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AMORPHOUS SILICON PHOTOVOLTAIC MODULES AND TEST DEVICES DESIGN, FABRICATION AND TESTING

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In July of 1984, Hughes and JPL initiated a contract for Hughes to design, fabricate and test 10 thin film Amorphous Silicon (a-Si) photovoltaic power modules. These modules were slated to be 1 ft x 4 ft in size. They were to be preceded by the delivery of 10 a-Si 4 in. square test devices.

This effort is very timely since thin film PV development has progressed to the point where intermediate load power applications are on the horizon. It's important to know if current a-Si submodule design and manufacturing processes yield a product that is compatible with the packaging needed to meet a 20 to 30 year life span expectancy. The term submodule is assigned to an interconnected assembly of 28 a-Si cells deposited on a 1 foot square glass superstrate. Our next viewgraph depicts a set of four of these submodules. Two are shown face up and two are inverted. Naturally these assemblies are equipped with electrical terminations which appear in the picture as copper tabs at the four corners of the inverted submodules. It is these submodules that we are interconnecting and packaging into power modules, as opposed to the interconnected individual crystalline cells packaged into todays PV modules.

The primary purpose of my talk today is to acquaint you with the experience gained and the lessons learned while performing this task. Since the primary objective of this effort is to evolve an environmentally survivable thin film module, an integral part of this program is the testing and evaluation of the various materials and manufacturing processes used in module fabrication. The test results help us identify and rectify problem areas which may prevent us from achieving the desired survivability. Final environmental testing will be performed by JPL to their Block V Design and Test Specifications for Intermediate load applications. To facilitate this testing, ten 4 in. square test devices have been delivered to JPL to allow them to characterize the spectral response of the a-Si cells and to build standard cells.

The a-Si test devices and submodules for this program were bought from an a-Si submodule manufacturer with whom Hughes has agreed to collaborate in establishing the requisite submodule design changes required to produce a field ready module. Some of these changes will be discussed later. The test devices are 4 in. squares cut from a 1 ft square submodule. This small device has 8 series interconnected a-Si cells which are terminated at the opposing edges. The rear surface configuration is shown on our next viewgraph. The rear surface is coated with a black vinyl protective paint with exception of the two termination pads and a bare strip down the center. This strip was provided at JPL's request to allow contact to the individual a-Si cells for detailed output characterization. The terminations consist of 1/2 in. wide copper foil tape with a conductive adhesive. This acrylic adhesive contains a 3% dispersion of tiny copper particles equal in size to the nominal adhesive thickness. It is applied full length along opposite edges of the test cell.

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Shortly after contract award, a kickoff meeting was held at JPL to share views on module design and testing. JPL cautioned us to seam the submodule edges to help minimize breakage due to thermally induced stresses. A lesson learned from the JPL Block II module installation at natural bridges is that a substantial percentage of modules having untempered glass superstrates have broken during their several years of environmental exposure. This information was relayed to the submodule manufacturer and the submodules were received with seamed edges.

The design philosophy employed during the module design effort is quite conservative in that it borrows heavily from current module design practice. Our next viewgraph lists the design features shared with current production modules.

The tempered low iron glass superstrate has become a standard feature on almost all intermediate load application modules. It withstands the physical rigors of JPL's hailstone, wind loading and thermal testing and also has an excellent track record of environmental survivability.

EVA has developed into the encapsulant of choice for most PV module manufacturers. Its lower cost, hygroscopic nature, thermosetting properties, and ease of processing have gained it a leading position over the silicones and PVB which were formerly popular.

Tedlar is a very commonly used module back cover. Its availability and excellent performance history made it our choice. Conveniently, it is available already laminated to a sheet of EVA.

An AMP J-box with its accommodation for an integral bypass diode was chosen as a simple, reliable module termination. Its successful history and availability made it an obvious choice. The fact that AMP donated them for this project is appreciated.

