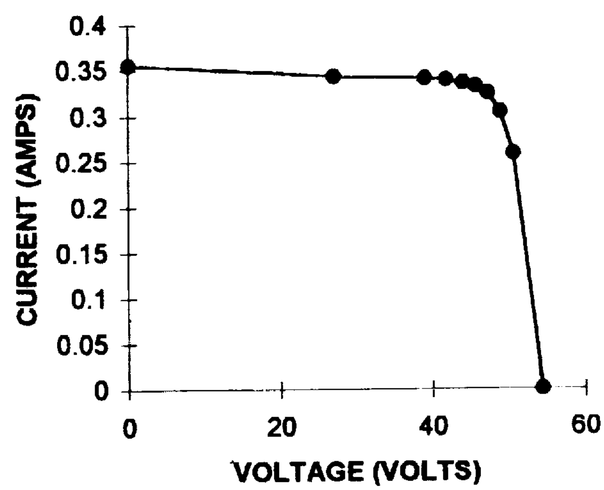
Voltage Ratio: 1.007 Current Ratio:1.32

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 cm^2
Target Temperature:	70 °C
Voltage Temp Coef.:	-0.24 %VOC / °C
Current Temp Coef:	17.1 uA/cm^2/°C

TEST TEMPERATURE 70 °C

VOLTS	AMPS	POWER
54.3458	0.0000	0.0000
50.5635	0.2586	13.0751
48.9110	0.3043	14.8817
47.2857	0.3243	15.3359
45.6584	0.3318	15.1516
44.0039	0.3358	14.7769
41.8348	0.3387	14.1700
39.0706	0.3403	13.2956
27.1366	0.3427	9.2990
0.0786	0.3549	0.0279



DATA CORRECTED TO TARGET TEMPERATURE

VOLTS	AMPS	POWER
54.34578	0	0
50.56348	0.258588	13.0751102
48.911	0.30426	14.88165995
47.2857	0.324324	15.33588704
45.65839	0.331848	15.15164441
44.00389	0.335808	14.77685695
41.83481	0.338712	14.16995149
39.07059	0.340296	13.29556652
27.13664	0.342672	9.298965331
0.078647	0.354948	0.027915489

RESULTS		
VOC:	54.348	V
ISC :	0.355	A
PMAX :	15.338	W
VMAX :	47.286	V
IMAX :	0.324	A
FF :	79.502	%
Eff :	19.426	%

ESCA

HOT-FLASH TEST

CKT:B @ 70°C

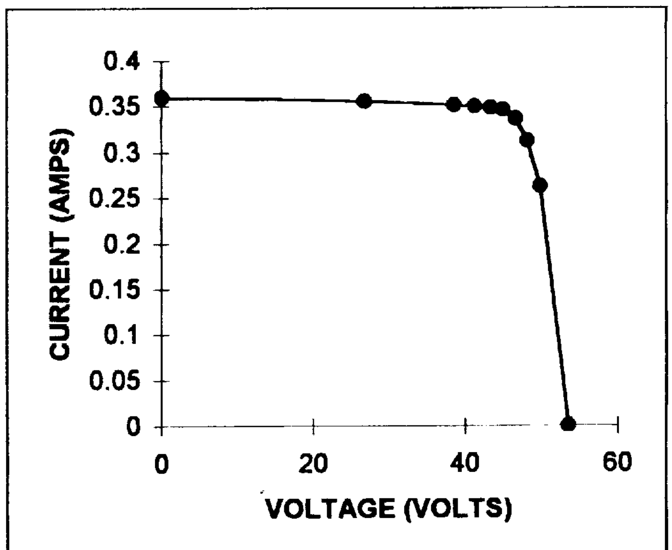
Adjustment made for the lost of the lexan glass

Voltage Ratio: 1.005 Current Ratio:1.32

Test date: 01/27/2000

PARAMETERS	
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 %VOC / °C
Current Temp Coef:	17.1 uA/cm^2/°C

TEST TEMPERATURE 70 °C		
VOLTS	AMPS	POWER
53.5404	0.0000	0.0000
49.7837	0.2628	13.0837
48.1686	0.3123	15.0436
46.5918	0.3363	15.6705
44.9788	0.3458	15.5555
43.3607	0.3480	15.0875
41.2502	0.3494	14.4130
38.5407	0.3509	13.5223
26.7762	0.3553	9.5148
0.0795	0.3590	0.0285



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
53.54037	0	0
49.78368	0.262812	13.08374851
48.16865	0.312312	15.04364586
46.5918	0.336336	15.67049964
44.97878	0.34584	15.55545955
43.36073	0.347952	15.08745099
41.25023	0.349404	14.41299362
38.54075	0.350856	13.52225163
26.77622	0.355344	9.514767343
0.079496	0.35904	0.028542064

RESULTS		
VOC:	53.540	V
ISC :	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

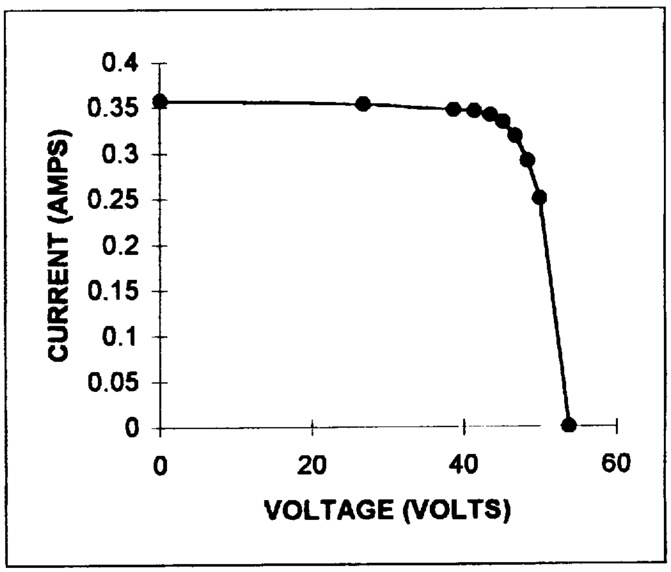
Adjustment made for the lost of the lexan glass

Voltage Ratio: 1.009 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 cm^2
Target Temperature:	70 °C
Voltage Temp Coef.:	-0.24 %VOC / °C
Current Temp Coef:	17.1 uA/cm^2/°C

TEST TEMPERATURE 70 °C		
VOLTS	AMPS	POWER
53.7686	0.0000	0.0000
50.0252	0.2500	12.5067
48.3987	0.2917	14.1189
46.7772	0.3180	14.8746
45.1588	0.3332	15.0455
43.5323	0.3412	14.8541
41.4033	0.3454	14.3025
38.6871	0.3470	13.4255
26.8757	0.3534	9.4969
0.0900	0.3573	0.0322



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
53.7686	0	0
50.02521	0.250008	12.50670295
48.3987	0.29172	14.11886964
46.77724	0.317988	14.87460099
45.1588	0.333168	15.04546841
43.5323	0.34122	14.85409004
41.40331	0.345444	14.30252364
38.68708	0.347028	13.4254993
26.87572	0.353364	9.496913336
0.090003	0.357324	0.032160161

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

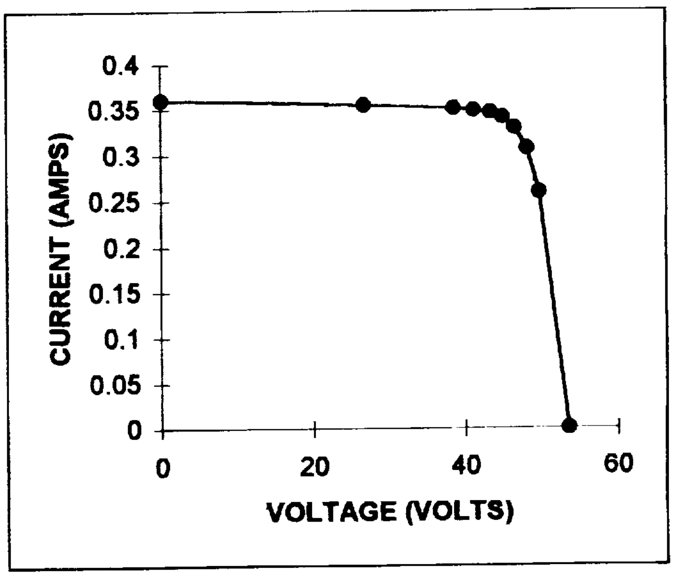
Adjustment made for the lost of the lexan glass

Voltage Ratio: 1.008 Current Ratio:1.33

Test date: 01/27/2000

PARAMETERS	
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 %VOC / °C
Current Temp Coef:	17.1 uA/cm^2/°C

TEST TEMPERATURE 70 °C		
VOLTS	AMPS	POWER
53.4996	0.0000	0.0000
49.7398	0.2592	12.8934
48.1612	0.3070	14.7838
46.5384	0.3289	15.3069
44.9044	0.3410	15.3129
43.3380	0.3465	15.0151
41.1919	0.3491	14.3811
38.5026	0.3513	13.5241
26.7221	0.3543	9.4680
0.0799	0.3602	0.0288



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
53.4996	0	0
49.73976	0.259217	12.89339137
48.16123	0.306964	14.78376442
46.53835	0.328909	15.30688282
44.90438	0.341012	15.3129338
43.33795	0.346465	15.01508354
41.19192	0.349125	14.38112907
38.50258	0.351253	13.52414533
26.72208	0.354312	9.467953609
0.079934	0.360164	0.028789493

RESULTS		
VOC:	53.500	V
ISC :	0.360	A
PMAX :	15.313	W
VMAX :	44.904	V
IMAX :	0.341	A
FF :	79.471	%
Eff :	19.397	%

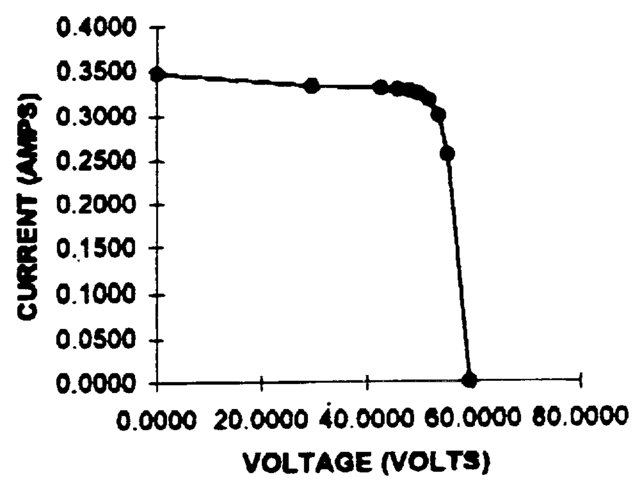
ESCA
QUAL COUPON
STRING:A (Tech2 cell)
POST-ACOUSTIC TEST

Test date: 01/31/2000

PARAMETERS	
Calibration Standard:	612-98
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

VOLTS	AMPS	POWER
59.3810	-0.0001	-0.0059
55.2440	0.2548	14.0762
53.4430	0.2986	15.9581
51.6800	0.3168	16.3722
49.9230	0.3234	16.1451
48.1050	0.3271	15.7351
45.7420	0.3286	15.0308
42.7710	0.3295	14.0930
29.6760	0.3327	9.8732
0.0043	0.3467	0.0015



DATA CORRECTED TO TARGET TEMPERATURE

VOLTS	AMPS	POWER
59.3810	-0.0001	-0.0059
55.2440	0.2548	14.0762
53.4430	0.2986	15.9581
51.6800	0.3168	16.3722
49.9230	0.3234	16.1451
48.1050	0.3271	15.7351
45.7420	0.3286	15.0308
42.7710	0.3295	14.0930
29.6760	0.3327	9.8732
0.0043	0.3467	0.0015

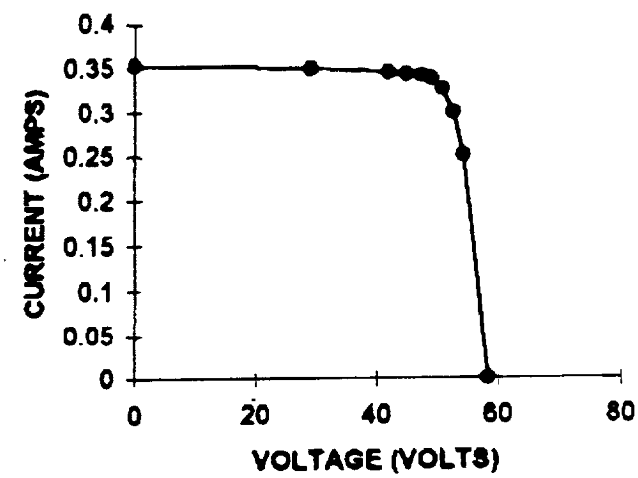
RESULTS		
VOC:	59.381	V
ISC :	0.347	A
PMAX :	16.372	W
VMAX :	51.680	V
IMAX :	0.317	A
FF :	79.525	%
Eff :	20.739	%

