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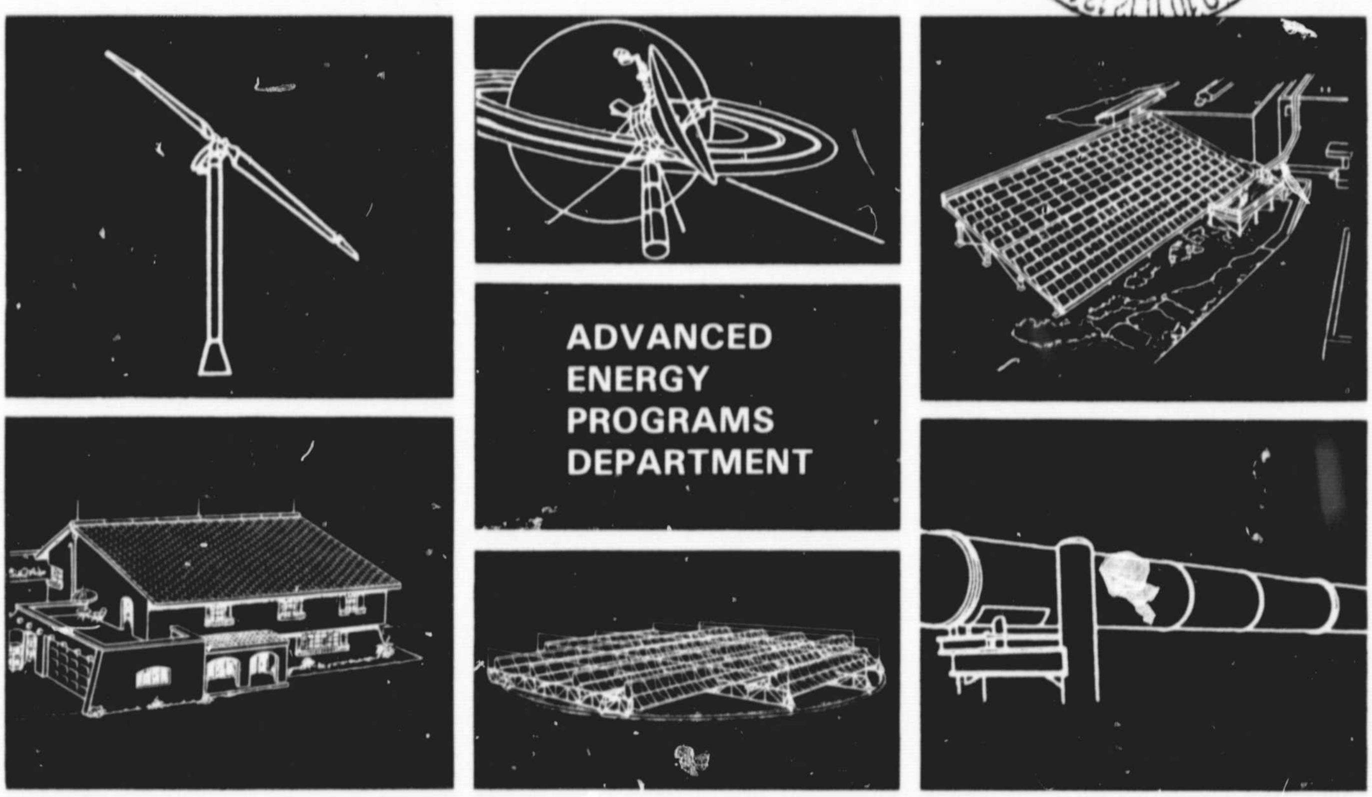
FINAL REPORT
INTEGRATED RESIDENTIAL PHOTOVOLTAIC ARRAY DEVELOPMENT

PREPARED UNDER JPL CONTRACT 955894
REPORT DATE: DECEMBER 11, 1981



ENERGY SYSTEMS AND TECHNOLOGY DIVISION

GENERAL ELECTRIC

DOE/JPL 955894-4
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FINAL REPORT

INTEGRATED RESIDENTIAL PHOTOVOLTAIC ARRAY DEVELOPMENT

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The JPL Flat-Plate Solar Array Project is sponsored by the U.S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of flat-plate solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DOE.

GENERAL ELECTRIC
ADVANCED ENERGY PROGRAMS DEPARTMENT
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KING OF PRUSSIA, PA 19406

ACKNOWLEDGEMENT

The results of the contract effort reported herein reflect the contributions of many people both within the General Electric Co. as well as within the supporting subcontractor organizations. Kulicke and Soffa Industries, Inc. provided all module production planning and supporting costing analysis. This work effort was directed by Mr. Max Bycer. Massdesign Architects and Planners, under the direction of Mr. Gordon Tully, provided the array installation details and formulated the installation cost estimates. Additional technical advice, related to the module-to-module interconnection methods, was supplied by AMP, Inc. The contribution of Mr. Jack Lawhead in this area is greatfully acknowledged.

Within the General Electric Co., Advanced Energy Programs Department, the following individuals made significant contributions to the content of this study.

N. F. Shepard, Jr.	Program Manager and Principal Investigator
R. Landes	Module size investigation and bypass diode integration study
J. Parker	Evaluation criteria definition and thermal analysis of bypass diode mounting concepts
R. Drummond	Conceptual design of various module/array configuration

Mr. R.S. Sugimura was the JPL Project Manager. Messrs. Bill Mayers and Abe Wilson of the JPL Technical Staff also provided many helpful suggestions throughout the course of this activity.

ABSTRACT

An advanced, universally-mountable, integrated residential photovoltaic array concept has been defined based upon an in-depth formulation and evaluation of three candidate approaches which were synthesized from existing or proposed residential array concepts.

Past residential photovoltaic array concepts emphasized the module as given. This study addresses the next level of detail by considering the impact of module circuitry and process sequence, and by identifying technology gaps and performance drivers associated with residential photovoltaic array concepts. The actual learning experience gained from the comparison of the problem areas of the hexagonal shingle design with the rectangular module design has led to what is considered an advanced array concept. Building the laboratory mockup provided actual experience and the opportunity to uncover additional technology gaps.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONT)

LIST OF TABLES

SECTION 1

SUMMARY

SECTION 1
SUMMARY

This report presents results of a conceptual analysis and a laboratory mockup construction to study advanced integrated residential photovoltaic array concepts. The scope of the study included module construction and support structure sequences considering the synergism between the array and roof. Factors associated with actual installation were experimentally verified by a laboratory mockup of the roof/array interface.

The approach was to select a specific module construction concept which appeared to be feasible and perform a complete analysis by detailing the module and support structure production paths and the associated costs. The information is useful to other concepts and identifies a number of factors which must be evaluated in the selection of other advanced array concepts.

The first stage of this concept evolution process, leading to the selection of an optimum integrated residential array, involved a review of existing or proposed arrays. This state-of-the-technology was evaluated against a set of criteria which was formulated to enable the selection of three baseline module/array concepts as candidates for a more detailed assessment of the relative merits when used in an integrated residential array application. The emphasis of this study was on a systems level approach to define and resolve technology/performance tradeoffs and to formulate an optimum solution which best meets these requirements.

The lessons learned from these existing array designs were incorporated into baseline module concepts which represent three different generic implementation approaches, including a rectangular overlapping shingle, an integrally mounted module with a plastic tray substrate, and a stand-off mounted moudle with an aluminum frame. An evaluation of the concept-to-concept differences led to the formulation of a unique approach incorporating the best features of each generic concept into an "optimized" module/array for residential applications.

The module design and installation concept depicted in Figure 1-1 and described in Table 1-1 was selected as the "optimized" integrated residential array approach. This frameless

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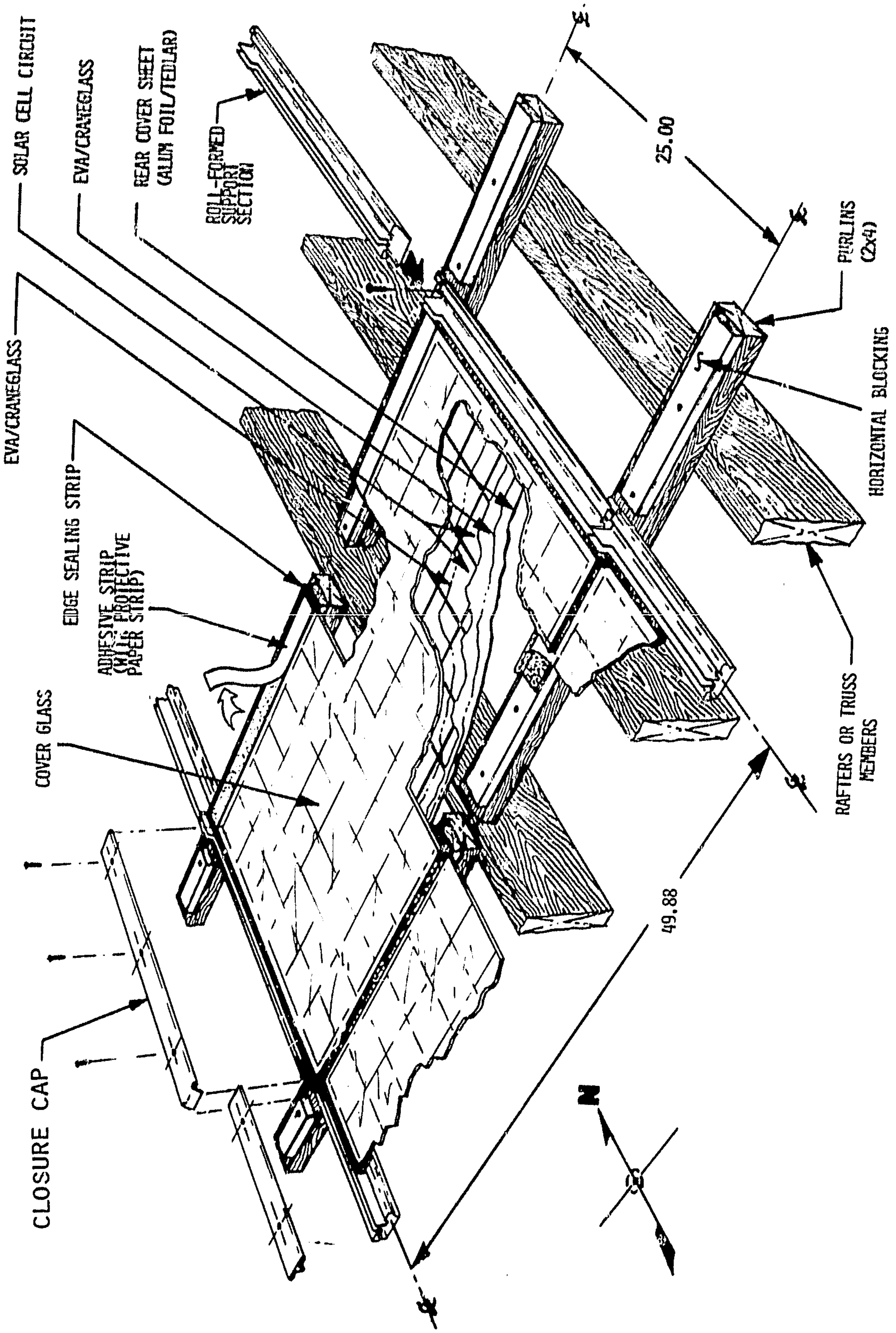

Figure 1-1. Selected Module/Array Design Concept

Table 1-1. Summary of Selected Module Design and Performance Characteristics

Characteristic	Value
Solar Cell Size	100 mm square
Electrical Circuit Configuration	36 series x 2 parallel
Total Solar Cell Area per Module	0.7200 m^2
Module Area	0.8045 m^2
Module Packing Factor	0.895
Glass Superstrate	5 mm thick, Annealed Sunadex
Encapsulant	EVA
Rear Cover	Aluminum Foil/Korad Laminate
Number of Bypass Diodes	3
Diode Type and Mounting	Chips integral with encapsulant laminate
Supporting Frame	None, rubber seal around perimeter
Module Maximum Power Output at Peak Power Conditions (100 mW/ cm^2 insolation and 25°C cell temperature)	97.2 W
Module Efficiency	12.1 percent

module design concept is used in conjunction with a unique roll-formed steel support channel and closure cap to produce a simple array installation which uses the sloping roof surface to the maximum advantage. The watertight integrity of the photovoltaic roof is assured by an overlapped seam between modules to shed the water running down the roof. The support channels are dovetailed together to form a continuous trough for the drainage of water which may leak through the clamped joints which run up the roof.

This design concept, which is akin to a batten/seam roof surface, provides the flexibility to be mounted as either an integral, direct or stand-off installation. The simplicity and watertight integrity of this photovoltaic roof surface was demonstrated by the fabrication and assembly of the full-size six module simulated roof section pictured in Figure 1-2.

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Figure 1-2. Prototype Roof Section Model

The selected module design description was used as the basis for the formulation of a production plan to fabricate the module at annual rates of 10,000, 50,000 and 500,000 m^2 of solar cell area. This planning was used along with a simplified costing methodology to estimate the module FOB factory price at each of these annual plant output levels with the results summarized in Figure 1-3 as a function of the assumed cost of solar cells.

Drawings were prepared to illustrate the methods to be used to install the selected module/array concept as an integral, direct and stand-off mount. These drawings were used as the basis for a detailed installation cost estimate for a typical residential size array consisting of 50 modules. Figure 1-4 presents the total installed array price, including the FOB factory price of the modules at the median production rate, as a function of the assumed cost of solar cells for each of the three methods of installation. These data illustrate the overriding impact of cell cost on the resulting installed price of the array. As depicted in Table 1-2, where

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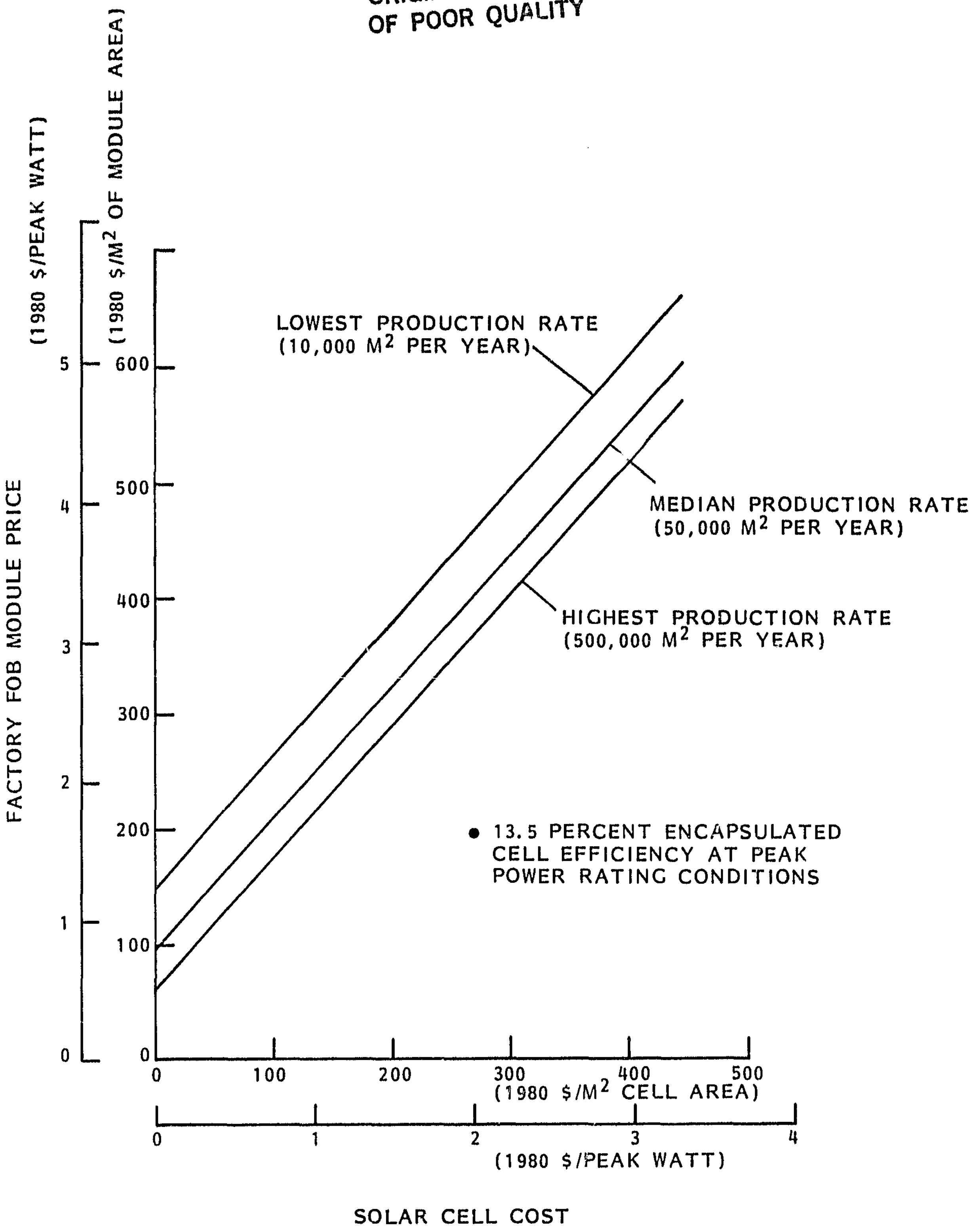

Figure 1-3. Factory FOB Module Price

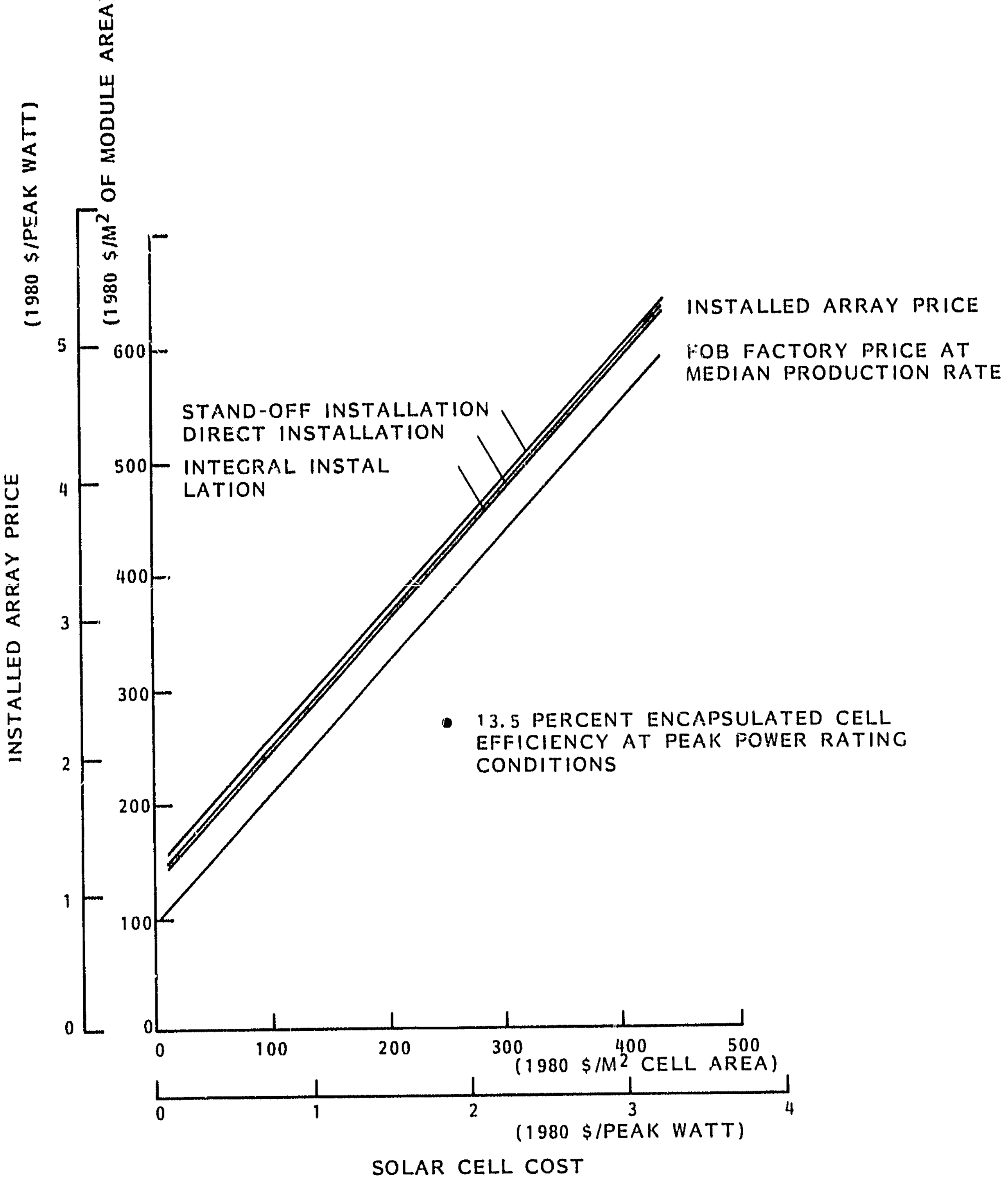

Figure 1-4. Installed Array Price

these cost elements are tabulated for a \$3.00/Watt cell cost, the price of the installation as an integral mount is only 7 percent of the total installed array price.

Table 1-2. Installed Array Price Breakdown at a \$3.00 per Watt Solar Cell Cost

	Price (1980 \$/watt)	Fraction of Total Installed Price
Solar Cells	3.00	0.61
Balance of Module Assembly	1.57	0.32
Total Module FOB Factory Price	4.57	0.93
Installation Price (Integral Mount)	0.32	0.07
Total Installed Array Price	4.89	1.00

SECTION 2

INTRODUCTION

SECTION 2
INTRODUCTION

The objective of this contract was to develop an optimized integrated residential photovoltaic array concept and to prepare detailed design definition which includes sufficient information to permit fabrication, assembly, and installation by a competent third-party. A prototypical simulated roof section of the optimized design concept was constructed to demonstrate the fabrication and installation features of the photovoltaic array. The program activity is organized into four major tasks as listed below.

Task 1 - Development of Conceptual Alternatives

Task 2 - Optimize Design of One Concept

Task 3 - Fabricate Prototype Array/Roof Section

Task 4 - Bypass Diode Integration

The Task 1 effort addresses the development and justification for the selection of three (3) generic integrated photovoltaic array design concepts for residential applications. This effort began with the formulation of a comprhensive set of criteria against which residential photovoltaic design concepts can be evaluated and rated. These concepts, which are represented by the four point designs developed under Sandia Contract 13-8779, were evaluated against the established criteria in an effort to synthesis three generic concepts which could be further modified and optimized by the evaluation of installation and mass production costs. A comparison among these three generic concepts led to conclusions which influenced the eventual selection of the single preferred module/array design.

Based on the results of the Task 1 evaluation, a single integrated residential array design concept was selected for further analysis and evaluation under Task 2. Detailed production design development and engineering trade-off studies will be performed to further optimize the design for minimum cost for the installed array. A set of drawings and specifications was prepared to describe the module and array design. Based on this detailed information, refined cost estimates were generated for three levels of annual production as defined in Table 2-1. In addition, a full-scale prototype array roof section was defined and a cost estimate prepared for its fabrication.

Table 2-1. Annual Production Rates for Use in Costing Analyses

Annual Production Rate (m^2/Year)	10,000	50,000	500,000
Number of Solar Cells	1,000,000	5,000,000	50,000,000
Number of Modules	13,889	69,444	694,444
Power Output at Peak Power Rating Conditions (MW)	1.35	6.75	67.5

The Task 3 activity included the fabrication of a full-scale representative prototype section of the selected residential photovoltaic array complete with electrical and mechanical interconnectors and array/roof interface hardware. This roof section, which was not electrically active, served as a model in identifying additional manufacturing, instllation, maintenance and other interface concerns.

The bypass diode integration task, which was intended to investigate the electrical, mechanical and thermal integration of bypass diodes within a residential photovoltaic module, was added to the contract work scope as a consequence of a module sizing study performed under Task 1 which indicated that the mechanical and thermal integration of bypass diodes represented an important design consideration. The results of this task activity are reported in Document No. DOE/JPL 955894-5.

The master program schedule for this activity, which is reproduced as Figure 2-1, traces the history of the task effort which culminated in the issuance of this final report.