The extruded aluminum frame sections designed for this job are depicted on our next viewgraph. Again, our goal was to minimize surprises. The sections are simple, open extrusions designed for self-tapping screw assembly. The only reason that an available extrusion couldn't be applied to this project is the extrusion's 0.4 in. wide laminate groove. This wide groove is required to grip the double glass laminate plus an adequate rubber gasket.

Our next viewgraph shows a typical section through a modules side rail/laminate interface. Beginning at the top we have the superstrate glass laminated to the a-Si submodule with a layer of EVA. The tedlar back cover is also bonded to the submodule back surfaces with EVA. The copper tape terminal is shown in section as it runs along the entire length of both module side rails.

Surrounding the entire periphery of each laminate is a layer of Kapton film tape. An enthusiastic vendor reported that this tape has a dielectric strength of 10,000 volts and it was thought that surely this would readily handle the 3,000 volt Hi Pot test requirement. To assure the electrical isolation between the circuit and the frame, a 0.06 thick rubber extrusion was applied along all edges of the laminate. This gasket was to protect the film tape from damaging contact with the frame and also to provide additional electrical insulation.

Figure 7 is a schematic diagram of the module. The 28 cell series are oriented across the module width and are interconnected in parallel along the modules 4 ft sides. The AMP J-box is located near a module end and accommodates the bypass diode.

Figure 8 defines the material used to wire the laminate assembly. Redundant copper ribbons join each submodule terminal end. Heavier copper ribbons bring the module output to the J-box area where they are attached to copper solder pads. After lamination, a 1/2 in. square of tedlar and EVA is removed from each solder pad and the AMP J-box leads are soldered on.

With the basic module design established and the required hardware and tools gathered, the fabrication effort began.

Component and process testing is an integral part of this type of prototype development effort and in this case it began with the submodule. The search for a locally available facility capable of accurately evaluating a-Si performance proved fruitless. JPL agreed that a comparative output evaluation would be sufficient to allow the matching of submodule peak power voltages for efficient assembly into modules. We were aware that a-Si modules tested in a simulator calibrated for crystalline modules would show a diminished reading, but the 45% loss of output indicated by our measurements on a Spire simulator took us completely by surprise. The submodule manufacturer suggested outdoor testing using a crystalline reference cell. This testing was performed and it resulted in higher output measurements than the Spire readings. As a final check, three submodules were returned and their initial output measurement was verified. Lamination testing could now begin.

Test laminations were made to settle two questions. First, would a craneglass layer be required between the glass panes to facilitate laminate evacuation and second, would the submodule protective back paint be compatible with the EVA encapsulant? The craneglass showed up as milky swirls in the first lamination sample, but destruction of the first laminate revealed a strong bond between the manufacturer's paint and our EVA. Test laminate No. 2 showed that eliminating the craneglass caused no visible lamination voids or defects.

Following lamination testing, submodules were grouped by their peak output voltage and functional laminate stacks were assembled. They were then interconnected in the manner shown on our viewgraph. Adjacent submodule edges were cushioned with a layer of teflon film tape to prevent contact. Kapton tape was used to hold the submodules together and in proper location on the tempered glass superstrate since the lamination tests had shown that the submodules tended to shift during lamination.

With all the known possibilities for failure accounted for, we laminated our first two laminates on a Spire type laminator. The result was disappointing. One of the submodules had broken during lamination resulting in a 50% lamination yield on our first attempt. Obviously our 30% failure allowance would not cover this low yield. We then used a laminating oven. It was rationalized that the oven's air heating and cooling would yield a softer laminating environment.

Oven lamination didn't yield improved results. Submodules kept breaking. We tried adding 15 minutes to the cooloff period. At first we thought it was helping - until the next submodule broke. Metal strips of laminate thickness were then placed around the laminate stacks to relieve possible edge pressure from the flexible laminating envelope cover - also to n avail.

Since our resources for lamination process improvement were exhausted, we were forced to look to the submodules for a solution. The edge quality of these units, while seamed, could still be improved. The submodule edges sometimes contained a number of chips, notches, and cracks. The seaming operation removed the sharp edges while the larger imperfections remained. It is felt that these defects were a possible source of submodule breakage and steps are being taken to eliminate this possibility in future laminations.