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 cm^2
Target Temperature:	28 °C
Voltage Temp Coef.:	-0.24 %VOC / °C

DATA CORRECTED TO 28°C		
VOLTS	AMPS	POWER
58.3560	-0.0001	-0.0058
54.2850	0.2508	13.6147
52.5830	0.2997	15.7531
50.7960	0.3265	16.5849
49.0340	0.3384	16.5931
47.2940	0.3417	16.1604
44.9250	0.3435	15.4317
41.9980	0.3455	14.5103
29.1810	0.3493	10.1929
0.0000	0.3530	0.0000



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
58.356	-0.0001	-0.005836
54.285	0.2508	13.614678
52.583	0.2997	15.753131
50.796	0.3265	16.584894
49.034	0.3384	16.593106
47.294	0.3417	16.16036
44.925	0.3435	15.431738
41.998	0.3455	14.510309
29.181	0.3493	10.192923
0	0.353	0

RESULTS		
VOC:	58.356	V
ISC :	0.353	A
PMAX :	16.593	W
VMAX :	49.034	V
IMAX :	0.338	A
FF :	80.550	%
Eff : | 21.018 | % |

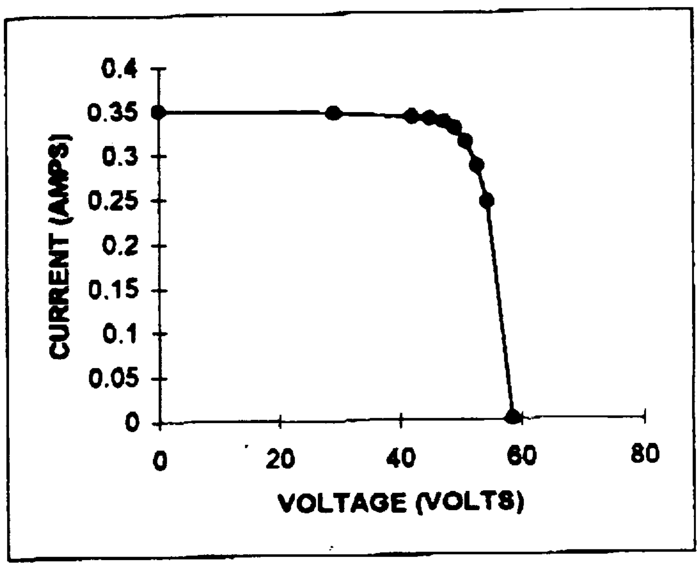
ESCA
QUAL COUPON
STRING:C
POST-ACOUSTIC TEST

Test date: 01/31/2000

PARAMETERS	
Calibration Standard:	512-38
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

VOLTS	AMPS	POWER
58.4880	-0.0001	-0.0058
54.4000	0.2436	13.2518
52.6660	0.2844	14.9782
50.9080	0.3115	15.8578
49.1460	0.3279	16.1150
47.3620	0.3351	15.8710
45.0590	0.3387	15.2615
42.1090	0.3408	14.3507
29.2210	0.3459	10.1075
0.0000	0.3504	0.0000



DATA CORRECTED TO TARGET TEMPERATURE

VOLTS	AMPS	POWER
58.488	-0.0001	-0.005849
54.4	0.2436	13.25184
52.666	0.2844	14.97821
50.908	0.3115	15.857842
49.146	0.3279	16.114973
47.362	0.3351	15.871006
45.059	0.3387	15.261483
42.109	0.3408	14.350747
29.221	0.3459	10.107544
0	0.3504	0

RESULTS		
VOC:	58.488	V
ISC :	0.350	A
PMAX :	16.115	W
VMAX :	49.146	V
IMAX :	0.328	A
FF :	78.632	%
Eff : | 20.413 | % |

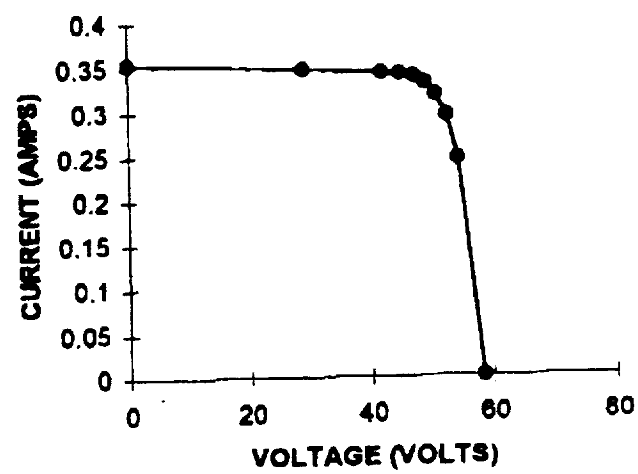
ESCA
QUAL COUPON
STRING:D
POST-ACOUSTIC TEST

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 cm^2
Target Temperature:	28 °C
Voltage Temp Coef.:	-0.24 %VOC / °C

DATA CORRECTED TO 28°C

VOLTS	AMPS	POWER
58.4320	-0.0002	-0.0117
54.3610	0.2447	13.3021
52.6010	0.2935	15.4384
50.8400	0.3165	16.0909
49.1150	0.3299	16.2030
47.3310	0.3378	15.9884
44.9710	0.3407	15.3216
42.0770	0.3420	14.3903
29.2250	0.3463	10.1206
0.0000	0.3534	0.0000



DATA CORRECTED TO TARGET TEMPERATURE

VOLTS	AMPS	POWER
58.432	-0.0002	-0.011686
54.361	0.2447	13.302137
52.601	0.2935	15.438394
50.84	0.3165	16.09086
49.115	0.3299	16.203039
47.331	0.3378	15.988412
44.971	0.3407	15.32162
42.077	0.342	14.390334
29.225	0.3463	10.120618
0	0.3534	0

RESULTS		
VOC:	58.432	V
ISC :	0.353	A
PMAX :	16.203	W
VMAX :	49.115	V
IMAX :	0.330	A
FF :	78.466	%
Eff :	20.524	%

ESCA

QUAL COUPON

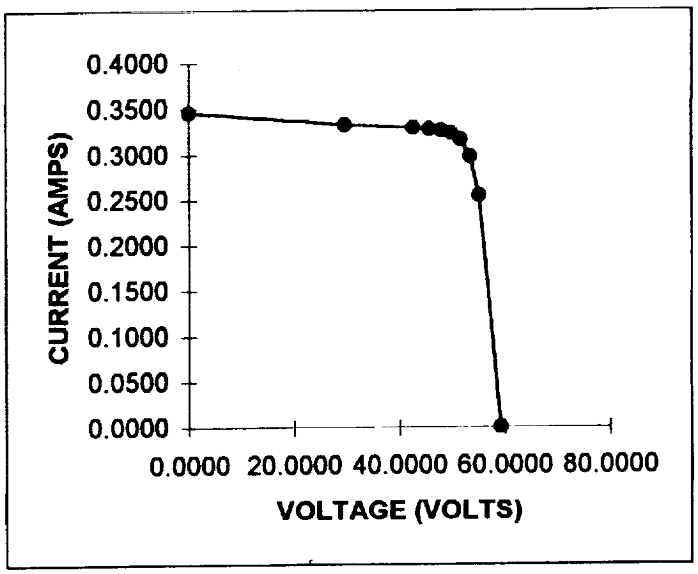
STRING:A (Tech2 cell)

POST-ENVIRONMENTAL

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:	28 °C
Voltage Temp Coef.:	-0.24 %VOC / °C

DATA CORRECTED TO 28°C		
VOLTS	AMPS	POWER
59.3490	-0.0001	-0.0059
55.1990	0.2548	14.0647
53.4370	0.2974	15.8922
51.6360	0.3166	16.3480
49.8750	0.3235	16.1346
48.1030	0.3262	15.6912
45.7080	0.3278	14.9831
42.7270	0.3293	14.0700
29.6690	0.3329	9.8768
0.0082	0.3460	0.0028



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
59.3490	-0.0001	-0.0059
55.1990	0.2548	14.0647
53.4370	0.2974	15.8922
51.6360	0.3166	16.3480
49.8750	0.3235	16.1346
48.1030	0.3262	15.6912
45.7080	0.3278	14.9831
42.7270	0.3293	14.0700
29.6690	0.3329	9.8768
0.0082	0.3460	0.0028

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

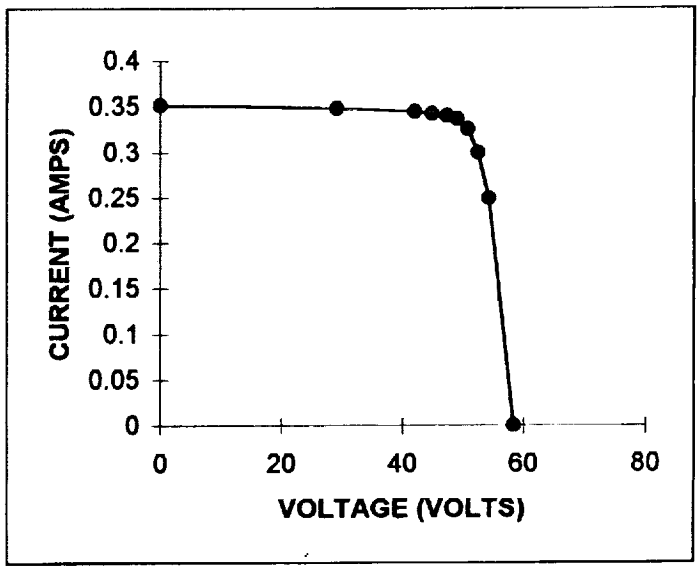
STRING:B

POST-ENVIRONMENTAL

Test date: 05/01/2000

PARAMETERS	
Calibration Standard:	512-98
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		
VOLTS	AMPS	POWER
58.3620	-0.0001	-0.0058
54.3040	0.2489	13.5163
52.5420	0.2994	15.7311
50.7820	0.3259	16.5499
49.0570	0.3371	16.5371
47.2830	0.3407	16.1093
44.9210	0.3424	15.3810
42.0160	0.3446	14.4787
29.1680	0.3482	10.1563
0.0146	0.3516	0.0051



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
58.362	-0.0001	-0.005836
54.304	0.2489	13.516266
52.542	0.2994	15.731075
50.782	0.3259	16.549854
49.057	0.3371	16.537115
47.283	0.3407	16.109318
44.921	0.3424	15.38095
42.016	0.3446	14.478714
29.168	0.3482	10.156298
0.0146	0.3516	0.0051334

RESULTS		
VOC:	58.362	V
ISC :	0.352	A
PMAX :	16.550	W
VMAX :	50.782	V
IMAX :	0.326	A
FF :	80.652	%
Eff :	20.964	%

ESCA

QUAL COUPON

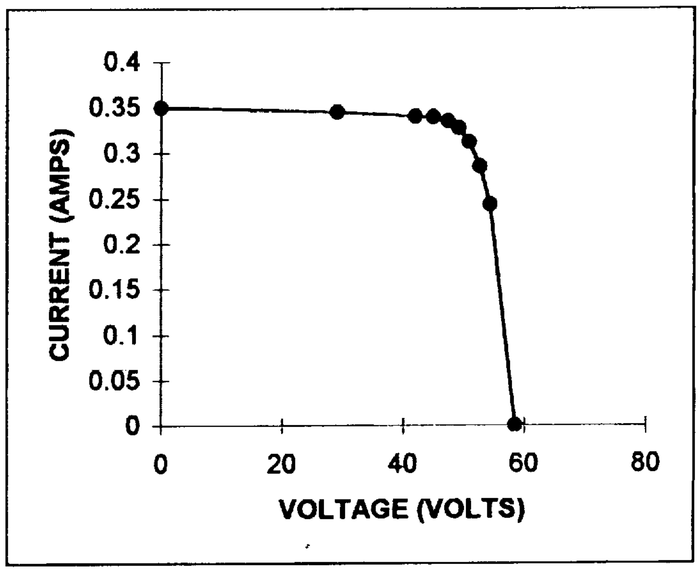
STRING:C

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 cm^2
Target Temperature:	28 °C
Voltage Temp Coef.:	-0.24 %VOC / °C

DATA CORRECTED TO 28°C		
VOLTS	AMPS	POWER
58.4940	-0.0001	-0.0058
54.4160	0.2434	13.2449
52.6580	0.2849	15.0023
50.8950	0.3117	15.8640
49.1710	0.3271	16.0838
47.4050	0.3348	15.8712
45.0450	0.3387	15.2567
42.0960	0.3399	14.3084
29.2450	0.3446	10.0778
0.0151	0.3492	0.0053