The module/array concept developed under this contract was designed to meet the requirements for Block V residential applications as reflected in JPL Documents 5101-162 and 5101-164. These documents contain several requirements which differ from those imposed

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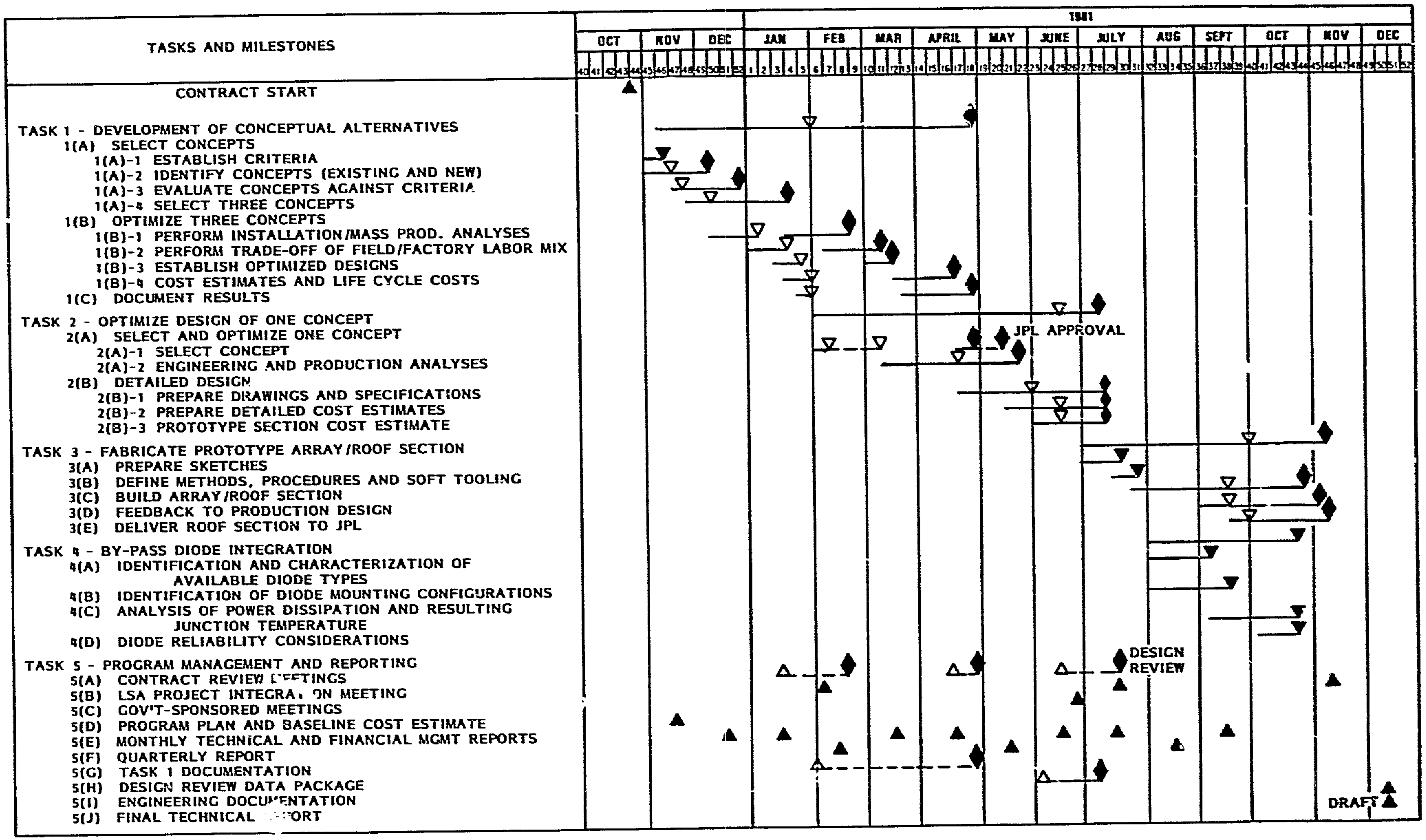

Figure 2-1. Master Program Schedule

on the Block IV procurement. These differences, which are felt to have a significant effect on module design, are enumerated below with a description of the current requirements.

1. Module output power referenced to Nominal Operating Conditions (NOC). NOC is defined as an irradiance level of 80 mW/cm^2, Air Mass (AM) 1.5 spectrum, and cell temperature equal to the Nominal Operating Cell Temperature (NOCT) which which is also referenced to a 80 mW/cm^2 insolation.

2. Inclusion of module peak power rating. The peak power rating of the module must be stated at 100 mW/cm^2 irradiance AM 1.5 spectrum, and 25°C cell temperature.

3. Ability to be series-connected to worst-case open-circuit voltage of 300 Vdc. All module circuitry, including output terminations, shall be insulated from external surfaces. The voltage isolation design shall provide capability of withstanding a worst-case, open-circuit system voltage of 300 Vdc, when modules are connected in series, at 100 mW/cm^2 irradiance and 0°C cell temperature. This capability shall be demonstrated by ability to withstand the 1500 Vdc high-voltage (hi-pot) test.

4. Cell string reliability and redundancy. Circuit redundancy shall be incorporated so that the loss in module output power at NOC shall be less than 10 percent under any of the following conditions:

   a. A single solar cell is separated into two parts by a single straight-line crack with any orientation or position within the cell.

   b. A single interconnect attachment point to a single solar cell is open-circuited.

   c. A single solar cell is short-circuited.

5. Module hot-spot endurance. The module shall be capable of withstanding, for its design life, the hot-spot heating caused when the module is short-circuited at 100 mW/cm^2 solar irradiance, 20°C air temperature, and any of the following conditions occur:

   a. Shadowing of any portion of any single solar cell.

   b. Separation of any single solar cell into two parts by a single straight-line crack with any orientation or position within the cell.

   c. Open-circuiting of any single interconnect attachment point to any single solar cell.

   d. Short-circuiting of any single solar cell.

This capability shall be demonstrated by the ability to withstand a specified Hot-Spot Endurance Test.

6. Maximum module open-circuit voltage. The module open-circuit voltage shall not exceed 30 Vdc under worst-case conditions of 100 mW/cm^2 and -20°C cell temperature.

7. Fire resistance. A photovoltaic module or panel in combination with a prescribed roof, and a photovoltaic module intended for mounting as the roof covering itself, shall meet the requirements of Class A, B, or C as defined in UL-790.

8. Humidity-freeze cycle test. A 10-day humidity-freeze cycle test at 85 percent relative humidity between the temperature extremes of 85 and -40°C is specified.

9. Thermal cycle test. The duration of the thermal cycle test has been increased to 200 cycles.

In addition to the design requirements explicitly derived from the Block V specifications, the contract statement of work stipulates that the following assumptions and constraints are to be imposed on this study activity:

1. The designs specified shall be compatible with low-cost, mass production processes currently in use

2. Details of development relative to cell and encapsulation processing are not within the scope of this effort.

3. Array design and installation shall be compatible with accepted building practices, electrical, safety and fire codes.

4. The array shall be roof-mounted, air-cooled, flat-plate, south-facing with a fixed tilt and a 20 year design life. Mounting configurations such as direct, integral, rack and stand-off shall be considered in the study.

5. The array design shall be modular in nature to permit expansion for various size houses between 140 and 280 m^2 of floor space.

6. Costs shall be identified in 1980 dollars.

7. Encapsulated cell areal efficiency shall be 135 Wp/m^2 at 100 mW/cm^2, AM 1.5, and 25°C. From this data the Contractor shall determine NOCT consistent with the specific design.

8. Array operating voltage shall be within the range of 100 to 300 Vdc.

9. A cell open circuit failure rate of one cell per ten thousand per year shall be used in circuit design trade-offs.

SECTION 3

TECHNICAL DISCUSSION

SECTION 3
TECHNICAL DISCUSSION

3.1 SYNTHESIS OF SELECTED DESIGN CONCEPT

3.1.1 DESCRIPTION OF THE RECOMMENDED DESIGN CONCEPT

3.1.1.1 General Features and Mounting Approach

The concept shown in Figure 3-1 was evolved as the selected integrated residential module/array design. This approach was developed as the result of an initial evaluation and further design optimization of three concepts as described in Sections 3.3 and 3.4 of this report and reflects the design synthesis of the best features of the approaches considered. In particular the concept shown in Figure 3-1 incorporates the following distinctive characteristics:

1. Employs the forces of gravity as the primary means of water shedding.
2. Provides an aesthetically attractive array installation with a horizontal overlapped joint and a low profile batten-type vertical joint.
3. A basic 2 x 4-ft. module size which offers a reasonable choice for residential-size installations where the flexibility to accommodate a wide variety of roof sizes and aspect ratios, while maintaining a nominal 200 vdc inverter input voltage level, is an important design consideration.
4. Incorporates a straight forward electrical circuit design which consists of 36 series connected pairs of 100mm square cells arranged with a bypass diode around each 12 series-cell group. These diodes are packaged within the encapsulant laminate in the inactive portion of the glass coverplate which is overlapped by the active area of the next higher course on the roof.

The watertight integrity of this roofing surface is assured by a simple module perimeter seal which uses the sloping roof surface to the maximum advantage. The east-west seams of the roof are sealed as an overlapped or shingled joint as shown in Figure 3-2. The rear side of the "L" shaped rubber extrusion on the upper, overlapping module is covered with a high-tack, pressure-sensitive adhesive which bonds to the inactive glass area of the lower module to form a secondary seal against the leakage of water at this joint.

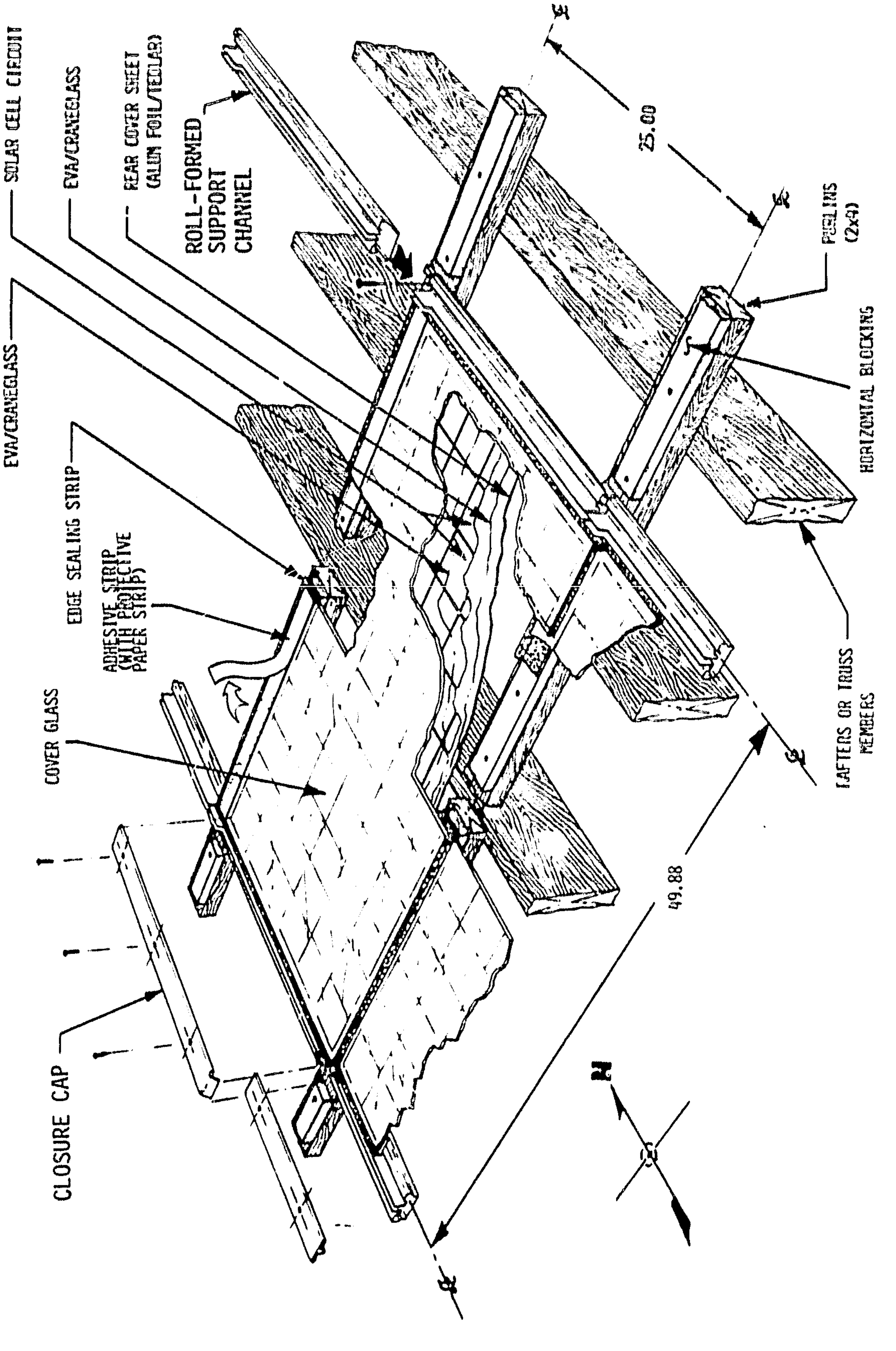

Figure 3-1. Selected Module/Array Concept

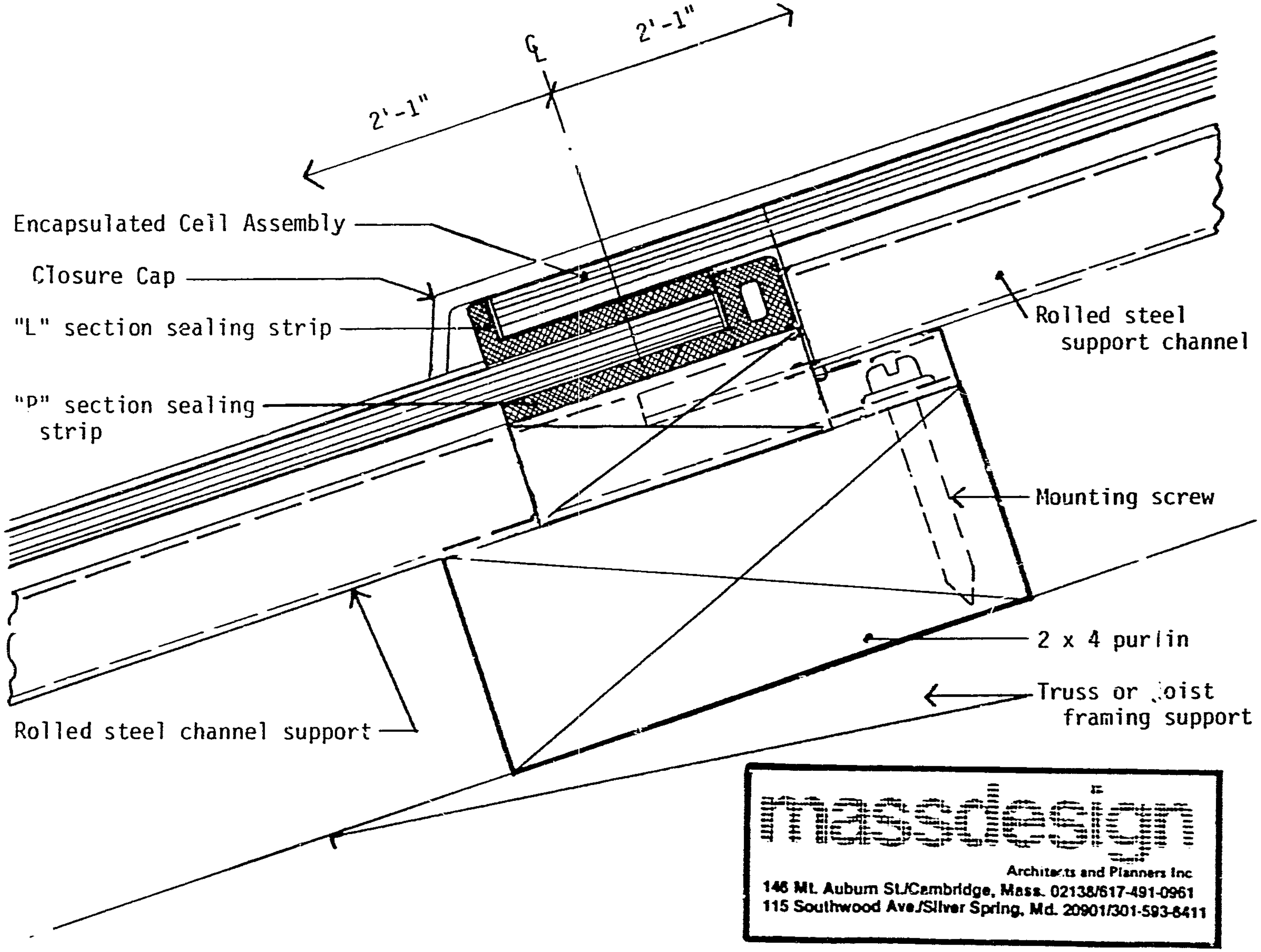

Figure 3-2. Sectional View Through Overlapping Joint

The joint along the roof slant height direction is sealed by clamping a "P"-shaped rubber extrusion in a roll-formed steel support channel as shown in Figure 3-3. These channels are assembled on the roof in a tongue and groove fashion as shown in Figure 3-4 to provide for drainage of any leakage water from one channel section to another with an ultimate discharge at the eave. Thus, water leakage into the building at this joint is prevented by three separate sealing or drain-off mechanisms. The first line of defense is the compression of the bulb of the "P" seal between the vertical wall of the support channel and the underside of the closure cap. Any water which leaks past this seal will drain directly into the channel interior where it will flow from one channel to another until it is finally discharged at the eave. Finally, to destroy the watertight integrity of the roof, leakage must occur past the seal between the top flat on the channel section and the leg of the "P" section.

The horizontal overlapped joint between two modules is clearly shown in Figure 3-5. Note the 1 x 2 blocking strip which is nailed to the horizontal purlins to provide the support for the overlapped joint.

3.1.1.2 Module Design Description

The module assembly shown in Figure 3-6 represents the component which is produced in the factory for ultimate delivery to the job site. This module consists of the encapsulated cell subassembly, which is the product of the EVA lamination process, surrounded by a simple elastomeric gasket frame made of two separate extruded forms. The "P" seal shown in Figure 3-7 is bonded around the parameter of the encapsulated cell subassembly on three sides as depicted in Figure 3-8. The "L"-shaped seal, which is depicted in the drawing of Figure 3-9, is bonded along the fourth side, as shown in Figure 3-10, to complete the module frame. An EPDM compound is used for both of these extruded shapes and a pressure-sensitive adhesive with a release paper is applied to the underside of the "L" seal to function as the field bond between overlapped modules along the long edge. A paper masking tape is applied over the inactive portion of the circuit along the upper long edge to keep the bonding area clean until the time that the field bond is made by removal of the masking tape and release paper from the "L" seal on the overlapping module.

