ERDA/JPL/954607-77/1
Distribution Category UC-63

QUARTERLY REPORT NO. 1

DEVELOPMENT AND TESTING OF SHINGLE-TYPE SOLAR CELL MODULES

JPL CONTRACT NO. 954607

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REPORT DATE: OCTOBER 5, 1977

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, under NASA Contract NAS7-100 for the U. S. Energy Research and Development Administration, Division of Solar Energy. The JPL Low-Cost Silicon Solar Array Project is funded by ERDA and forms part of the ERDA Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays.

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ABSTRACT

The initial task efforts to develop a shingle-type solar cell module, which is suitable for use in place of shingles on the sloping roof of residential or commercial buildings, are reported. Several promising shingle module design concepts are presented. Based on these concepts, development efforts are proceeding on bonding of solar cells to glass with polyvinyl butyral film, laminating the multilayer shingle substrate, and embedding solar cells within a methyl methacrylate casting. Testing of various fastener approaches for the interconnection of adjacent modules on the roof has been started. The configuration of each of these interconnector concepts is discussed.

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SECTION 1
SUMMARY

Two basic design concepts for photovoltaic roof shingle modules have been advanced to form the basis for the initial evaluation tasks which are intended to develop the data on which to formulate a detailed module design solution. Three important design areas have been addressed during this initial evaluation period. The first of these relates to the configuration of the shingle substrate which constitutes that flexible portion of the module which is overlapped by the higher courses of the roof installation. A composite laminate construction consisting of outer layers of B.F. Goodrich *FLEXSEAL* and an epichlorohydrin closed cell foam core has been selected for the substrate. The *FLEXSEAL* roofing system uses a synthetic rubber called *HYPALON* which is supplied by DuPont. A nylon fabric reinforced laminate of this *HYPALON* film has been specified to insure adequate tear resistance and tensile strength for this application.

The second of these initial evaluation tasks is concerned with the solar cell mounting within the shingle module. This mounting arrangement must be adequate to protect the solar cells from breakage during the handling which is associated with installation and to provide the environmental protection necessary to enable the solar cells to perform with a design life goal of 15 years. Two design solutions are being developed to accomplish this solar cell mounting. The first of these designs sandwiches the interconnected solar cells between a sheet of tempered low-iron glass on the front surface and a sheet of fiberglass/epoxy on the rear side. The solar cells are bonded to this glass coverplate with polyvinyl butyral film. RTV 162 is used to fill-in the intervening space between these two sheets.

A second, and potentially lower cost, solution to the solar cell mounting problem involves embedding the interconnected solar cells within a methyl methacrylate casting. This approach is being pursued with the aid of a firm which specializes in such processing.

The method to be used for the interconnection of adjacent modules on the roof is the subject of the last of these initial evaluation tasks. Three candidate design approaches for this

interconnection have been identified. Simulated shingles, which are joined together with each of these interconnector types, have been fabricated and assembled onto a roof section test fixture. This specimen is currently undergoing a series of tests which include random vibration, temperature cycling and humidity exposure.

SECTION 2

INTRODUCTION

The general scope of work under this contract involves the design, development, fabrication and testing of a solar cell module which is suitable for use in place of shingles on the sloping roof of residential or commercial buildings. Modules of this type employ a semi-flexible substrate which is suitable for mounting on an independent rigid surface such as plywood roof sheathing. As specified in the contract statement of work, these modules shall be capable of producing an electrical power output of 80 W/m^2 of installed module area at a module temperature of $60^{o}C$ with an insolation of 1 kW/m^2. The installed weight of these shingle type modules shall not exceed 250 kg/kW of peak power output. As a design goal these modules shall be designed for a leak-free service life of at least fifteen (15) years. An implicit requirement is that the shingle not sustain damage during the normal handling associated with installation on a roof. The vulnerability to the localized bearing loads associated with walking or kneeling on the installed shingles does not constitute a design requirement but will be assessed as part of this development effort. The program is organized into six major tasks as given below.

Task No.	Description
1	Substrate Evaluation and Testing
2	Solar Cell Tray Evaluation and Testing
3	Module Interconnection and Testing
4	Shingle Module Design
5	Fabrication and Acceptance Testing of Modules
6	Qualification Testing of Modules

The first three activities, the progress on which is reported herein, are devoted to the investigation of important design aspects which must be resolved before a satisfactory shingle design can be finalized. However, since the substrate materials selection, solar cell mounting tray design and module interconnector configuration are strongly interrelated, it was first necessary to formulate several specific design concepts for the complete shingle so that the effort on the first three task activities could be focused on these specific design solutions. In this way the development activity associated with these initial efforts could, at the same time, evolve an optimum overall design solution which can be further refined during the Task 4 activity which is scheduled for the next reporting period.

The fabrication and acceptance testing of fifty (50) shingle modules constitutes the Task 5 activity which is scheduled to begin before the end of this year. An additional six modules of each design selected for fabrication will be subjected to a qualification testing program consisting of a temperature cycling test over the range of -40 to 90°C, an humidity exposure test and a mechanical integrity test.

SECTION 3

TECHNICAL DISCUSSION

3.1 DEVELOPMENT OF DESIGN CONCEPTS

The concept of a hexagon-shaped overlapping photovoltaic roof shingle was first introduced during the course of the work on the residential systems portion of ERDA Contract No. EY-76-C-04-3686 as reported in Reference 1. Using this original design approach as a starting point, several other promising concepts for the mounting, support and interconnection of the solar cells within the module have been formulated as shown in Figure 3-1. Concept A on this figure represents the tray construction of this original concept which is represented by the early feasibility model shown in Figure 3-2. In this design an aluminum tray provides the structural rigidity necessary to prevent solar cell breakage during normal handling, which is defined to include the cantilever loading of the entire module weight from a built-in support at any corner of the hexagon. This tray also provided the mold to contain the silicone encapsulant while it cured. A dielectric film (white epoxy paint) was used between the solar cells and the metallic tray to prevent the shorting of solar cells. Extensive handling of this module has revealed that the tray construction, as represented by this design, does not supply the required rigidity to prevent solar cell breakage.

Concept B of Figure 3-1 is an attempt to provide greater flexural rigidity for the solar cell mounting by sandwiching the cells between a sheet of tempered glass on the top surface and a fiberglass/epoxy laminate material on the rear surface.

In Concept C the solar cells are individually encapsulated between discs of strengthened or tempered glass using a sealing method similar to that used in the insulating glass industry. These encapsulated cells are attached to the underside of a transparent substrate film which has been prepared with a printed circuit pattern to permit the N and P leads from each sealed solar cell assembly to be soldered together as indicated in the sketch.

1. "Final Report - Conceptual, Design and Systems Analysis of Photovoltaic Systems," Report No. ALO-3686-14, March 19, 1977