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
58.494	-0.0001	-0.005849
54.416	0.2434	13.244854
52.658	0.2849	15.002264
50.895	0.3117	15.863972
49.171	0.3271	16.083834
47.405	0.3348	15.871194
45.045	0.3387	15.256742
42.096	0.3399	14.30843
29.245	0.3446	10.077827
0.0151	0.3492	0.0052729

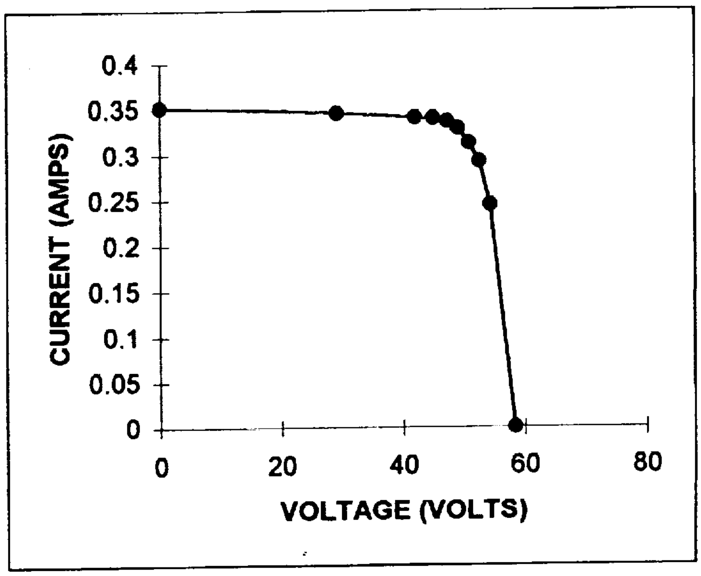
RESULTS		
VOC:	58.494	V
ISC :	0.349	A
PMAX :	16.084	W
VMAX :	49.171	V
IMAX :	0.327	A
FF :	78.742	%
Eff :	20.373	%

ESCA
QUAL COUPON
STRING:D
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:	28 °C
Voltage Temp Coef.:	-0.24 %VOC / °C

DATA CORRECTED TO 28°C		
VOLTS	AMPS	POWER
58.4270	-0.0001	-0.0058
54.3420	0.2445	13.2866
52.5810	0.2916	15.3326
50.8590	0.3126	15.8985
49.0960	0.3282	16.1133
47.3160	0.3364	15.9171
45.0070	0.3396	15.2844
42.0550	0.3407	14.3281
29.2040	0.3456	10.0929
0.0121	0.3518	0.0043



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
58.427	-0.0001	-0.005843
54.342	0.2445	13.286619
52.581	0.2916	15.33262
50.859	0.3126	15.898523
49.096	0.3282	16.113307
47.316	0.3364	15.917102
45.007	0.3396	15.284377
42.055	0.3407	14.328139
29.204	0.3456	10.092902
0.0121	0.3518	0.0042568

RESULTS		
VOC:	58.427	V
ISC :	0.352	A
PMAX :	16.113	W
VMAX :	49.096	V
IMAX :	0.328	A
FF :	78.393	%
Eff :	20.411	%

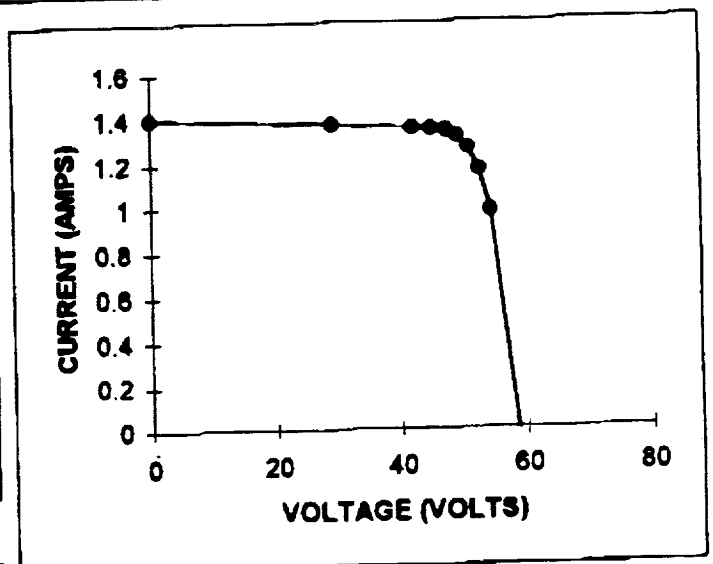
ESCA
QUAL COUPON
POST-ACOUSTIC TEST
FULL PANEL

Test date: 01/31/2000

PARAMETERS	
Calibration Standard:	512-98
No. of Series Cells:	24
No. of Parallel Cells:	4
Area per Cell :	24.312 cm^2
Target Temperature:	28 °C
Voltage Temp Coef.:	-0.24 %VOC / °C

DATA CORRECTED TO 28°C

VOLTS	AMPS	POWER
58.6620	-0.0066	-0.3872
54.5550	0.9801	53.4694
52.7950	1.1635	61.4270
51.0670	1.2608	64.3853
49.3090	1.3137	64.7772
47.5430	1.3382	63.6220
45.1800	1.3472	60.8665
42.2380	1.3540	57.1903
29.3420	1.3704	40.2103
0.0000	1.4002	0.0000



DATA CORRECTED TO TARGET TEMPERATURE

VOLTS	AMPS	POWER
58.662	-0.0066	-0.387169
54.555	0.9801	53.469356
52.795	1.1635	61.426983
51.067	1.2608	64.385274
49.309	1.3137	64.777233
47.543	1.3382	63.622043
45.18	1.3472	60.866496
42.238	1.354	57.190252
29.342	1.3704	40.210277
0	1.4002	0

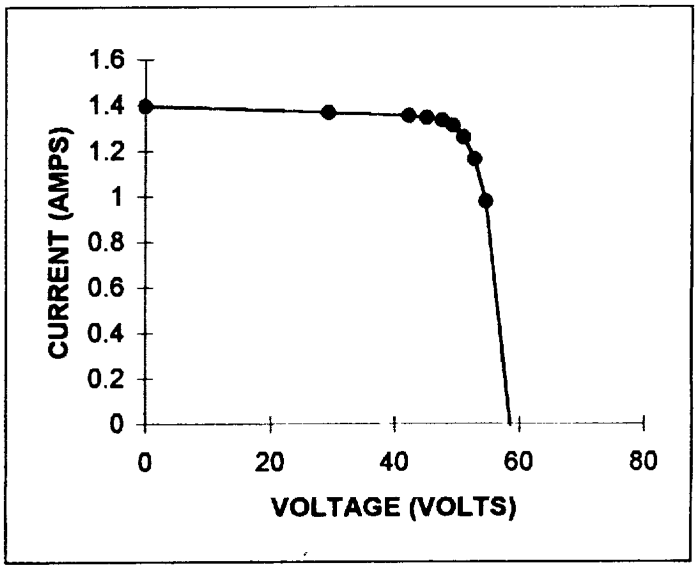
RESULTS		
VOC:	58.662	V
ISC :	1.400	A
PMAX :	64.777	W
VMAX :	49.309	V
IMAX :	1.314	A
FF :	78.863	%
Eff :	20.513	%

ESCA
QUAL COUPON
POST-ENVIRONMENTAL
FULL PANEL

Test date: 05/01/2000

PARAMETERS		
Calibration Standard:	512-98	
No. of Series Cells:	24	
No. of Parallel Cells:	4	
Area per Cell :	24.312	cm^2
Target Temperature:	28	°C
Voltage Temp Coef.:	-0.24	%VOC / °C

DATA CORRECTED TO 28°C		
VOLTS	AMPS	POWER
58.6610	-0.0056	-0.3285
54.5810	0.9781	53.3857
52.8150	1.1611	61.3235
51.0520	1.2580	64.2234
49.2910	1.3099	64.5663
47.5280	1.3338	63.3928
45.1660	1.3458	60.7844
42.2290	1.3527	57.1232
29.3270	1.3669	40.0871
0.0000	1.3952	0.0000



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
58.661	-0.0056	-0.328502
54.581	0.9781	53.385676
52.815	1.1611	61.323497
51.052	1.258	64.223416
49.291	1.3099	64.566281
47.528	1.3338	63.392846
45.166	1.3458	60.784403
42.229	1.3527	57.123168
29.327	1.3669	40.087076
0	1.3952	0

RESULTS		
VOC:	58.661	V
ISC :	1.395	A
PMAX :	64.566	W
VMAX :	49.291	V
IMAX :	1.310	A
FF :	78.890	%
Eff :	20.446	%

ESCA

PRE-HOT FLASH TEST INSIDE THE HOT BOX WITH COVER @ 28°C

QUAL COUPON

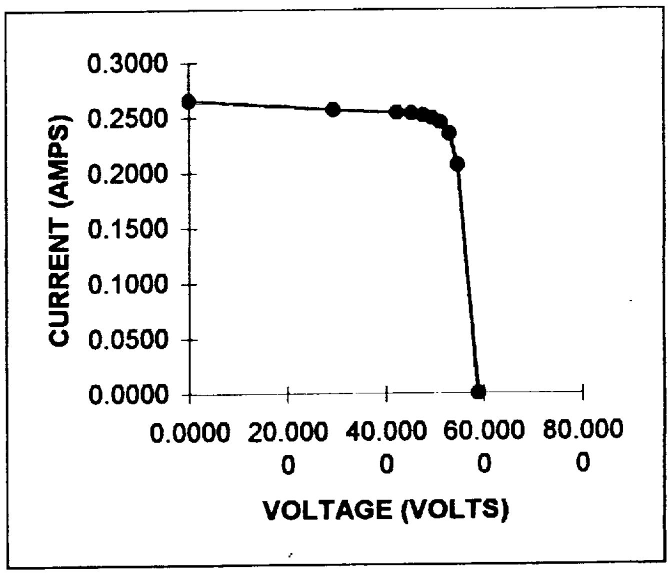
POST-ENVIRONMENTAL TEST

CKT:A

Test date: 05/01/2000

PARAMETERS	
Calibration Standard:	512-98
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		
VOLTS	AMPS	POWER
58.9250	0.0000	0.0000
54.8140	0.2067	11.3301
53.0420	0.2352	12.4755
51.2900	0.2457	12.6020
49.5170	0.2498	12.3693
47.7440	0.2520	12.0315
45.3890	0.2535	11.5061
42.4140	0.2545	10.7944
29.4760	0.2569	7.5724
0.0096	0.2654	0.0025



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
58.9250	0.0000	0.0000
54.8140	0.2067	11.3301
53.0420	0.2352	12.4755
51.2900	0.2457	12.6020
49.5170	0.2498	12.3693
47.7440	0.2520	12.0315
45.3890	0.2535	11.5061
42.4140	0.2545	10.7944
29.4760	0.2569	7.5724
0.0096	0.2654	0.0025

RESULTS		
VOC:	58.9250	V
ISC :	0.2654	A
PMAX :	12.6020	W
VMAX :	51.2900	V
IMAX :	0.2457	A
FF :	80.5819	%
Eff :	15.9628	%

ESCA

PRE-HOT FLASH TEST INSIDE THE HOT BOX WITH COVER @ 28°C

QUAL COUPON

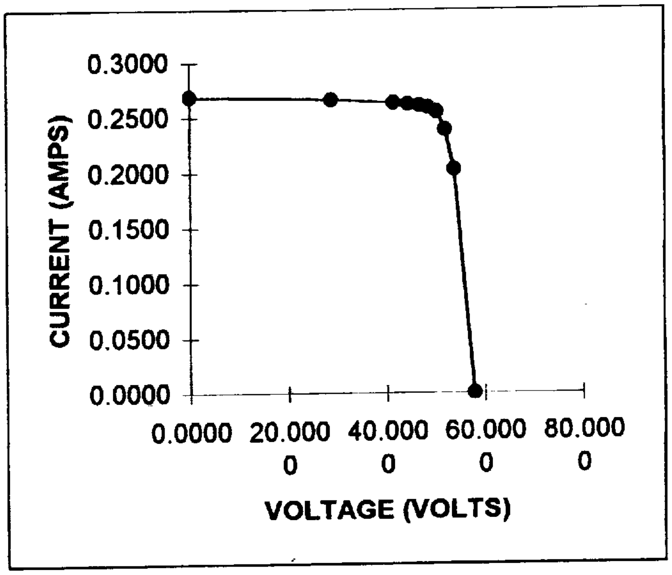
POST-ENVIRONMENTAL TEST

CKT:B

Test date: 05/01/2000

PARAMETERS	
Calibration Standard:	512-98
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		
VOLTS	AMPS	POWER
57.8320	0.0000	0.0000
53.8080	0.2025	10.8961
52.0680	0.2387	12.4286
50.3280	0.2546	12.8135
48.5890	0.2591	12.5894
46.8250	0.2605	12.1979
44.5080	0.2616	11.6433
41.6530	0.2627	10.9422
28.9110	0.2660	7.6903
0.0000	0.2687	0.0000