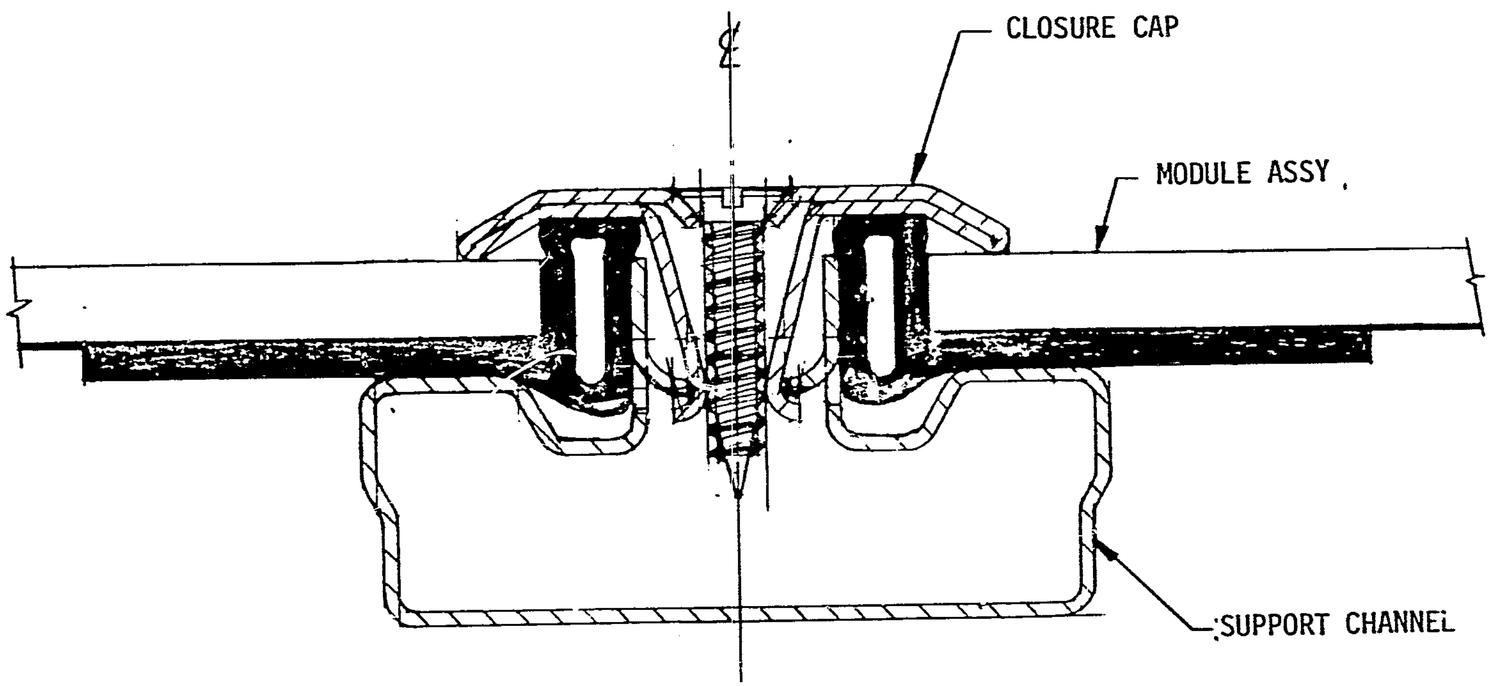

Figure 3-3. Sectional View Through Support Channel Showing Clamping Method

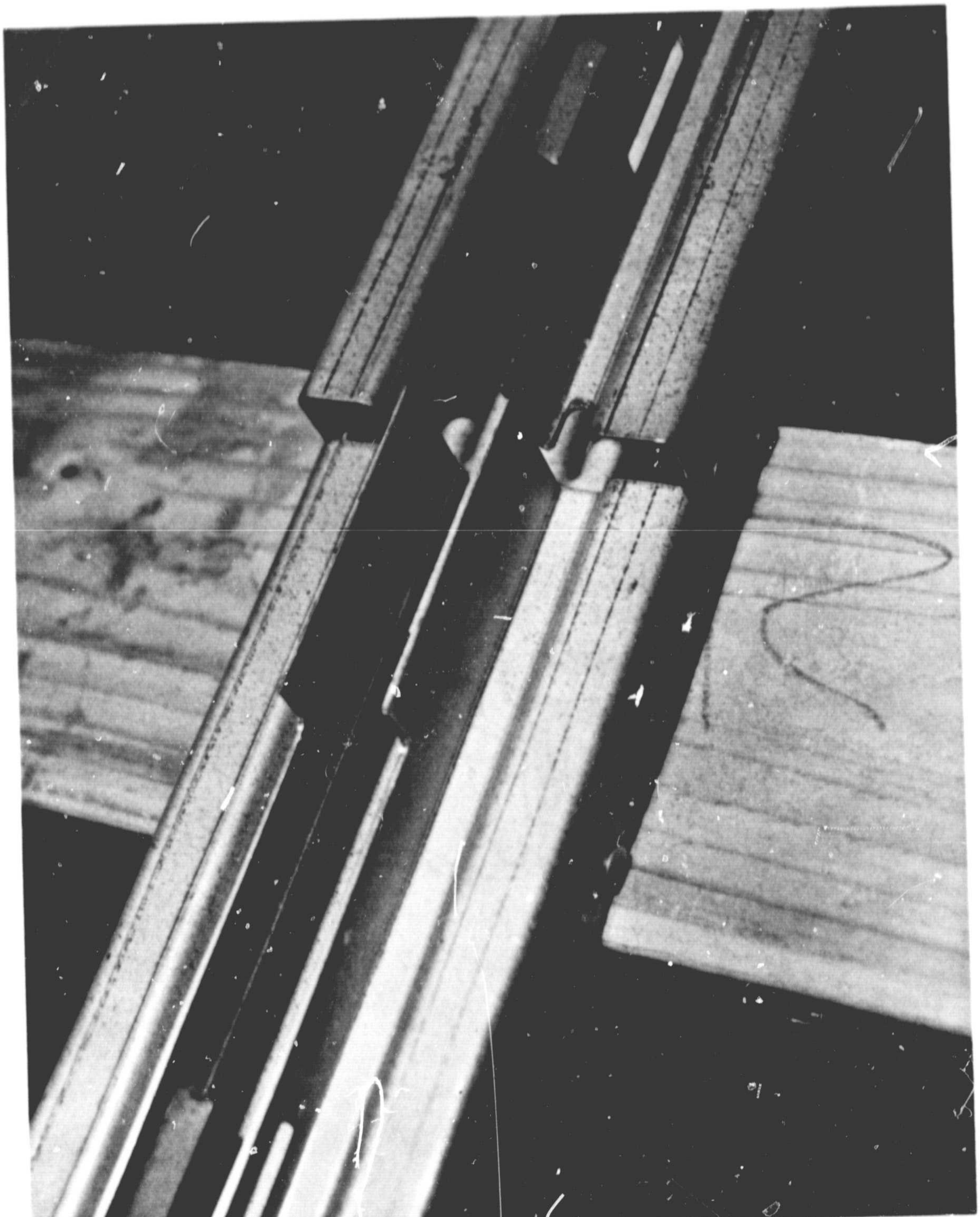

Figure 3-4. Interlock of Two Support Channels

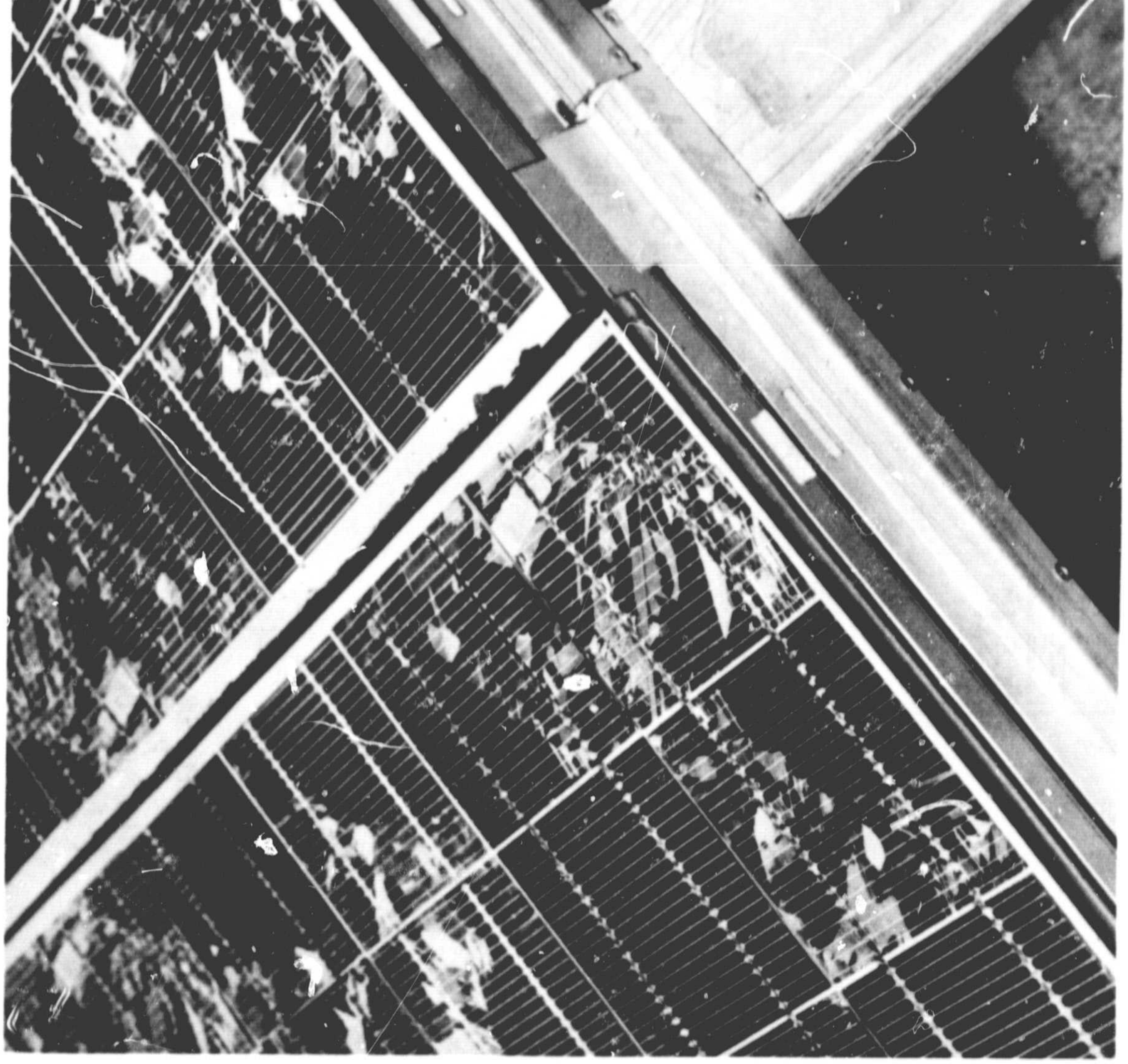

Figure 3-5. Overlapped Joint at Support Channel Interface

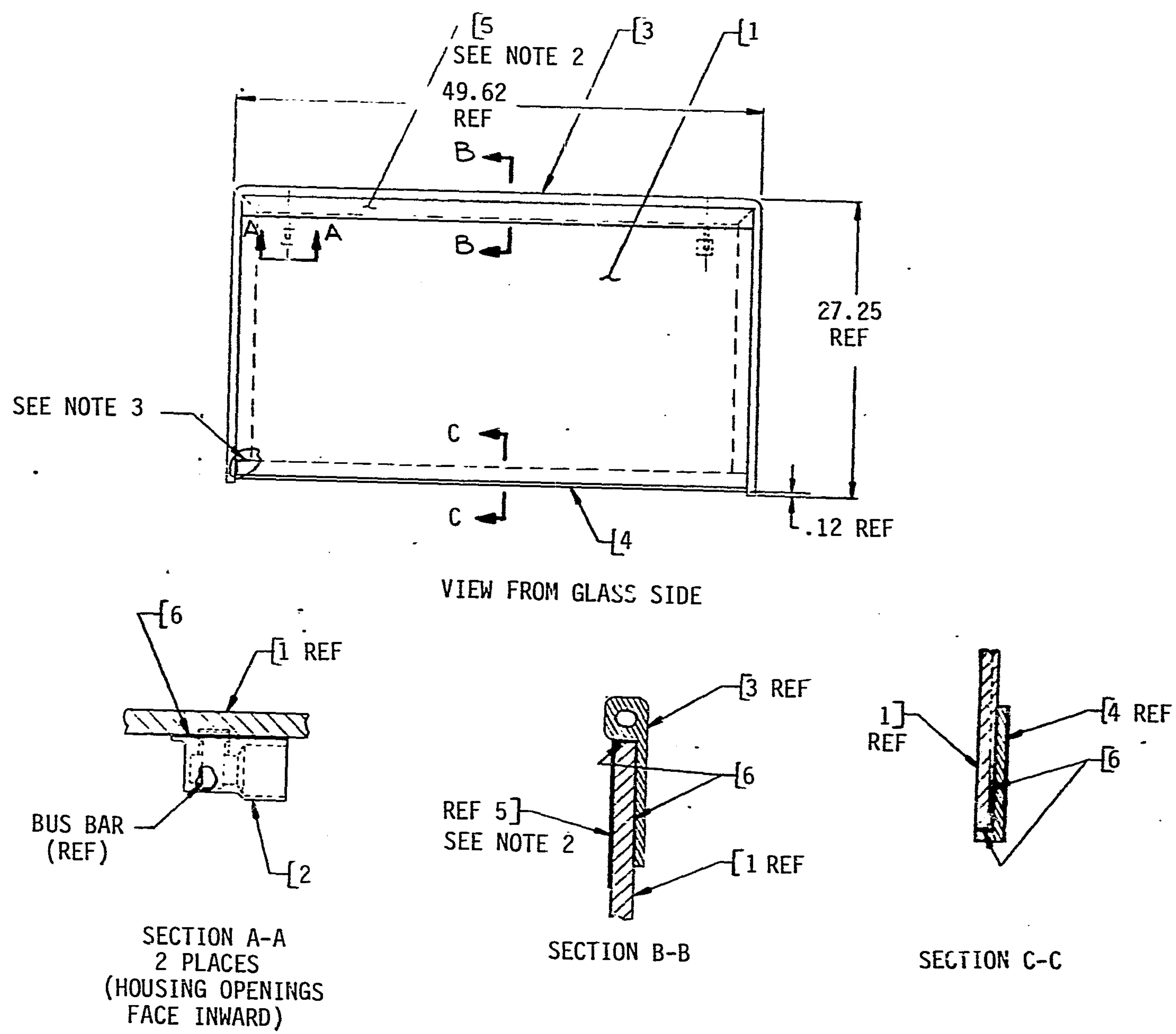

Figure 3-6. Module Assembly Drawing

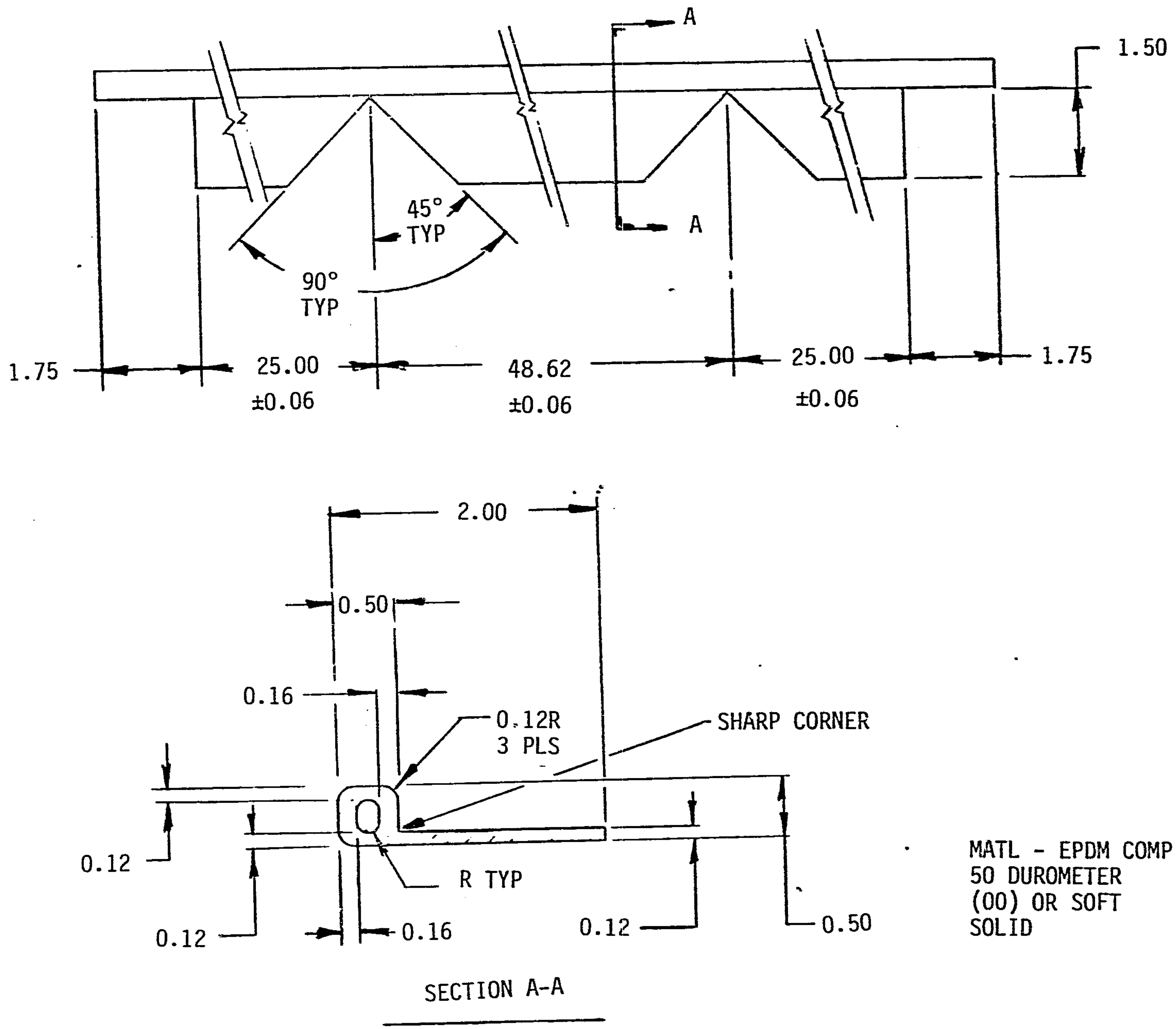

Figure 3-7. "P" Seal Framing Extrusion

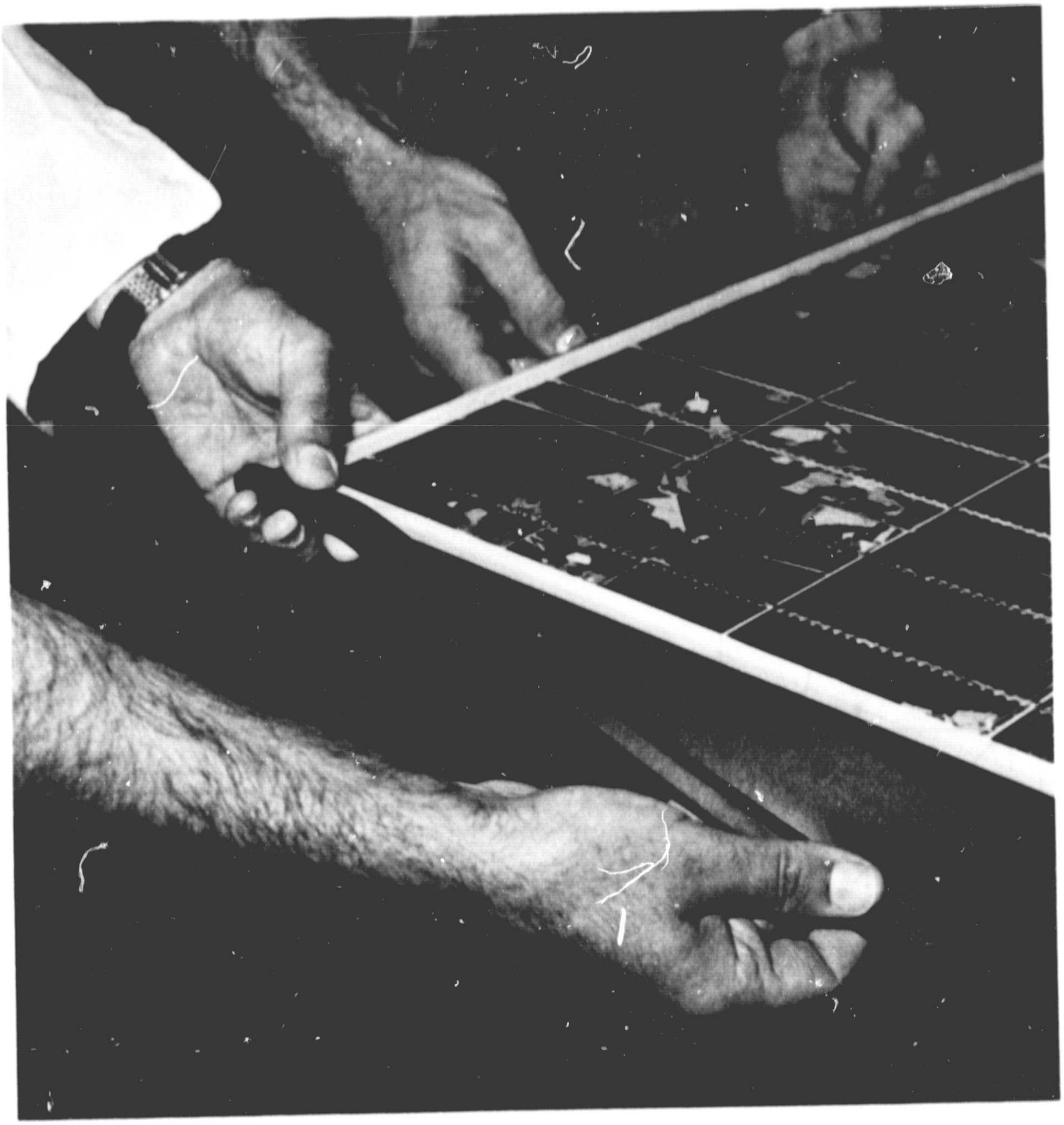

Figure 3-8. "P" Seal Attachment to Module

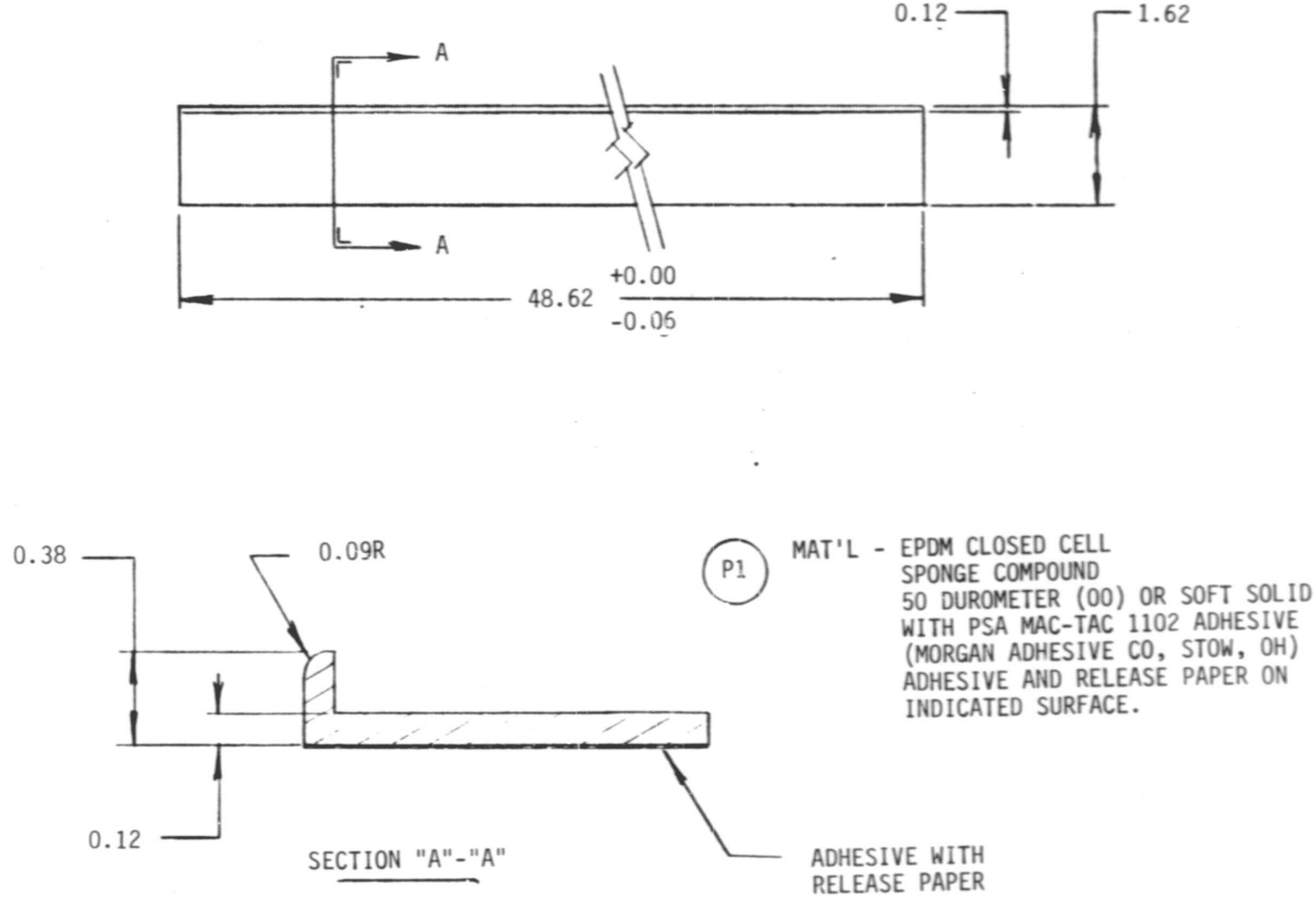

Figure 3-9. "L" Seal Framing Extrusion

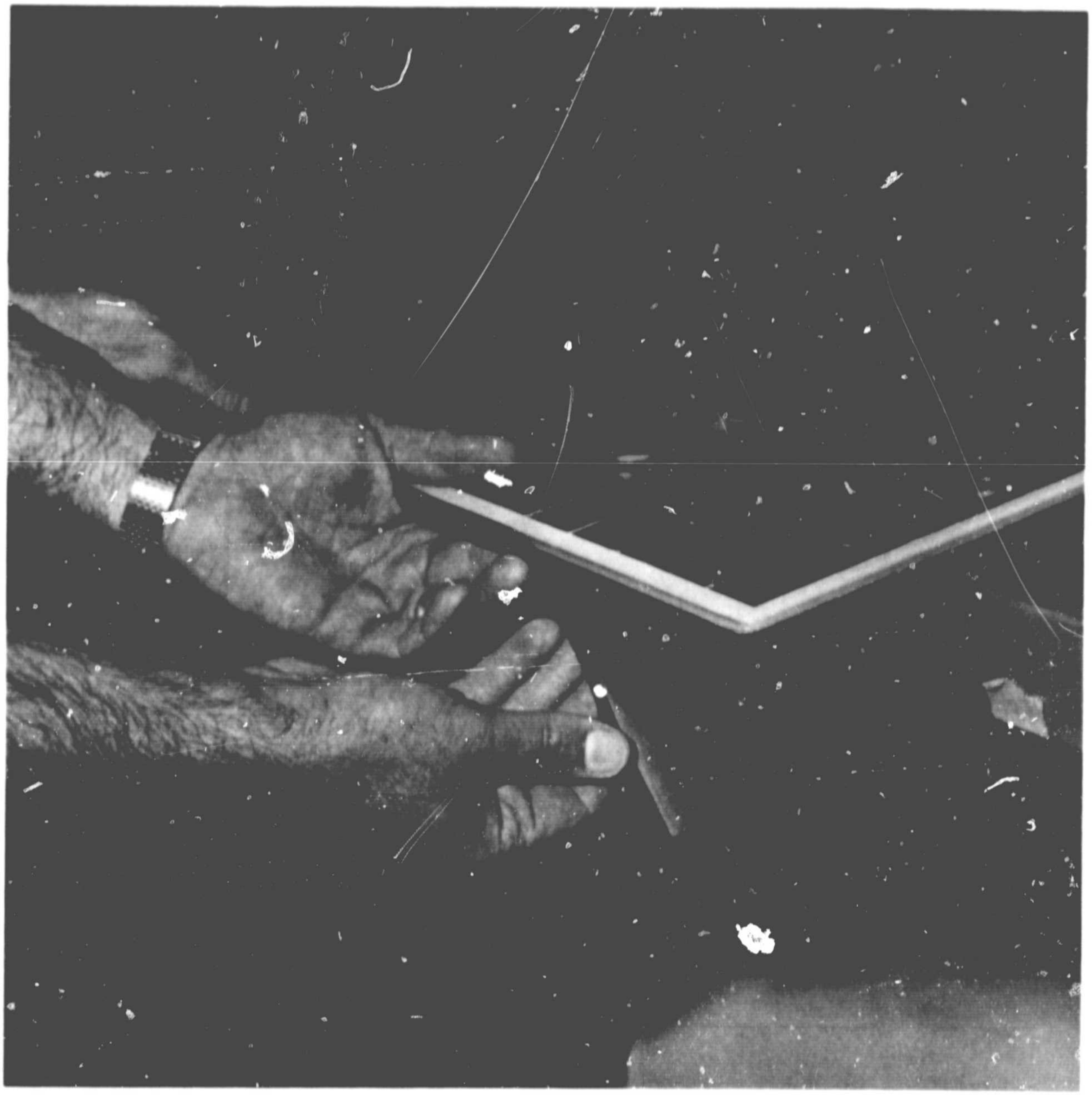

Figure 3-10. "L" Seal Attachment to Module

Two AMP, Inc. Solarlok bus bar housings are installed by bonding to the rear cover sheet as shown in Figure 3-11.

3.1.1.3 Electrical Circuit Design

The module electrical circuit is built around a circuit element consisting of six series connected pairs of 100 mm square cells. Six of these twelve-cell elements are arranged side-by-side to form the complete circuit as shown in Figure 3-12. By alternating the polarity of adjacent circuit elements it is possible to make the series connection between elements with a simple interconnector strip. This arrangement also permits the convenient installation of bypass diodes around each group of twelve series-connected cell pairs as shown in Figure 3-13.

The resulting electrical circuit design, consisting of 36 series-connected cell pairs, provides an open-circuit voltage of less than 30 vdc under 100 mW/cm^2 illumination conditions with a -20°C cell temperature. As shown in Figure 3-14, this circuit arrangement should produce a module maximum power output of 97.2 watts under peak power rating conditions (100 mW/cm^2 insolation with 25°C cell temperature) with the specified 13.5 percent encapsulated cell efficiency. Under Nominal Operating Conditions (NOC) the maximum power output of this module would be reduced to 63.8 W assuming a NOCT of 61°C, which might be typical of an integral or direct mounting. The resulting module efficiency at NOC would be 9.9 percent. The use of two parallel 100 mm square cells in the selected circuit design provides a short-circuit current capability of approximately 6.4 amperes at the peak power rating conditions.