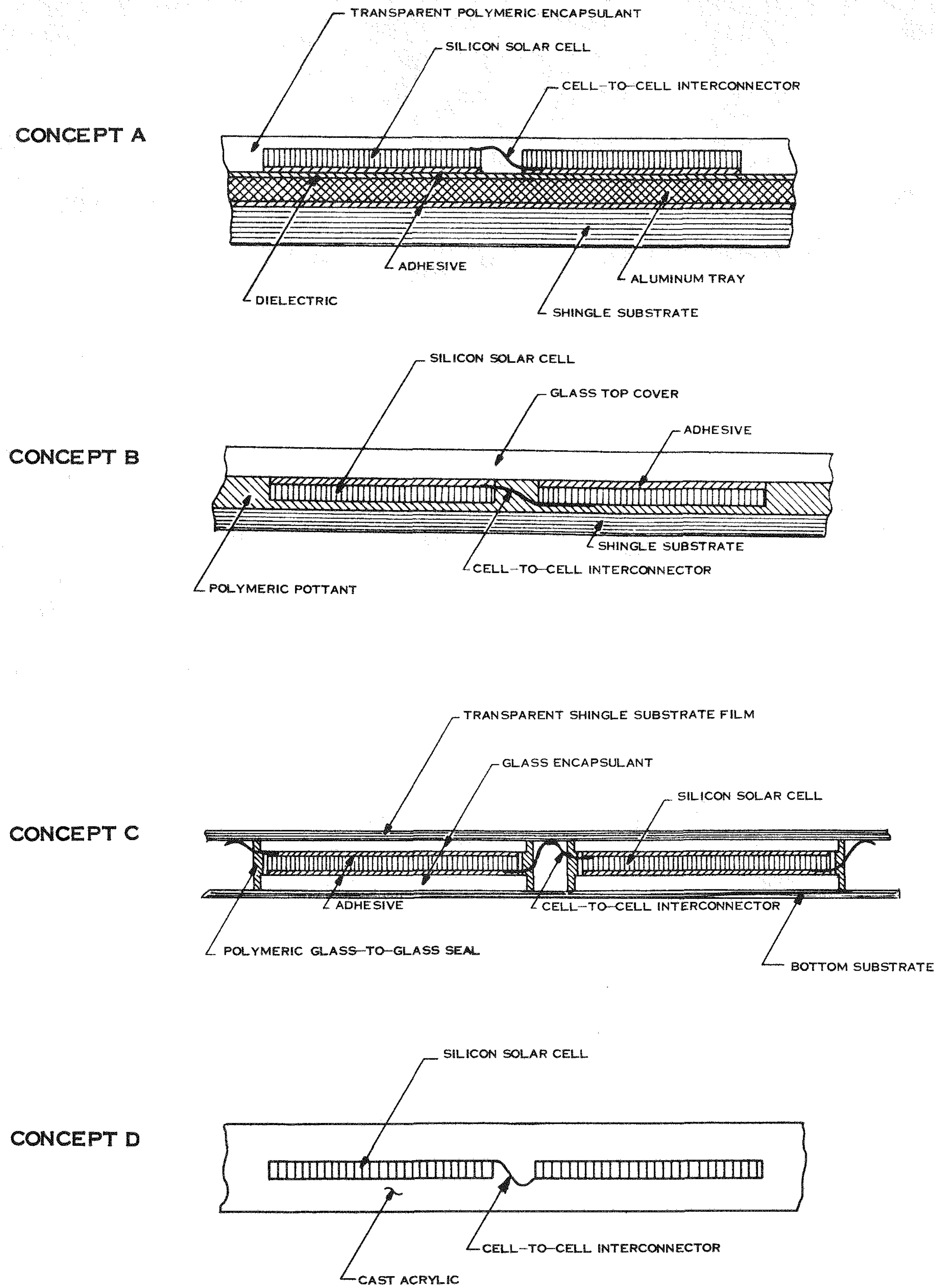

Figure 3-1. Design Concepts for Solar Cell Mounting

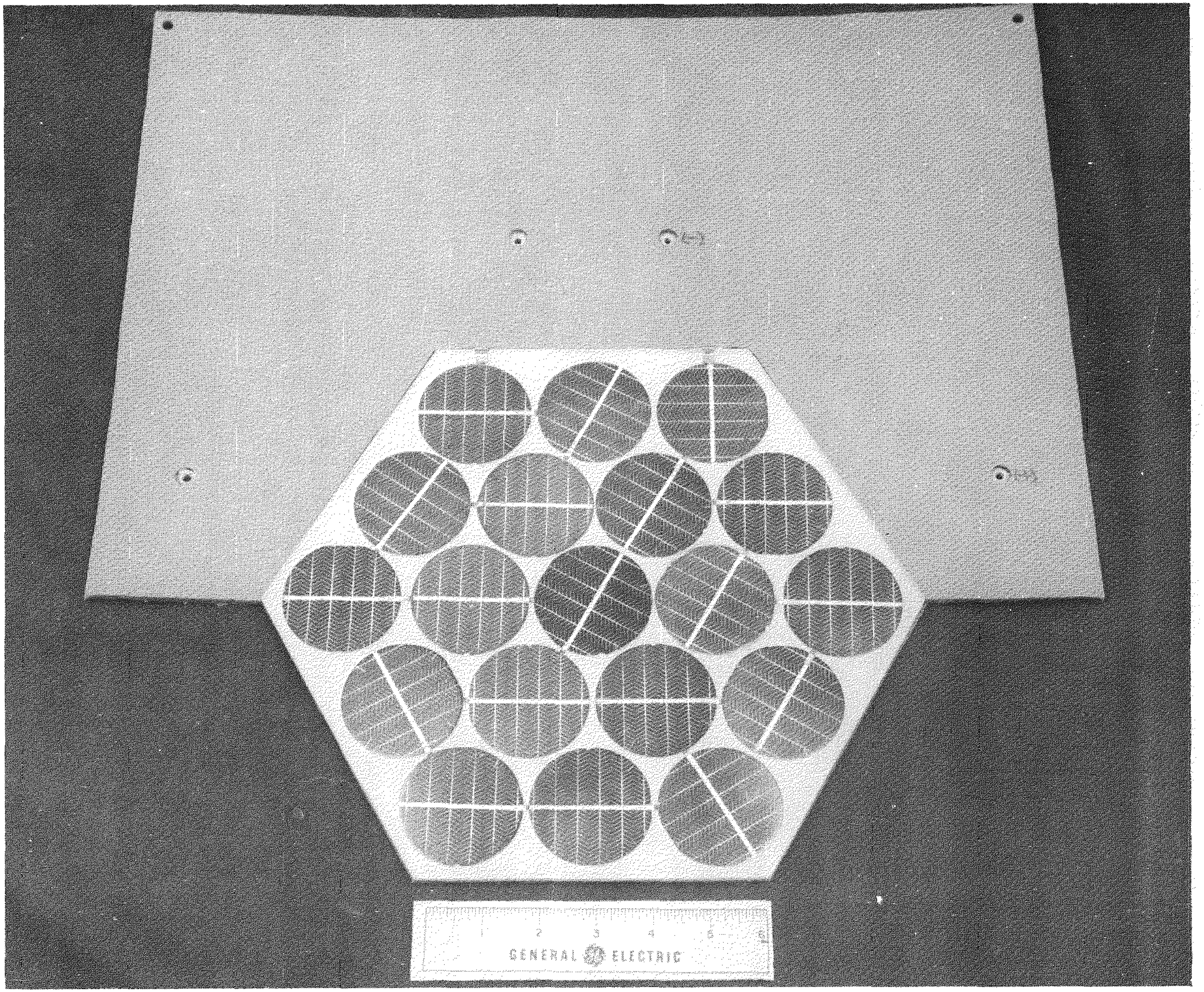

Figure 3-2. Original Design for Shingle-Type Solar Cell Module

Concept D shows an approach to solar cell mounting which encapsulates the interconnected cells within a methyl methacrylate casting. This material has been suggested by at least one of the LSSA encapsulation task contractors as an extremely promising single component encapsulant (Reference 2).

Using these four candidate design concepts an evaluation of the area utilization for the hexagon-shaped modules was performed in order to assess the performance of these various design options relative to the contract requirement to supply 80 Watts per square meter of module area at 60°C. Table 3-1 gives the theoretical maximum area utilization (or packing factor) for perfect circles placed within a hexagon. Both the seven and nineteen cell configurations are of practical interest for the range of solar cell diameters from 53 to 100 mm. Table 3-2 gives a preliminary assessment of the various mounting concepts shown in Figure 3-1 for cell diameters of 53 and 100 mm and for module arrangements of seven and nineteen cells. For Concepts A, B, and D, the assumption is made that the minimum gap between adjacent cells is 0.5 and 1.0 mm for 53 and 100 mm diameter cells, respectively. For Concept C, the maximum diameter of the sealed glass discs is 54.41 and 101.52 mm for 53 and 100 mm diameter cells, respectively, and there is no gap allowed between sealed cell assemblies. For all concepts an edge gap of 1.0 mm has been allowed where the cell circumference is tangent to the perimeter of the hexagon-shape. The total solar cell area per module, referred to in Table 3-2, is calculated based on the nominal cell diameter. The relative transmittance factor has been included in this comparative evaluation to account for the estimated difference between concepts due to differing optical interfaces and index of refraction mismatches. Concept B has been assigned a unity transmittance assuming the application of an effective antireflection coating on the front surface of the glass. Concepts A and D are estimated to have slightly lower overall transmittances due to index of refraction mismatch at the air interface as well as transmission losses in the bulk polymeric material. Concept C has been assigned the highest overall transmission loss because of the additional optical associated with the outer transparent coversheet.

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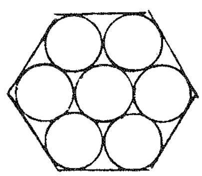
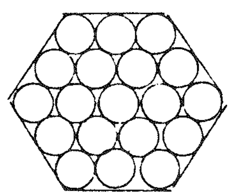
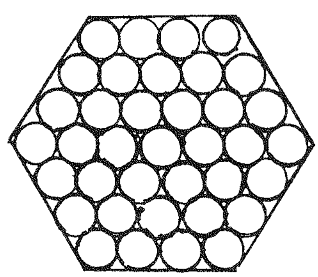
2. "Solar Cell Encapsulation Systems," Springborn Laboratories, presentation at the LSSA 7th Project Integration Meeting, August 10, 1977

Table 3-1. Theoretical Maximum Area Utilization for Circles Inside an Hexagon Shape

Configuration	No. of Cells	Area Utilization
	1	0.9069
	7	0.8505
	19	0.8647
	37	0.8740

The results of this comparative evaluation reveal that the combination of seven cells of 53 mm diameter results in a shingle size which is considered to be too small. On the other hand, nineteen cells of 100 mm diameter yield a shingle size which is considered to be too large. Concept B, with the tempered glass top cover, would seem to provide the best electrical performance. The minimum electrical performance of the 53 mm diameter cells is specified to be 11.1 mW/cm^2 at 60^oC as compared to 9.6 mW/cm^2 for the 100 mm diameter cells. This lower apparent performance for the 100 mm cells makes

Table 3-2. Comparison of Candidate Design Concepts

Concept	Nominal Solar Cell Diameter (mm)	Number of Cells per Module	Total Solar Cell Area per Module (cm^2)	Length of Shingle (mm)	Module Area (cm^2)	Module Area Utilization Factor	Relative Transmittance	Output Power at 60°C (watts)	Areal Power Output at 60°C (watts/m^2 at module area)	Remarks
A1	53	7	154.433	257.3	191.1	0.808	0.99	1.698	88.85	Shingle Too Small
A2	53	19	419.175	419.1	507.0	0.827	0.99	4.608	90.89	
A3	100	7	549.779	482.7	672.6	0.817	0.99	5.225	77.68	
A4	100	19	1492.257	786.5	1785.7	0.836	0.99	14.183	79.43	Shingle Too Large
B1	53	7	154.433	257.3	191.1	0.808	1.00	1.715	89.74	Shingle Too Small
B2	53	19	419.175	419.1	507.0	0.827	1.00	4.655	91.81	
B3	100	7	549.779	482.7	672.6	0.817	1.00	5.278	78.47	
B4	100	19	1492.257	786.5	1785.7	0.836	1.00	14.326	80.23	Shingle Too Large
C1	53	7	154.433	261.0	196.6	0.786	0.98	1.681	85.50	Shingle Too Small
C2	53	19	419.175	424.2	519.5	0.807	0.98	4.562	87.82	
C3	100	7	549.779	483.9	676.0	0.813	0.98	5.172	76.51	
C4	100	19	1492.257	788.5	1794.8	0.831	0.98	14.039	78.22	Shingle Too Large
D1	53	7	154.433	257.3	191.1	0.808	0.99	1.698	88.85	Shingle Too Small
D2	53	19	419.175	419.1	507.0	0.827	0.99	4.608	90.89	
D3	100	7	549.779	482.7	672.6	0.817	0.99	5.225	77.68	
D4	100	19	1492.257	786.5	1785.7	0.836	0.99	14.183	79.43	Shingle Too Large

the arrangement of seven cells of this size seem outside the contract performance goal of 80 W/m^2 at 60^oC. However, it is very likely that the actual measured performances of the 100 diameter cells, on an areal basis, will be as high as that specified for the 53 mm cells. Limited experience with the production of these larger diameter cells would generally make it necessary to quote conservatively low minimum electrical performance specifications. If the 11.1 mW/cm^2 performance is achieved on the 100 mm diameter cells, it will be possible to surpass the 80 W/m^2 contract goal with the seven cell module.

As a result this evaluation and a series of two internal design reviews, the design concepts shown in Figure 3-1 have been narrowed down to two specific shingle design solutions which form the basis for the initial feasibility evaluations and process development activities. The first of these design concept layouts, which is identified as Concept B, is shown in Figure 3-3. This concept employs nineteen 53 mm diameter solar cells which are bonded to the underside of a single hexagon-shaped piece of tempered low-iron glass. The glass coverplate along with the rear side sheet of fiberglass/epoxy supplies the required structural rigidity for the solar cell mounting. The substrate laminate, which will be discussed in Section 3.2, carries the flexible printed circuit which enables the electrical interconnection between adjacent modules on the roof. In the design shown in Figure 3-3, this interconnection is accomplished by a four-pronged nail which penetrates the circular copper pads embedded within the substrate. The design of this fastener is discussed in Section 3.4. Figure 3-4 shows a variation of the Concept B design, called Concept B', which uses sheet metal screws to fasten to modules to the roof. These screws penetrate through holes in the glass coverplate and apply clamping pressure between copper pads on the overlapping shingles. The configuration of this joint is further discussed in Section 3.4.

Figure 3-5 is a layout drawing of Concept D which uses seven 100 mm diameter solar cells which are embedded within a methyl methacrylate casting. The substrate configuration is similar to Concept B except that the flexible printed circuit board has been sandwiched between two layers of the 3.2 mm (0.125 inch) thick foam to accommodate the increased thickness of the casting. The method of module interconnection is similar to the Concept