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
57.8320	0.0000	0.0000
53.8080	0.2025	10.8961
52.0680	0.2387	12.4286
50.3280	0.2546	12.8135
48.5890	0.2591	12.5894
46.8250	0.2605	12.1979
44.5080	0.2616	11.6433
41.6530	0.2627	10.9422
28.9110	0.2660	7.6903
0.0000	0.2687	0.0000

RESULTS		
VOC:	57.8320	V
ISC :	0.2687	A
PMAX :	12.8135	W
VMAX :	50.3280	V
IMAX :	0.2546	A
FF :	82.4579	%
Eff :	16.2307	%

ESCA

PRE-HOT FLASH TEST INSIDE THE HOT BOX WITH COVER @ 28°C

QUAL COUPON

POST-ENVIRONMENTAL TEST

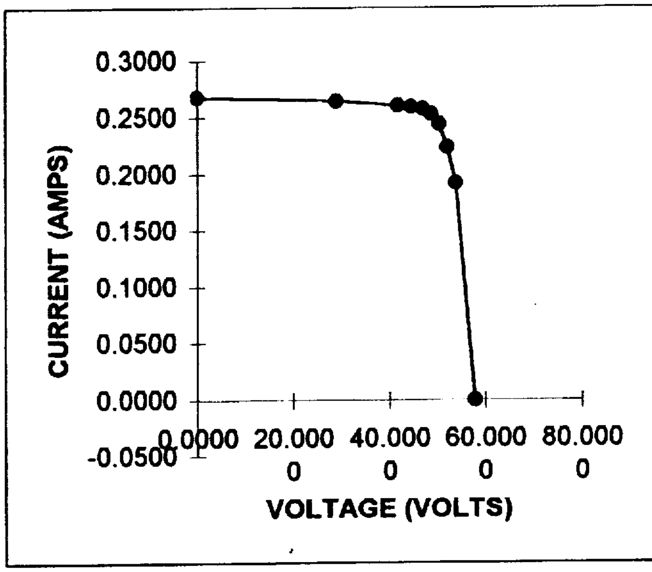
CKT:C

Test date: 05/01/2000

PARAMETERS	
Calibration Standard:	512-98
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

VOLTS	AMPS	POWER
57.9640	-0.0001	-0.0058
53.9330	0.1919	10.3497
52.1640	0.2234	11.6534
50.4390	0.2438	12.2970
48.7120	0.2532	12.3339
46.9430	0.2576	12.0925
44.6240	0.2593	11.5710
41.7310	0.2604	10.8668
28.9920	0.2645	7.6684
0.0000	0.2676	0.0000



DATA CORRECTED TO TARGET TEMPERATURE

VOLTS	AMPS	POWER
57.9640	-0.0001	-0.0058
53.9330	0.1919	10.3497
52.1640	0.2234	11.6534
50.4390	0.2438	12.2970
48.7120	0.2532	12.3339
46.9430	0.2576	12.0925
44.6240	0.2593	11.5710
41.7310	0.2604	10.8668
28.9920	0.2645	7.6684
0.0000	0.2676	0.0000

RESULTS		
VOC:	57.9640	V
ISC :	0.2676	A
PMAX :	12.3339	W
VMAX :	48.7120	V
IMAX :	0.2532	A
FF :	79.5161	%
Eff :	15.6232	%

ESCA

PRE-HOT FLASH TEST INSIDE THE HOT BOX WITH COVER @ 28°C

QUAL COUPON

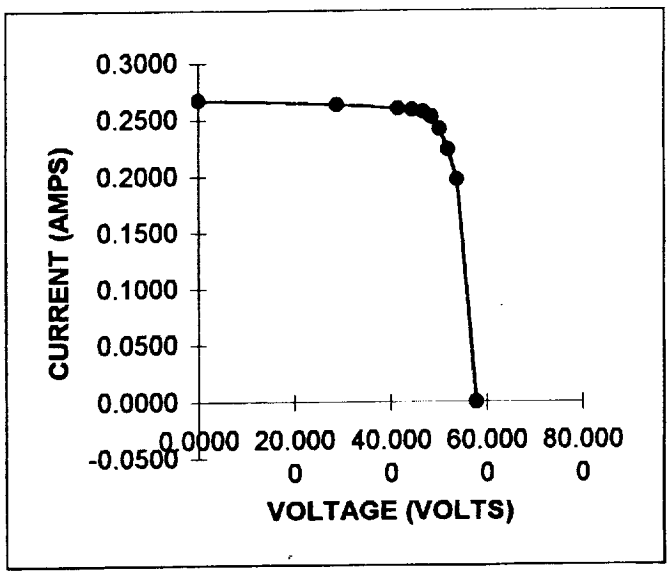
POST-ENVIRONMENTAL TEST

CKT:D

Test date: 05/01/2000

PARAMETERS	
Calibration Standard:	512-98
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		
VOLTS	AMPS	POWER
57.8810	-0.0001	-0.0058
53.8580	0.1967	10.5939
52.0780	0.2236	11.6446
50.3510	0.2415	12.1598
48.6280	0.2527	12.2883
46.9000	0.2570	12.0533
44.5780	0.2586	11.5279
41.6920	0.2599	10.8358
28.9480	0.2631	7.6162
0.0000	0.2672	0.0000



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
57.8810	-0.0001	-0.0058
53.8580	0.1967	10.5939
52.0780	0.2236	11.6446
50.3510	0.2415	12.1598
48.6280	0.2527	12.2883
46.9000	0.2570	12.0533
44.5780	0.2586	11.5279
41.6920	0.2599	10.8358
28.9480	0.2631	7.6162
0.0000	0.2672	0.0000

RESULTS		
VOC:	57.8810	V
ISC :	0.2672	A
PMAX :	12.2883	W
VMAX :	48.6280	V
IMAX :	0.2527	A
FF :	79.4546	%
Eff :	15.5655	%

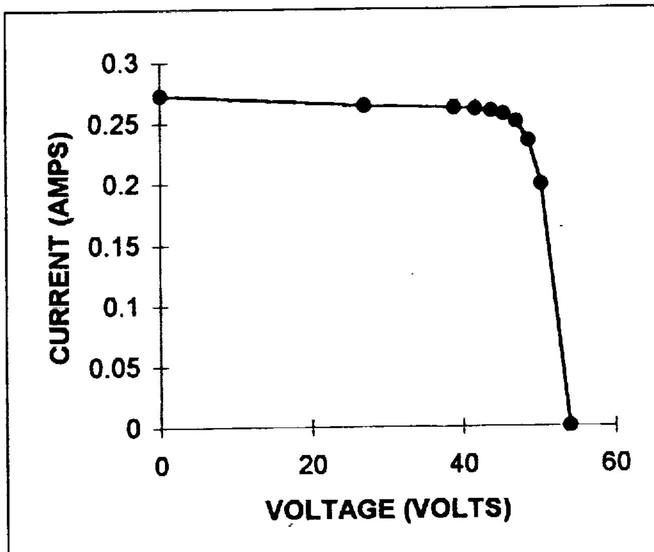
ESCA
HOT-FLASH TEST
QUAL COUPON
CKT:A

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 %VOC / °C
Current Temp Coef:	17.1 uA/cm^2/°C

TEST TEMPERATURE 70 °C		
VOLTS	**AMPS**	**POWER**
54.0400	0.0000	0.0000
50.2630	0.1993	10.0174
48.6460	0.2346	11.4124
47.0340	0.2507	11.7914
45.3870	0.2568	11.6554
43.7800	0.2595	11.3609
41.6250	0.2611	10.8683
38.8950	0.2620	10.1905
26.9910	0.2644	7.1364
0.0783	0.2728	0.0214



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	**AMPS**	**POWER**
54.04	0	0
50.263	0.1993	10.017416
48.646	0.2346	11.412352
47.034	0.2507	11.791424
45.387	0.2568	11.655382
43.78	0.2595	11.36091
41.625	0.2611	10.868288
38.895	0.262	10.19049
26.991	0.2644	7.1364204
0.0783	0.2728	0.0213602

RESULTS		
VOC:	54.0400	V
ISC :	0.2728	A
PMAX :	11.7914	W
VMAX :	47.0340	V
IMAX :	0.2507	A
FF :	79.9846	%
Eff :	14.9361	%

ESCA

HOT-FLASH TEST

QUAL COUPON

CKT:B

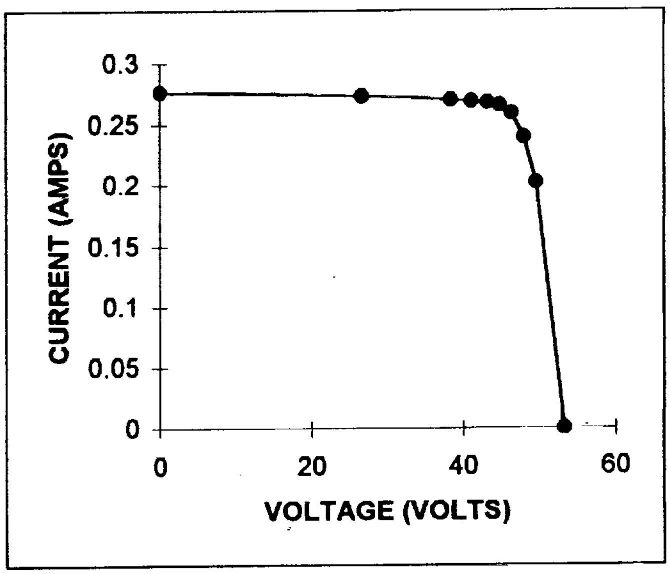
POST-ENVIRONMENTAL TEST

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 %VOC / °C
Current Temp Coef:	17.1 uA/cm^2/°C

TEST TEMPERATURE 70 °C

VOLTS	AMPS	POWER
53.2790	0.0000	0.0000
49.5540	0.2025	10.0347
47.9690	0.2397	11.4982
46.3580	0.2592	12.0160
44.7550	0.2661	11.9093
43.1510	0.2679	11.5602
41.0350	0.2690	11.0384
38.3570	0.2699	10.3526
26.6360	0.2733	7.2796
0.0776	0.2761	0.0214



DATA CORRECTED TO TARGET TEMPERATURE

VOLTS	AMPS	POWER
53.279	0	0
49.554	0.2025	10.034685
47.969	0.2397	11.498169
46.358	0.2592	12.015994
44.755	0.2661	11.909306
43.151	0.2679	11.560153
41.035	0.269	11.038415
38.357	0.2699	10.352554
26.636	0.2733	7.2796188
0.0776	0.2761	0.0214254

RESULTS		
VOC:	53.2790	V
ISC :	0.2761	A
PMAX :	12.0160	W
VMAX :	46.3580	V
IMAX :	0.2592	A
FF :	81.6840	%
Eff :	15.2205	%

ESCA

HOT-FLASH TEST

QUAL COUPON

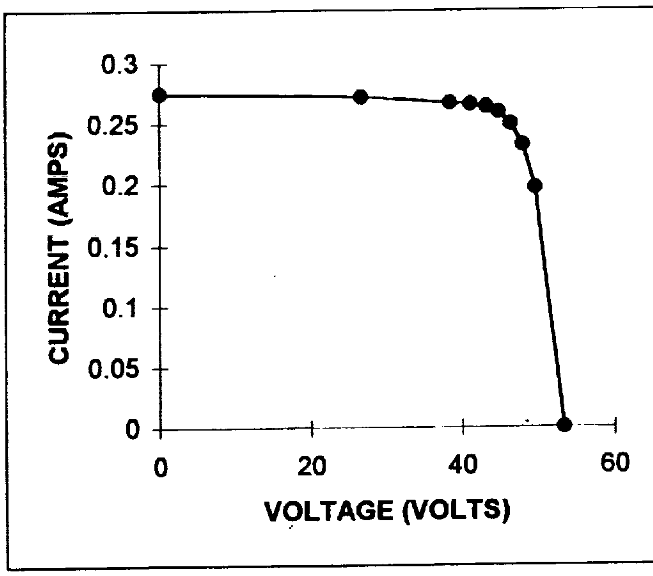
CKT:C

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 %VOC / °C
Current Temp Coef:	17.1 uA/cm^2/°C