3.1.1.4 Encapsulated Cell Subassembly

3.1.1.4.1 General Description

The encapsulated cell subassembly shown in Figure 3-15 is the major component of the module and consists of a laminated construction of the glass superstrate, the solar cell circuit elements, which are sandwiched between layers of EVA film, and a rear cover sheet. Three bypass diodes are packaged within the laminate under an extended edge of

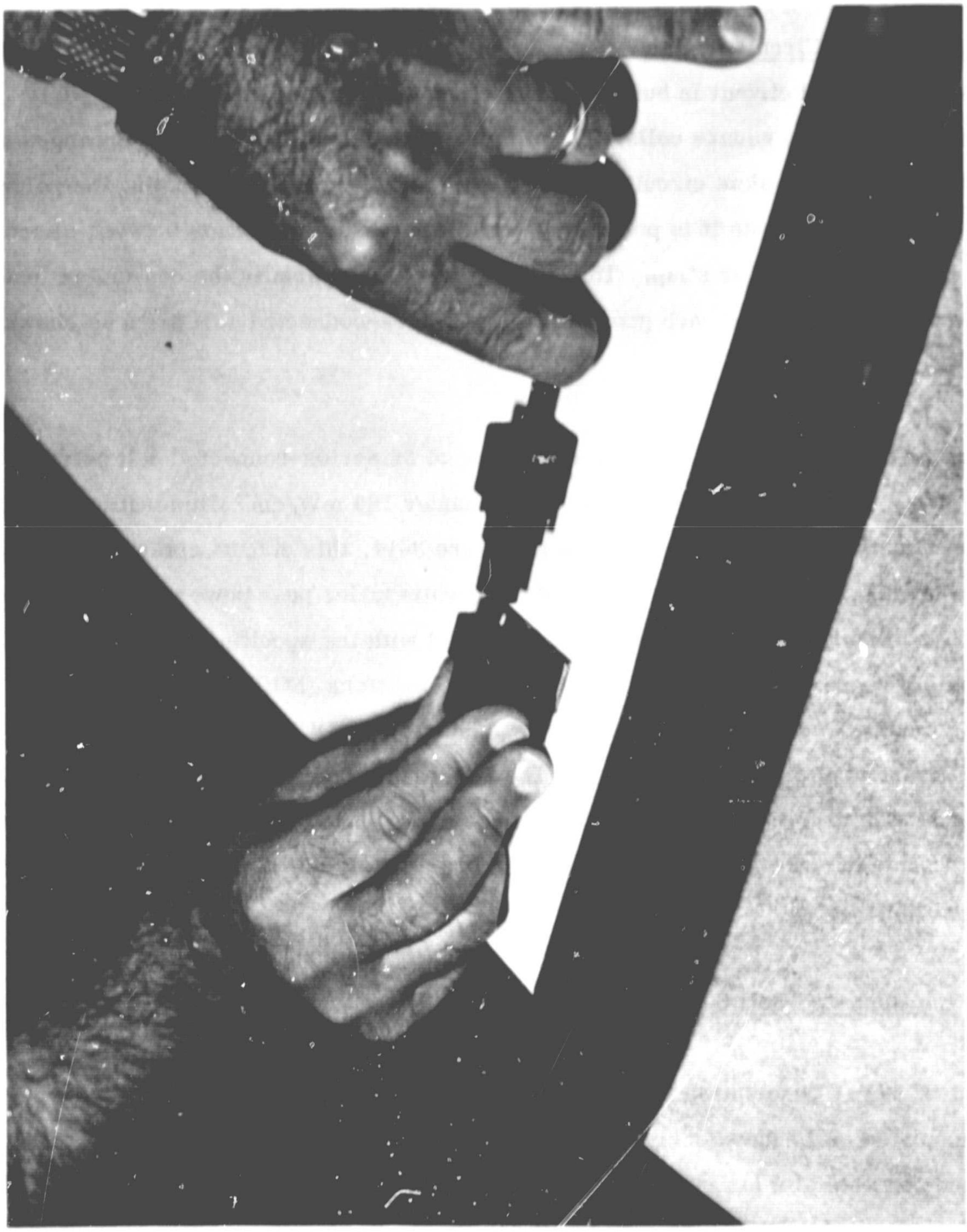

Figure 3-11. Solarlok Interconnection System

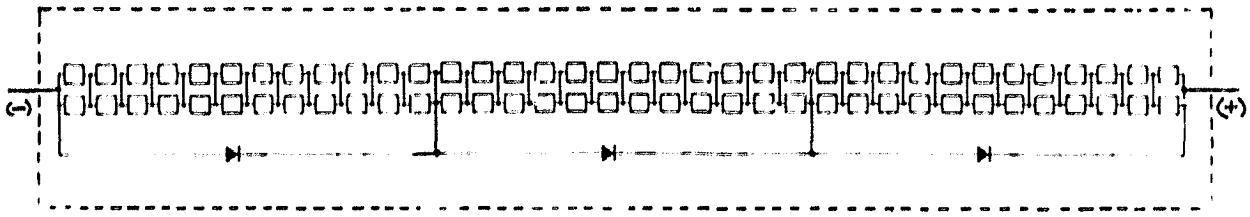

Figure 3-12. Module Electrical Circuit Schematic

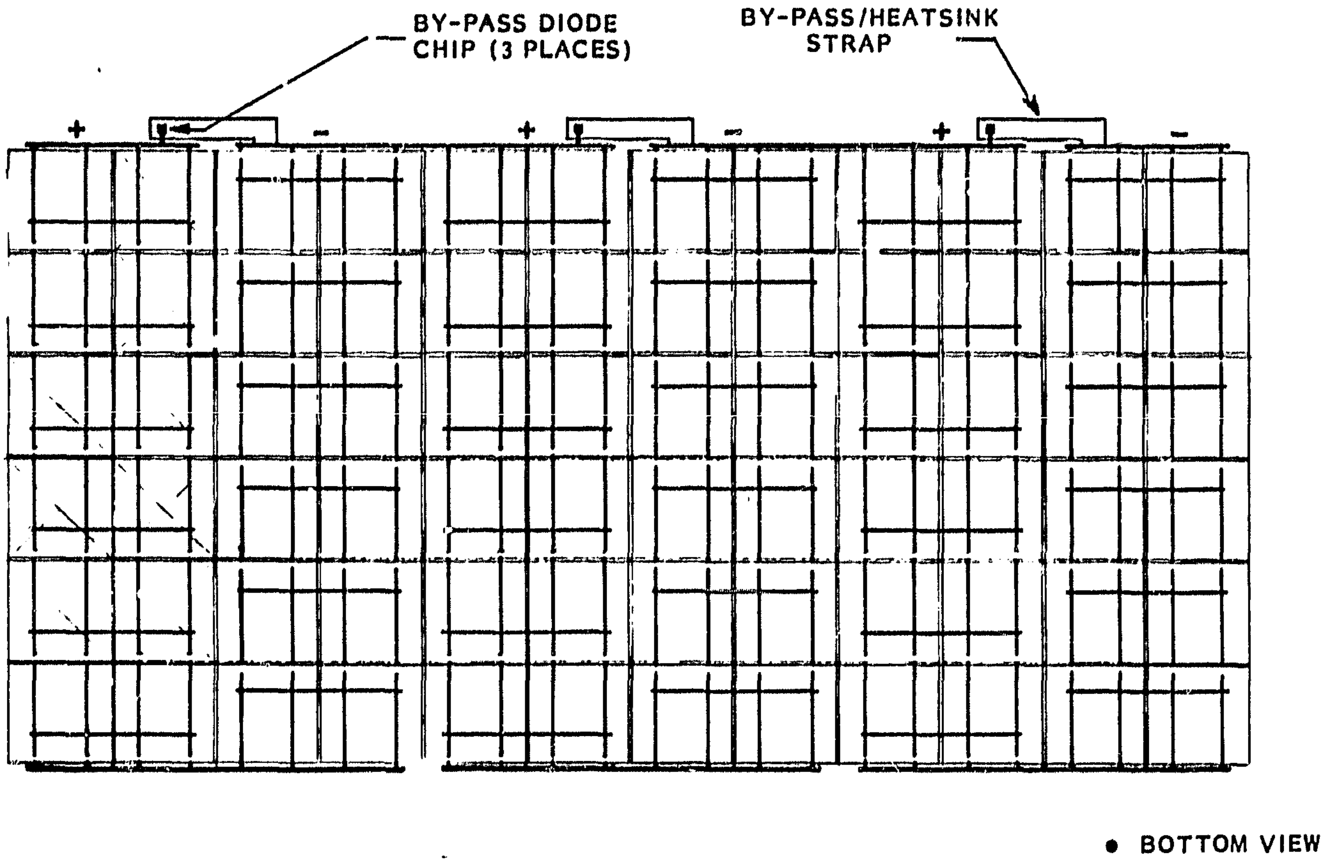

Figure 3-13. Arrangement of Electrical Circuit Elements

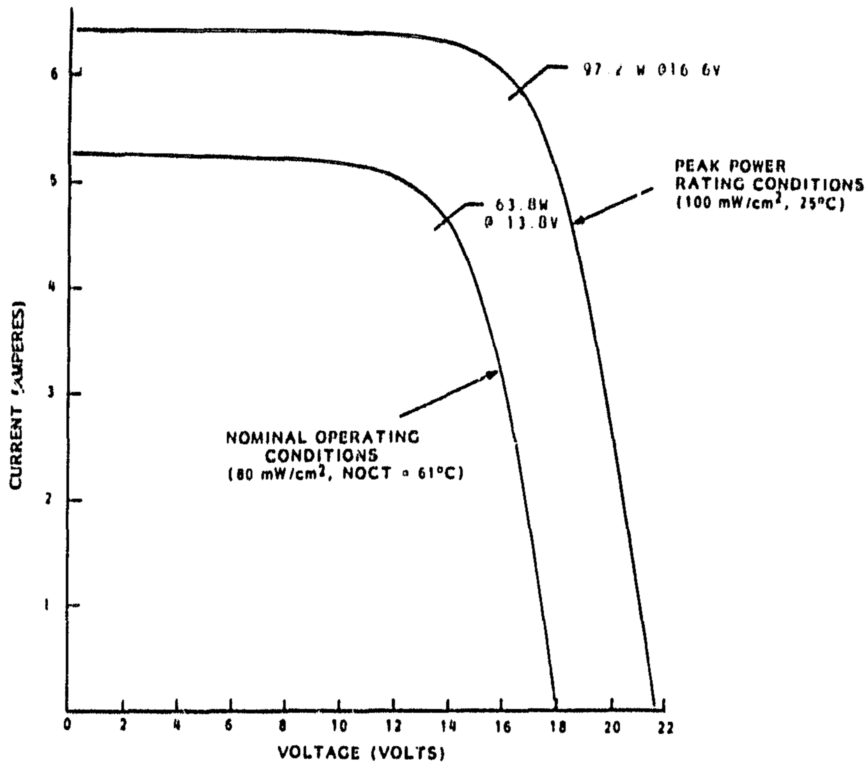

Figure 3-14. Module I-V Characteristics

the glass superstrate which will be ultimately covered by the overlapped joint with the leading edge of the module above. Thus with this module mounting approach it is possible to conveniently house the bypass diode chips, mounted on heat spreader fins, without sacrificing exposed frontal area.

The positive and negative circuit terminations, which are located in opposite corners of the long edge adjacent to the inactive diode mounting strip, exit through slots in the rear cover sheet as shown in Section B-B of Figure 3-15. AMP Solarlok bus bars are incorporated as part of the lamination with insulator strips provided as required to isolate these conductors from the rear surface of the solar cells.

3.1.1.4.2 Glass Superstrate

A glass coverplate of 5 mm (0.188 inch) thick thermally-tempered Sunadex or Heliolite glass was selected as the superstrate for the module. Both these products are high-transmission, low-iron rolled soda-lime solar glass with an embossed pattern on one side and a matte

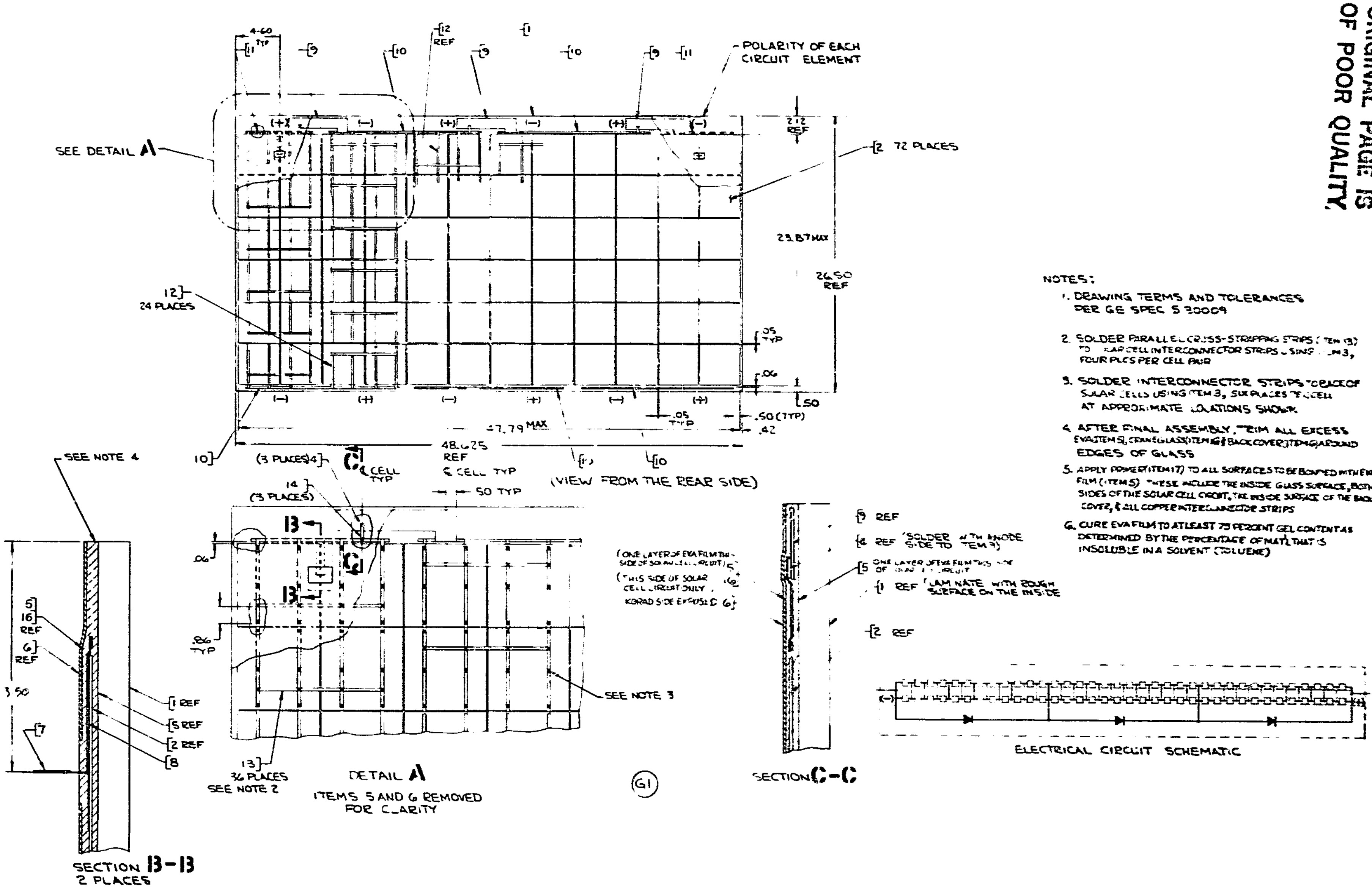

Figure 3-15. Encapsulated Cell Subassembly

surface on the other side. In either case the lamination is performed with the embossed pattern on the inside so that the exposed surface is relatively smooth to aid the self-cleaning of the module. The structural analysis of this glass coverplate, which was presented in the third quarterly report, indicates that annealed glass of this thickness is adequate to meet the loading requirements of this application. However, during the course of laminating the simulated modules for the prototype roof section model, as reported in Section 3.2, it was found that annealed glass of this size and thickness was subject to breakage under the loading conditions imposed by the double vacuum chamber laminator.

3.1.1.4.3 Encapsulant

Ethylene Vinyl Acetate (EVA) film is used as the encapsulant in the selected module design. This film adhesive system, which was developed under the sponsorship of the JPL FSA Project, offers the potential for a low-cost encapsulant with the physical and chemical properties necessary to meet the long-operating life requirements when exposed in the outdoor environment. EVA sheet material, which is specially formulated for solar photovoltaic applications, is currently available from Rowland, Inc. Berlin, CT in a nominal 0.018 inch thickness. This film is extruded using DuPont Elvax 150 as the base material with the Springborn A9918 additive package. An embossed texture on the film permits rolling without an intermediate layer of anti-blocking paper. The estimated cost of this material as a function of quantity ordered is given in Figure 3-16.

The laminate construction consists of a single layer of EVA film between the solar cell circuit and the glass coverplate. Another layer of film plus a sheet of Craneglass is positioned behind the solar cell circuit to act as the bonding agent for the rear cover sheet. The Craneglass, which is impregnated with EVA during the lamination process, provides a positive physical separation between the rear side of the solar cell circuit and the aluminum foil inside layer of the rear cover sheet.

The present state of the technology for EVA lamination requires that a primer be applied to all surfaces to be bonded. Efforts are currently underway to incorporate the primer into the bulk EVA material, thus eliminating the process steps associated with primer application

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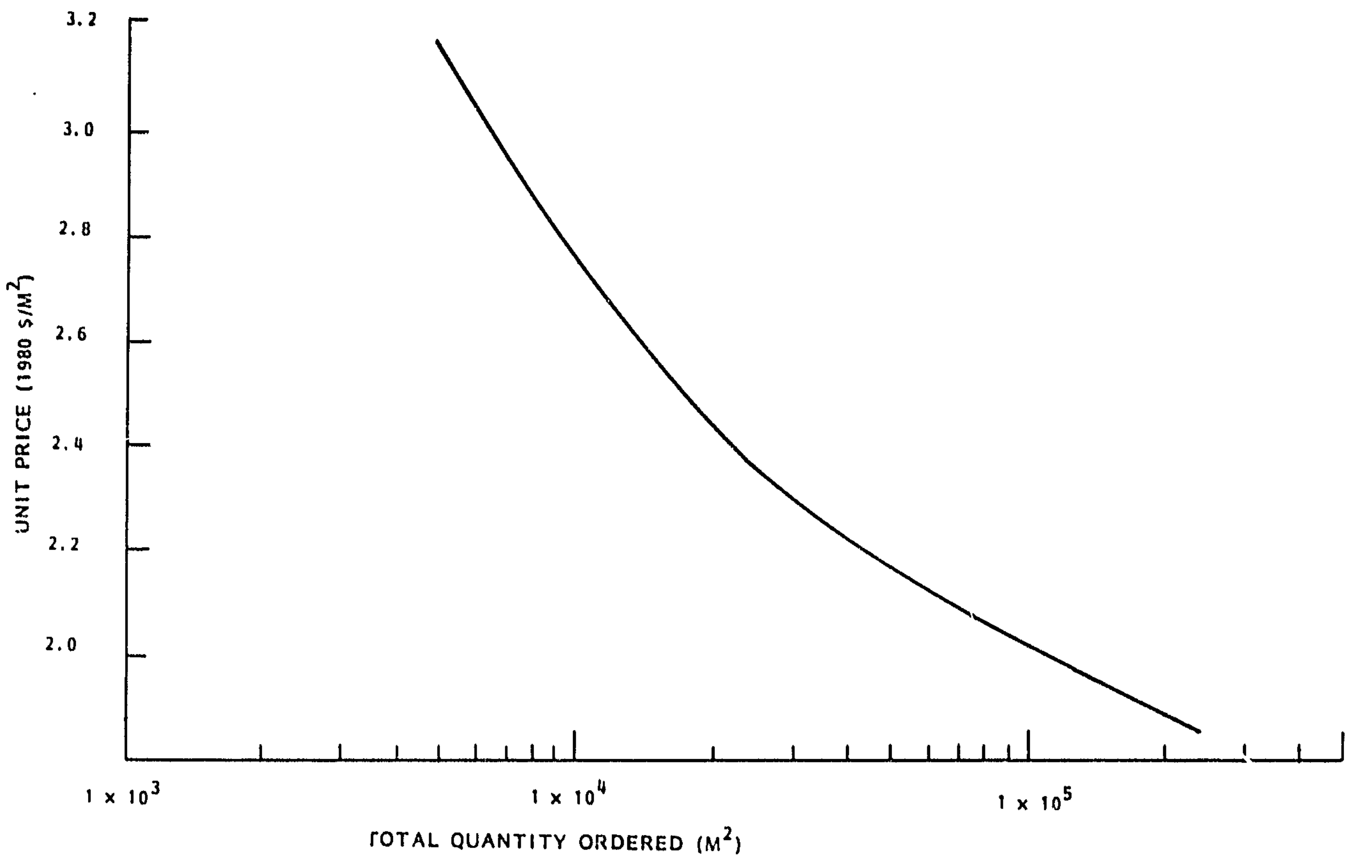

Figure 3-16. Estimated Price of Elvax 150 Sheet Containing the Springborn A9918 Additive Package

and drying. Present EVA lamination processing is performed on a batch basis with a 50 to 60 minute cycle time in the vacuum laminator. Process studies currently underway at DuPont have indicated that a 2 minute vacuum lamination step is sufficient to effect a bonding of the laminate surfaces. The laminated assemblies are then subjected to an elevated temperature cure cycle under ambient pressure to increase the gel content of the EVA.

3.1.1.4.4 Rear Cover Sheet

The rear cover sheet is a laminate of 18 μm (0.0007 inch) thick aluminum foil to 76 μm (0.003 inch) thick white Korad film. This sheet functions as both the rear side vapor barrier and the dielectric insulating layer on the exposed rear surface of the module. Thus on the rear side there are two dielectric layers between the active solar cell circuit elements and the outside environment: the rear EVA/Craneglass layer and the Korad outer skin of the rear cover sheet.

3.1.1.4.5 Bypass Diode Installation

Three bypass diode cells of the configuration specified in Figure 3-17 are installed as an integral part of each encapsulated cell subassembly as shown in Detail A of Figure 3-15. An "L" shaped, 0.020 inch thick copper strap is used both as a heat spreader to fin the localized heat generated within the diode chip and as the anode lead of the diode. A steady-state thermal model for the diode mounting configuration was formulated as shown in Figure 3-18 and used to develop the input to a steady-state multi-dimensional heat transfer computer code. The model consists of 30 nodes including the heat generating node representing the diode chip and two boundary condition nodes. The back face of the diode and its mounting surface was assumed to be adiabatic while the temperature of the outside surface of the foam tape and uncovered surface of the glass was defined as 60°C.

With the open-circuit failure or the complete shadowing of a pair of solar cells within the bypassed group, the forward conducting diode would be required to dissipate approximately 4.8 watts. Under these conditions the proposed diode mounting configuration would limit the chip junction temperature to 120°C which is near the upper extreme of temperature endurance for the cured EVA encapsulant.

3.1.2 MODULE PRODUCTION COST ANALYSIS

3.1.2.1 Assumptions and Constraints

The selected module design described in Section 3.1.1 was analyzed with respect to manufacturing costs under three annual production rate scenarios: 10000, 50000 and 500000 m^2 of solar cell area. As shown in Table 2-1 these production rates represent 13889, 69444 and 694444 modules per year, respectively.