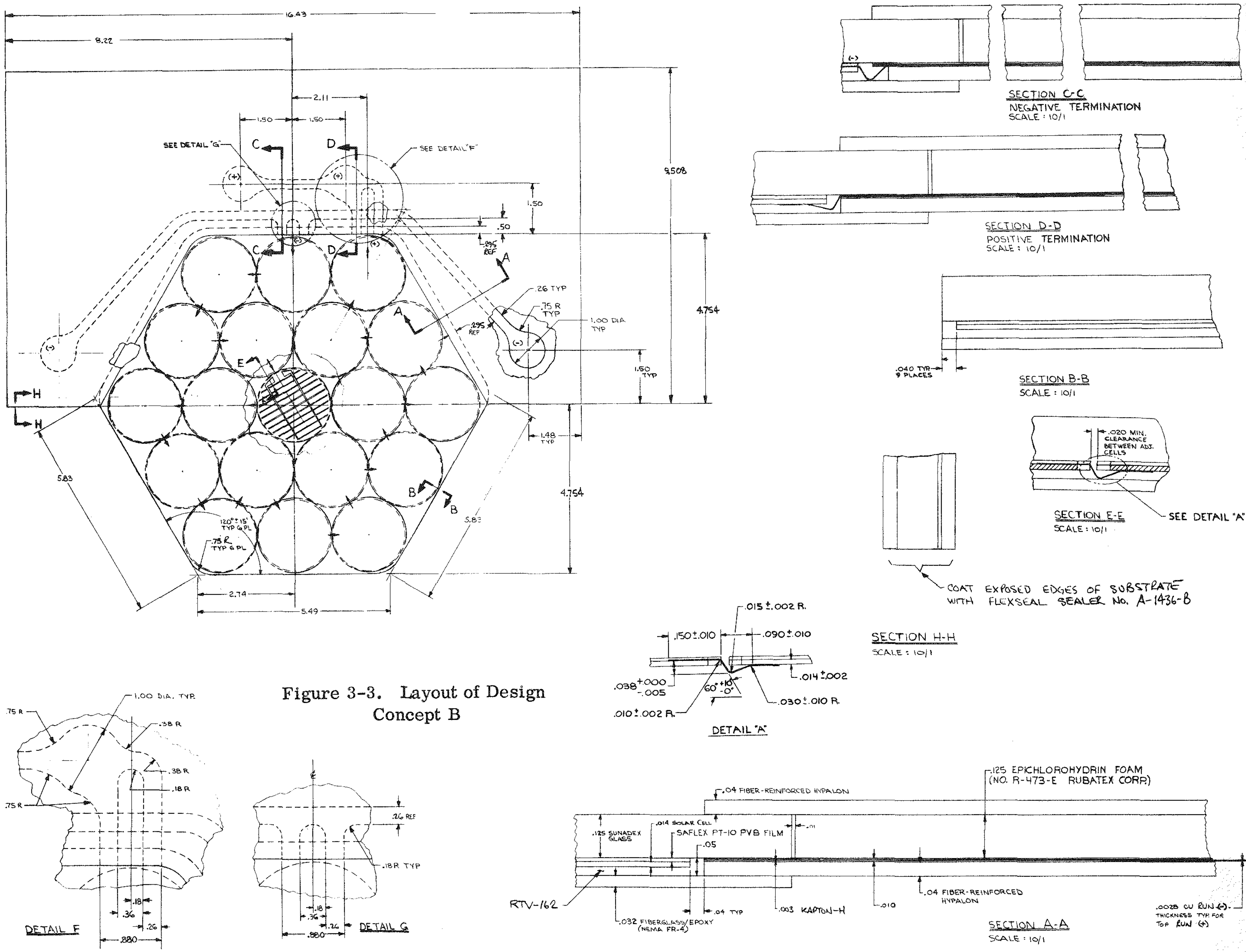
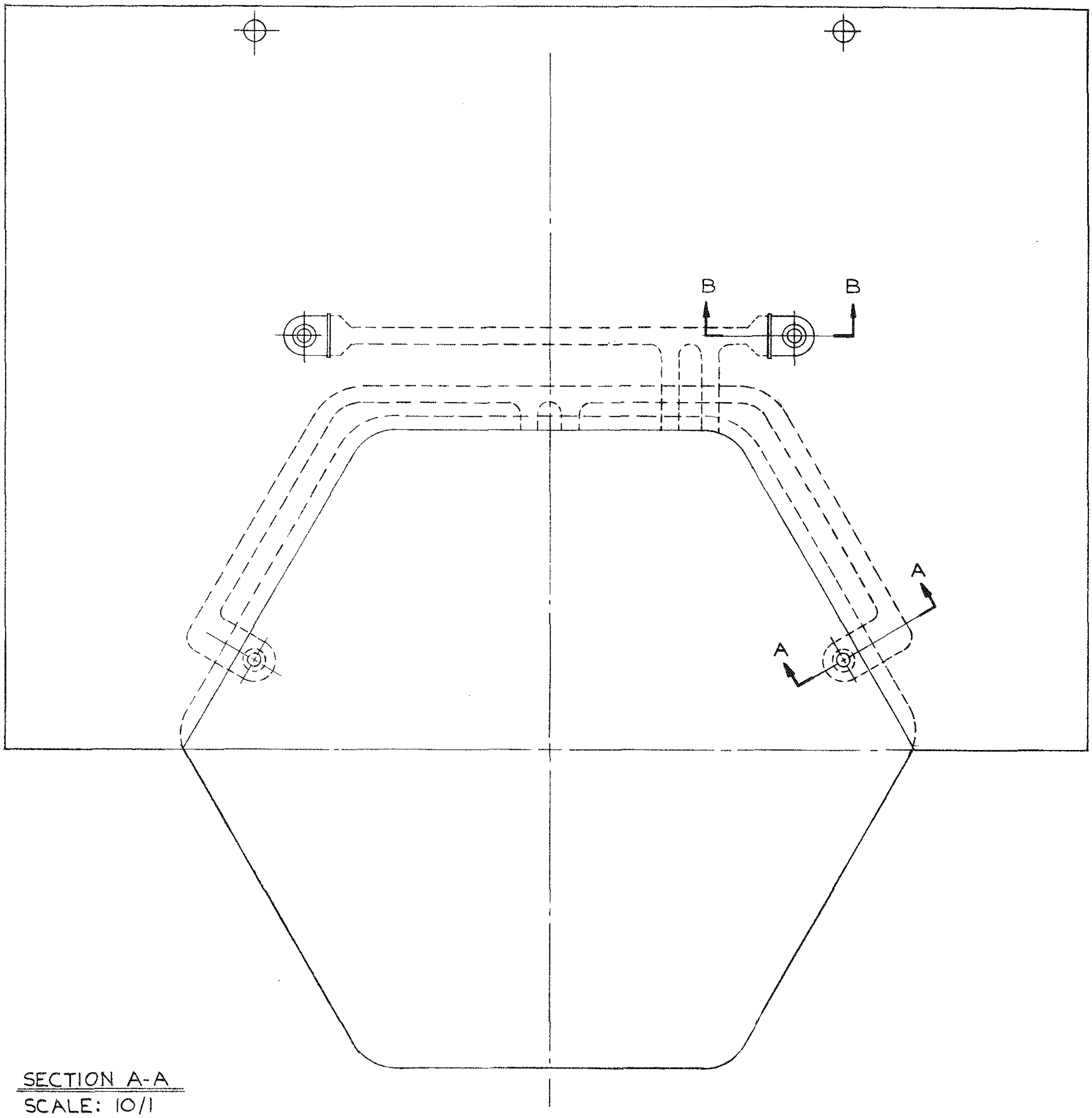


Figure 3-3. Layout of Design Concept B



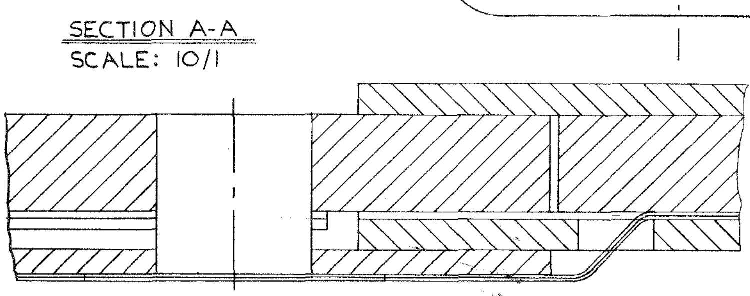
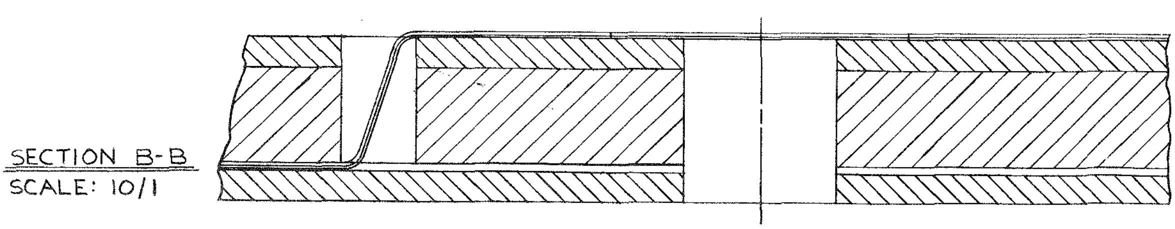


Figure 3-4. Layout of Design Concept B'



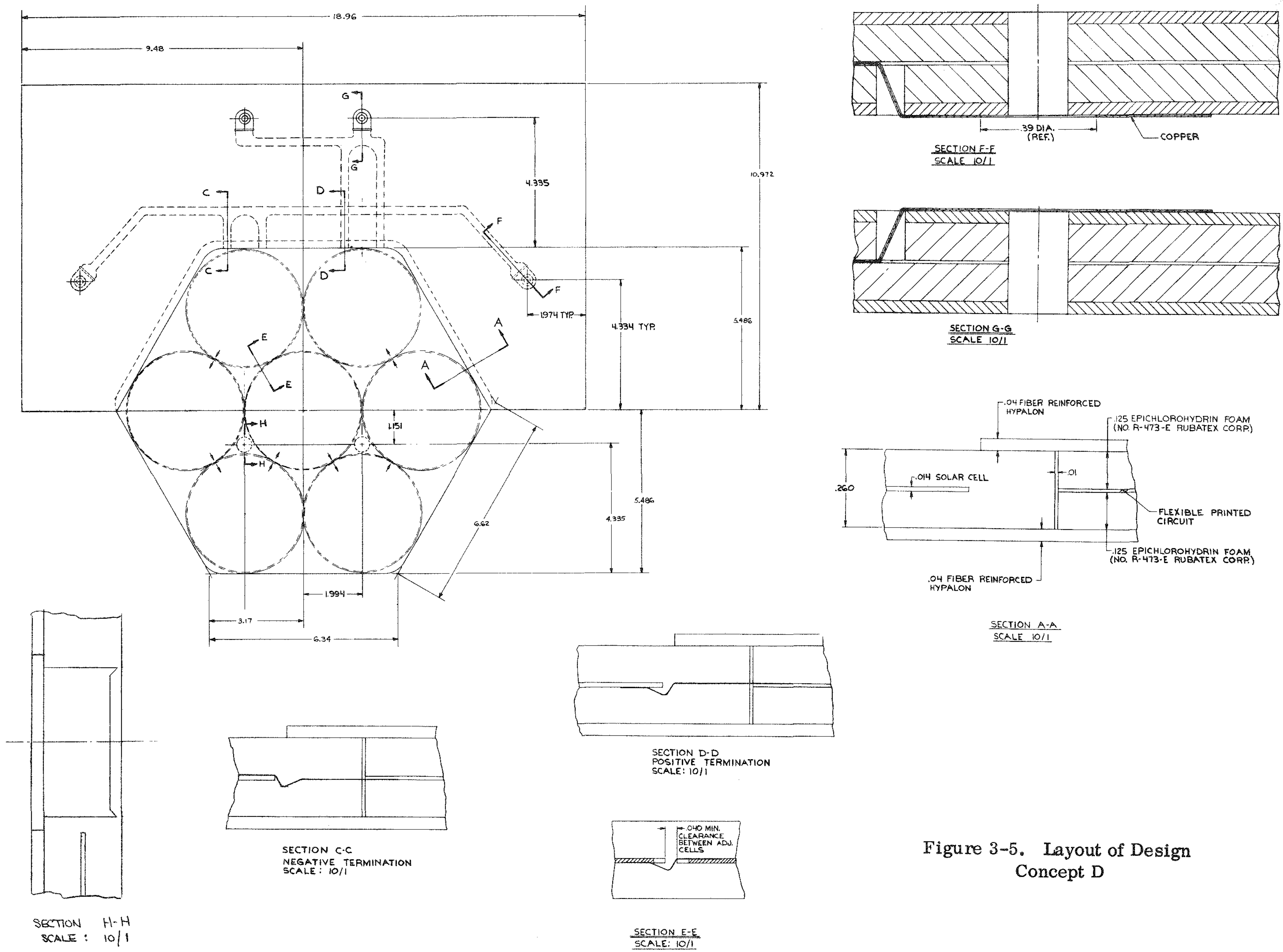


Figure 3-5. Layout of Design Concept D

B' configuration except that the sheet metal screws are under the MMA casting with access for removal through two knock-out holes in the casting.