After our module component resources were exhausted, we had 7 visually acceptable laminates. These units had patches of tedlar and EVA removed from their terminal solder pads, the AMP terminal loops were soldered on, and the AMP J-Boxes bonded in place with the recommended scotchgard #3501 epoxy.

The terminated laminates were then electrically tested and the numbe of acceptable units fell from 7 to 6. The low output module was the first one successful laminated and we failed to insulate the bus strips leading to the solder pads on this laminate. It seems likely that the copper ribbon or a solder pad shorted through the submodules protective paint to the electrically active aluminum cell layer beneath. The healthy laminates were then edge-taped with kapton film to provide the HiPot insulation and rubber gasket segments were cut and installed into the framing parts.

Initial attempts to fit a frame to a laminate were foiled by a sticky, incompletely cured rubber gasket material. This material exhibited a tendency for the gasket channel legs to fold into the frame groove rather than slip over the laminate. To ease the assembly task, a rubber lubricant was applied to the gasket and laminate edges. Assembly then progressed smoothly.

After framing and a final cleanup, the modules (as shown on our next slide) were taken to the HiPot testing area. An Associated Research 5 KV tester was used. On the initial HiPot test, the module failed so completely that the tester was deemed suspect. Testing a standard module restored our confidence in the tester. We tested more amorphous modules with continued failures. Subsequent investigation showed the rubber lubricant to be quite conductive and the rubber insulating gasket without lubricant passed an Amp of current over an inch of length at 500 volts. Obviously, improved insulating materials and methods are called for.

A meeting was held at JPL on the eleventh of this month to discuss design improvements. A few salient points were agreed on. First, the sharp corners at the submodule edge imperfections are electrical stress points which can increase the electrical pressure significantly during HiPot testing. We now have another reason to improve submodule edge finish. Second, rubber is not necessarily a good insulator. Fillers can increase conductivity dramatically - carbon black being a leading contender for this honor. Third, the distance from the module circuit to the frame should be increased. Crystalline modules typically have the circuits inboard about 1/4 to 1/2 in. from the frame. Our modules have the a-Si circuit about a sixteenth of an inch from the aluminum frame.

These lessons have been integrated into an improved module design whose edge configuration is depicted on Figure 10. To implement this new arrangement, we will acquire superstrate glass about 1/2 in. larger in length and width. While this change adds a 1/8 in. wide inactive border around the modules periphery, it will also eliminate the 2% average output loss experienced by our laminates due to frame shading. In fact, the elimination of cell shading at oblique sun angles will further reduce module efficiency losses in the field.

To accommodate the larger superstrate, new longer frame pieces will be fabricated and a thicker gasket of greatly improved electrical resistance will be used. EPDM and silicone rubber both promise to provide the required insulation; HiPot testing them will firm up the choice. The kapton tape has been eliminated from this design. We feel that the HiPot requirement can be met without it and at $26.00 per roll, it is not conducive to the attainment of low cost goals.

SUMMARY

The Submodules initially received were very early production units. Future units are expected to reflect improvements in glass cutting and finishing processes. We are looking forward to greatly improved lamination yields and to an acceptable HiPot capability in the future.