The approach taken by K&S in the formulation at the basic production plan for each of the annual factory output levels attempts to minimize the manufacturing costs of the module by the optimum mix of automated processing equipment and applied labor. The degree to which the plant is automated varies significantly over the range of annual outputs to be considered in the analysis. At the lowest rate investigated (viz., 10,000 m^2 per year) a minimum of

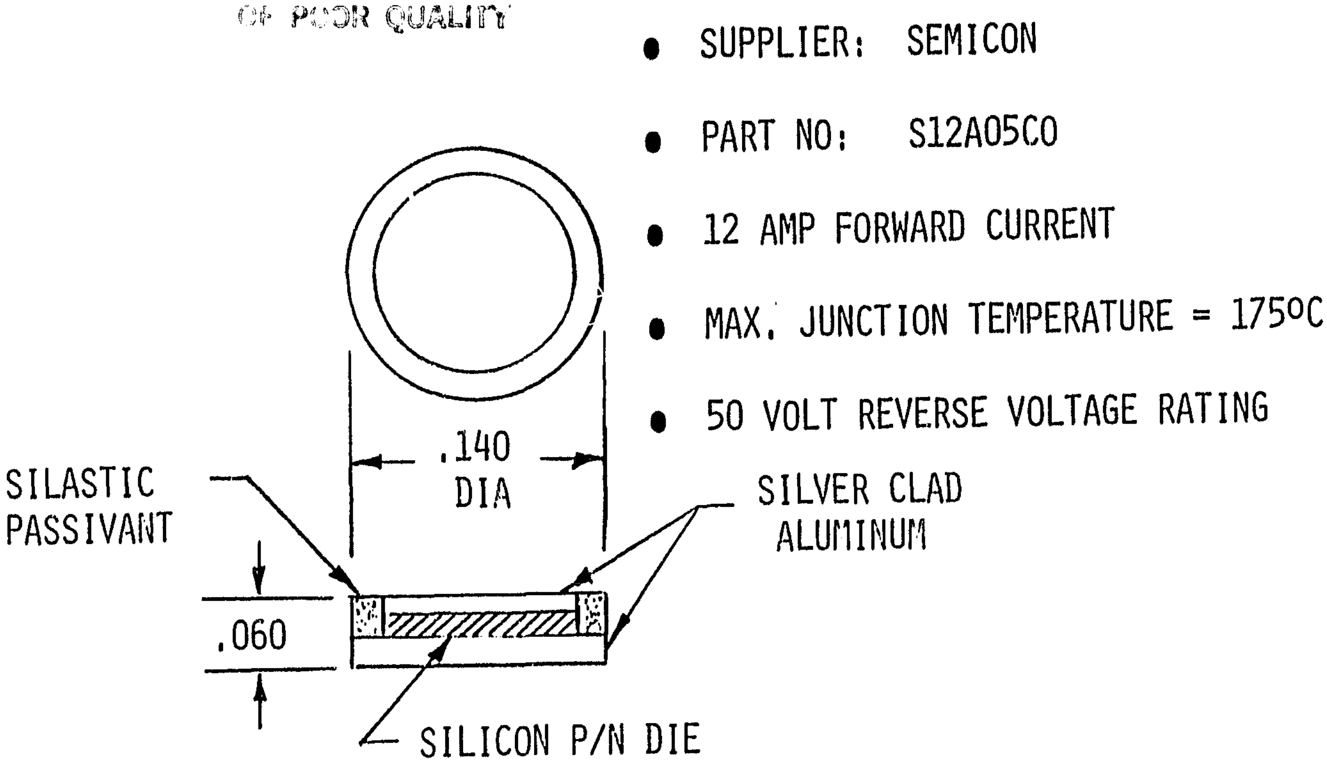

Figure 3-17. Bypass Diode Cell Configuration

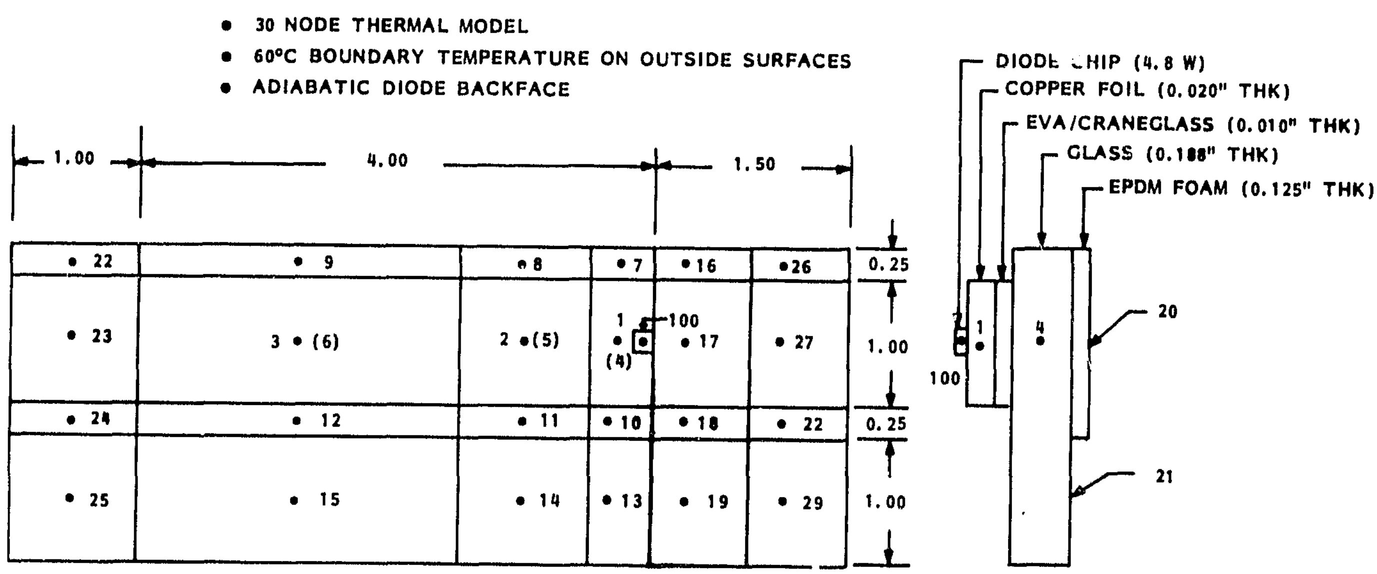

Figure 3-18. Thermal Model for Bypass Diode Installation

automated processing is indicated, whereas at the highest level, which represents a factory output rate of approximately 100 modules per hour, the level of process automation is well beyond the realm of experience in the photovoltaic module manufacturing industry.

For the cases considered, the effort was concentrated on proposing a production flow which attempts to anticipate problems which could develop in a normal plant operation for this type of product, and then set forth a realistic building block approach and arrangement of associated functional work stations. This approach attempted to consider the following factors:

1. Optimum unit for handling and storing.
2. Optimum arrangement of equipment so as to minimize the negative effect to output if a particular machine goes down.
3. Adequate buffers in production flow.
4. Functions best accomplished in continuous flow vs. functions best accomplished in batches.
5. Optimum utilization of manpower.
6. Achieving output requirements with a balanced line factory based on reasonable projections for output and technological advances for equipment involved.
7. Optimum cost effective logistical arrangement.

Since the assumptions and estimates used were applied equally to all production rates considered, they are useful or valid from a relative comparison or evaluation standpoint.

Solder reflow was the interconnect technique utilized in this study for all production rates since it represents the present state-of-the-art and indications are that it will continue to be the main interconnect technique for the immediate future.

3.1.2.2 Process Design and Plant Layout

3.1.2.2.1 Lowest Production Rate

At the lowest production rate to be considered in this analysis (viz., 10,000 m^2 per year) the plant is assumed to operate on a one (1) eight-hour shift per day for six (6) days per week throughout the year with nine (9) holidays and a one (1) week plant shutdown. This operating schedule results in 297 working days per year or 2376 working hours per year. A production rate of 5.85 completed modules per working hour is required to meet the required annual throughput.

The materials handling and storage requirements were based on weekly shipments of incoming goods with a one week safety stock. This sets the warehouse space requirements at two weeks supply of production requirements. The production floor would be supplied before each day's shift. It is conceived this delivery would take place while the preceding shift was still on duty. Therefore, ideally, the production floor should accommodate two shifts supply of materials.

Using a plant operating time of 297 days per year it seemed that a one shift operation would be most practical and cost effective in meeting the production rate requirements of this case with the level of automation which was judged to be appropriate. The process flow diagram and plant floor layout are shown in Figures 3-19 and 3-20, respectively.

The input to the production line assembly area are completed solar cells as received from the cell processing plant. In order to avoid the cost of cassettes for this production rate, it is assumed the cells will be stored and brought to the assembly area in stacks, like coins. The operator loads cells from the stack onto the rotary table of a semi-automatic tabbing machine. The cell is automatically fluxed and the interconnect is bonded to the front contacts of the cell. The operator removes and stacks the tabbed cells.

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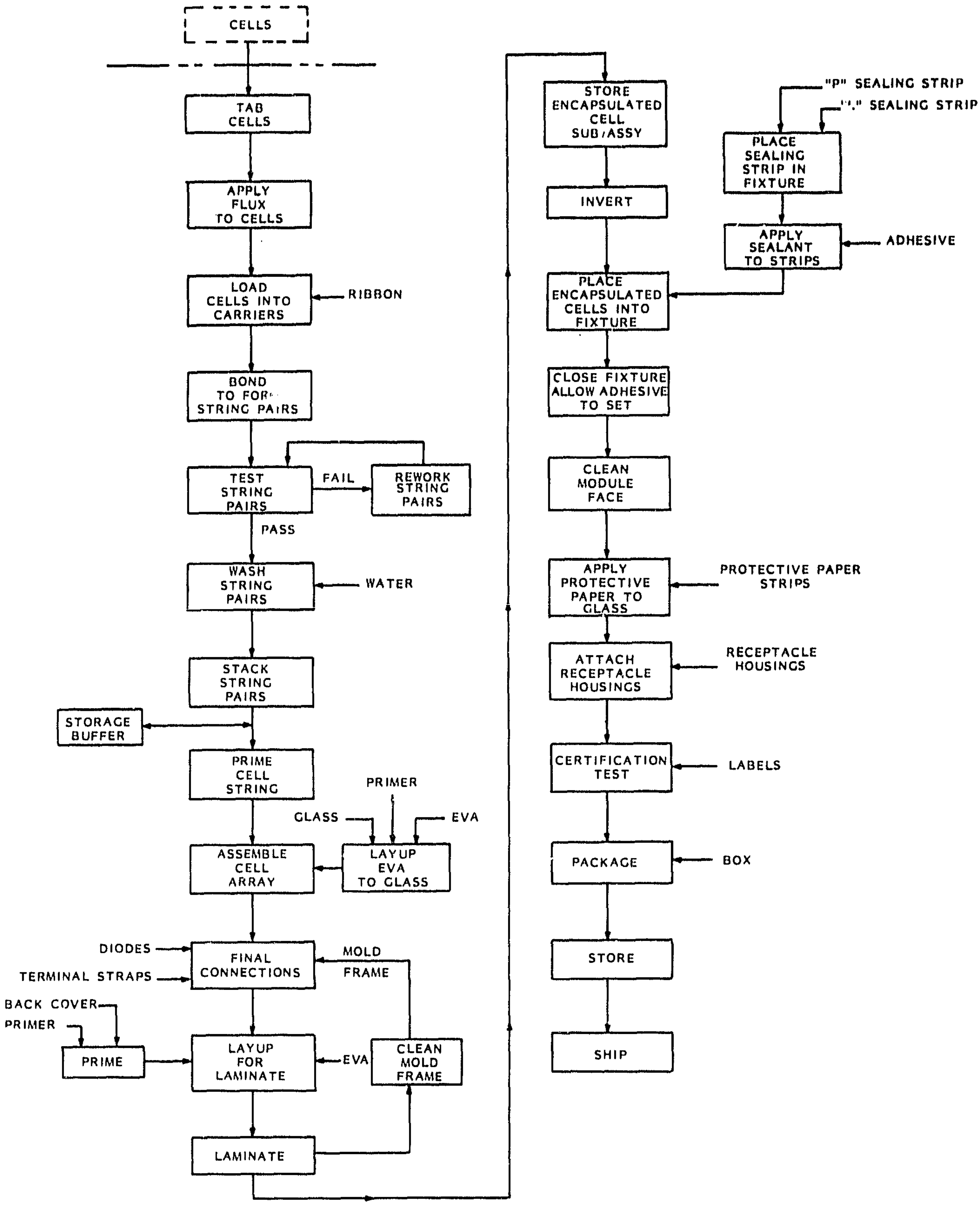

Figure 3-19. Process Flow Diagram for Lowest Production Rate

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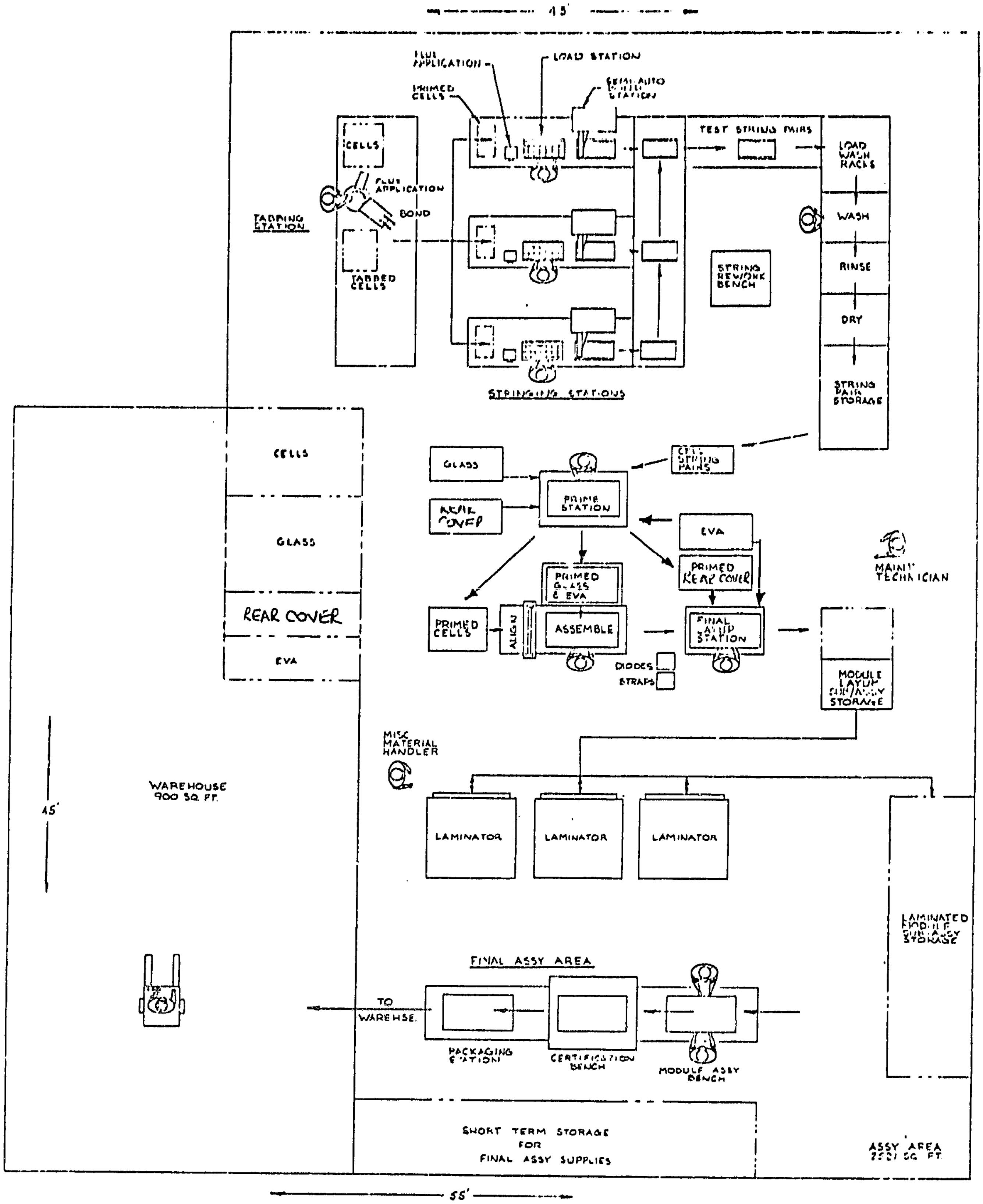

Figure 3-20. Plant Layout for Lowest Production Rate

The tabbed cells are then transferred to a stringing subassembly station. Each cell is manually fluxed and then placed onto a carrier, which acts as a loading fixture, along with the remaining parallel and end bus ribbons. The carrier is placed in a semi-automatic bonding machine which makes all of the second interconnect and parallel bonds. The operator loads the next carrier while the first one is being bonded. The time to complete the tasks for each string pair at the stringing station are estimated as follows:

• Flux and Load - 10 sec/cell x 12 cells	=	120 sec
• Place parallel interconnects = 5 sec/cell x 12	=	60 sec
• Transfer Carrier	=	30 sec
• Unload and Check	=	30 sec
		240 sec = 4 min/string pair

Thus, in order to average an output of a string pair every 1.5 minutes, three (3) semi-automatic stringing machines are required. It is envisioned that the semi-automatic stringing machine will be configured to accomplish the series and parallel bonds (8 bonds/cell or 96 bonds/cell string pair) as well as the bus bonds (8 bonds/string pair) during the above time cycle.

The string pairs are then tested for open-circuit voltage at a low illumination level. There is a rework station shown to perform any required repairs on those strings that do not pass the electrical test. The tested string pairs are transferred to a cleaning station.

In the cleaning station, the cell string pairs are washed and rinsed to remove any flux residue and dried. The string pairs are removed from the carrier and placed onto racks. These racks are first placed in the wash tank which spray cleans the flux residue. The string pairs are moved to a rinse tank, and then on to a drying station. Upon drying, the strings are placed in a buffer storage area, to await further processing.

The string pairs are then brought to a priming station where primer is applied to both sides of the cells. At this station the glass superstrate is also primed. After priming the glass, a precut sheet of EVA is placed on the glass. The primed cell string pairs and the primed glass/EVA combination are moved to an alignment station. Also at the priming station the rear cover sheet is primed and moved to the final connection/lay-up station.

An operator at the alignment station actuates a system to pick-up a cell string pair and place it in the module array format on the glass/EVA combination.

The glass/EVA/cell string pair subassembly is then delivered to the final connection/lay-up station, placed in a mold frame, and the bus and diode connection straps are joined to the string pairs. The EVA/Craneglass and primed rear cover are then applied to complete the laminate subassembly.

This operation is repeated until a complete load for a laminator is accumulated, at which time the operator loads (and unloads) the laminators.

The laminator is assumed to accommodate five (5) encapsulated cell subassemblies in a single load. Assuming a 60-minute cycle to accomplish the laminating with adequate curing time, three laminators are needed to keep pace with the rest of the production and allow ample additional time for handling.

From this station, the mold frames are recirculated and the encapsulated cell subassemblies are then transported to the module storage area ready for final assembly.

The final assembly steps include the installation of sealant strips and the application of a bead of cement around the strips prior to the placement of the encapsulated cell subassembly. The Solarlok receptacles are installed and the module is illuminated as part of the electrical certification prior to packaging for delivery to the warehouse area.

The estimated cost of the equipment required for this plant is listed in Table 3-1 along with the associated utility service requirements. The manpower requirements for the assembly area and warehouse area are enumerated in Table 3-2.

Table 3-1. Equipment and Utility Requirements for the Lowest Production Rate

Item	Estimated Cost (1980 $)	Utility Services
Cell Tab and String	180 K	2.5 kW 2 cfm air 1.5 gpm water
Wash and Rinse Station	10 K	10 gpm water
String Storage 150 @ $3	0.5 K	
Priming Station	6 K	0.4 kW
Array Assembly	12 K	0.2 kW
Final Connection/Lay-up Bench	10 K	0.5 kW
Laminators 3 @ 60K	180 K	18 kW 0.3 cfm air 1.2 gpm water
Sealant Dispenser	3 K	0.1 kW
Assembly Bench	10 K	0.3 kW
Test Station	50 K	0.5 kW
Box Station	1 K	
Miscellaneous Handling Equipment	3 K	0.5 kW
Totals	465.5 K	23 kW 2.3 cfm air 12.7 gpm water

Table 3-2. Direct Plant Labor Requirements for the Lowest Production Rate

Work Assignment	Labor (Persons)
Cell tabbing	1
String pair assembly	3
Washing and stacking string pairs	1
Priming glass, rear cover and cells and placing EVA on glass	1
Aligning and placing string pairs on glass/ EVA	1
Making diode, bus and terminal connections and final lay-up	1
Load and unload laminators, clean mold frames, move material from warehouse to assembly floor - assist in warehouse (misc. mat'l. handling)	1
Final assembly - install gaskets, make final test and package	2
Plant and machine maintenance technician	1
Warehousing, shipping and receiving	1
Total	13

3.1.2.2.2 Median Production Rate

At the 50,000 m^2 per year production rate the plant is assumed to operate on three (3) eight-hour shifts per day for six (6) days per week throughout the year with nine (9) holidays and a one (1) week plant shutdown. This operating schedule results in 297 working days per year or 7128 working hours per year. A production rate of 9.74 completed modules per working hour is required to meet the required annual throughput. This rate results in a calculated interconnector tabbing and stringing machine cycle time which is possible with the present state-of-the-art for interconnector assembly equipment.

As in the previous case, the materials handling and storage requirements were based on weekly shipments of incoming goods with a one week safety stock. This sets the warehouse space requirements at two weeks supply of production requirements. The production floor would be supplied before each shift. It is conceived this delivery would take place while the preceding shift was still on duty, therefore, ideally, the production floor should accommodate two shifts supply of material.

The production flow diagram for this median annual throughput is shown in Figure 3-21 with the corresponding plant floor layout as depicted in Figure 3-22. The manufacturing line accepts solar cells in cassettes as the input to the cell interconnect machine which automatically applies flux to the cells, solders the interconnector strips to the front contact, solders the rear joints to form series strings, applies parallel cross-strap strips and end bus strips to the cell string pairs, tests the string pairs for open-circuit voltage at a low illumination level and transfers the tested string pairs to a conveyor for transport through the cleaning station. There is a rework station shown to perform any required repairs on those strings that do not pass the electrical test.

In the cleaning station, the cell string pairs are raised to remove any flux residue and dried. The cleaned string pairs are then automatically picked up by a transfer mechanism and delivered to a stacker where the string pairs are stacked in carriers. The string pairs are the basic handling unit from this point through the laminating stations and, as such, are the basic inventory unit within the production line. They are accumulated within this stacker

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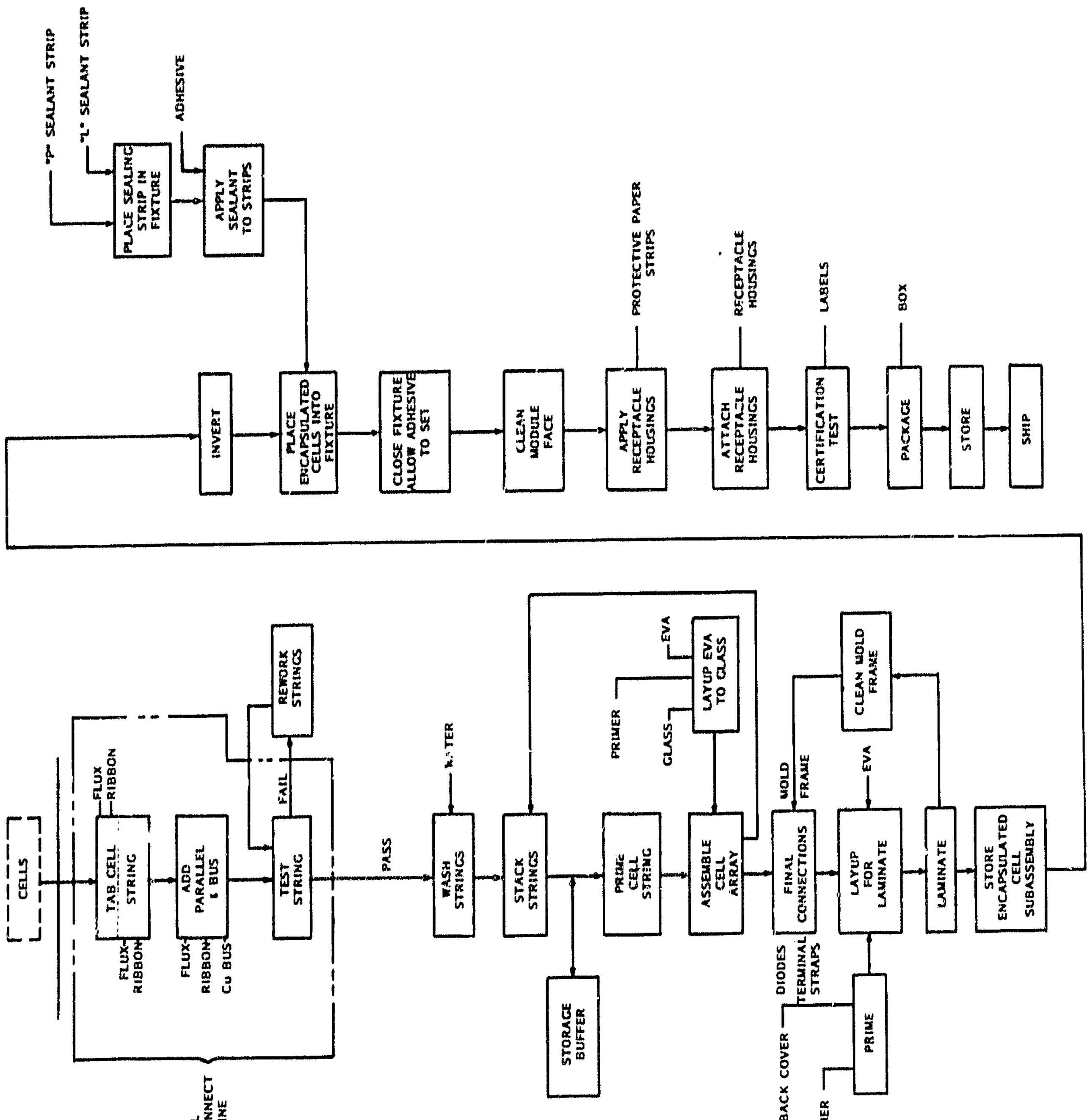

Figure 3-21. Process Flow Diagram for Median Production Rate

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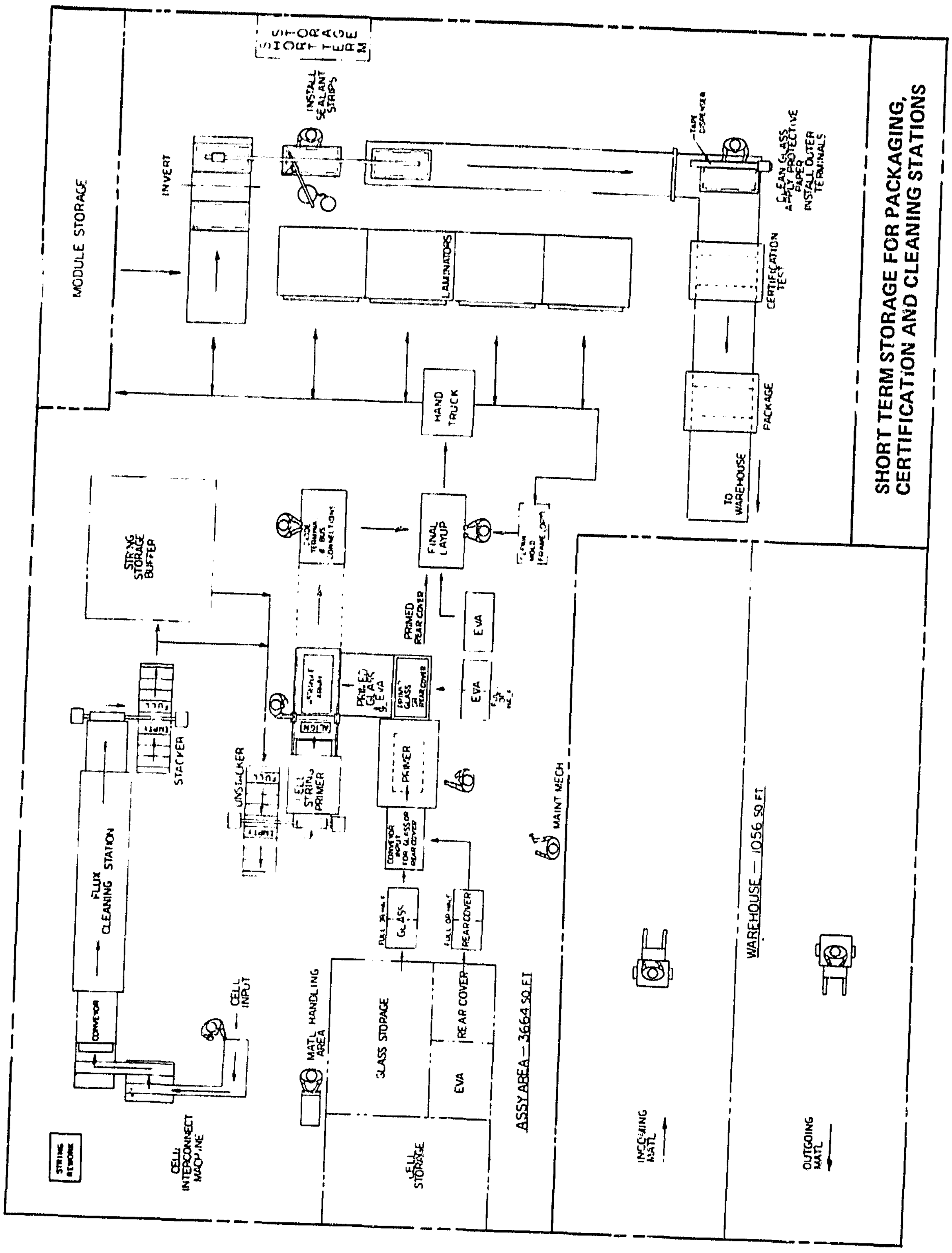

Figure 3-22. Plant Layout for Median Production Rate

and taken to a buffer storage area. Proper inventory control and management of this area will permit the down-line assembly stations of the plant to continue to function even if the cell interconnect or flux cleaning stations are down, or vice versa, by allowing these up-stream stations to continue to produce cell strings up to the maximum desired safety stock level if any of the down-line stations are not in operation.