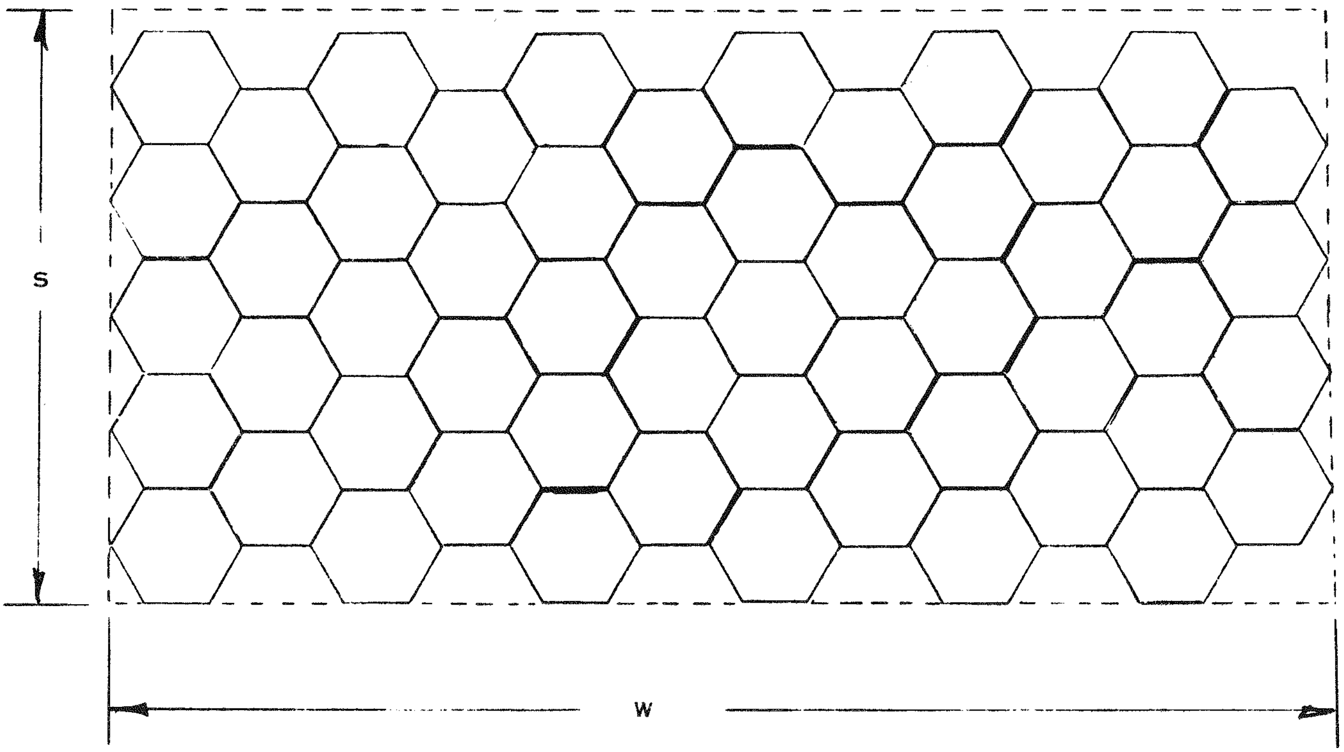


Figure 3-6. Arrangement of Shingle Modules on a Rectangular Roof

Using the module designs described above, the area utilization when mounted on a rectangular roof structure was analyzed using the diagram given in Figure 3-6. The unused space within the first course, along the gable on each side, and along the ridge contributes to the overall area utilization as shown in Figure 3-7 for the Concept B module design with nineteen 53 mm diameter cells. The distance from the top of the hexagon on the upper course to the ridge of the roof is a function of the placement of the copper printed circuits runs within the substrate material. For the case shown in this example, this distance is 63.5 mm. These results indicate the importance of mounting small areas on roof sections which are narrow from gable-to-gable and long from eave-to-ridge.

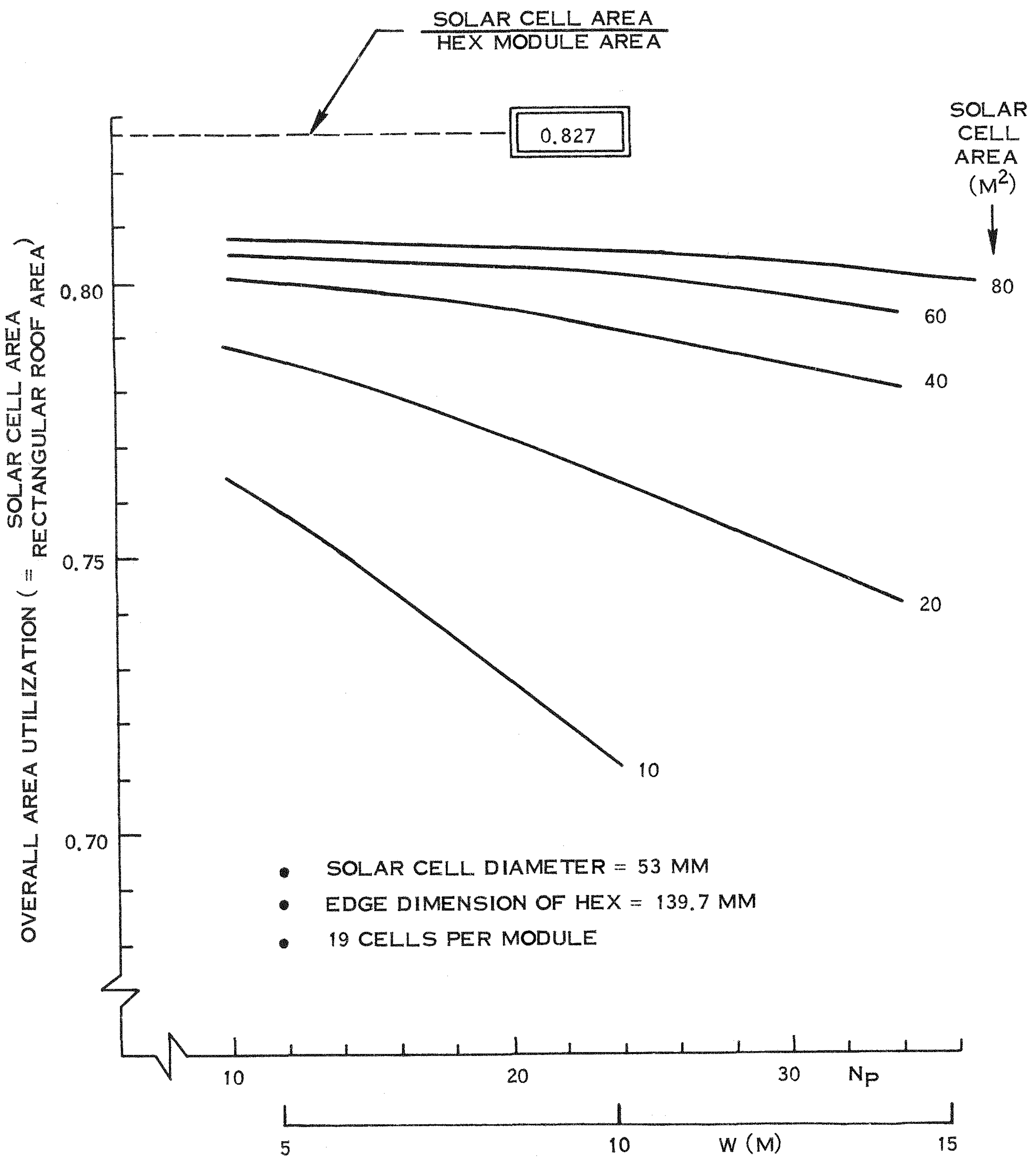


Figure 3-7. Ove

As a point of comparison with two representative modules from the Block II procurement, the Nebraska irrigation installation was used as an example of the area utilization associated with these types of rectangular modules. The total nominal solar cell area for this installation is 291.66 m^2 (Reference 3). The two module types are mounted on a total of 28 frames, each with dimensions of 2.46 x 7.85 m, for a total mounting frame surface area of 540.71 m^2. Thus, the overall area utilization (or packing factor) for this installation is 0.54.

3.2 SUBSTRATE EVALUATION AND TESTING (TASK 1)

The substrate portion of the shingle is defined as that flexible portion of the module which is overlapped by the higher courses of the roof installation. The function of the substrate is to provide a relatively low density, low cost, watertight surface which, when overlapped, will form an overall watertight installation on a sloping roof. The substrate also contains the flexible printed circuit board conductors which allow for the interconnection of adjacent modules on the roof. Figure 3-8 shows a cross-sectional view of the selected substrate configuration which is compatible with the Concept B design. An adaptation of this substrate, which uses two layers of the foam material, is also compatible with the Concept D design.

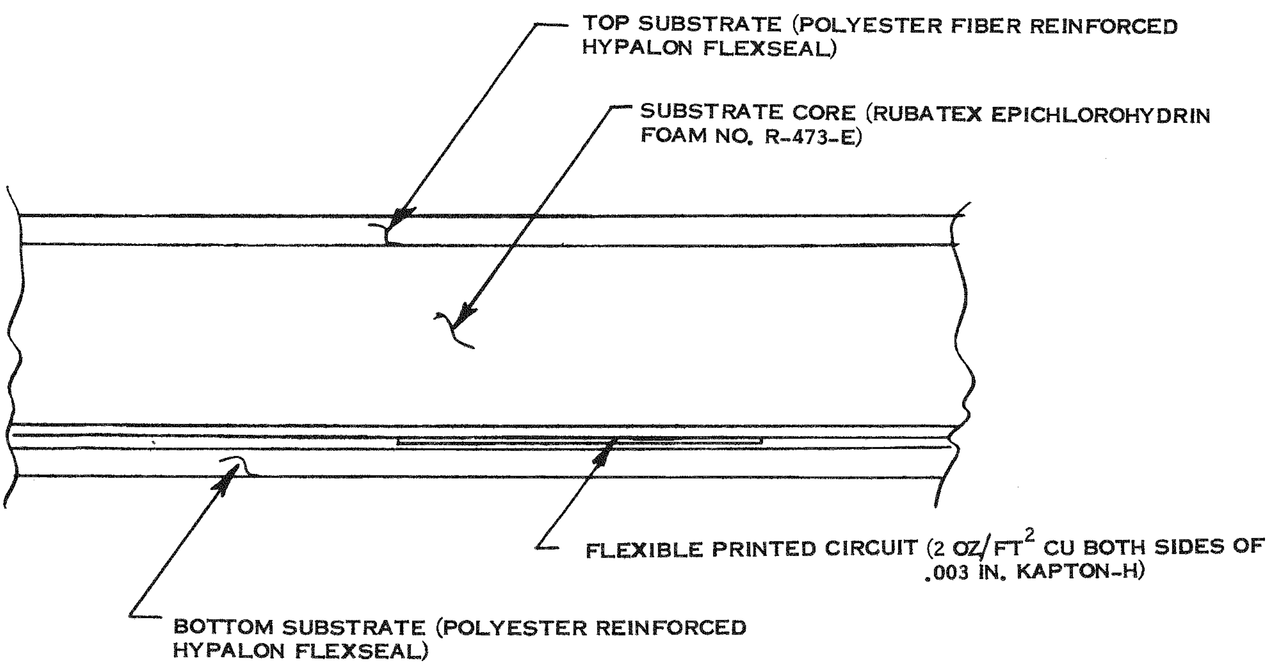


Figure 3-8. Cross-Section Through Shingle Substrate

3. Private communication with S. Sacco, MIT-LL, September 15, 1977

The polyester fiber-reinforced *HYPALON FLEXSEAL* provides a proven weather-resistant outer layer for the assembly. The top substrate layer will be laminated with the white side of the *FLEXSEAL* facing out to provide the low solar absorptance desired for any exposed areas of the shingle. Table 3-3 summarizes the properties of unsupported *HYPALON*. The closed cell epichlorohydrin foam material provides a low density, high temperature resistant filler material to achieve a nearly uniform thickness over the entire surface area of the shingle. Table 3-4 lists the pertinent physical properties of this foam material.