Figure 1. JPL Contract No. BD-802409

WITH: HUGHES AIRCRAFT COMPANY

FOR: AMORPHOUS SILICON PHOTOVOLTAIC MODULES AND TEST DEVICES

DELIVERABLES: 10 EA. - 1 FT. X 4 FT. aSi MODULES WITH A MINIMUM OUTPUT EFFICIENCY OF 3 PERCENT

10 EA. - 4 INCH SQUARE aSi TEST DEVICES

6 EA. - DESIGN DRAWING SETS

1 EA. - AN ORAL PRESENTATION WITH 25 SETS OF PRESENTATION MATERIAL

DURATION: 11 MONTHS

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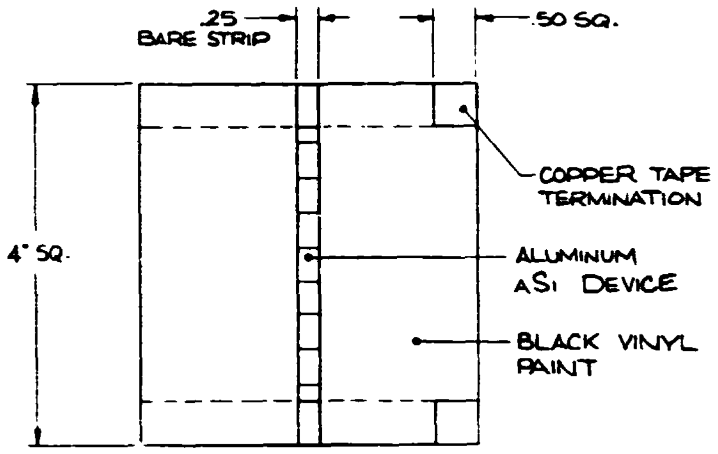
Figure 2. Four Submodules Prior to Final Framing Assembly Steps

Figure 3. a-Si Test Device Details



REAR VIEW

Figure 4. Shared Module Design Features

- TEMPERED LOW IRON GLASS SUPERSTRATE
- EVA ENCAPSULANT
- TEDLAR BACK FILM
- AMP NO. 121033-1 J-BOX WITH BYPASS DIODE
- EXTRUDED ALUMINUM FRAME