The cell string pairs are then taken to the unstacking station, where a transfer mechanism automatically advances them through a cell string primer system which applies a primer coat to the cells in preparation for the laminating step. The unstacker transfer system delivers each cell string pair to an aligning fixture. An operator at this station actuates a system to pick up a cell string pair and deposit it in the module array assembly area.

While these operations are taking place, another operator, with the aid of handling devices, picks up a glass superstrate from the production line storage area and places it face on a conveyor which carries it through a primer station, where a primer coat is applied to the glass on the side which will contact the EVA encapsulant. As it comes out of the primer area, sheets of EVA are placed on the glass. This glass/EVA combination is then delivered by conveyor to the assembly station. Primed cell string pairs are then placed in position on the EVA sheet until a module circuit has been completed. Also, at the primer station, the rear cover sheet is primed and moved to the final lay-up station.

The glass/EVA/cell subassembly is then delivered by conveyor to the final connection station, placed in a mold frame, and the bus and diode connecting straps are joined to the cell string pairs. It is envisioned that this could be accomplished with the aid of bonding tooling and a support anvil under the bus bars. It would utilize an innocuous flux, and, since it is not applied to the cleaned cell, no further cleaning operations would be required.

From this station the completed subassembly in its mold frame is moved by conveyor to a final lay-up station where an operator places the next sheets of EVA/Craneglass and a primed sheet of rear cover material onto the module array to complete the sandwich to be laminated. This operation is repeated until a complete load for a lamination station is accumulated, at which time this operator loads (and unloads) the laminators.

The laminator has been configured to accommodate five (5) encapsulated cell subassemblies in a single load. Assuming a 60-minute cycle to accomplish the laminating with adequate curing time, four laminators are needed to keep pace with the rest of the production and still provide extra time for handling purposes.

From this station, the mold frames are recirculated, and the encapsulated cell subassemblies are then transported to the final assembly area where the elastomeric frame is installed and the module assembly is completed, tested and boxed as described Section 3.1.2.2.1.

The estimated cost of the equipment required for this plant is listed in Table 3-3 along with the associated utility service requirements. The direct plant labor requirements for the assembly and warehouse areas are enumerated in Table 3-4.

3.1.2.2.3 Highest Production Rate

At the 500,000 m^2 per year production rate the plant is assumed to operate on three (3) eight hour shifts per day for six (6) days per week throughout the year with nine (9) holidays and a one (1) week plant shutdown. This operating schedule results in 297 working days per year or 7128 working hours per year. Thus, a production rate of 97.4 completed modules per working hour is required to meet the required annual throughput.

As in the two previous cases, the materials handling and storage requirements were based on weekly shipments of incoming goods with a one week safety stock. This sets the warehouse space requirements at two weeks supply of production requirements. The production floor would be supplied before each shift. It is conceived that this delivery would take place while the preceding shift was still on duty, therefore, ideally, the production floor should accommodate two shifts supply of materials.

The basic approach employed to achieve the highest plant production was to set up a more continuous production sequence flow than at lesser production requirements with associated automated equipment and the necessary personnel to meet the stated production requirements

Table 3-3. Equipment and Utility Requirements for the Median Production Rate

Item	Estimated Cost (1980 $)	Utility Services
Cell Interconnect and String	375 K	2.5 kW 6 cfm air 1.5 gpm water
Cassettes (2000 Boxes @ $5)	10	
String Rinsing Machine	60	1.0 kW 10 gpm water
String Stacker	8	0.2 kW
String Storage and Buffer Area (500 Boxes @ $2)	1	
Unstacker	8	0.2 kW
Cell Priming Machine	30	0.5 kW
Array Assembly Station	12	0.2 kW
Diode, Terminal and Bus Connections (Including 2 Weld Heads, Fixturing Automatic Feed Mechanism)	35	0.5 kW
Final Layup	2	
Primer Dispensing Station	15	
Laminators (4 @ $60 K)	240	24.0 kW 0.04 cfm air 1.6 gpm water
Conveyors and Misc. Handling Aids	53	0.5 kW
Module Invert	3	
Robotic Arm (Includes Sealant Dispenser)	20	0.8 kW
Assembly Fixture	10	0.3 kW
Overhead Vacuum Transfer	5	0.2 kW
Roller Conveyors	3	
Terminal Bench (Tilt Table)	2	0.1 kW
Test Station	50	0.5 kW
Box Station	1	
Totals	943 K	31.5 kW 6 cfm air 13.1 gpm water

Table 3-4. Direct Plant Labor Requirements for the Median Production Rate

Work Assignment	Labor (Persons)
Tend interconnects and washing stations	1
Tend cell priming and array assembly	1
Diode terminal and bus station	1
Operate primer station	1
Final layup Load, unload laminator Deliver modules to output conveyor and buffer Storage	1
General material handling and relief	1
Move module laminate assembly to assembly bench Take precut gasket from dispenser with adhesive applied Apply gasket to module assembly along with closing cement Move completed assembly to terminal and certification bench	1
Install outer terminal covers Perform certification test Place module in carton Move packaged modules into warehouse Bring cartons to short term storage area	1
Plant and machine maintenance technician	1
Warehousing, shipping and receiving	2
Total	11

in the most economical manner. Also, the basic approach took into consideration that maximum production activity would have to continue in the event of any production process or equipment problems.

Therefore, upon examining the requirements at each step of the production process, it was decided that the plant would be divided into five (5) 100,000 m^2 production lines. Each line would have several stations where the partially completed production could be removed for transfer to another production line in the event of machine breakdown downstream as well as receiving partially completed production from another line in the event of machine breakdown in that line, Thus, this approach is intended to provide a flexible approach to achieve maximum production under realistic operating conditions.

The production flow in each of these five 100,000 m^2 lines is as shown in Figure 3-23. Each of these basic production lines accepts cells in stacks as the input to each of two separate tabbing and stringing machines which automatically applies flux to the cells, solders the interconnector strips to the front contact, solders the rear joints to form series strings, applies parallel cross-strap strips and end bus strips to the cell string pairs, tests the string pairs for open-circuit voltage at a low illumination level and transfers the tested string pairs to a conveyor for transport through the cleaning station and cell priming. The string pairs are the basic handling unit from this point through to the laminating stations and as such, can be the basic inventory unit. There is a rework area (common for all lines) shown to perform any required repairs on those strings that do not pass the electrical test.

In the cleaning station, the cell string pairs are rinsed to remove any flux residue and dried. The cells are then primed and dried. The cleaned and primed string pairs are then automatically picked up by a transfer mechanism and stacked in carriers for transport to another production line or buffer storage, as required.

The cell string pairs are then unstacked at an alignment platform. After the string pair is automatically aligned, a transfer arm picks it up and deposits it on the glass/EVA superstrate laminate subassembly at the array assembly area.

The glass superstrate laminate subassemblies are prepared at the Glass Preparation Station as shown in Figure 3-24. This station supplies the entire plant (108/hr). Glass is stacked by the attendant at the input of the machine. It is automatically unloaded onto a conveyor. As it moves through a priming chamber a coat of primer is sprayed on it. After it exists the chamber, a layer of EVA and Craneglass is placed on the glass. At this point heat may be applied at local points to "tack" the EVA-Craneglass to the glass. These superstrate laminate subassemblies are then automatically loaded into racks (25 - 30 each rack) and

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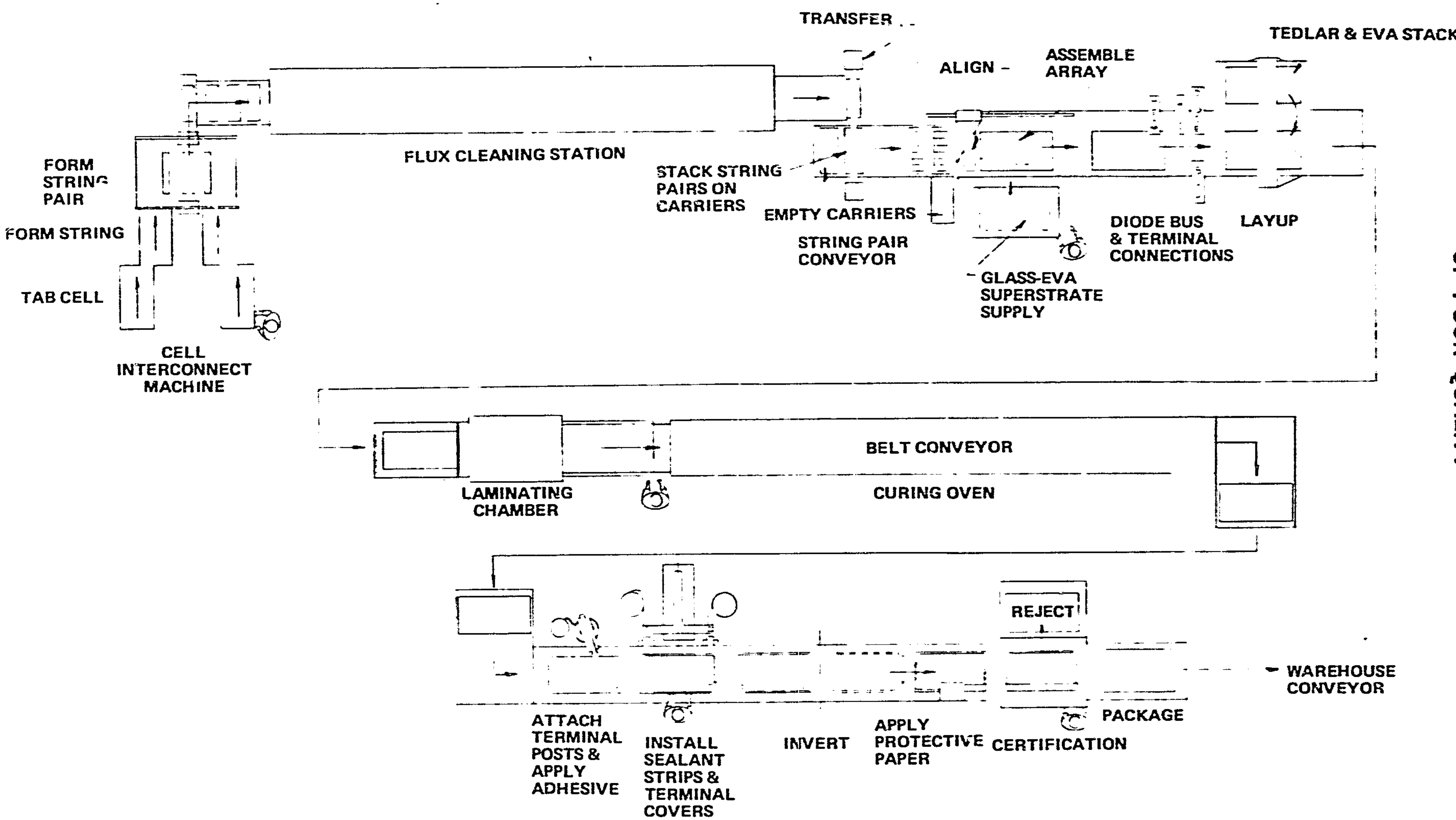

Figure 3-23. Production Flow in Each of Five 100,000 m^2 Lines

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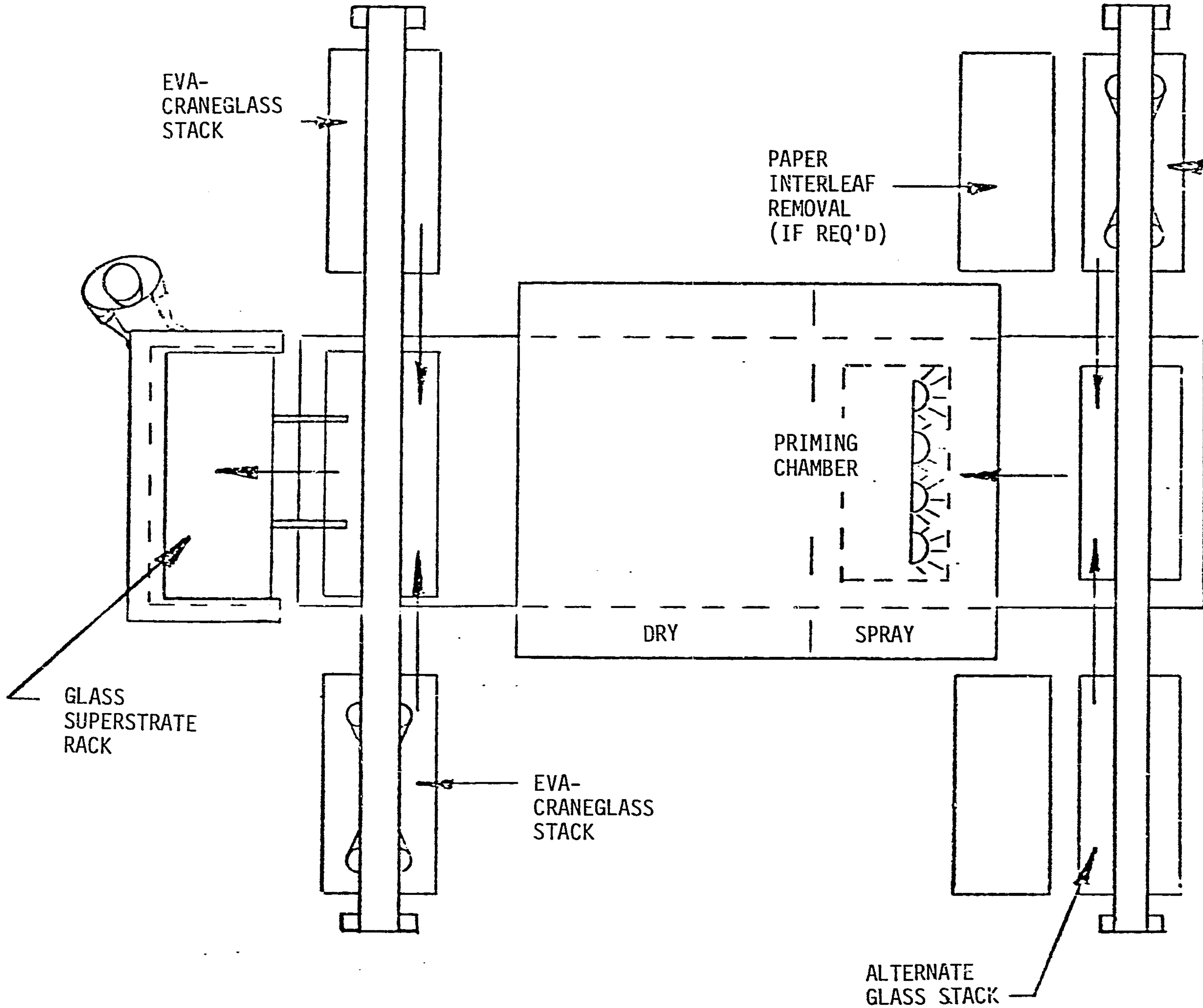


Figure 3-24. Glass Preparation Station

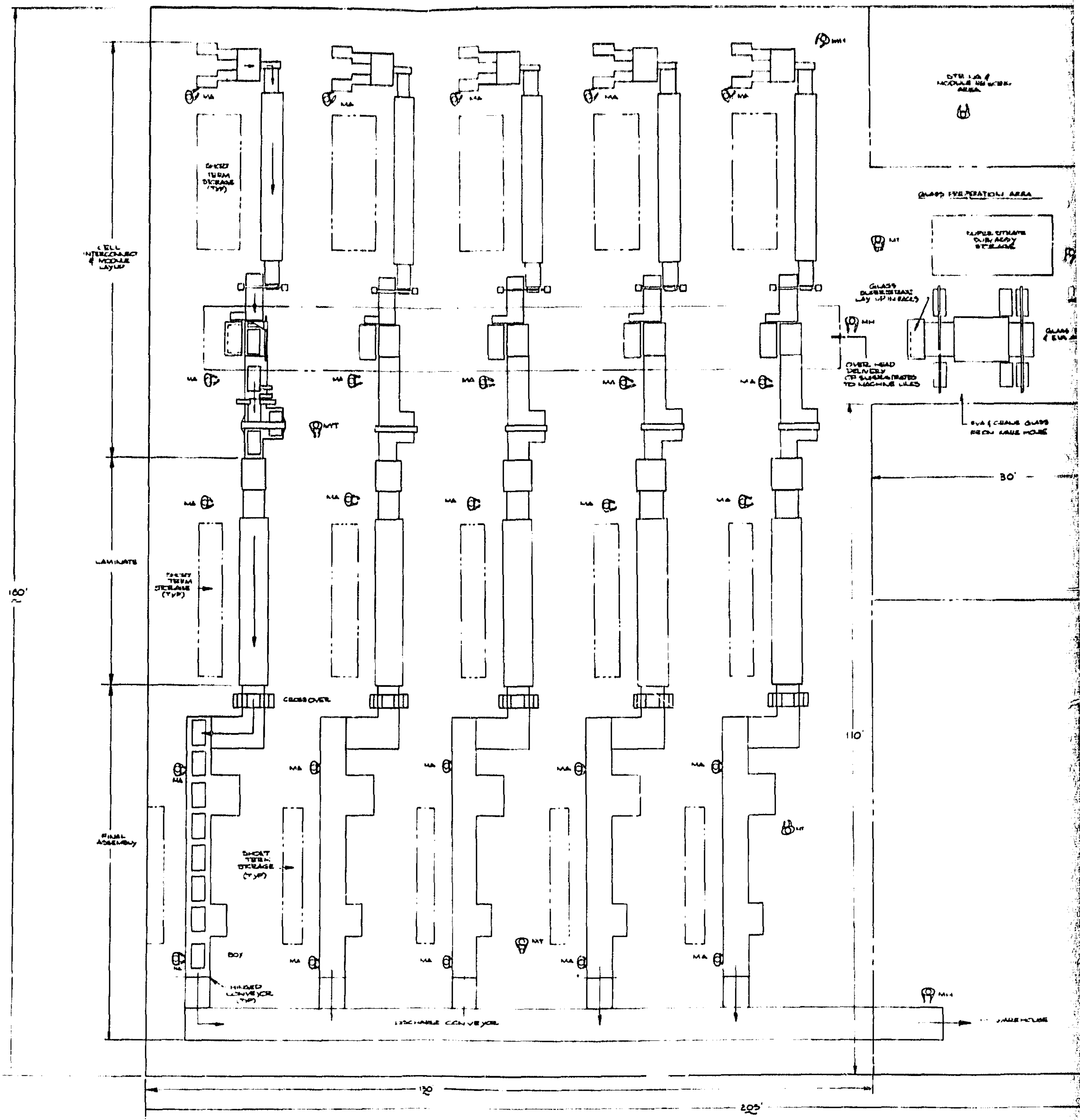
delivered by overhead conveyor to each production line, where they are automatically unloaded at the array assembly area.

The glass/EVA/cell subassembly is indexed to the final connection station where the terminal straps, interstring bus and diodes are installed. The subassembly is indexed to the lay-up station where a back cover/EVA sheet is placed. A single component back cover/EVA co-extrusion is envisioned for use in for the proposed plant.

From this station the completed subassembly lay-up is transported by conveyor to a laminating chamber. It is envisioned that with the need to produce solar modules at the rate stated, a continuous flow process would be available for such high production applications. The evacuation and lamination cycle time for such a process is assumed to be about 2 minutes since there is no chamber heat-up or cool-down time. The subassembly is then transported, by conveyor, directly into a belt furnace for curing. The subassembly is indexed through the oven so that its residence time is approximately 15 minutes. This curing time has been determined to be practical by several manufacturers. The encapsulated cell subassembly is discharged from the curing oven onto a conveyor which moves it to the final assembly area.

The final assembly operations require attachment of terminal posts, installation of rubber gasket strips and terminal covers. The module is illuminated as part of the electrical certification prior to packaging for delivery to the warehouse area.

The physical layout of the 500,000 m^2 per year production plant, consisting of 36,900 ft^2 of total area, is shown in Figure 3-25. Each of the five (5) basic production lines is designed to allow the output of one part of the machine line to be taken to another line for further processing in case there is any process or equipment problems downstream in the line. In order to allow the factory personnel to cross over from one production line to another without having to go all the way to one end, a step crossover is shown near the middle of each line. Also, the gravity conveyor at the end of the line of the packaging station is shown to be a hinged conveyor, thus allowing the workers to move from line to line at that end of the factory.