The candidate adhesive systems for laminating the substrate composite include those shown in Table 3-5.

Table 3-3. Summary of Properties for Unsupported DuPont *HYPALON*

Physical Property	Test Method	Value
Tensile Strength	ASTM D412	3447 kPa, minimum
Elongation at Break	ASTM D412	400%, minimum
Permanent Set at Break	ASTM D412	50%, maximum
Brittleness Temperature	ASTM D746	-49°C
Flame Resistance	ASTM D568	Self Extinguishing
Resistance to Water (Change in weight after 7 days immersion at 24°C)	ASTM D471	4%, maximum
Moisture Vapor Transmission (After 7 days at room temperature)	ASTM E96 (Procedure E)	5.7×10^{-11} kg/Pa·s·m^2, maximum
Resistance to Discoloration (Color change after 50 hrs under RS sunlamp)	ASTM D1148	Less than a Gardner No. 1 Standard
Resistance to Ozone (Condition after exposure to 300 pphm ozone in air 1 week at 38°C with sample at 50% elongation)	ASTM D1143	No cracks at 10X magnification

Table 3-4. Physical Properties of Closed Cell Epichlorohydrin Foam (*RUBATEX* No. R-473-E)

Property	Units	Value
Compression Deflection	(kPa) (psi)	69-90
Shore 00 Durometer		60-80
Density	(kg/m^3)	240-480
Water Absorption by Weight	(% max.)	5
Temperature Range	(°C)	
Low (flex without cracking)		-29
High continuous		149
High intermittent		163
Compression Set (13 mm thick sample compressed 50% 22 hours at 21°C and 24 hours recovery)	(%)	10-20
Lineal Shrinkage (7 days at 70°C)	(%, max.)	5
Tensile Strength (min)	(MPa) (psi)	1.34 195
Elongation	(%, min.)	225

Table 3-5. Candidate Adhesive Systems

Manufacturer	Product Description	Product Use
Hughson Chemicals, Lord Corporation	*CHEMLOK* 7002 Urethane Adhesive	Adhesive for bonding plastics, rubber, and fabric
	CHEMLOK 7200 Polyisocynate polymers	Curing agent used with *CHEMLOK* 7002
	CHEMLOK AP-134 Primer	Primer for glass surfaces
	CHEMLOK Y5323 Primer	Primer for epichlorhydrin foam
B. F. Goodrich Adhesive Products	CA 1056 Neoprene Contact Adhesive	Adhesive for bonding *HYPALON* to surfaces
	A-1436-B Flexseal I Edge Cement	Interior and exterior sealer of *HYPALON*
	A-934-BY Primer	Primer for glass and metal surfaces
	A-178-B Primer	Primer for PVC and other foams

Both of the systems listed in Table 3-5 have been initially evaluated using ASTM D903, "Test for Peel or Stripping Strength of Adhesive Bonds." This test was used to evaluate the adhesive bonds between *HYPALON* and epichlorhydrin foam, the foam and fiberglass/epoxy circuit board, the circuit board and *HYPALON*, and *HYPALON* and glass.

The test was modified slightly to allow for the testing of several adhesive bonds utilizing the minimum number of specimens. Specimens, prepared following the diagram shown in Figure 3-9 for Type A, were tested for the *HYPALON* and fiberglass circuit board adhesion and the *HYPALON* and foam adhesion. The test was run first to test the one adhesive bond and then again to test the other adhesive bond. Figure 3-10 shows the general arrangement of the specimen in the testing machine.

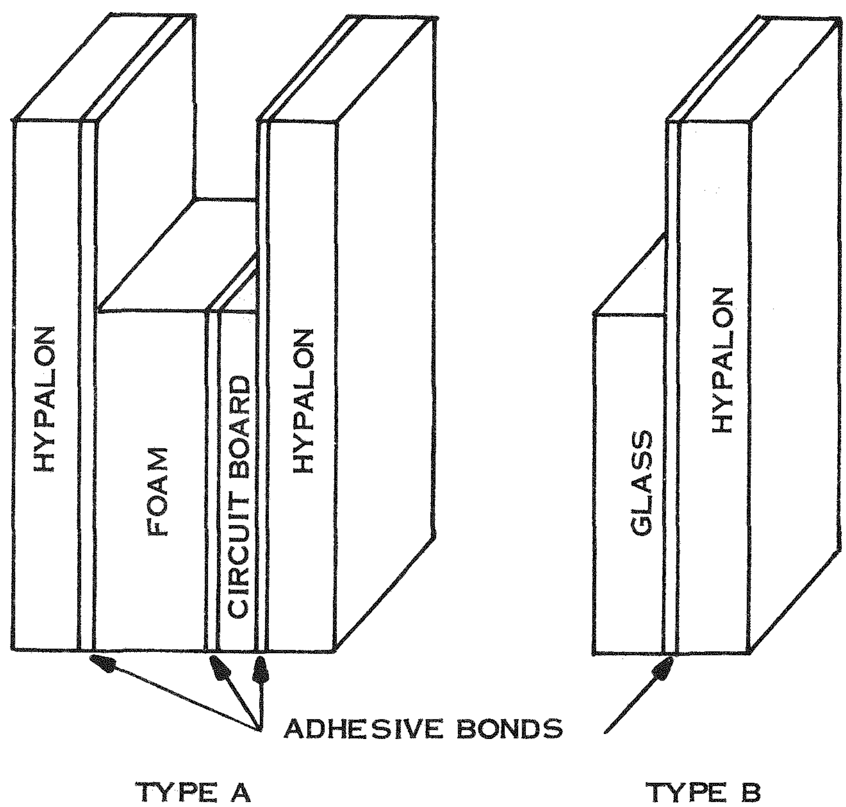


Figure 3-9. Peel Test Specimens

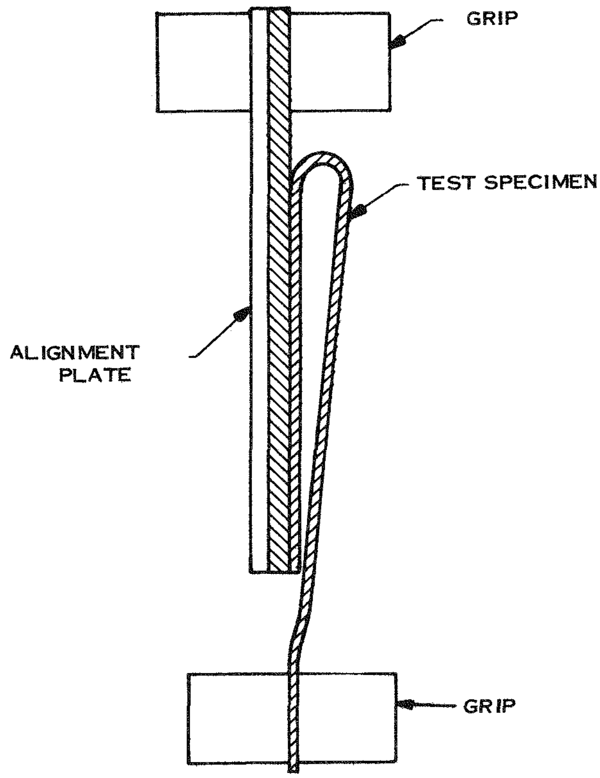


Figure 3-10. Arrangement of Specimen Under Test

The specimens were prepared as described in Table 3-6. The preliminary results of these peel tests are given in Table 3-7. These data indicate that both of the adhesive systems form a very good bond with *HYPALON* and foam. In both cases the foam pulled apart leaving the bond intact. The adhesive bond between the *HYPALON* and fiberglass/epoxy circuit board is not very good with either of the systems tested. The B.F. Goodrich system produced the superior bond between the *HYPALON* and glass.

Based on these preliminary test results and the visual evaluation of the specimens, the B.F. Goodrich system has been selected for bonding *HYPALON* to glass, *HYPALON* to *HYPALON*, and *HYPALON* to foam. The *CHEMLOK* system would be used to bond the fiberglass/epoxy circuit board to either *HYPALON* or the epichlorohydrin foam.

Table 3-6. Adhesive System Test Specimens

A. <u>Type A Specimens</u>

1. *HYPALON* on fiberglass/epoxy circuit board
   a. B.F. Goodrich CA-1056 with primer A-934-BY
   b. *CHEMLOK* 7002 and curing agent 7200 with primer AP-134
2. Fiberglass circuit board on foam
   a. B.F. Goodrich CA-1056 with primer A-178-B and A-934-BY
   b. *CHEMLOK* 7002 and curing agent 7200 with primer AP-134*
3. Foam on *HYPALON*
   a. B.F. Goodrich CA-1056 with primer A-178-B
   b. *CHEMLOK* 7002 and curing agent 7200 with primer AP-134*

B. <u>Type B Specimens</u>

1. *HYPALON* on glass
   a. B.F. Goodrich CA-1056 with primer A-934-BY
   b. *CHEMLOK* 7002 and curing agent 7200 with primer AP-134

*This primer was used, but the primer for this type of foam is Y5323. It had not been received at the time of the test.

Table 3-7. Adhesive System Peel Test Results

Specimen Description	Peel Strength (N/m)	
	B.F. Goodrich	*CHEMLOK*
HYPALON on fiberglass/epoxy	1580	1750
HYPALON on foam	1580	1580
HYPALON on glass	3850	1050

3.3 SOLAR CELL TRAY EVALUATION AND TESTING (TASK 2)

The evaluation of the two basic concepts for solar cell mounting, viz., Concepts B and D, has proceeded as discussed below in Sections 3.3.1 and 3.3.2, respectively. In addition the necessity to know solar cell flexure strength led to the experimental determination of these data as discussed in Section 3.3.3.

3.3.1 SOLAR CELL MOUNTING IN CONCEPT B

In Concept B the interconnected array of solar cells is sandwiched between a tempered glass coverplate on the front surface and a fiberglass/epoxy protective sheet on the rear surface. The glass coverplate provides the majority of the structural rigidity necessary to prevent solar cell breakage during normal handling.

The drawing of the hexagon-shaped tempered glass coverplate for Concepts B and B' is reproduced as Figure 3-11. This drawing, along with a request for a cost quotation for a limited quantity of development parts, was sent to each of the four possible sources of supply listed below.

1. Corning Glass Works, Inc.
   Corning, NY
2. PPG Industries, Inc.
   Pittsburgh, PA
3. ASG Industries, Inc.
   Kingsport, TN
4. Artistic Glass Products Co.
   Quakertown, PA

As a result of this inquiry, Artistic Glass Products was selected as the supplier for the several preproduction coverplates required to complete the evaluation of the solar cell mounting under the Task 2 activity. These initial development pieces made use of both *ASG SUNADEX* and *LO-IRON* glasses with iron oxide contents of 0.01 and 0.05 percent, respectively. The outside surface of each coverplate was coated with a single layer magnesium fluoride antireflection coating.