TEST TEMPERATURE 70 °C		
VOLTS	AMPS	POWER
53.3230	0.0000	0.0000
49.5790	0.1968	9.7571
47.9740	0.2322	11.1396
46.4080	0.2493	11.5695
44.7990	0.2593	11.6164
43.1700	0.2640	11.3969
41.0760	0.2661	10.9303
38.3880	0.2671	10.2534
26.6430	0.2717	7.2389
0.0893	0.2748	0.0245



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
53.323	0	0
49.579	0.1968	9.7571472
47.974	0.2322	11.139563
46.408	0.2493	11.569514
44.799	0.2593	11.616381
43.17	0.264	11.39688
41.076	0.2661	10.930324
38.388	0.2671	10.253435
26.643	0.2717	7.2389031
0.0893	0.2748	0.0245396

RESULTS		
VOC:	53.3230	V
ISC :	0.2748	A
PMAX :	11.6164	W
VMAX :	44.7990	V
IMAX :	0.2593	A
FF :	79.2756	%
Eff :	14.7144	%

ESCA

HOT-FLASH TEST

QUAL COUPON

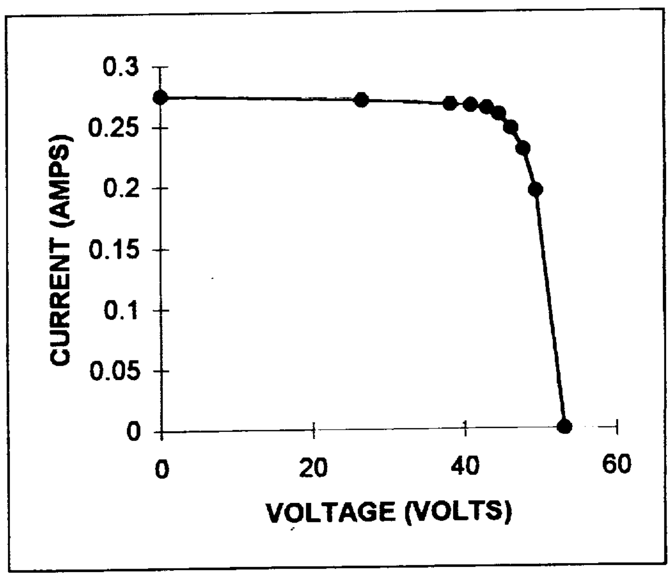
CKT:D

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 %VOC / °C
Current Temp Coef:	17.1 uA/cm^2/°C

TEST TEMPERATURE 70 °C		
VOLTS	AMPS	POWER
53.1230	0.0000	0.0000
49.4230	0.1957	9.6721
47.8140	0.2295	10.9733
46.2040	0.2468	11.4031
44.6360	0.2583	11.5295
43.0330	0.2640	11.3607
40.9180	0.2660	10.8842
38.2330	0.2671	10.2120
26.5650	0.2706	7.1885
0.0847	0.2749	0.0233



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
53.123	0	0
49.423	0.1957	9.6720811
47.814	0.2295	10.973313
46.204	0.2468	11.403147
44.636	0.2583	11.529479
43.033	0.264	11.360712
40.918	0.266	10.884188
38.233	0.2671	10.212034
26.565	0.2706	7.188489
0.0847	0.2749	0.023284

RESULTS		
VOC:	53.1230	V
ISC :	0.2749	A
PMAX :	11.5295	W
VMAX :	44.6360	V
IMAX :	0.2583	A
FF :	78.9500	%
Eff :	14.6043	%

ESCA

HOT-FLASH TEST

CKT:A @ 70°C

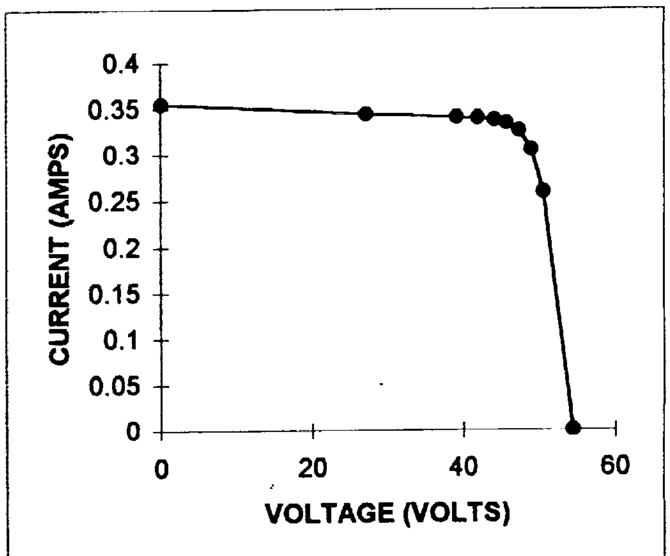
Adjustment made for the lost of the lexan glass

Voltage Ratio: 1.007 Current Ratio:1.30

Test date: 05/01/2000

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 %VOC / °C
Current Temp Coef:	17.1 uA/cm^2/°C

TEST TEMPERATURE 70 °C		
VOLTS	AMPS	POWER
54.4183	0.0000	0.0000
50.6148	0.2591	13.1138
48.9865	0.3050	14.9399
47.3632	0.3259	15.4362
45.7047	0.3338	15.2581
44.0865	0.3374	14.8726
41.9164	0.3394	14.2277
39.1673	0.3406	13.3404
27.1799	0.3437	9.3423
0.0788	0.3546	0.0280



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
54.41828	0	0
50.61484	0.25909	13.11379915
48.98652	0.30498	14.93990948
47.36324	0.32591	15.4361529
45.70471	0.33384	15.25806005
44.08646	0.33735	14.87256728
41.91638	0.33943	14.22767517
39.16727	0.3406	13.34037046
27.17994	0.34372	9.342287946
0.078848	0.35464	0.02796269

RESULTS		
VOC:	54.418	V
ISC :	0.355	A
PMAX :	15.436	W
VMAX :	47.363	V
IMAX :	0.326	A
FF :	79.985	%
Eff :	19.553	%

ESCA

HOT-FLASH TEST

CKT:B @ 70°C

Adjustment made for the lost of the lexan glass

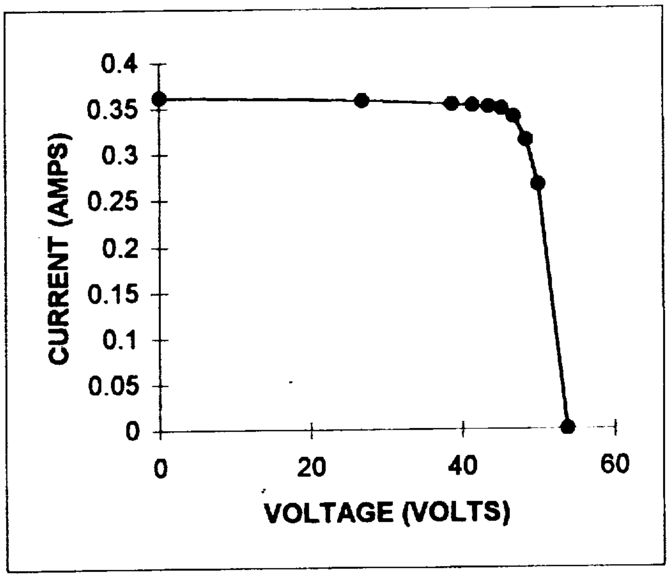
Voltage Ratio: 1.009 Current Ratio:1.31

Test date: 05/01/2000

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 %VOC / °C
Current Temp Coef:	17.1 uA/cm^2/°C

TEST TEMPERATURE
70 °C

VOLTS	AMPS	POWER
53.7585	0.0000	0.0000
50.0000	0.2653	13.2637
48.4007	0.3140	15.1982
46.7752	0.3396	15.8826
45.1578	0.3486	15.7416
43.5394	0.3509	15.2801
41.4043	0.3524	14.5905
38.7022	0.3536	13.6839
26.8757	0.3580	9.6221
0.0783	0.3617	0.0283



DATA CORRECTED TO TARGET TEMPERATURE

VOLTS	AMPS	POWER
53.75851	0	0
49.99999	0.265275	13.26374629
48.40072	0.314007	15.1981652
46.77522	0.339552	15.88262018
45.1578	0.348591	15.74160092
43.53936	0.350949	15.2800945
41.40432	0.35239	14.59046656
38.70221	0.353569	13.68390275
26.87572	0.358023	9.622127334
0.078298	0.361691	0.028319827

RESULTS		
VOC:	53.759	V
ISC :	0.362	A
PMAX :	15.883	W
VMAX :	46.775	V
IMAX :	0.340	A
FF :	81.684	%
Eff :	20.118	%

ESCA
HOT-FLASH TEST
CKT:C @ 70°C

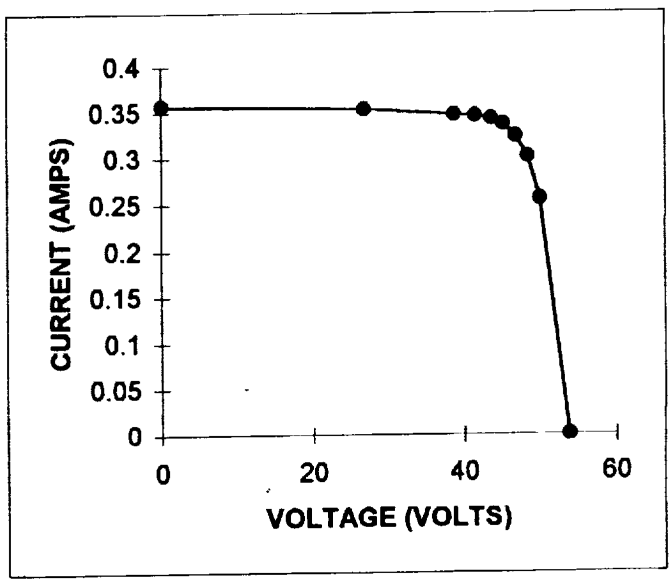
Adjustment made for the lost of the lexan glass

Voltage Ratio: 1.009 Current Ratio:1.30

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 %VOC / °C
Current Temp Coef:	17.1 uA/cm^2/°C

TEST TEMPERATURE 70 °C		
VOLTS	AMPS	POWER
53.8029	0.0000	0.0000
50.0252	0.2558	12.7984
48.4058	0.3019	14.6118
46.8257	0.3241	15.1757
45.2022	0.3371	15.2372
43.5585	0.3432	14.9493
41.4457	0.3459	14.3373
38.7335	0.3472	13.4494
26.8828	0.3532	9.4953
0.0901	0.3572	0.0322



DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
53.80291	0	0
50.02521	0.25584	12.79844998
48.40577	0.30186	14.61176452
46.82567	0.32409	15.17573204
45.20219	0.33709	15.23720656
43.55853	0.3432	14.9492875
41.44568	0.34593	14.33730547
38.73349	0.34723	13.44943043
26.88279	0.35321	9.495269196
0.090104	0.35724	0.032188646

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

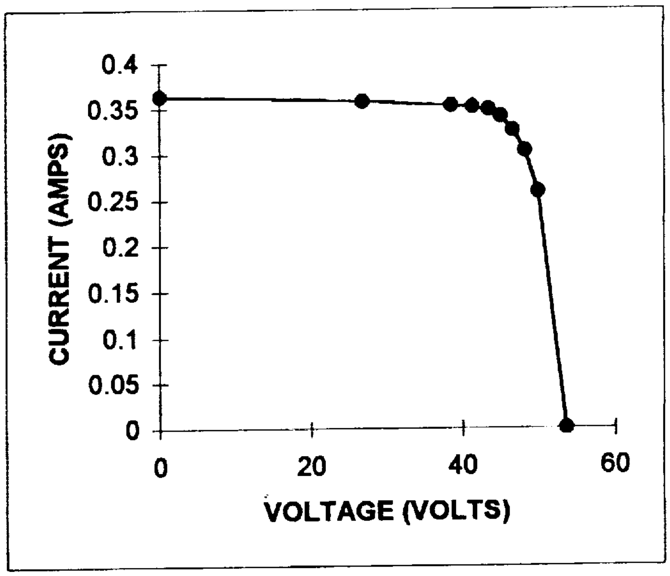
Voltage Ratio: 1.009 Current Ratio:1.32

Test date: 05/01/2000

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 %VOC / °C
Current Temp Coef:	17.1 uA/cm^2/°C

TEST TEMPERATURE 70 °C		
VOLTS	AMPS	POWER
53.6011	0.0000	0.0000
49.8678	0.2583	12.8821
48.2443	0.3029	14.6151
46.6198	0.3258	15.1876
45.0377	0.3410	15.3559
43.4203	0.3485	15.1311
41.2863	0.3511	14.4964
38.5771	0.3526	13.6012
26.8041	0.3572	9.5742
0.0855	0.3629	0.0310

DATA CORRECTED TO TARGET TEMPERATURE		
VOLTS	AMPS	POWER
53.60111	0	0
49.86781	0.258324	12.88205138
48.24433	0.30294	14.61513612
46.61984	0.325776	15.18762369
45.03772	0.340956	15.35588222
43.4203	0.34848	15.1311051
41.28626	0.35112	14.49643231
38.5771	0.352572	13.60120424
26.80409	0.357192	9.574204729
0.085462	0.362868	0.031011534



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	%

Appendix 4 - Acoustic Environment Test Report

wyle laboratories

TEST REPORT

REPORT NO.:	43899
OUR JOB NO.:	43899
CONTRACT:	N. A.
YOUR P.O. NO.:	55246

COMPOSITE OPTICS INCORPORATED
9617 Distribution Avenue
San Diego, CA 92121

15 PAGE REPORT

04 February 2000

REPORT

ON

ACOUSTIC NOISE TESTS

OF ONE

TEST PANEL

FOR

COMPOSITE OPTICS, INC.