Figure 5. a-Si Module Frame Sections

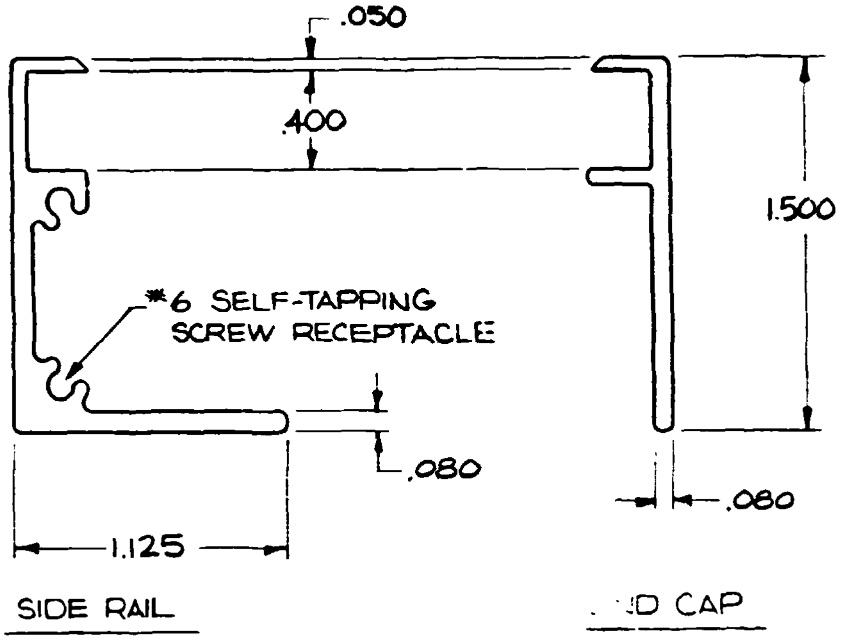


Figure 6. a-Si Module Edge Section

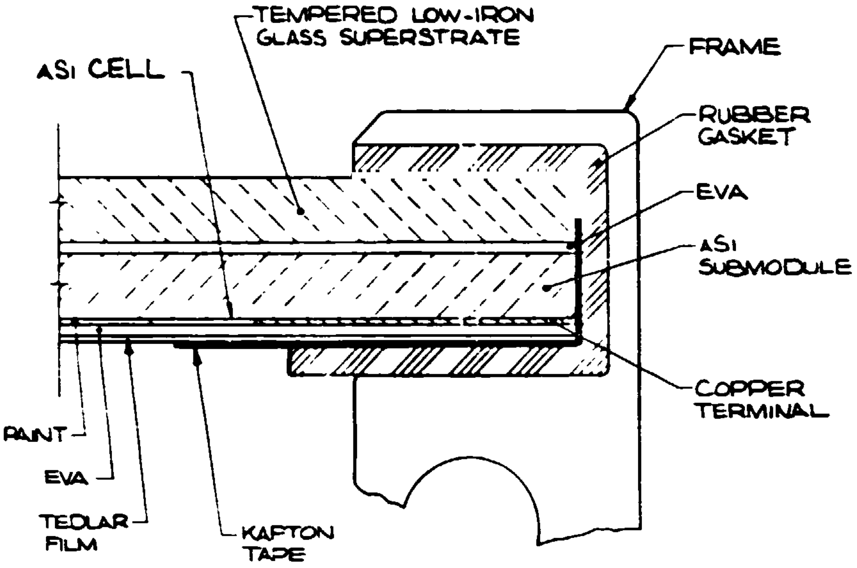


Figure 7. a-Si Module Electrical Schematic

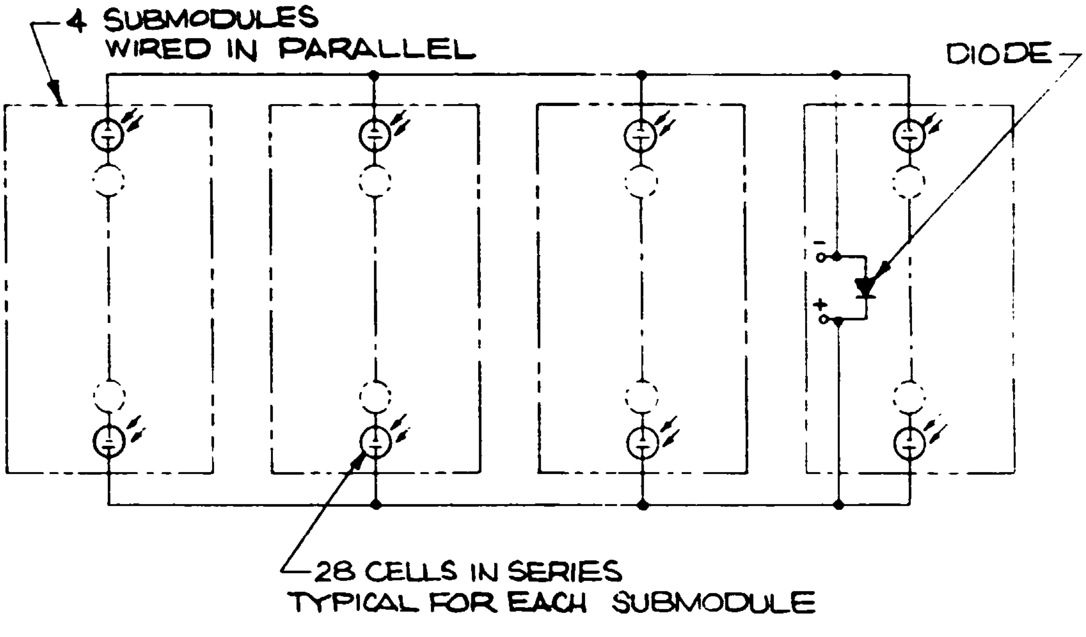


Figure 8. a-Si Module Interconnections

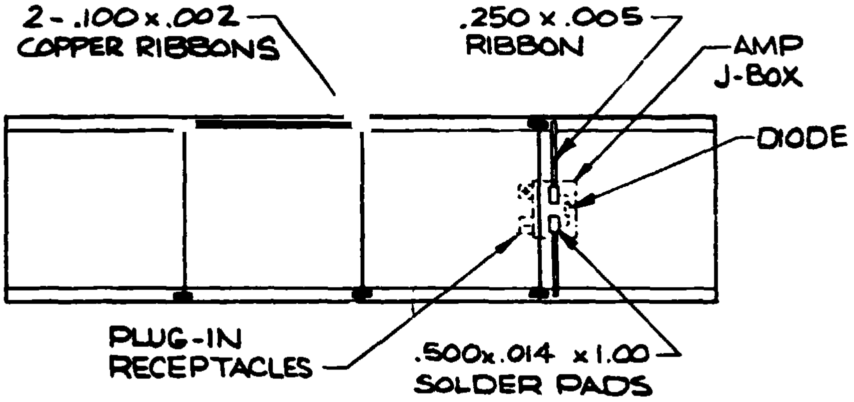


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Figure 9. Two Framed Module Assemblies