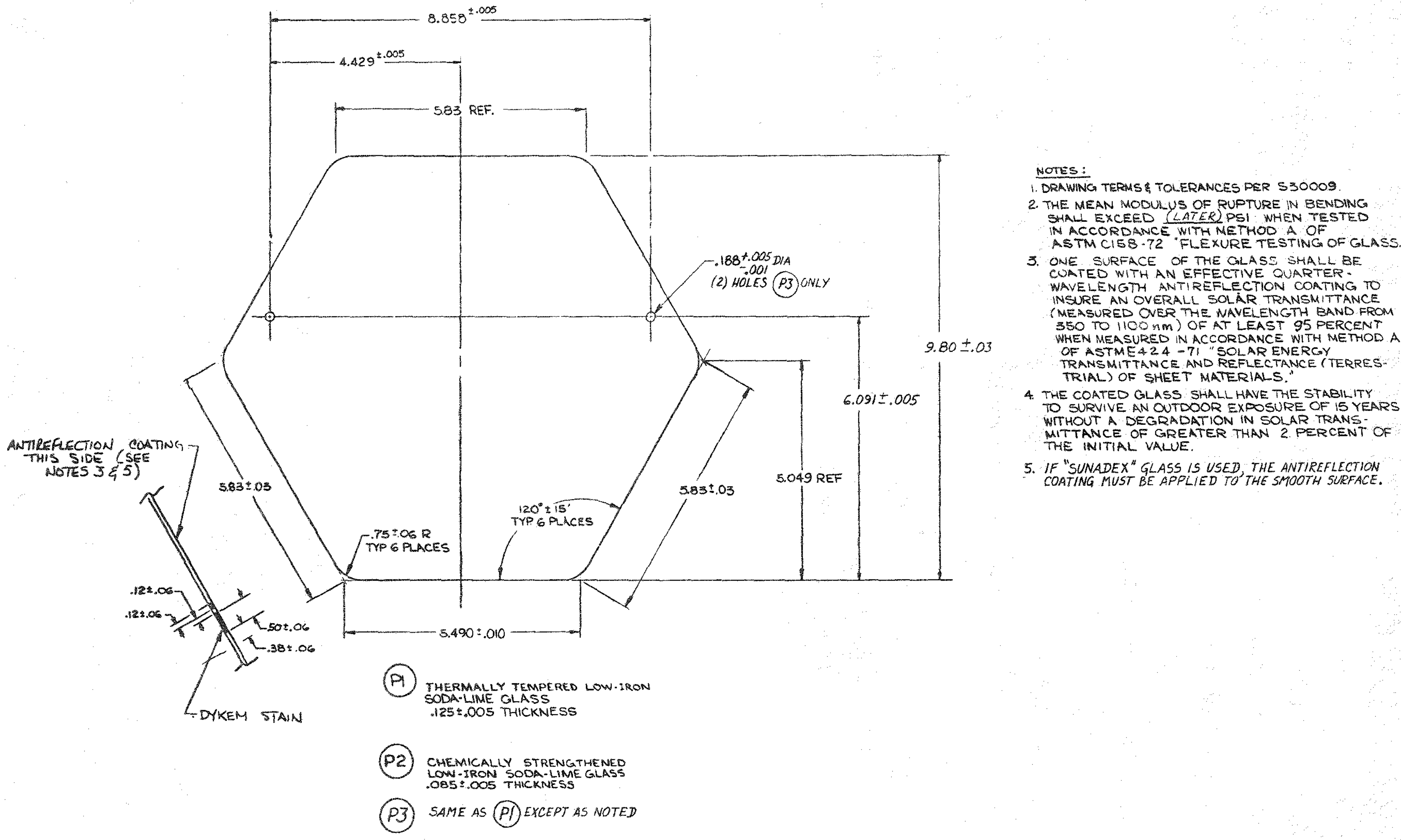


Figure 3-11. Drawing of Glass Coverplate for Concepts B and B'

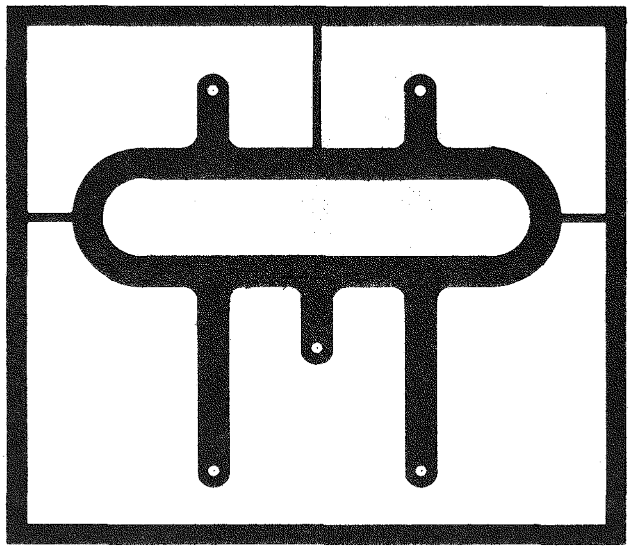


Figure 3-12. Interconnector for 53 mm Diameter Solar Cells

The solar cell interconnector shown in Figure 3-12 has been designed for use with the 53 mm diameter cells in the Concept B design. This interconnector will be fabricated from nominal 50 μm thick electrolytic tough pitch (alloy no. 110) copper and will be plated with a nominal 12 μm thick solder on both sides.

Monsanto's *SAFLEX* PT-10 polyvinyl butyral (PVB) film has been selected for the bond layer between the glass and the solar cell. This material is recommended by Monsanto for applications of this type which require high clarity. When a layer of this material was fused to window glass, the transmission through the glass was changed as shown in Figure 3-13.

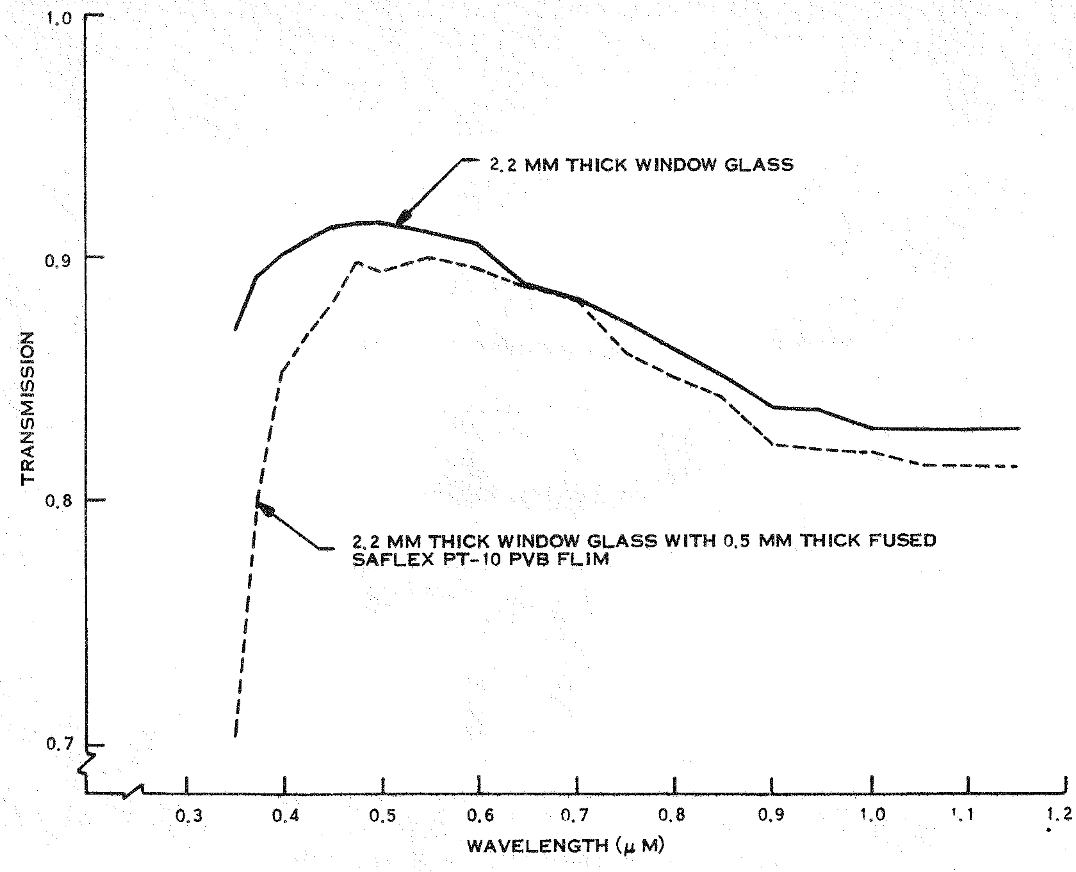


Figure 3-13. Transmission of PVB Film on Window Glass

The rear side of the hexagon solar cell mounting area will be covered with 0.8 mm (0.032 inch) thick *TEXTOLITE* grade 11637 (NEMA Grade FR-4) sheet. This material provides a relatively impervious sheet to protect the rear side from damage if the shingle is dropped onto a raised object.

This high modulus rear sheet also contributes to the overall stiffness of the solar cell mounting by virtual of the separation distance between it and the glass top coverplate. The intervening space surrounding the solar cells between the top and bottom covers is filled with RTV162 sealant which provides the primary encapsulant. This material, the properties of which are summarized in Table 3-8, has been selected for its white color and neutral cure by-products, which will not cause corrosion of copper and other sensitive metals.

Table 3-8. Physical Properties of RTV162

Property		Valve
Specific Gravity		1.08
Shore A Durometer		33
Tensile Strength		
	(MPa)	2.8
	(psi)	400
Elongation	(%)	500
Tear Strength		
	(N/m)	12260.
	(lb/in)	70
Heat Resistance	(°C)	
High Continuous		205
High Intermittent		260

3.3.2 SOLAR CELL MOUNTING IN CONCEPT D

The development of a methyl methacrylate embedding process for the interconnected solar cells in support of the Concept D design is being pursued with the aid of K.R.B., Inc. in Red Lion, PA, a firm which specializes in embedding items in MMA. Several single cell specimens will be embedded within a 6.6 mm (0.26 inch) thick by 76 mm (3 inch) square MMA casting. Assuming that this process produces satisfactory results, the next step will be the development of a process to embed a seven cell array of interconnected 100 mm diameter cells.

3.3.3 SOLAR CELL FLEXURE STRENGTH

The lack of available data on the flexure strength of terrestrial silicon solar cells coupled with the obvious importance of this parameter in the determination of the minimum required flexural rigidity for the solar cell mounting led to the experimental determination of solar cell flexure strength. Twelve beam specimens were cut from Spectrolab terrestrial solar cells and subjected to a four point bending test similar to that specified in ASTM C158-72 "Flexure Testing of Glass". These specimens were approximately 12.7 mm wide by 43 mm long by 0.4 mm thick and were loaded in a fixture with 38.1 mm span between the supporting points and 19.05 mm span between the loading points. The active surface of the cell was the tensile side of the beam for all test runs. The results of this testing, as presented in Table 3-9, show a large range for the values of ultimate flexure strength and indicate a great dependence on the surface finish of the edges of the beam specimen. The single specimen with rough cut, unpolished edges exhibited an ultimate bending strength which was 56 percent lower than the lowest value for the specimens with polished edges.

3.4 MODULE INTERCONNECTION AND TESTING (TASK 3)

The module interconnector provides the electrical connection between adjacent shingles on the roof. Figure 3-14 shows the electrical schematic for a typical segment of the installation. On this figure each dot represents a module interconnector. Three specific interconnector designs have been selected for experimental evaluation as part of this task activity. The first of these designs, which is compatible with Concept B, is the four-pronged nail shown in Figure 3-15. When driven with a hammer, this nail pierces the two overlapping shingle substrates thus, making contact between the layers of copper which are embedded within each substrate. Each prong of this fastener has been tapered to provide some amount of swaging of the copper foil as the penetration is made. Barbs on the tip of each prong provide a firm grip within the plywood sheathing.