STATE OF CALIFORNIA
COUNTY OF LOS ANGELES } S. S.

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.

C. Glaretas

SUBSCRIBED and sworn to before me this 7th day of FEB, 20 00

Prairie Witkamp

PRAIRIE WITKAMP
Commission # 1236213
Notary Public - California
Los Angeles County
My Comm. Expires Oct 2, 2003

W-781

DEPARTMENT Acoustics

TEST ENGINEER F. E. Hermoso

TEST WITNESS

(Not Applicable)

DCAS-QAR VERIFICATION

QUALITY ASSURANCE G. Montgomery

TABLE OF CONTENTS

LIST OF ATTACHMENTS

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

LIST OF PHOTOGRAPHS

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.

2.2 Composite Optics, Incorporated, FAX, dated 28 May 1999.

2.3 ANSI/NCSL Z540–1–1994, Calibration—Calibration Laboratories and Measurement and Test Equipment—General Requirements which supersedes MIL–STD–45662A, Calibration Systems Requirements, 10 June 1980.

2.4 Wyle Laboratories Western Test and Engineering Operation El Segundo Facility Quality Assurance Program Manual for ISO 9001 Compliance, Rev. 04, dated 20 January 2000.

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 ^{O}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.

ACOUSTIC TEST LEVELS AND RESULTS

1/3 OCTAVE BAND CENTER FREQUENCY (Hz)	MEASURED 1/3 OCTAVE BAND SOUND PRESSURE LEVELS (dB*)
31.5	122.5
40	124.7
50	129.0
63	130.1
80	129.9
100	131.1
125	131.8
160	131.0
200	132.7
250	133.4
315	134.2
400	133.5
500	131.2
630	128.0
800	125.2
1000	123.1
1250	120.8
1600	119.9
2000	119.4
2500	117.2
3150	113.9
4000	113.5
5000	112.8
6300	112.1
8000	112.3
10000	112.6
Allowable Overall SPL	142.8

*dB-Ref.: 2.0×10^{-5} Pa

ATTACHMENT "ACO–A"

ACOUSTIC NOISE TEST

wyle laboratories

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

Sheet Number 1 of 1

Approved Costa Glaretas Date January 28, 2000

wyle laboratories

Test: ACOUSTIC NOISE

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

Part No: NA S/N: NA

Test By: F.E. HERMOSO Witness: Date. 1-28-2000

EQUIPMENT	MANUFACTURER	MODEL NO.	RANGE	WYLE No.	CALIBRATION DATE	CALIBRATION DUE	ACCURACY
Modulator	Wyle	WAS 3000	10,000 Hz	S/N 014	N.A	N.A	N.A
Acoustic Control System	Wyle	ACS	20 Hz to 10 kHz 8 Channels	W13866	System Cal. Prior to Use		N.A
1/3 Octave Real Time Analyzer	Norwegian Electronics	830	0.8 Hz to 20 kHz	W9453	System Cal. Prior to Use		±0.20 dB
1/3 Octave Spectrum	Norwegian Electronics	731	20 Hz to 20 kHz	W11063	System Cal. Prior to Use		± 0.20 dB
Sound Level	Bruel & Kjaer	4230	94dB @ 1000 Hz	W12103	7-22-99	7-22-00	± 0.13 dB
Pistonphone (if Sound Level Calibrator is not used)	Bruel & Kjaer	4228	124 dB @ 250 Hz	W12107	5-19-99	5-19-00	± 0.10 dB
Acoustic Microphone	PCB	106M55	90 to 190 dB 10 Hz to 10 kHz	(NONE)	Prior to use Sound Level Calibrator		N.A
Power Amplifier	Techron	7560	600 Watts	W10354	N.A	N.A	N.A
Power Amplifier	Ling	8004/8008	4kVA	N.A	N.A	N.A	N.A
FFT Analyser	Ono Sokki	CF-350	1Hz to 40KHz 1mv to 50 Volts	W10788	System Cal. Prior to use		N.A
Tape Recorder	Teac	RX-832	32 Channels	W14047	System Cal Prior to use		N.A

W614 C Q.C. Approval

wyle laboratories

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:

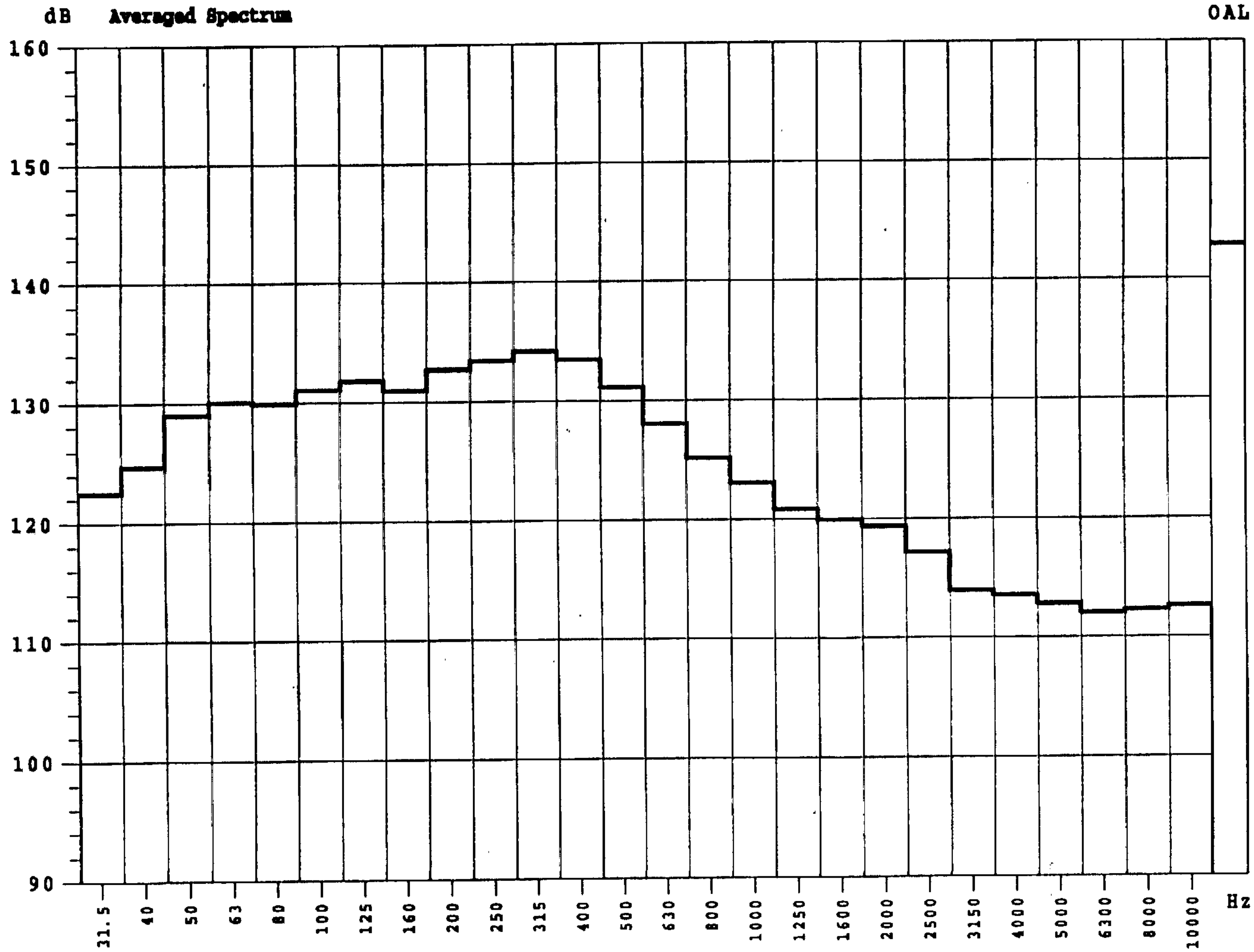
Qualification Test was completed with no apparent damage to the specimen.
Measured acoustic noise data are shown on 1/n octave plots.

Tested By F.E. HERMOSO

W614A-82 QA Form
Approval ______

Engineer F.E. HERMOSO

WYLE LABORATORIES	
ACOUSTIC TEST	
COMPOSITE OPTICS, INC. 43899, PANEL	
0dB 4-CONTROL MIC AVERAGE	JANUARY 28, 2000



31.5 Hz	122.5 dB
40.0 Hz	124.7 dB
50.0 Hz	129.0 dB
63.0 Hz	130.1 dB
80.0 Hz	129.9 dB
100.0 Hz	131.1 dB
125.0 Hz	131.8 dB
160.0 Hz	131.0 dB
200.0 Hz	132.7 dB
250.0 Hz	133.4 dB
315.0 Hz	134.2 dB
400.0 Hz	133.5 dB
500.0 Hz	131.2 dB
630.0 Hz	128.0 dB
800.0 Hz	125.2 dB
1000.0 Hz	123.1 dB
1250.0 Hz	120.8 dB
1600.0 Hz	119.9 dB
2000.0 Hz	119.4 dB
2500.0 Hz	117.2 dB
3150.0 Hz	113.9 dB
4000.0 Hz	113.5 dB
5000.0 Hz	112.8 dB
6300.0 Hz	112.1 dB
8000.0 Hz	112.3 dB
10000.0 Hz	112.6 dB