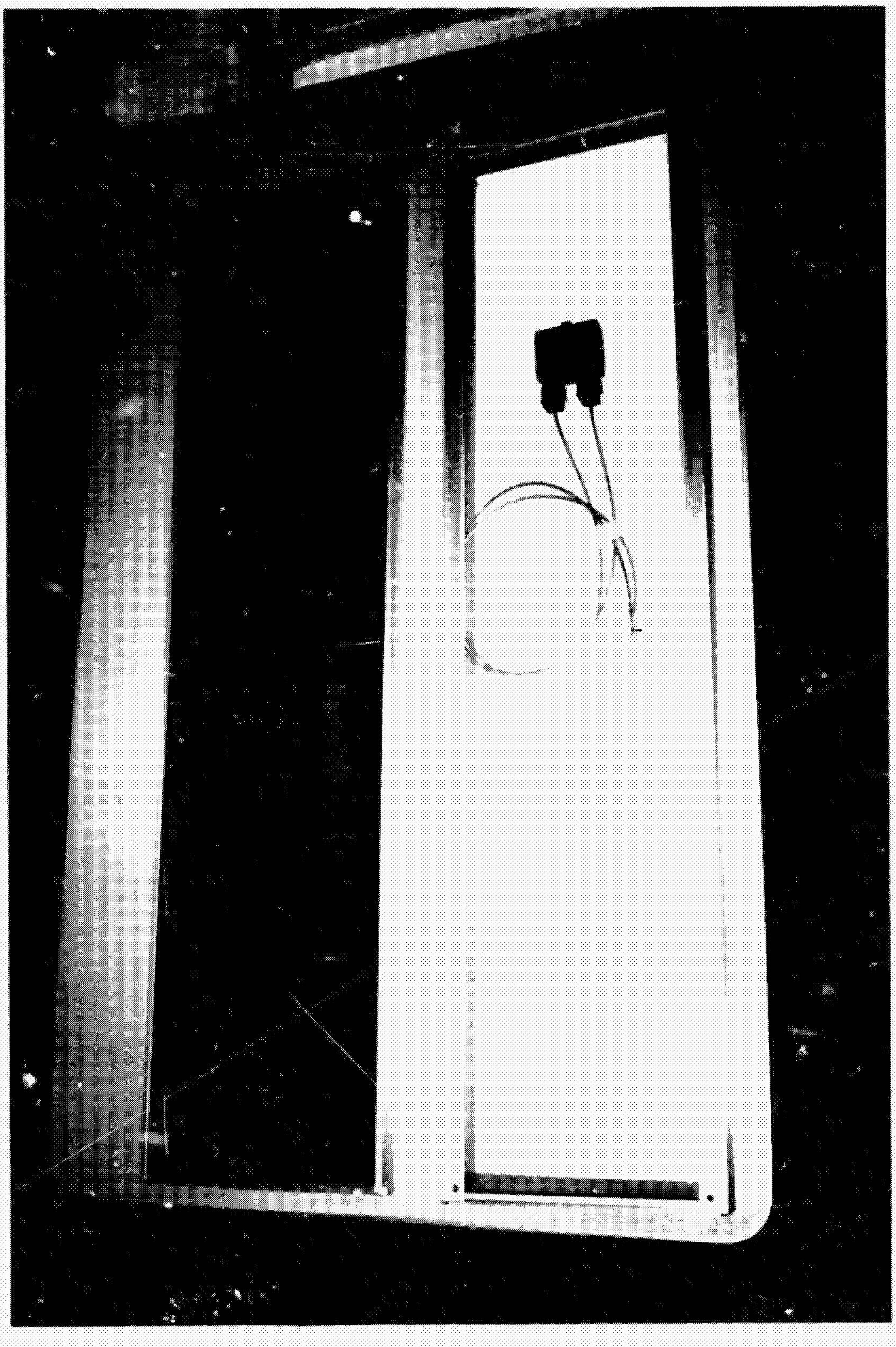
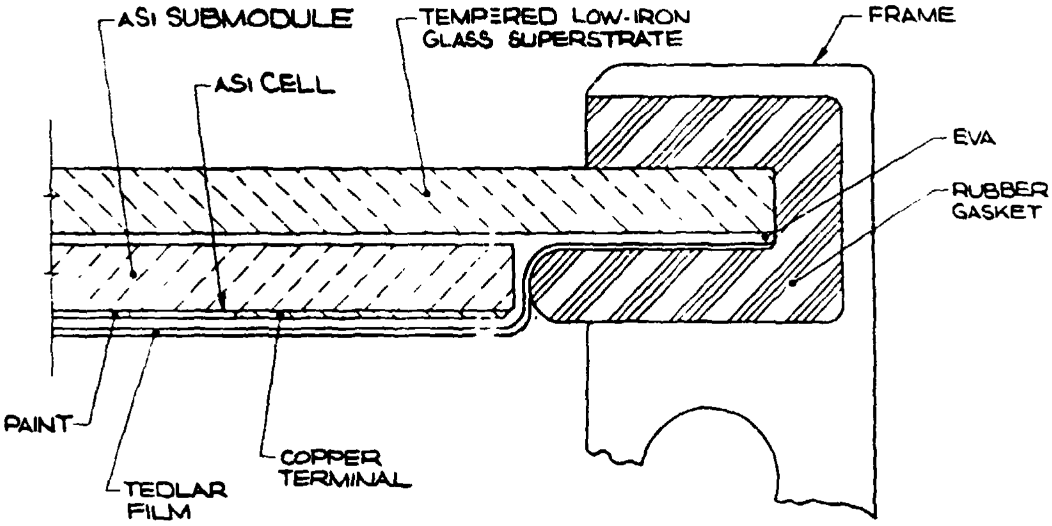