The replacement of a damaged shingle, which has been installed using this nail, is felt to represent a significant problem which will require that the nail be pried out by a screw driver which is slipped between the overlapped layers of the shingle. The distance to the edge has been minimized to enable this removal, but the subsequent reinstallation of a replacement shingle with these nails would appear to be a difficult, if not impossible, task.

With the objective of providing for ease of removal and replacement, two additional module interconnector design concepts were formulated for evaluation. The first of these is a sheet metal screw pressure contact design as shown in Figure 3-16. This interconnector design, which uses a standard No. 8 pan head sheet metal screw, is compatible with either Concepts B' or D. As shown in Figure 3-16, the sheet metal screws are driven through two accurately

Table 3-9. Results of Solar Cell Flexure Strength Test

Specimen No.	Ultimate Flexure Strength		Remarks
	(MPa)	(psi)	
1	138.6	20,100	Polished edges - 600 paper
2	93.1	13,000	↑
3	181.3	26,300	
4	202.7	29,400	
5	111.7	16,200	
6	117.9	17,000	
7	95.1	13,800	
8	109.6	15,900	
9	94.5	13,700	
10	108.9	15,800	↓
11	117.2	17,000	Polished edges - 600 paper
12	40.7	5,900	Air Brazive Cut - No Polishing

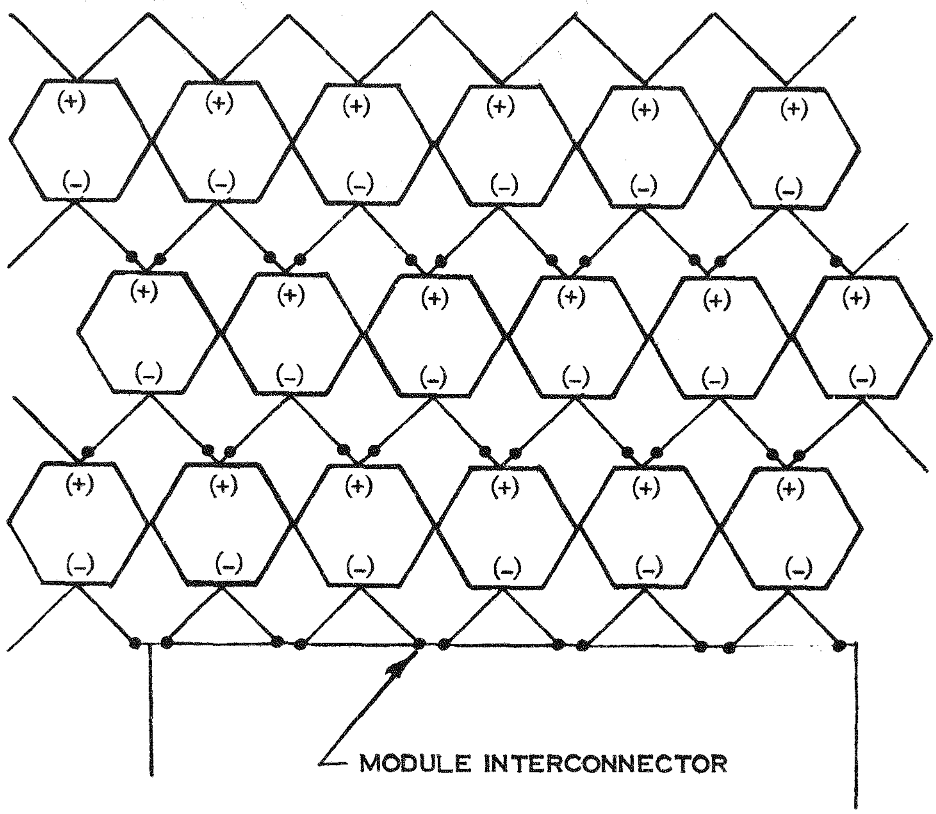


Figure 3-14. Electrical Schematic of Module Interconnection

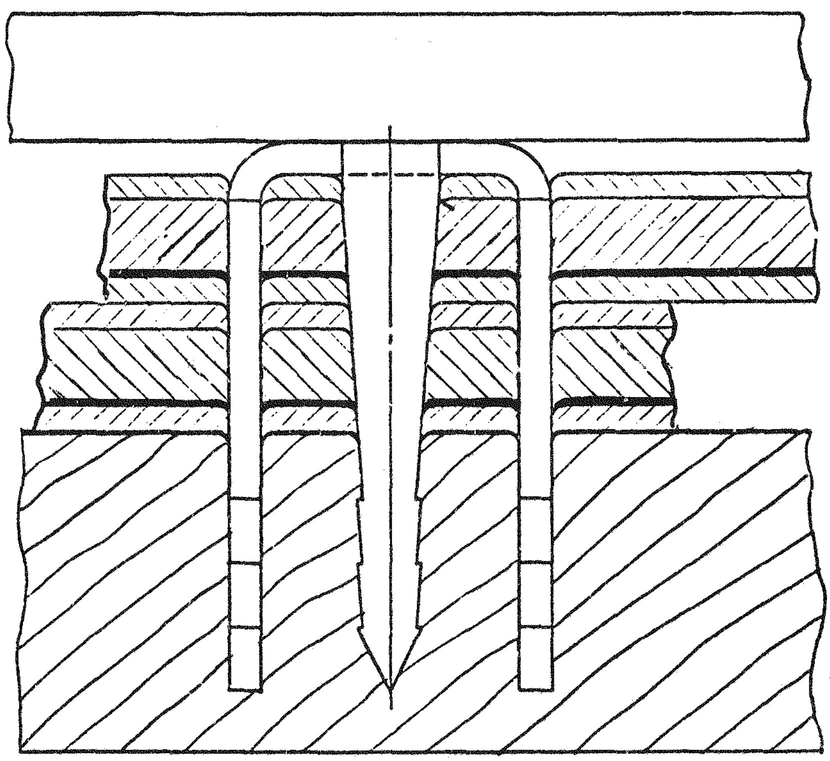


Figure 3-15. Four-Pronged Nail Module Interconnector

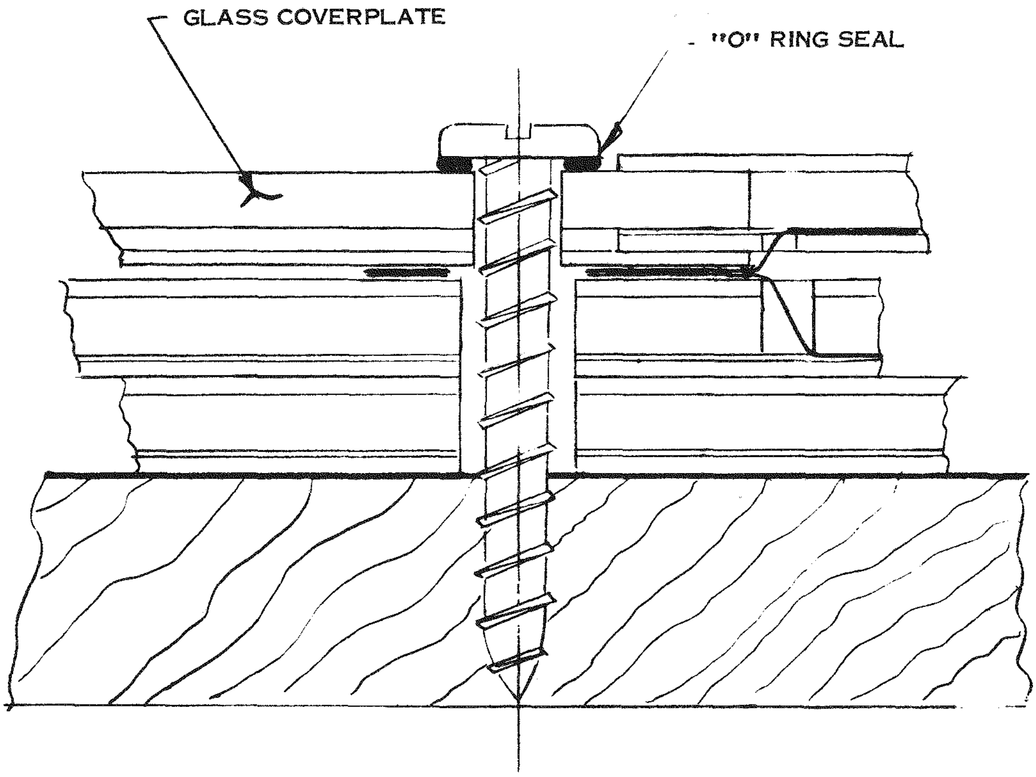


Figure 3-16. Sheet Metal Screw Module Interconnector

located holes in the glass coverplate of the Concept B' design. The screw enters the plywood roof sheathing and is torqued to provide a positive clamping pressure between the two mating copper pads on the overlapping shingles. An "O" ring under the screw head provides a water-tight seal with the glass coverplate and also serves as to preload indicator and locking devices for the screw. In the event that an occasional nail head or other obstruction in the plywood prevents the screw from entering the sheathing, the sheet metal screw is replaced with a machine screw of shorter length which is engaged with a single thread nut which is slipped between the second and third layers. Consequently, there will be no attachment to the roof at each such location, but since each shingle is held to the roof at six places, the absence of an occasional attachment is of little concern.

The third interconnector design, shown in Figure 3-19, uses battery snap fasteners to make the electrical connection between adjacent modules. These snap fasteners are similar to those commonly used on 9 Volt transistor batteries, except that a larger size is dictated by the higher current carrying requirement. Sample fasteners of this type have been obtained from the Carr Division of TRW. With only minor modifications, this interconnector is compatible with Concept B. The two parts of the snap fastener are riveted through the circular copper pads as shown in Figure 3-17.

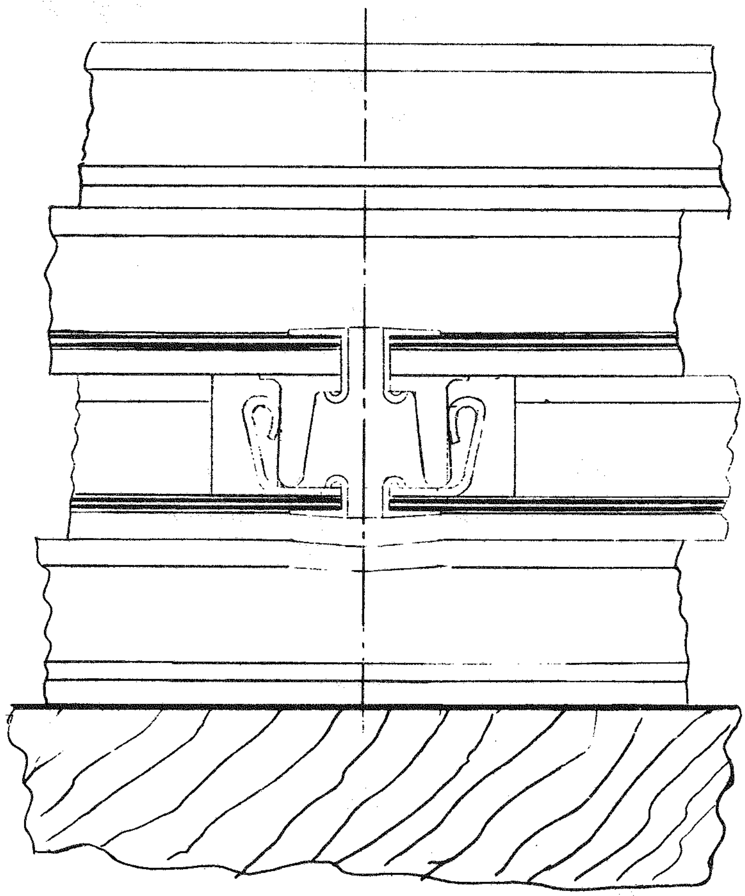


Figure 3-17. Battery Snap Fastener Module Interconnector

The attachment of each single to the roof is accomplished with standard roofing nails along the uppermost edge of the shingle. The snap fasteners provide additional security against wind lifting. In the event that replacement is required, it will be an easy matter to disengage the snap fasteners by prying up with a thin plastic tool which is slipped between the attached layers. The roofing nails can be removed by shearing off with the tool commonly used to shear nails in slate roofing shingles. Upon replacement, the new shingle is engaged with the snap fasteners only.