OASPL: 142.8 dB

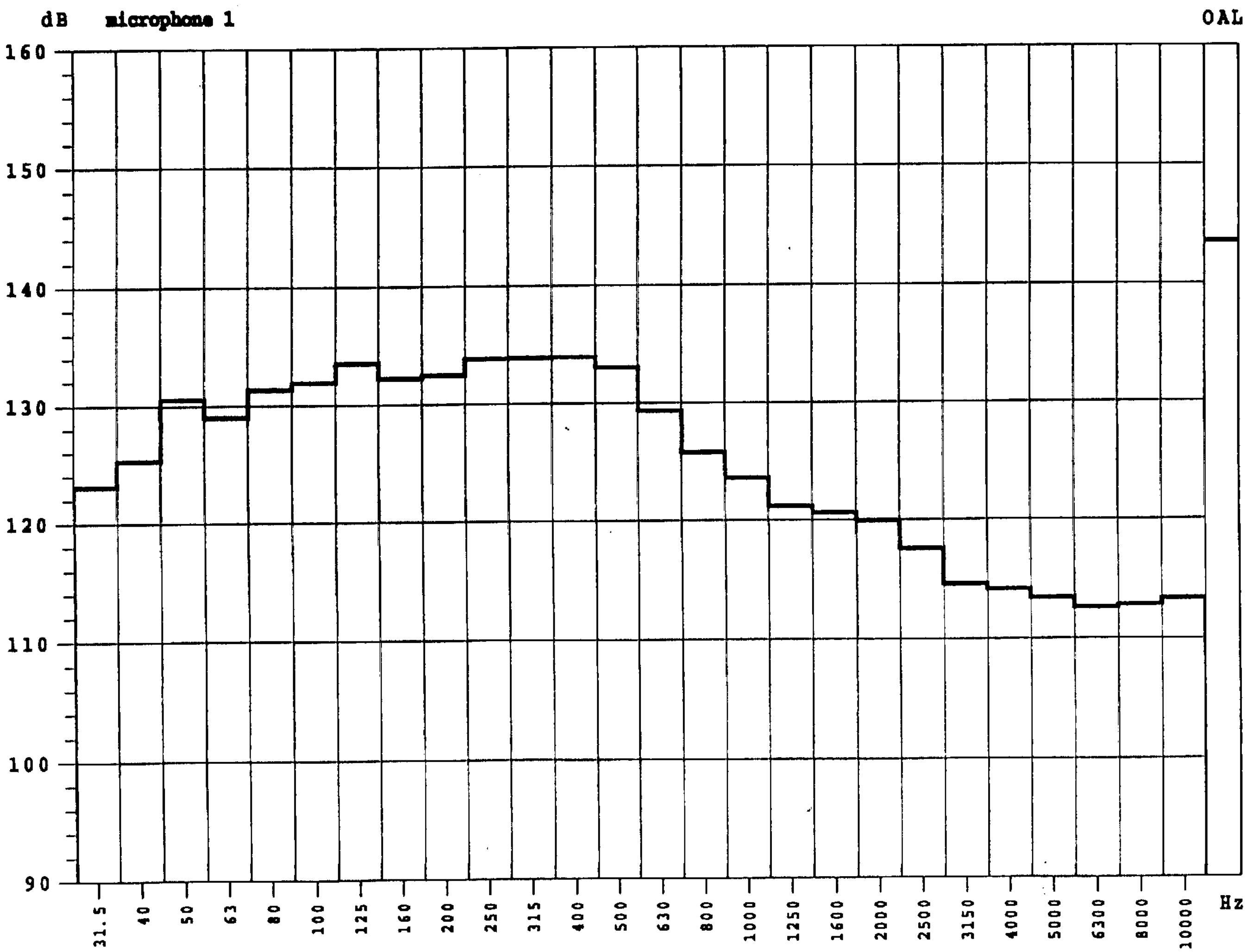
WYLE LABORATORIES

ACOUSTIC TEST

COMPOSITE OPTICS, INC. 43899, PANEL

0dB CONTROL MIC -1

JANUARY 28, 2000

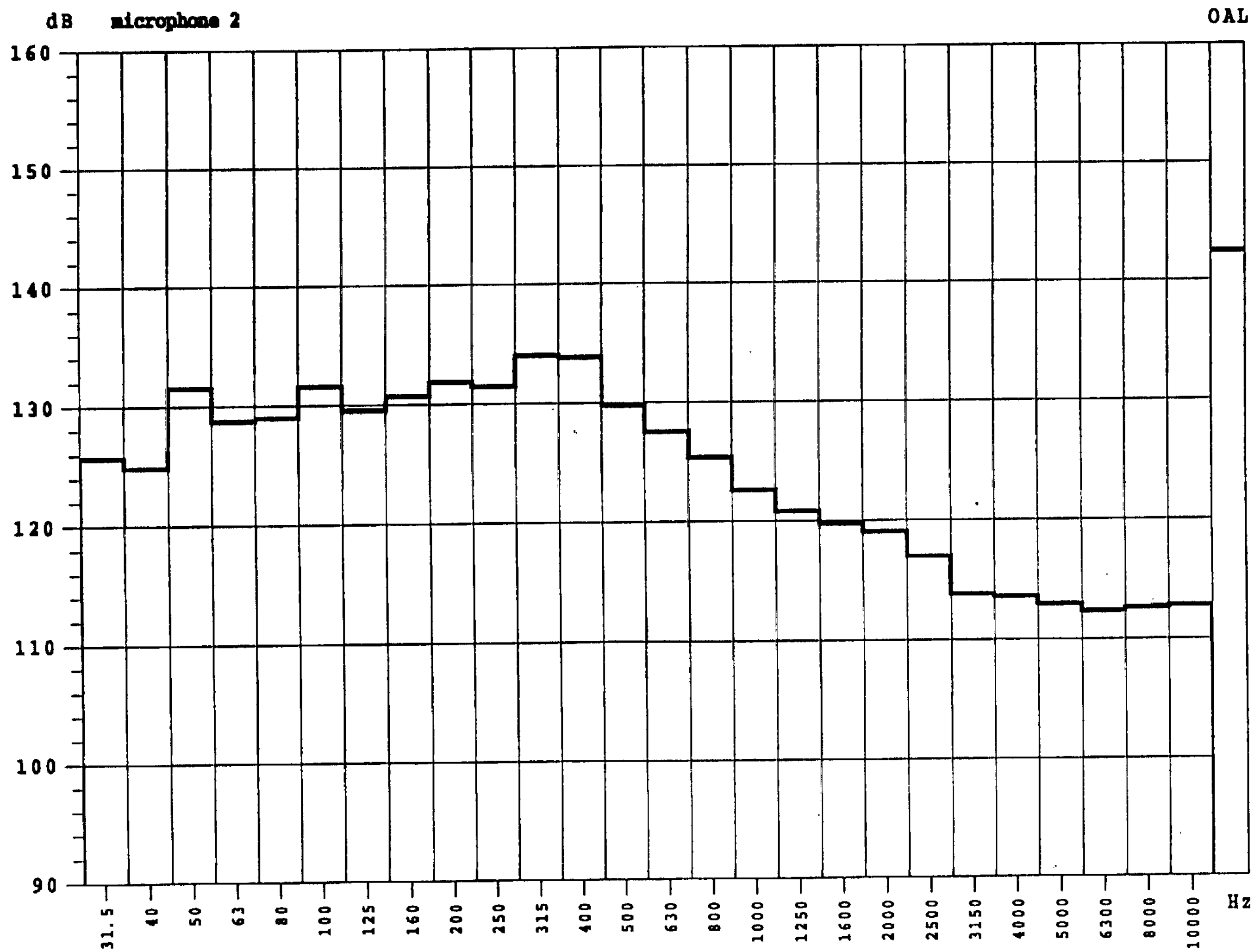


31.5 Hz	123.1 dB
40.0 Hz	125.3 dB
50.0 Hz	130.5 dB
63.0 Hz	129.0 dB
80.0 Hz	131.3 dB
100.0 Hz	131.9 dB
125.0 Hz	133.6 dB
160.0 Hz	132.2 dB
200.0 Hz	132.5 dB
250.0 Hz	133.9 dB
315.0 Hz	133.9 dB
400.0 Hz	134.0 dB
500.0 Hz	133.1 dB
630.0 Hz	129.3 dB
800.0 Hz	125.7 dB
1000.0 Hz	123.6 dB
1250.0 Hz	121.2 dB
1600.0 Hz	120.6 dB
2000.0 Hz	119.9 dB
2500.0 Hz	117.6 dB
3150.0 Hz	114.6 dB
4000.0 Hz	114.2 dB
5000.0 Hz	113.4 dB
6300.0 Hz	112.6 dB
8000.0 Hz	112.8 dB
10000.0 Hz	113.3 dB

OASPL: 143.5 dB

wyle laboratories

WYLE LABORATORIES	
ACOUSTIC TEST	
COMPOSITE OPTICS, INC. 43899, PANEL	
0dB CONTROL MIC -2	JANUARY 28, 2000



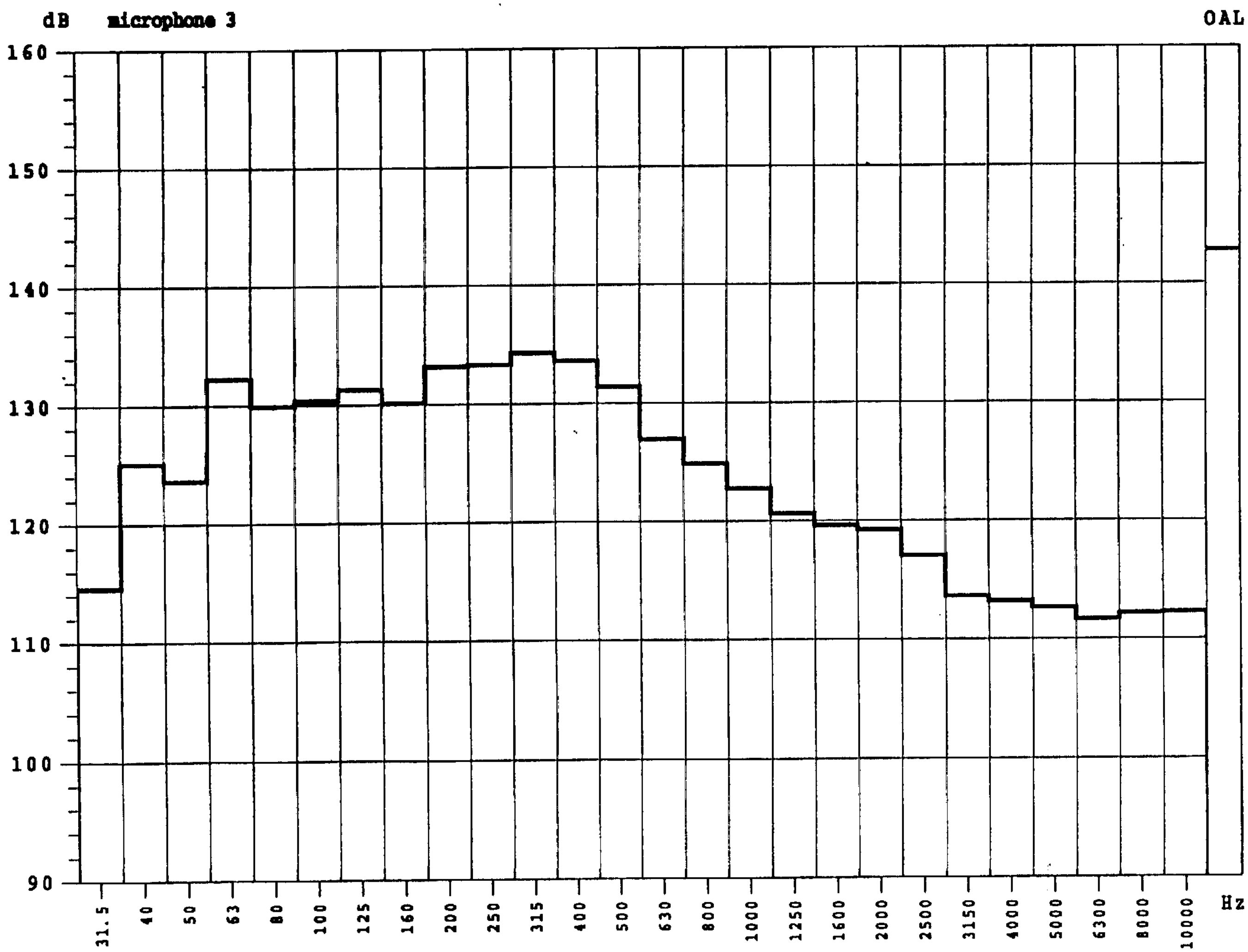
31.5 Hz	125.7 dB
40.0 Hz	124.9 dB
50.0 Hz	131.6 dB
63.0 Hz	128.7 dB
80.0 Hz	129.0 dB
100.0 Hz	131.6 dB
125.0 Hz	129.6 dB
160.0 Hz	130.7 dB
200.0 Hz	131.9 dB
250.0 Hz	131.5 dB
315.0 Hz	134.0 dB
400.0 Hz	133.8 dB
500.0 Hz	129.8 dB
630.0 Hz	127.5 dB
800.0 Hz	125.4 dB
1000.0 Hz	122.6 dB
1250.0 Hz	120.8 dB
1600.0 Hz	119.8 dB
2000.0 Hz	119.1 dB
2500.0 Hz	117.0 dB
3150.0 Hz	113.8 dB
4000.0 Hz	113.6 dB
5000.0 Hz	113.0 dB
6300.0 Hz	112.4 dB
8000.0 Hz	112.7 dB
10000.0 Hz	112.8 dB