Figure 10. Improved Module Edge Section



DISCUSSION

YERKES: I would like to know, after you have gone through this, what your opinions are about, say, offering a mass-produced module for large-scale use that uses a lot of 1 ft^2 parts? Is that something you think could be done cheaply, or should we get away from that? What are your thoughts on that, now that you have done it?

VAN LEEUWEN: Well, I think laminating several 1 ft^2 parts into a larger module is a good way to lose a lot of good pieces, because I have not been able to disassemble a laminate, and I don't know of anyone else that has. And if you can successfully produce submodules of the size of the finished module it would eliminate the frustration of having one pane break out of four and having to throw all four away. So I would think that the larger amorphous part would be more desirable. If lamination yields and techniques are improving to the point where yield is high, then it probably is a very viable thing to do that. However, you are still burdened with the interconnecting task, putting several pieces together into a large one.

LESK: What is the advantage of using two panes of glass with EVA between, instead of one for the upper part of the module?

VAN LEEUWEN: This submodule is a non-tempered unit. Its strength is, I think, not high. The baseline requirements of this effort were to produce something that would pass the JPL Block V test, which includes hailstone impact.

ROYAL: You mentioned that you had done some measurements. Did you do indoor measurements, and if so, where and how did you do it?

VAN LEEUWEN: On a Spire simulator set up for testing crystalline modules with a crystalline standard. A standard simulator set up to test a crystalline module -- if you put an amorphous module in it, the power will fall almost by half. The spectral response must be radically different to do that, and going outdoors then brought this up less than half way back to the original readings.

CLARK: We were able to filter the reference cell on the Spire tester, crank up the light level and obtain readings within 10% to 12% accuracy. You can use the Spire tester if you fix the reference cell to respond closer to what amorphous might.