The experimental evaluation of these three interconnection configurations consists of the mounting of six simulated shingles of each type on a section of plywood roof structure as shown in Figure 3-18. This test fixture has been made compatible with a vibration exciter to enable the performance of a low frequency, low amplitude vibration test with the objective of accelerating any fastener loosening which might occur over the life of the roof installation. During this vibration exposure, a test current will be passed through the printed circuit and interconnector joints of each of the three simulated installations, and the voltage drop will be continuously recorded to detect any changes in total series resistance. This initial vibration test will be followed by a temperature cycling and humidify exposure. Following these environmental exposures, the simulated roof section will again be subjected to the vibration test.

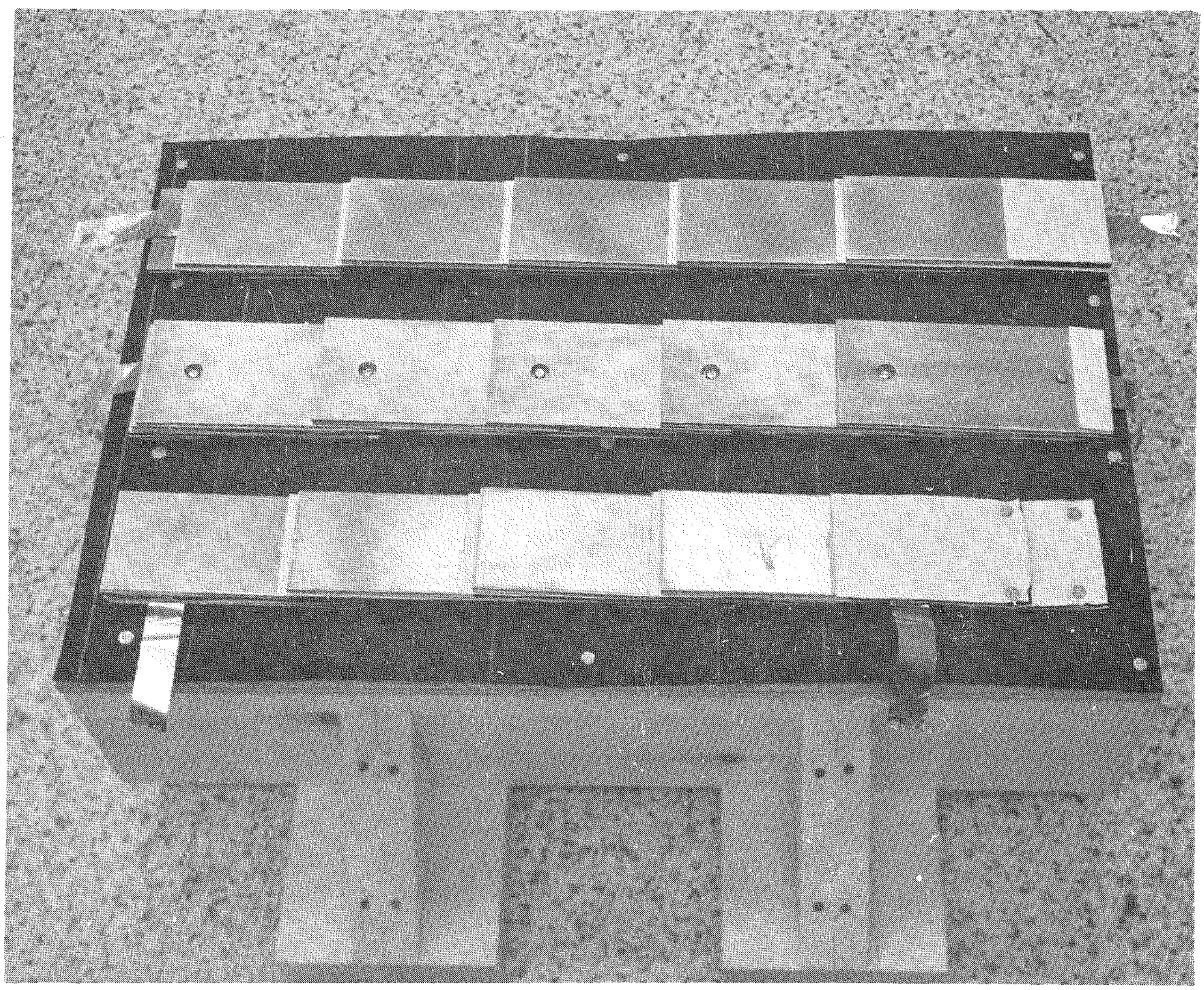


Figure 3-18. Simulated Shingles Mounted to Test Fixture for Module Interconnector Evaluations

SECTION 4
CONCLUSIONS

The progress to date indicates that the goal of providing a photovoltaic roofing shingle with the required 80 watts per square meter of module area at 60°C is achievable. Comparisons with existing Block II rectangular modules indicates a significant improvement in overall area utilization (or packing factor). These shingle modules are particularly adaptable to installation on the sloping roofs of both existing and new residential or commercial buildings since no changes in conventional roof construction are imposed by the photovoltaic installation.

Although the current design concepts are being developed for an hexagon-shaped shingle geometry to effectively accommodate circular solar cells, the basic design concepts could apply equally to hexagon or rectangular-shaped solar cells within a rectangular shingle geometry.

The cost of the material content of the shingle, other than the solar cells, will continue to be an overriding concern during the remaining contract effort. Those designs which use tempered low-iron glass as the top cover face a significant challenge with respect to the cost of material and processing of this component. A low-cost, durable antireflection coating for soda-lime glass must be developed if this approach is to be economically feasible.

Designs which embed the solar cells within a methyl methacrylate casting appear to be extremely attractive from an overall cost standpoint. It remains to be determined if this encapsulation approach will provide adequate protection for the solar cells within the environmental constraints imposed by this application. The relatively small size and compact shape of the individual shingle modules makes this embedding process particularly attractive for this application.

SECTION 5
RECOMMENDATIONS

It is recommended that a wind resistance test be substituted for the mechanical integrity test which is currently specified as part of the module qualification testing program. This wind resistance testing should follow the general procedure specified in ASTM D3161, "Wind-Resistance of Asphalt Shingles." The qualification test shingle modules would be mounted to a simulated roof structure consisting of plywood sheathing attached to rafters. Several combinations of roof slope angle and angle of incidence to the wind direction could be investigated to determine resistance to blow-up or blow-off in a 27 m/s wind speed.

SECTION 6

NEW TECHNOLOGY

No items of new technology have been reported during this period.

SVS9310
28 January 1977
Rev A 23 June 1977

Rev B 20 July 1977

COMPONENT SPECIFICATION
FOR A
TERRESTRIAL SOLAR CELL

Prepared by: N. F. Shepard, Jr.
Development Engineer

Date: 28 Jan 1977

GENERAL ELECTRIC COMPANY
SPACE DIVISION
P.O. BOX 8555
PHILADELPHIA, PA. 19101

SECTION 1

SCOPE

This specification establishes the requirements for the design and construction of a specific type of silicon solar cell which is intended for terrestrial applications.

SECTION 2

APPLICABLE DOCUMENTS

The following documents, of the issue noted, form a part of this specification to the extent specified herein. In the event of conflict, the requirements of this document shall govern.

Other Documents

NASA TMX-71771 July 1975	Interim Solar Cell Testing Procedures for Terrestrial Applications.

SECTION 3

REQUIREMENTS

3.1 CELL CONFIGURATION

The cell configuration shall be circular with a diameter as specified in Table 1. Flats or other edge imperfections are permissible at any position around the circumference of the cell provided that the cell fits within a perfect circle of the specified maximum diameter. The solderable area on the top contact shall accommodate two adjacent redundant joints. The separation distance between these two contact areas shall be at least 0.15D but not greater than 0.25D, where D is the nominal cell diameter.

3.2 ELECTRICAL PERFORMANCE

The minimum electrical power output of the bare cell when operated at 60°C shall be as specified in Table 1. The supplier shall specify the corresponding electrical output at 28°C which assures the achievement of the requirement. In no case shall the output at 28°C be less than the value specified in Table 1. The testing conditions specified in paragraph 4.4 shall apply.

3.3 ANTIREFLECTIVE COATING

The antireflective coating shall prevent an electrical performance loss due to encapsulation with the equivalent of 2mm thickness of RTV-670.

3.4 DOCUMENTATION

The vendor shall supply a configuration control drawing for the cell supplied in conformance to this specification.

Table 1. Requirements for Circular Terrestrial Solar Cells

Requirement	Solar Cell Type Number			
	0	1	2	3
1) Cell Diameter (mm)	53.±0.13	57.±0.13	76.±0.18	100.±0.25
2) Minimum Electrical Power Output at 60°C (mW)	245.	245.	436.	754.
3) Minimum Electrical Power Output at 28°C (mW)	290.	290.	515.	891.

SECTION 4

QUALITY ASSURANCE PROVISIONS

4.1 RESPONSIBILITY FOR INSPECTION

The supplier shall be responsible for the performance of the mechanical inspection and electrical performance test as specified herein.

4.2 SOURCE INSPECTION AND RETEST

GE-SD reserves the right to perform source acceptance inspection at any time during the effective period of the contract. Such action will be preceded by written notification from GE-SD. Further, GE-SD reserves the right to perform any or all of the inspections and tests specified herein at any time after receipt of shipment of cells delivered to this specification and to reject any cell found to be out of specification.

4.3 MECHANICAL INSPECTION

Each cell shall be mechanically inspected to assure conformance to the requirements of paragraph 3.1.

4.4 ELECTRICAL PERFORMANCE TEST

The electrical performance of each cell shall be measured under an air-mass-one solar simulator which has a total irradiance of 100 mW/cm^2 and a normalized spectral distribution per the requirements of "Interim Solar Cell Testing Procedures for Terrestrial Applications". The solar cell under test shall be maintained at a temperature which is not less than 28°C. Each solar cell shall be identified with the measured current at an agreed upon test voltage. In no case shall the power output at this test voltage be less than the required output at 28°C. This electrical performance measurement shall be made using pressure contact on the top surface only at those two adjacent locations specified to be the interconnect solder joint interfaces.

SECTION 5

PREPARATION FOR DELIVERY

5.1 SHIPPING CONTAINERS

Solar cells shall be shipped in containers which are adequate to protect the cells from damaging mechanical forces, dust and moisture. Dessicant may be supplied at the option of the supplier.

5.2 CELL IDENTIFICATION

Each solar cell shall be marked on the rear with an identifying serial number. Each shipment of cells shall be accompanied by a list of serialized cell numbers and corresponding measured current at the test voltage.

*U.S. GOVERNMENT PRINTING OFFICE: 1978-740-094/1171