OASPL: 142.5 dB

JOB NO. 43899

PAGE NO. ACO.A.8

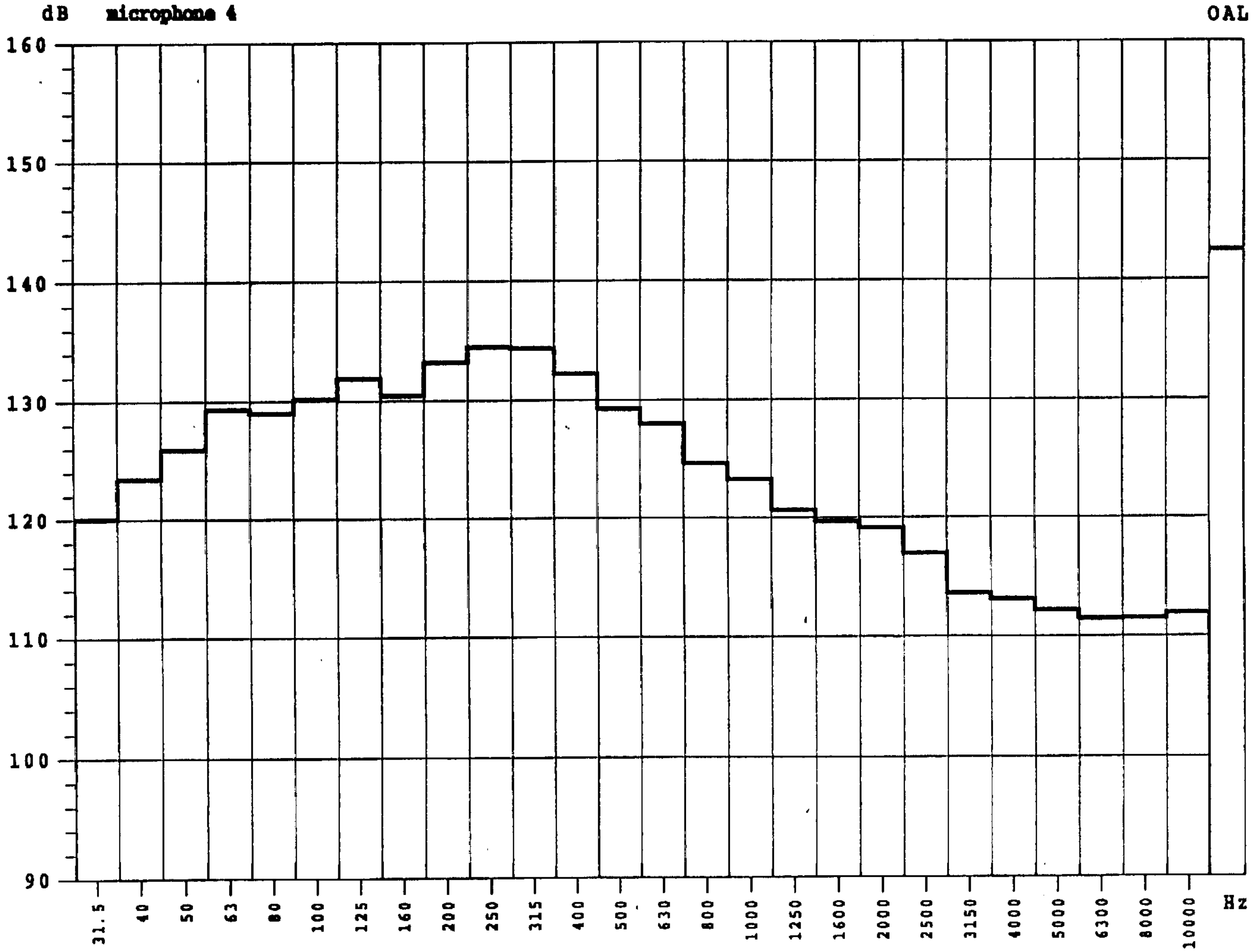
WYLE LABORATORIES
ACOUSTIC TEST
COMPOSITE OPTICS, INC. 43899, PANEL
0dB CONTROL MIC -3 — JANUARY 28, 2000



31.5 Hz	114.6 dB
40.0 Hz	125.1 dB
50.0 Hz	123.7 dB
63.0 Hz	132.3 dB
80.0 Hz	129.9 dB
100.0 Hz	130.4 dB
125.0 Hz	131.3 dB
160.0 Hz	130.1 dB
200.0 Hz	133.2 dB
250.0 Hz	133.3 dB
315.0 Hz	134.3 dB
400.0 Hz	133.6 dB
500.0 Hz	131.4 dB
630.0 Hz	127.0 dB
800.0 Hz	124.9 dB
1000.0 Hz	122.7 dB
1250.0 Hz	120.7 dB
1600.0 Hz	119.6 dB
2000.0 Hz	119.3 dB
2500.0 Hz	117.1 dB
3150.0 Hz	113.6 dB
4000.0 Hz	113.2 dB
5000.0 Hz	112.7 dB
6300.0 Hz	111.7 dB
8000.0 Hz	112.2 dB
10000.0 Hz	112.3 dB

OASPL: 142.8 dB

WYLE LABORATORIES
ACOUSTIC TEST
COMPOSITE OPTICS, INC. 43899, PANEL
0dB CONTROL MIC -4 — JANUARY 28, 2000



31.5 Hz	120.0 dB
40.0 Hz	123.5 dB
50.0 Hz	125.9 dB
63.0 Hz	129.3 dB
80.0 Hz	129.0 dB
100.0 Hz	130.2 dB
125.0 Hz	131.9 dB
160.0 Hz	130.5 dB
200.0 Hz	133.2 dB
250.0 Hz	134.5 dB
315.0 Hz	134.4 dB
400.0 Hz	132.2 dB
500.0 Hz	129.3 dB
630.0 Hz	128.0 dB
800.0 Hz	124.6 dB
1000.0 Hz	123.3 dB
1250.0 Hz	120.7 dB
1600.0 Hz	119.7 dB
2000.0 Hz	119.1 dB
2500.0 Hz	117.0 dB
3150.0 Hz	113.6 dB
4000.0 Hz	113.1 dB
5000.0 Hz	112.2 dB
6300.0 Hz	111.5 dB
8000.0 Hz	111.5 dB
10000.0 Hz	111.9 dB

OASPL: 142.5 dB

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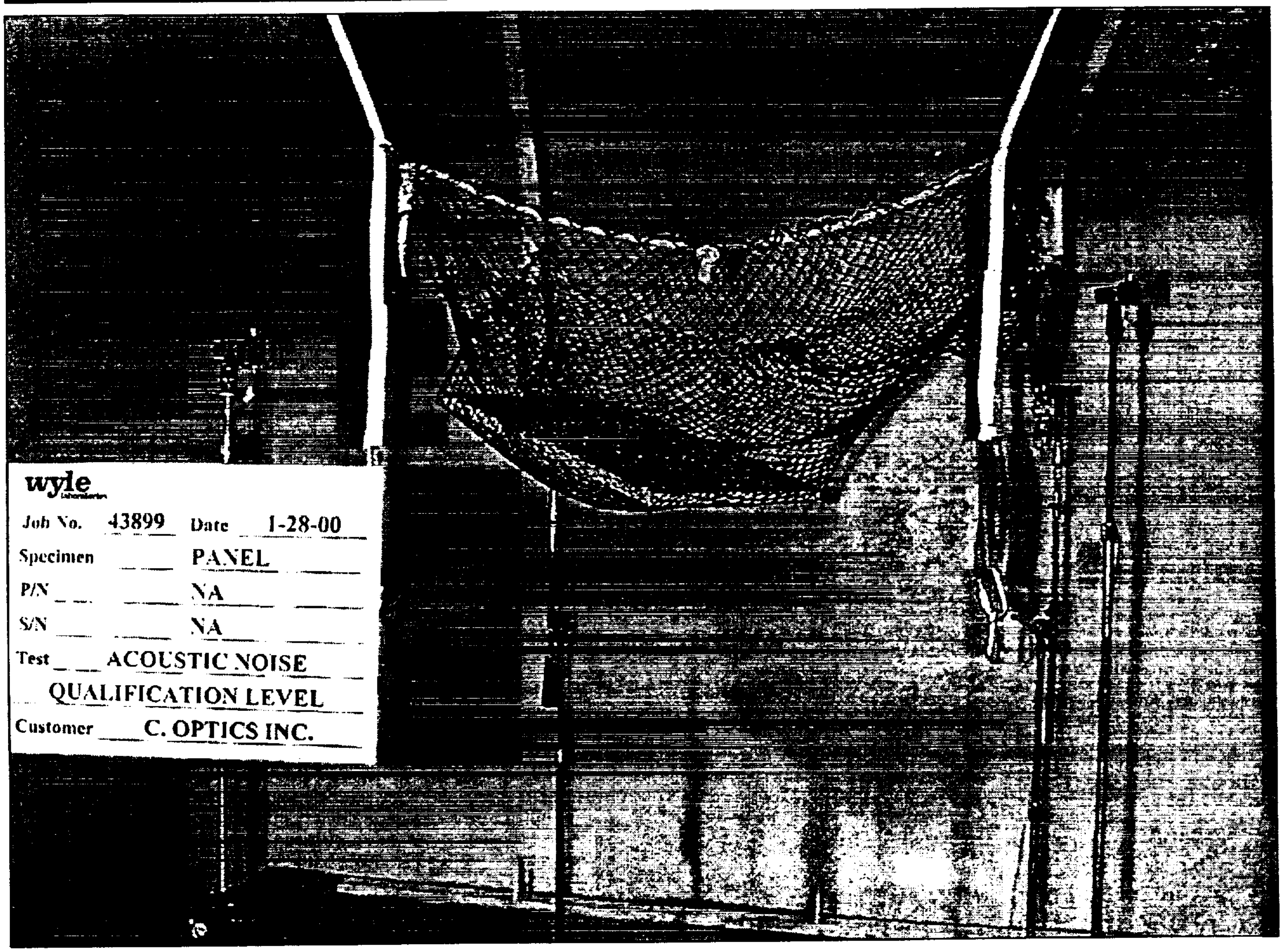

PHOTOGRAPH 1

ACOUSTIC NOISE TEST SETUP

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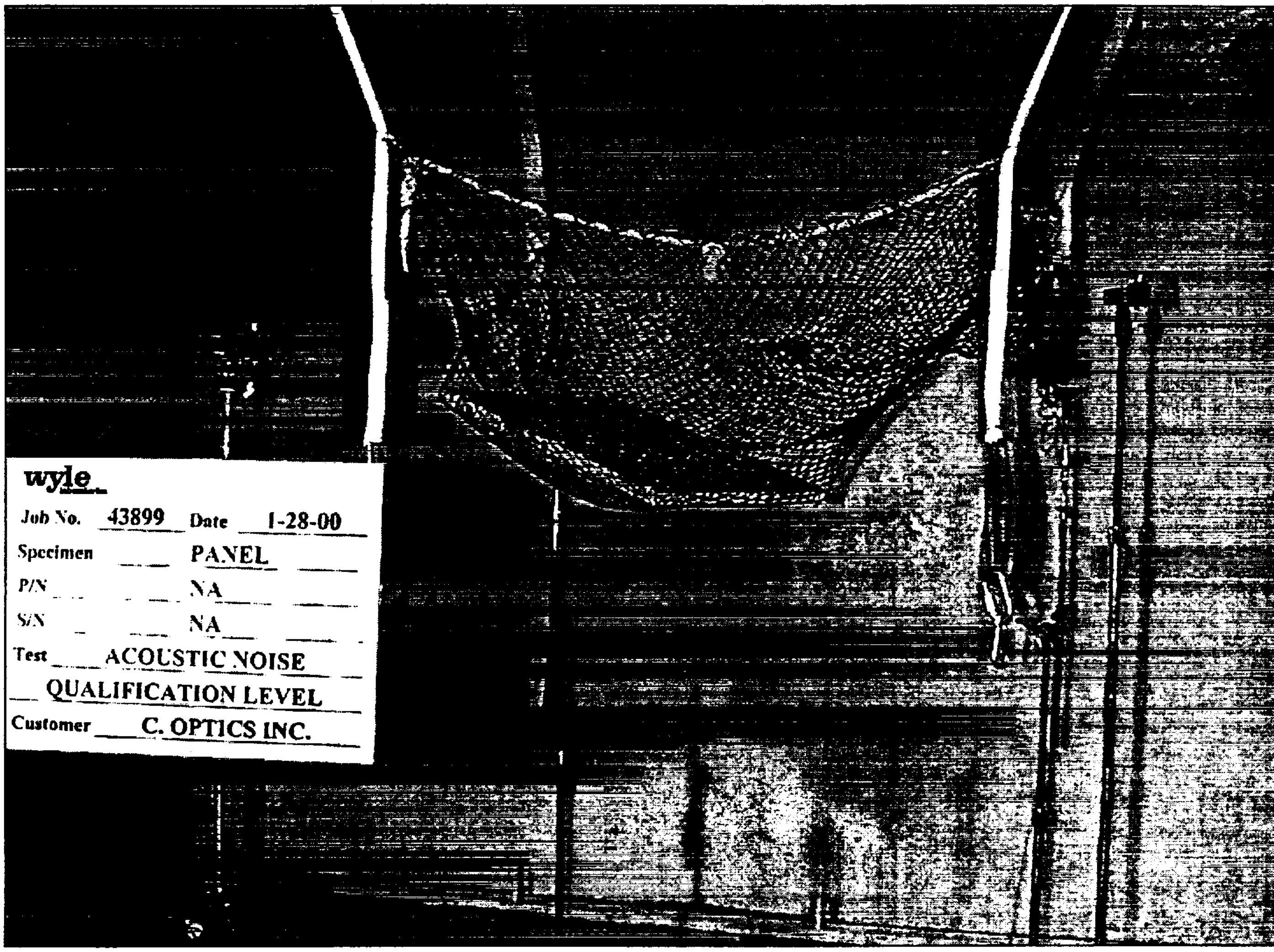

PHOTOGRAPH 1

ACOUSTIC NOISE TEST SETUP

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13. ABSTRACT *(Maximum 200 words)*

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 meat 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.

14. SUBJECT TERMS
Electrostatic, Solar Panels, Photovoltaics, Environmental Interactions, Graphite Fiber Reinforced Composites

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