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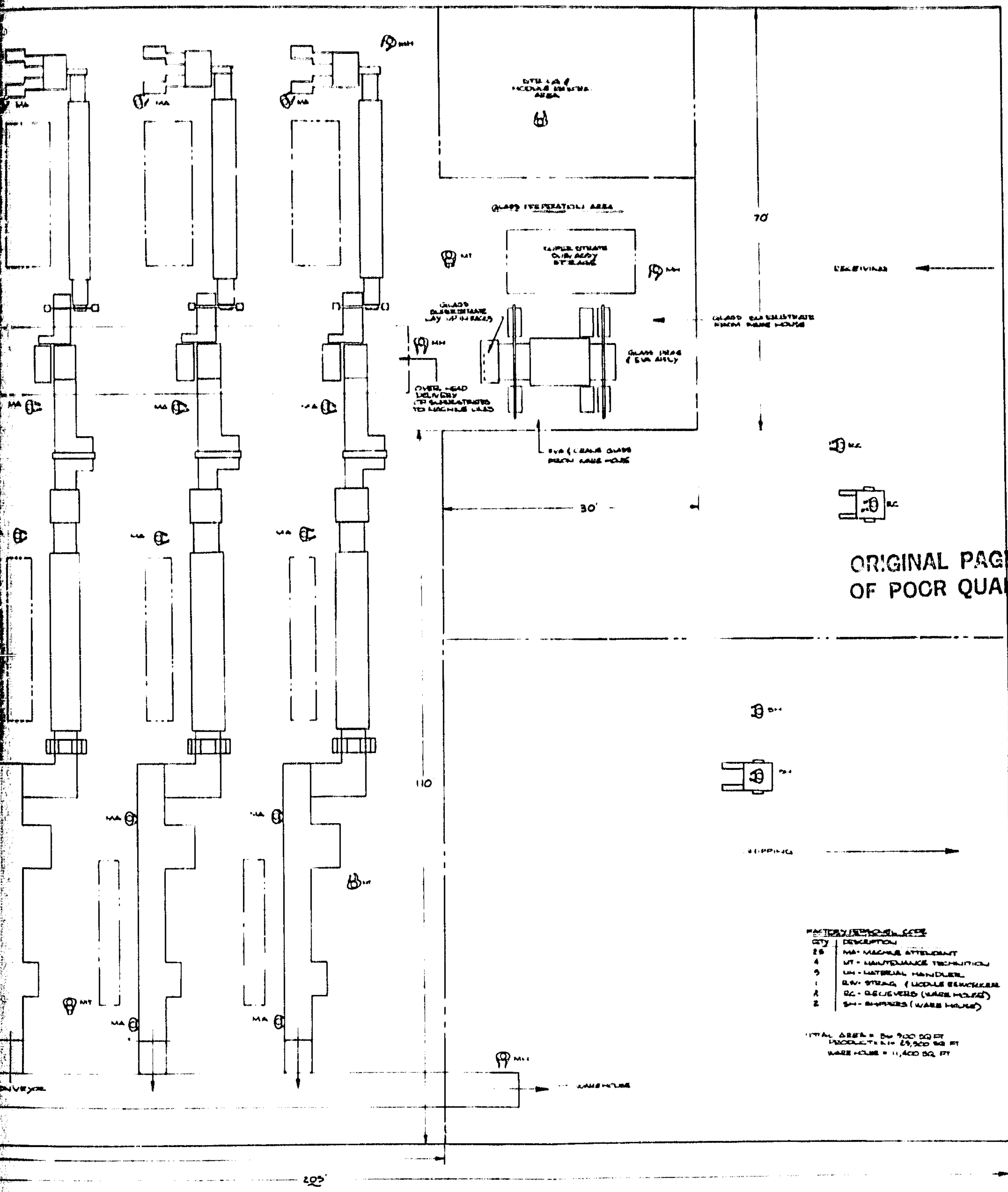

Figure 3-25. Plant Layout for Highest Production Rate

As noted earlier, the plant includes a glass preparation station, which prepares the glass superstrate subassemblies for all five production lines. These subassemblies are delivered in stacks to each production line via an overhead conveyor system. At each production line, material handling equipment would assist the machine attendant in the operation of the equipment of each production line.

The estimated cost of the equipment for each proposed production plant is tabulated in Table 3-5 along with the estimated consumption of utility services.

With each line having automatic equipment in virtually every area of the operation, the personnel required would be mostly machine attendants, who would see that their area of the production line is kept fed with input material, and that the machine in their area is operating properly. In addition, there would be material handlers to move the necessary materials to and from each production line. Finally, several maintenance technicians were included to respond to any equipment or process problems in order to minimize any machine downtime. A total of 39 personnel/shift is estimated to operate the proposed production plant with work assignments as specified in Table 3-6.

3.1.2.3 Direct Material Cost

The direct material costs for the selected module design were estimated for the median production rate assuming that materials are ordered on an annual basis in the quantities required for the next year's production. Each material or component within the module was identified along with the calculated quantity required to complete the assembly. The cost of the major items within the module assembly, such as the glass cover plate, rear cover sheet and the rubber sealing extrusions, were obtained by the solicitation of firm quotations. The other less significant material costs were obtained from informal phone quotations, or, in some cases, reflect engineering estimates based on the nature of the material.

The direct material inventory presented in Table 3-7 reflects the expected costs for the selected module design when purchased in the quantities required to meet the median annual production rate. It is estimated that the purchased price of these same materials in the

Table 3-5. Equipment and Utility Requirements for the Highest Production Rate (Total for Entire Plant)

Item	Estimated Cost (1980 $)	Utility Services
Cell Interconnect and String	2750K	25KW 50 CFM air 15 GPM water
String Rinsing and Cell Priming	550	10 KW 90 GPM water
String Stack and Transfer	60	1.5 KW
Array Assembly Machine	90	5 KW
Diode, Terminal & Bus Connection Machine	250	7.5 KW 1.0 GPM water
Lay-Up Machine	20	1.0 KW
Lamination Machine	300	64 KW
Curing Oven (Belt Furnace)	200	200 KW
Transfer Conveyor and Cooling	20	5 KW 10 GPM water
Terminal Post and Adhesive Station (incl. robot arm)	150	5.0 KW
Sealant Strip and Terminal Cover Station	75	2.5 KW
Module Invert	25	1.0 KW
Module Index Conveyor	25	1.0 KW
Paper Applicator Station	10	0.5 KW
Test Station	360	3.5 KW
Box Station	10	-
Module Conveyor	9	2.5 KW
Misc. Handling Equipment (incl. 2 fork lifts)	100	1.0 KW
Glass Superstrate Assy. Station		
Glass Unstacker	25	0.4 KW
Glass Prime	20	0.7 KW
EVA/Craneglas Unstack	30	0.4 KW
Glass Stack Elevator	5	0.5 KW
Overhead Glass Conveyor	20	2.5 KW
Totals	5104K	340.5 KW 50 CFM air 116 GPM water

Table 3-6. Direct Plant Labor Requirements for the Highest Production Rate

Work Assignment	Labor (Persons)
Tend Interconnect and Washing Station	5
Tend Array Assembly and Diode, Terminal and Bus Stations	5
Tend Lay-Up, Laminate and Cure Stations	5
Installs Terminals and Sealant Strips	5
Tends Paper Application, Test and Box Stations, Moves finished modules to module conveyor	5
Operates the Glass Prime and EVA Application Machine	1
Operate Module Rework Area	1
Maintenance Mechanics	4
Material Handlers	4
Warehouse Personnel	4
Total	39

Table 3-7. Direct Material Inventory

Item Description	Part Number	Quantity Required Per Module	Estimated Cost Per Module (1980 $)
Solar Cell	SVS10161	72	--
Glass Coverplate	47B258419P1	1	11.92
EVA	-	1.663 m^2	3.57
Craneglass	-	0.831 m^2	0.18
Primer	-	80 ml	0.85
Back Cover	47B258420P1	1	3.52
By-Pass Diode with Mounting Strap	-	3	4.02
Solarlok Bus Bar	-	2	0.26
Solarlok Housing	-	2	0.80
"L" Section Sealing Strip	47B258418P1	1	1.40
"P" Section Sealing Strip	47B258417P1	1	1.58
Insulator Strip	47B258425P1	3	0.15
Tin-Plated Copper Foil (75 μm thk)	-	0.09 m^2	0.41
Sealing Strip Bonding Adhesive	-	29 g	0.22
Solder	-	6 g	1.86
Protective Paper Tape	217 (3M)	0.047 m^2	0.08
Total			30.82

volume required for the lowest production rate would result in a 20 percent increase in the total material cost per module, thereas the highest annual production rate would yield a total material cost which is 10 percent less than the median rate value. The cost of the solar cells has not been included in this material inventory tabulation since it is intended to present the module production cost parametrically as a function of the solar cell cost.

3.1.2.4 Summary of Process and Cost Parameters

The significant cost-related elements in the proposed production plants to manufacture the selected module concept at the three rates considered in this analysis are summarized in Table 3-8. The following are some general comments as a result of the study of the production flow process for the various product requirements:

1. A production requirement of 10,000 m^2 or below would require a one shift operation, with a moderate investment in equipment, mostly semiautomatic.

2. By operating on a three-shift basis, and with a modest increase in automation equipment, 50,000 m^2/year requirement can be accomplished with only slightly more factory floor space. Actually, because the equipment is more automatic, less people are needed per shift at this production rate than at the 10,000 m^2/year production rate.

3. It is recommended that the 50,000 m^2/year production line be duplicated up to a requirement of at least 150,000 m^2/year rather than going to the highly automated 100,000 m^2/year basic production line proposed in the 500,000 m^2/year production plant. Several duplicate lines allow the margin of safety of having product turned out by other lines if one production line is down. At a 200,000 m^2/year production requirement, it would be a matter of management preference as to whether the production should be accomplished by four (4) 50,000 m^2/year line or two (2) 100,000/ m^2/year lines. At greater production requirements, the 100,000 m^2/year line is recommended because it should result in the most cost effective production approach.

The production-related parameters summarized in Table 3-8 were used along with the direct material cost to determine the total module cost in accordance with the methodology outlined in Table 3-9. The direct labor cost is calculated using an average hourly rate of \$7.00 with a 25 percent escalator to account for labor inefficiencies and other non-productive activities.

Table 3-8. Summary of Production Parameters

PARAMETER	VALUE: LOWEST PRODUCTION RATE	VALUE: MEDIAN PRODUCTION RATE	VALUE: HIGHEST PRODUCTION RATE
MANPOWER (NO. OF EMPLOYEES/SHIFT)	13	11	39
FLOOR SPACE (FT^2)	3421	4720	36900
UTILITY SERVICES			
ELECTRICITY (kW)	23.0	31.5	340.5
AIR (CFM)	2.3	6.0	50.
WATER (GPM)	12.7	13.1	116.
EQUIPMENT COST (1980 $)	465,500	943,000	5,104,000
PROCESS YIELD (%)			
LAMINATION	98	98	98
FINAL ASSEMBLY	99.5	99.5	99.5
PLANT OPERATING HOURS PER YEAR	2376	7128	7128
ANNUAL PRODUCTION RATE (MODULES)	13,889	69,444	694,444

Table 3-9. Production Cost Methodology

Production Costs Are Calculated As The Sum Of (1980 $):

1. Direct Labor

$$= \frac{(\text{No. Of Employees})\ (\text{Plant Operating Hours per Year})\ (1.25)\ (7.00)}{(\text{Annual Production Rate})}$$

2. 170 Percent Labor Overhead
3. Direct Material
4. 3 Percent Material Overhead
5. Cost of Capital Equipment

$$= \frac{(\text{Original Cost})}{(5\ \text{Yrs.})\ (\text{Annual Production Rate})}$$

6. Floor Space Rental

$$= \frac{(5.50)\ (\text{Floor Space Required} - \text{Ft}^2)}{(\text{Annual Production Rate})}$$

7. Utility Services

(a) Electricity $= \dfrac{(\text{Power - kW})\ (\text{Plant Oper. Hrs. per Yr.})\ (0.04)}{(\text{Annual Production Rate})}$

(b) Compressed Air Facility $= \dfrac{(\text{cfm})\ (20)}{(5\ \text{Yrs.})\ (\text{Annual Production Rate})}$

(c) Chilled Water Facility $= \dfrac{(\text{gpm})\ (17)}{(5\ \text{Yrs.})\ (\text{Annual Production Rate})}$

The expenses associated with process related utility services were accounted for as shown in Item 7 of Table 3-9. The most significant of these is the charge for electricity which is prorated over the annual production rate at $0.04 per kWh.

Table 3-10 applies this methodology in calculating the module production cost for each of the annual production rates. It should be emphasized again that the direct material cost for each module does not include the cost of the solar cells. The estimated FOB factory price, which includes a 20 percent mark-up for profit and warranty service, varies from $119.66 per module for the lowest production rate to $48.68 per module for the highest rate.

Table 3-10. Production Cost Summary

COST CATEGORY	1980 $ PER MODULE		
	LOWEST PRODUCTION RATE	MEDIAN PRODUCTION RATE	HIGHEST PRODUCTION RATE
DIRECT LABOR	19.46	9.88	3.50
LABOR OVERHEAD	33 08	16.80	5.95
COST OF CAPITAL EQUIPMENT	6.70	2.71	1.47
COST OF UTILITY SERVICES	0.16	0.13	0.14
FLOOR SPACE RENTAL	1.35	0.37	0.29
DIRECT MATERIAL *	37.83	31.52	28.37
MATERIAL OVERHEAD	1.14	0.95	0.85
SUBTOTAL	99.72	62.36	40.57
PROFIT AND WARRANTY (20%)	19.94	12.47	8.11
TOTAL FACTORY FOB PRICE	119.66	74.83	48.68

* DOES NOT INCLUDE THE COST OF SOLAR CELLS.

The module FOB factory prices is presented in Figure 3-26 as a function of the cost of the solar cells. Both parameters are expressed in 1980 dollars per unit area, where 0.8045 m^2 is used as the module area. The dollar per peak watt scale, which is also included for each variable, is based on the specified encapsulated cell efficiency of 13.5 percent at 100 mW/cm^2 insolation and 25°C cell temperature.

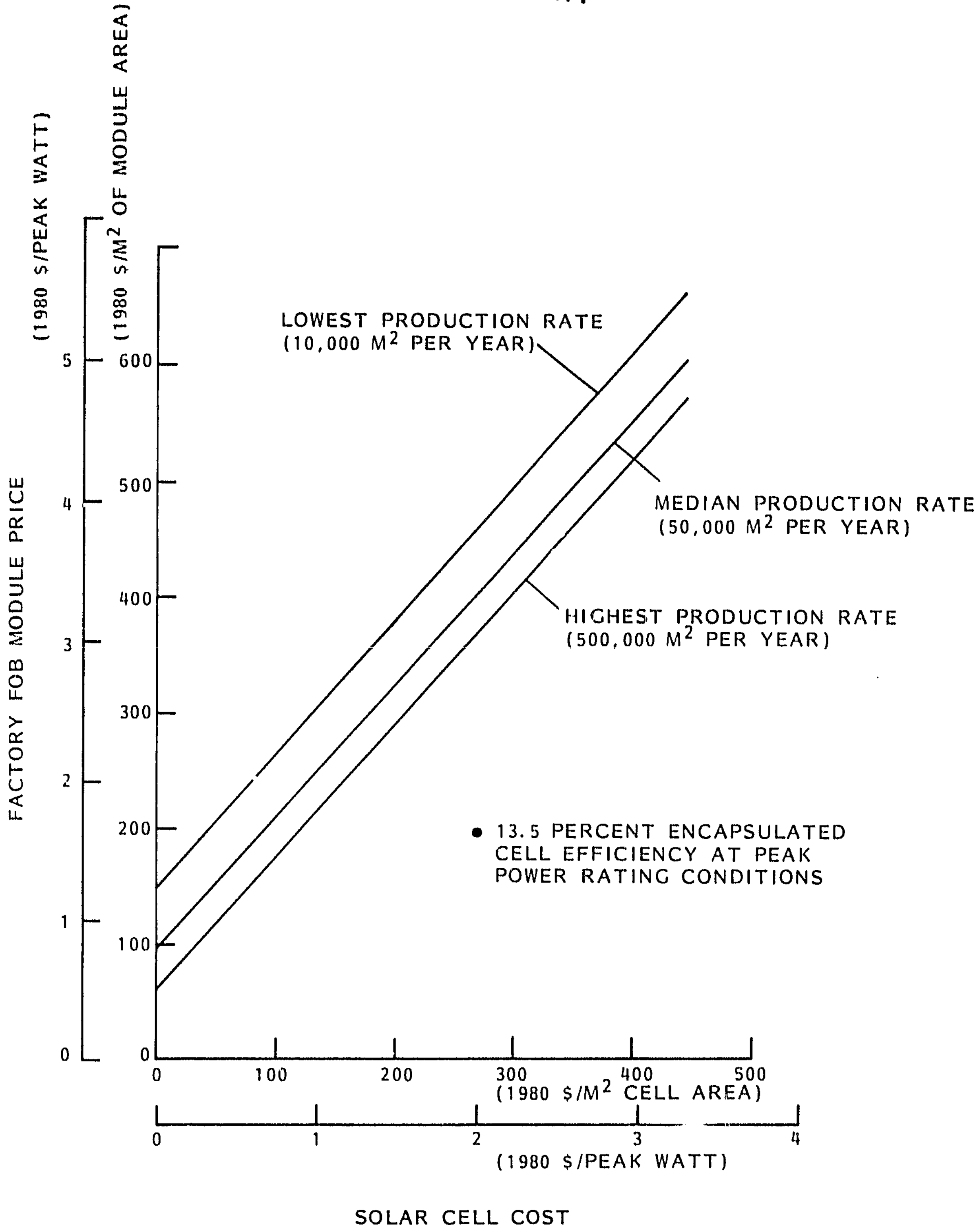

Figure 3-26. Module Production Cost as a Function of Solar Cell Cost

3.1.3 ARRAY INSTALLATION DETAILS

3.1.3.1 Array Layout and Electrical Interconnection

A roof-mounted, residential photovoltaic installation consisting of 50 modules, arranged as shown in Figure 3-27, has been selected as a representative system configuration for use in the development of installation design details and a corresponding cost estimate. This array is felt to be near the low extreme of practical system sizes for grid-connected residential installations and could be expected to produce a maximum power output of 4.9 kW under the peak power rating conditions of 100 mW/cm^2 insolation and 25°C cell temperature. Existing inverter designs are available at this power rating with a nominal dc input voltage in the 200 volt range. The array shown in Figure 3-27 is configured as four separate, diode-isolated branch circuits which supply a common dc bus at the inverter input. Two of these branch circuits consist of 12 series connected modules while the other two have 13 modules each. This arrangement makes full use of the available area with only a minimum power loss due to the voltage mismatch of parallel-connected branch circuits with differing numbers of series elements. The circuit arrangement shown in Figure 3-27 minimizes the voltage available at the eave by providing the dc return, which is at ground potential, as one of the connections to each of the bottom modules in four of the five columns of the array. In the extreme right-hand column the bottom module is connected as the third module above the circuit return.

The module-to-module interconnections are shown in Figure 3-27 and enlarged in Figure 3-28 to more clearly show the routing of the cable between the two module receptacles. The AMP Solarlok system is ideally suited to this interconnection scheme and has been selected as the basis for the calculation of module fabrication and installation costs. The module interconnecting cables are routed between the support channels and the horizontal blocking, as shown in Figure 3-28 to accommodate the direct and stand-off mounting arrangements. For an integral mount these cables could loop beneath the purlins to permit the electrical wiring to be performed after module installation is completed.

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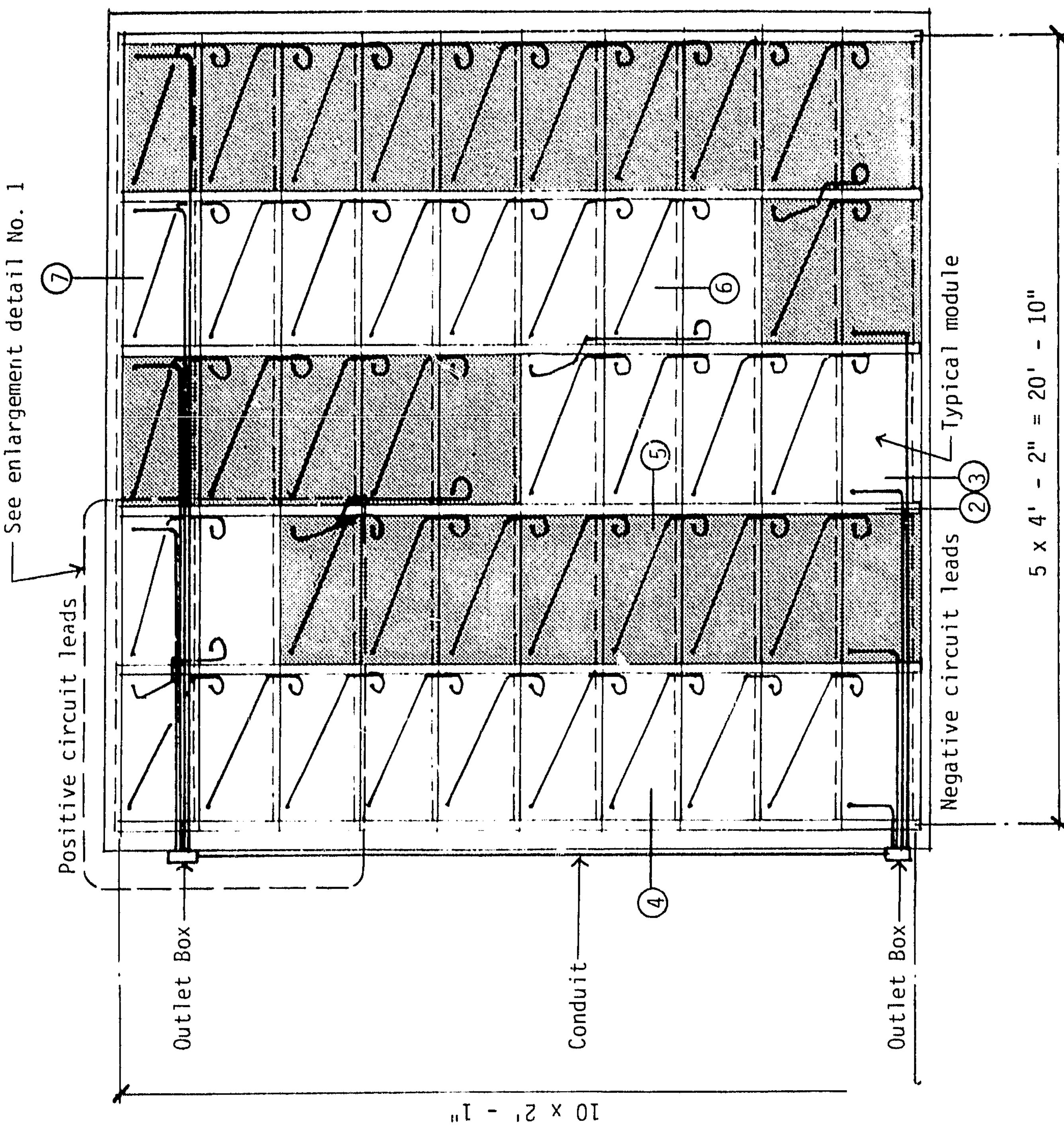

Figure 3-27. Array Layout and Wire Routing

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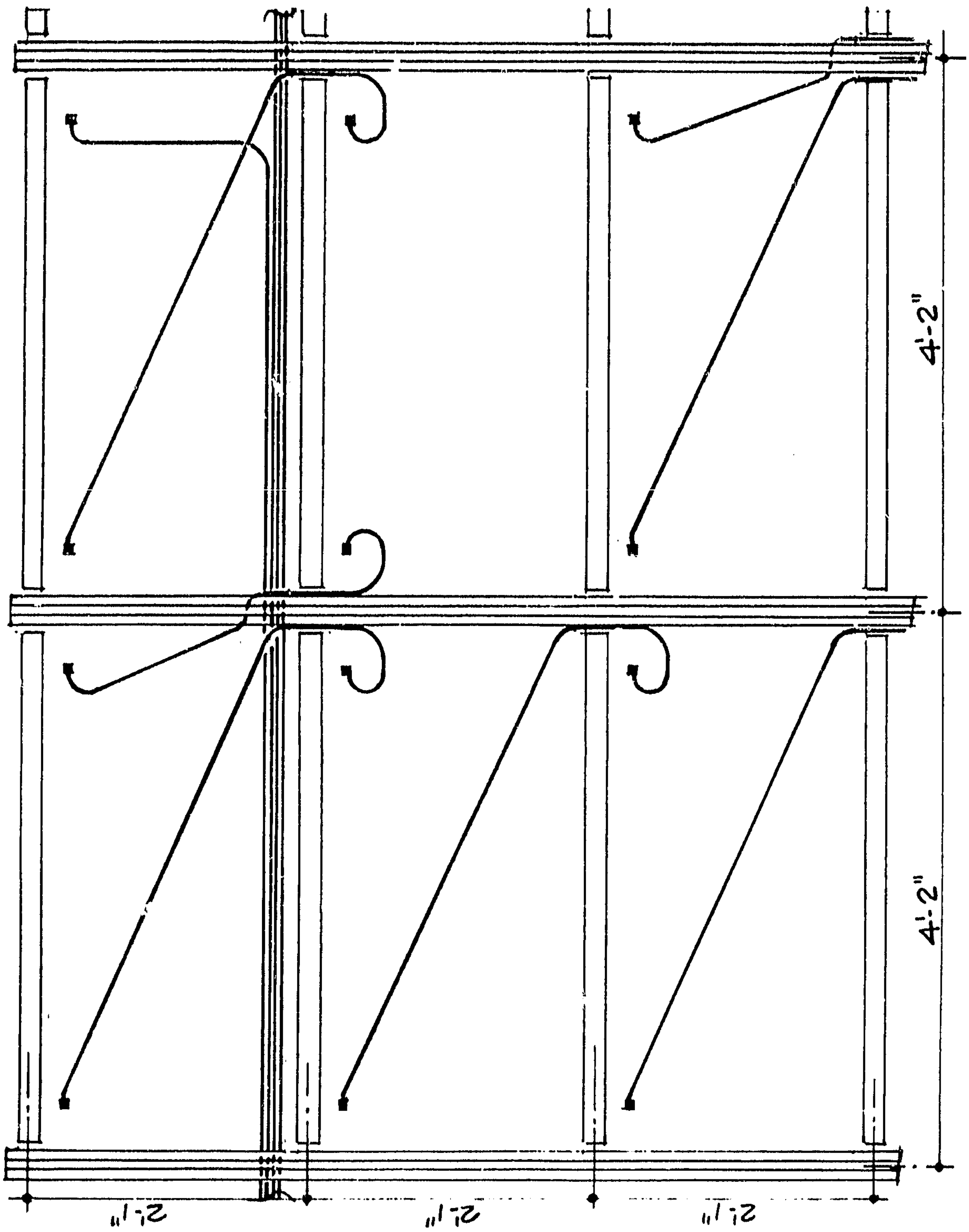

Figure 3-28. Module-to-Module Wiring Detail (Array Upper-left Corner)

3.1.3.2 Roof Interface and Clamping Hardware

The selected module design, as described in Section 3.1.1.2 incorporates a rubber seal around the perimeter which is configured to provide a watertight roofing surface upon assembly into an array using specially-designed mounting and clamping hardware. The first of these is the roll-formed steel support channel shown in Figure 3-29. This component functions as the principal mounting interface with the roof structure and provides the sealing surfaces which function with the module elastomeric frame to prevent the entry of water. These channels are designed to dovetail together, front-to-back, to form a flow trough for any water which might leak past the "P"-shaped rubber seal. Wood screws are used to attach these channels to the purlins. One hole, located near the top of each channel to prevent water leakage when assembled, is provided for this purpose.

The roll-formed closure cap shown in Figure 3-30 interfaces with the support channel and module to complete the joint as shown in Figure 3-31. Sheet metal screws inserted through holes in this closure cap, at three locations per strip, force the curled lip of the strip to engage the formed tabs in the support channel. The modules are then held between this closure cap on the top and the support channel on the bottom. There is no need to provide watertight gasketing around these sheet metal screws since any water leakage will run down the nexted support channels and drip off at the eave. A final stop for possible water leakage into the building is provided by the pressure of the P seal leg against the top flat surfaces of the support channel.

The producibility of these two principal module mounting components has been discussed with a fabricator specializing in the roll-forming of steel parts of this type. However, it should be emphasized that the designs presented herein have not been optimized with respect to the total production cost. Before any large scale production of these parts is undertaken, it is important to perform a detailed design optimization study to minimize the total cost, including the tooling, raw material and labor components. The results of such producibility studies will be strongly influenced by the production quantities required. If these quantities are sufficiently large to justify the initial tooling investment associated with the roll-forming dies, it is particularly important to refine the component designs to minimize the cost of such

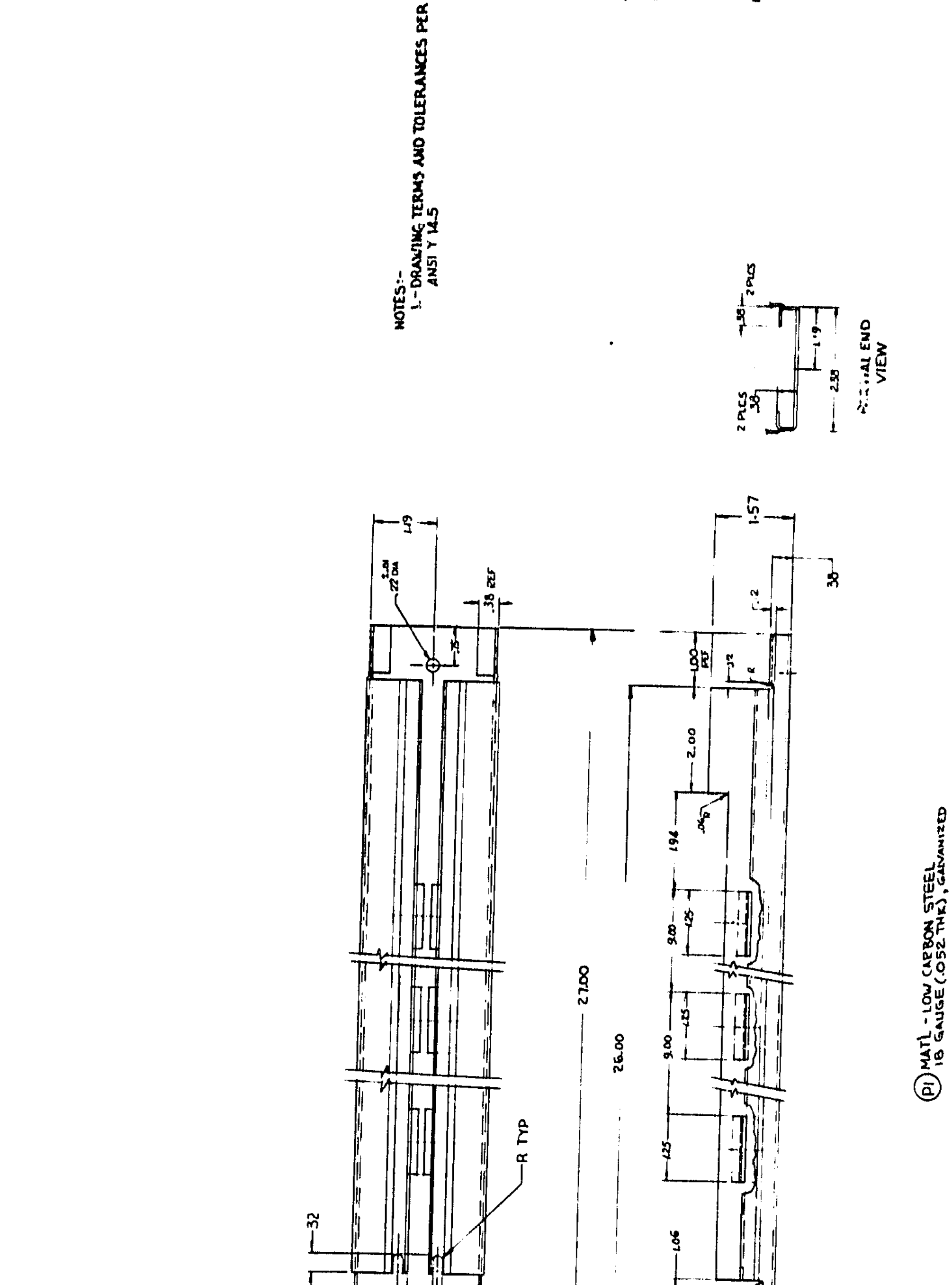

Figure 3-29. Support Channel

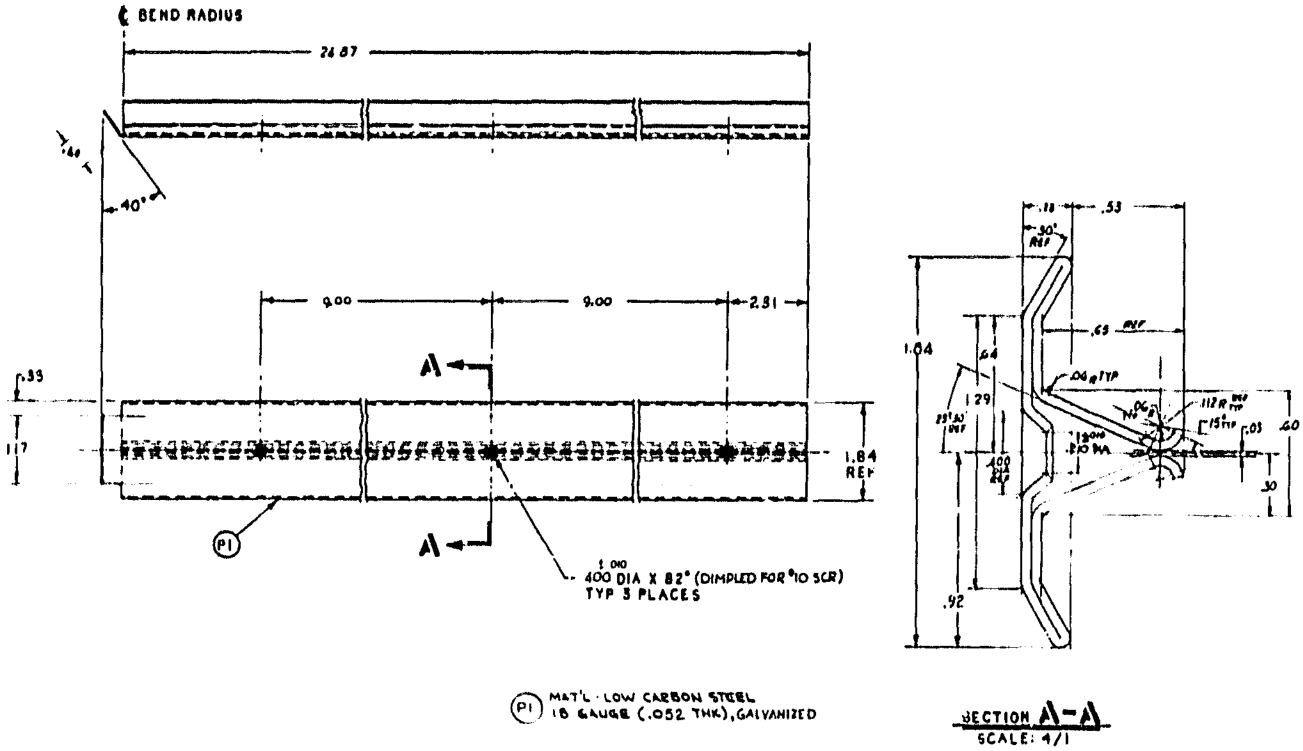

Figure 3-30. Closure Cap

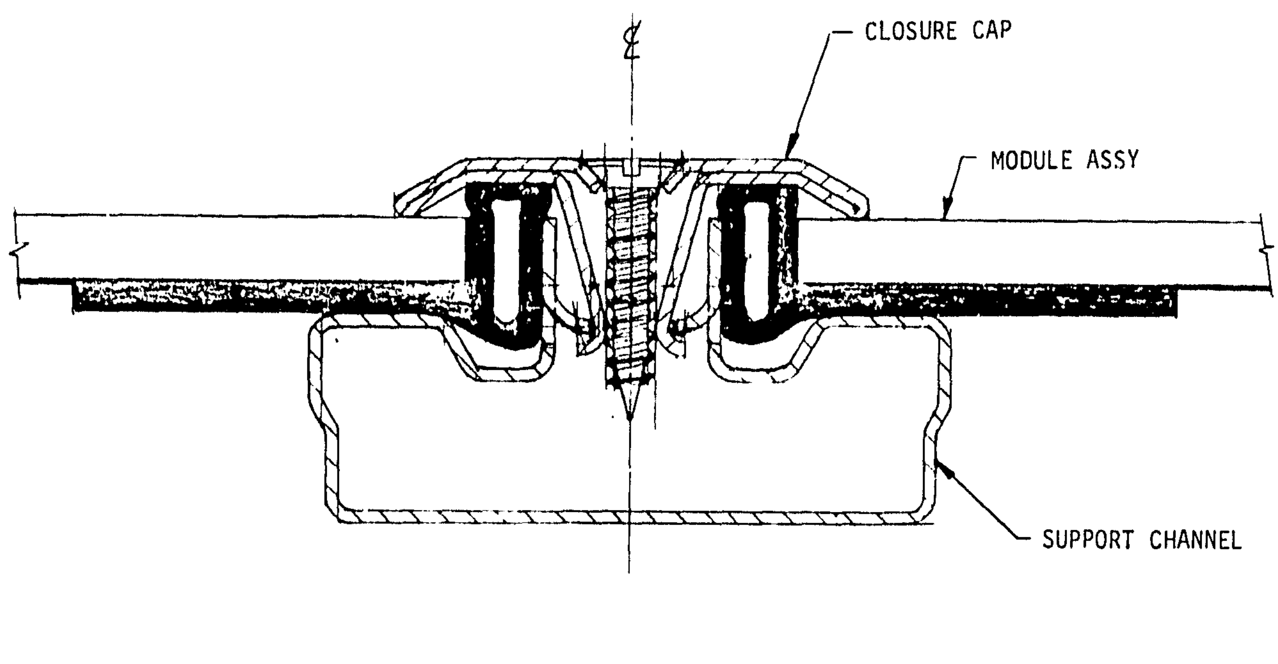

Figure 3-31. Module Clamping and Sealing Detail

tooling. At these high production levels, it is equally important to design the part to perform its function with the minimum raw material content. Special attention should be given to design details such as bend radii and sheet gage.

At the part production rates associated with the lower extreme of the range to be considered in this study, it is probably more cost effective to consider the fabrication of these parts as aluminum or plastic extrusions.

3.1.3.3 Integral Mount Roof Interface Details

Figures 3-32 through 3-36 show the installation details which pertain to the integral mounting approach. As depicted in Figure 3-32 the modules are mounted to a system of horizontal purlins which provide the lateral support between the roof trusses or joists. The joint between overlapping modules is supported by wooden blocking which is nailed to the purlins at 25 inch spacing up the roof. A high-tack, pressure-sensitive adhesive on the underside of the "L"-shaped rubber extrusion provides a bonded seal in the overlapped area as an extra protection against water leakage.

The eave details shown in Figures 3-33 and 3-34 reveal the method used to allow leakage water from the support channel trough to drop over the fascia. A short piece of the top section of support channel is cut to fit over the eave so that any water dripping down the trough formed by these nested channels can run over the underlayment of flashing and drip through on insect screen. The watertight surface of the modules is continued to the eave with a short width of sheathing covered with flashing.

At the rake the roofing surface can be continued beyond the modules by using sheathing which is cut to fit within the support channels and closure cap as shown in Figure 3-35. Folded flashing which fits under the closure caps continues the watertight surface over the fascia at the rake.

Figure 3-36 shows a typical detail at the ridge of the roof where the photovoltaic modules on the south side are transitioned to standard asphalt shingles on the north side. The roof outline

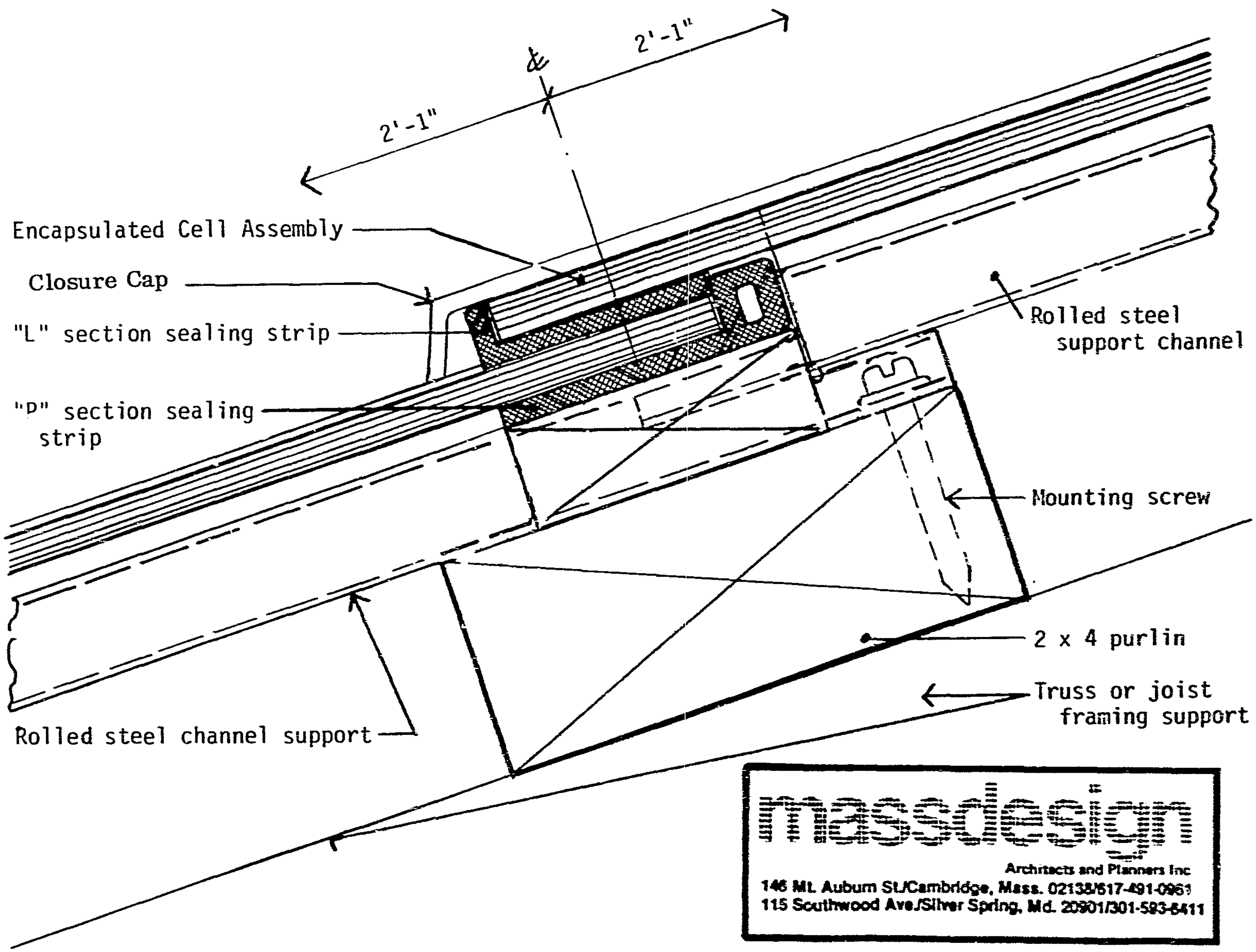

Figure 3-32. Typical Overlapped Joint (Integral Mount)

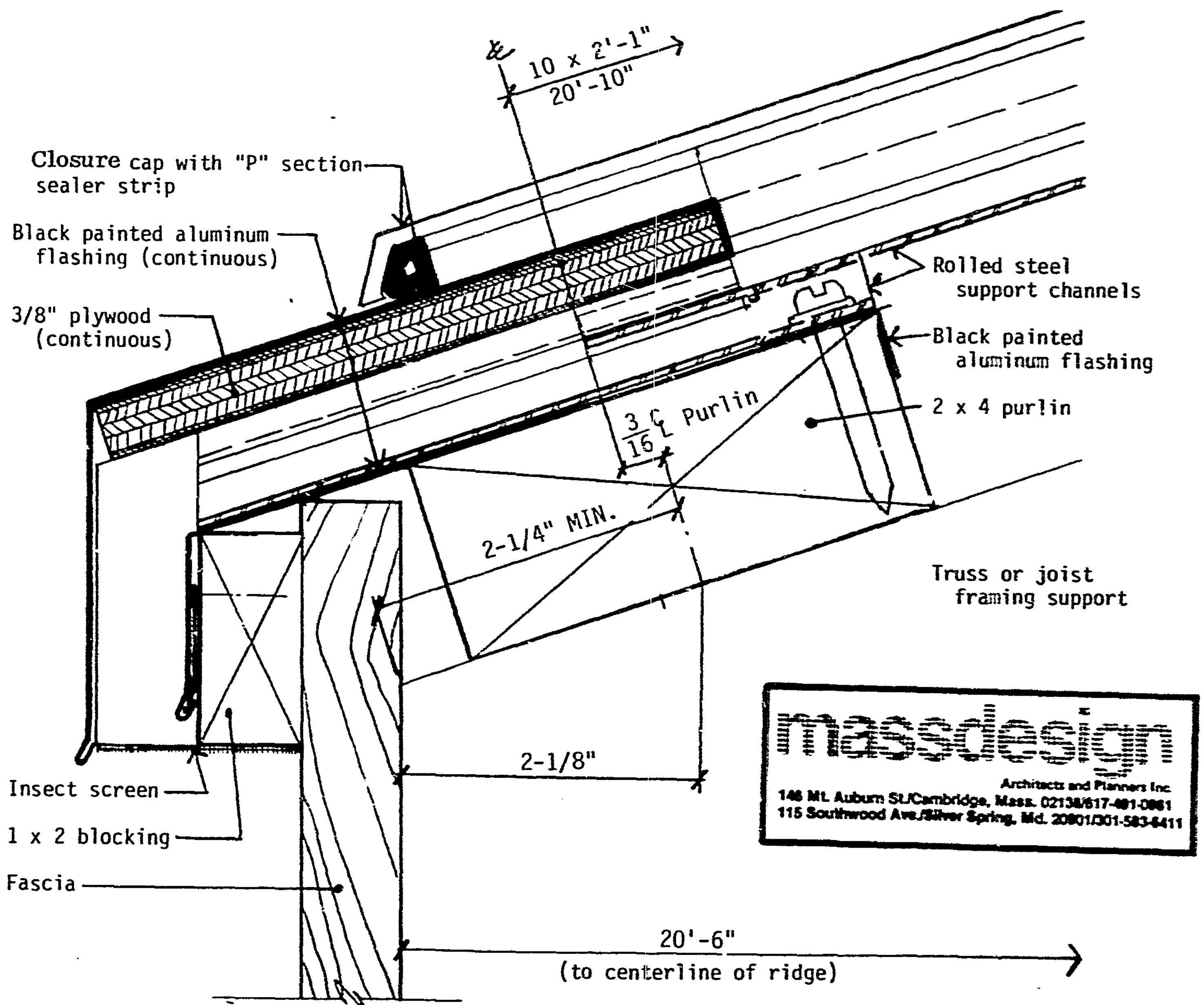

Figure 3-33. Eave Detail at Support Channel (Integral Mount)

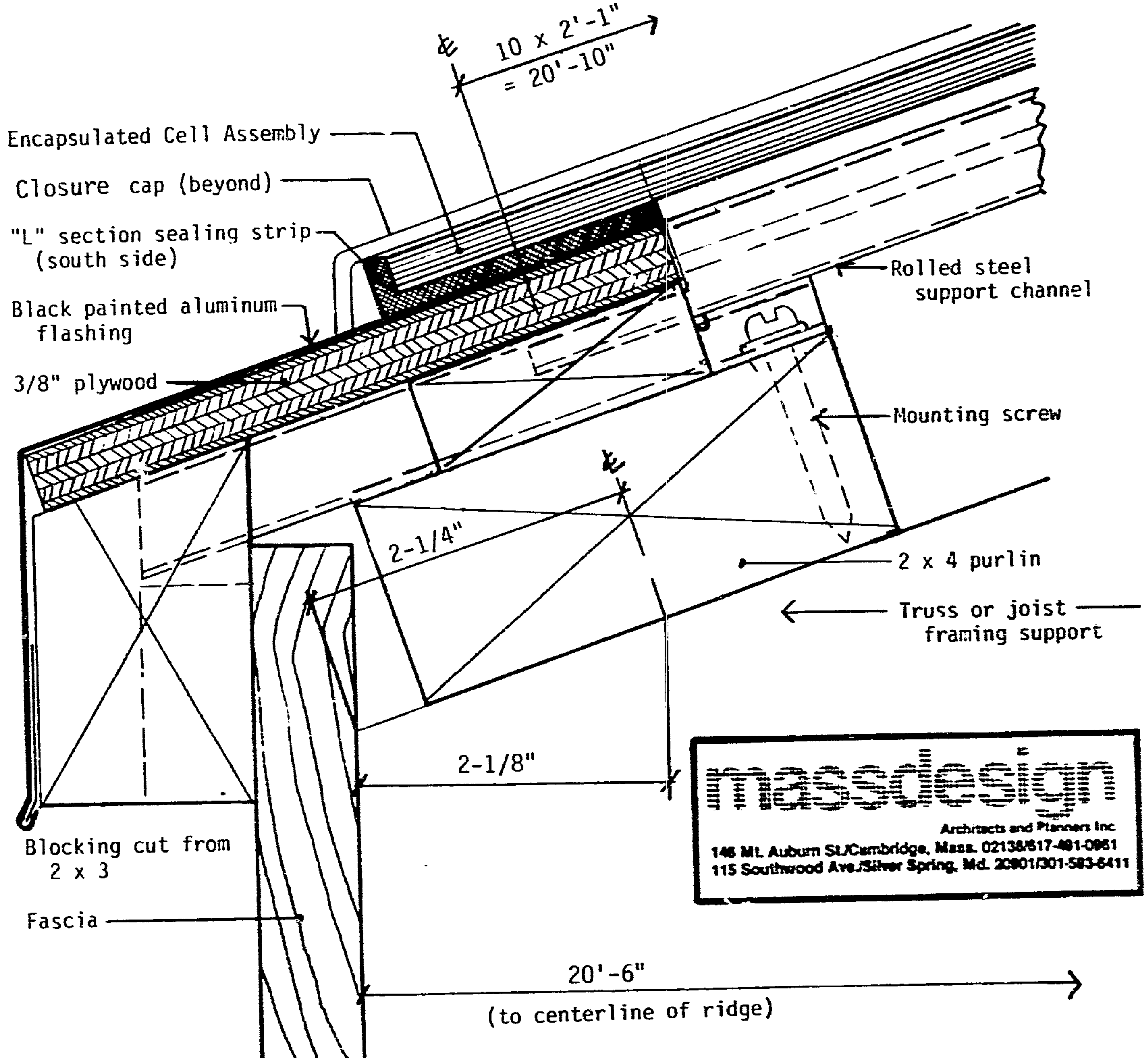

Figure 3-34. Eave Detail Between Support Channels (Integral Mount)

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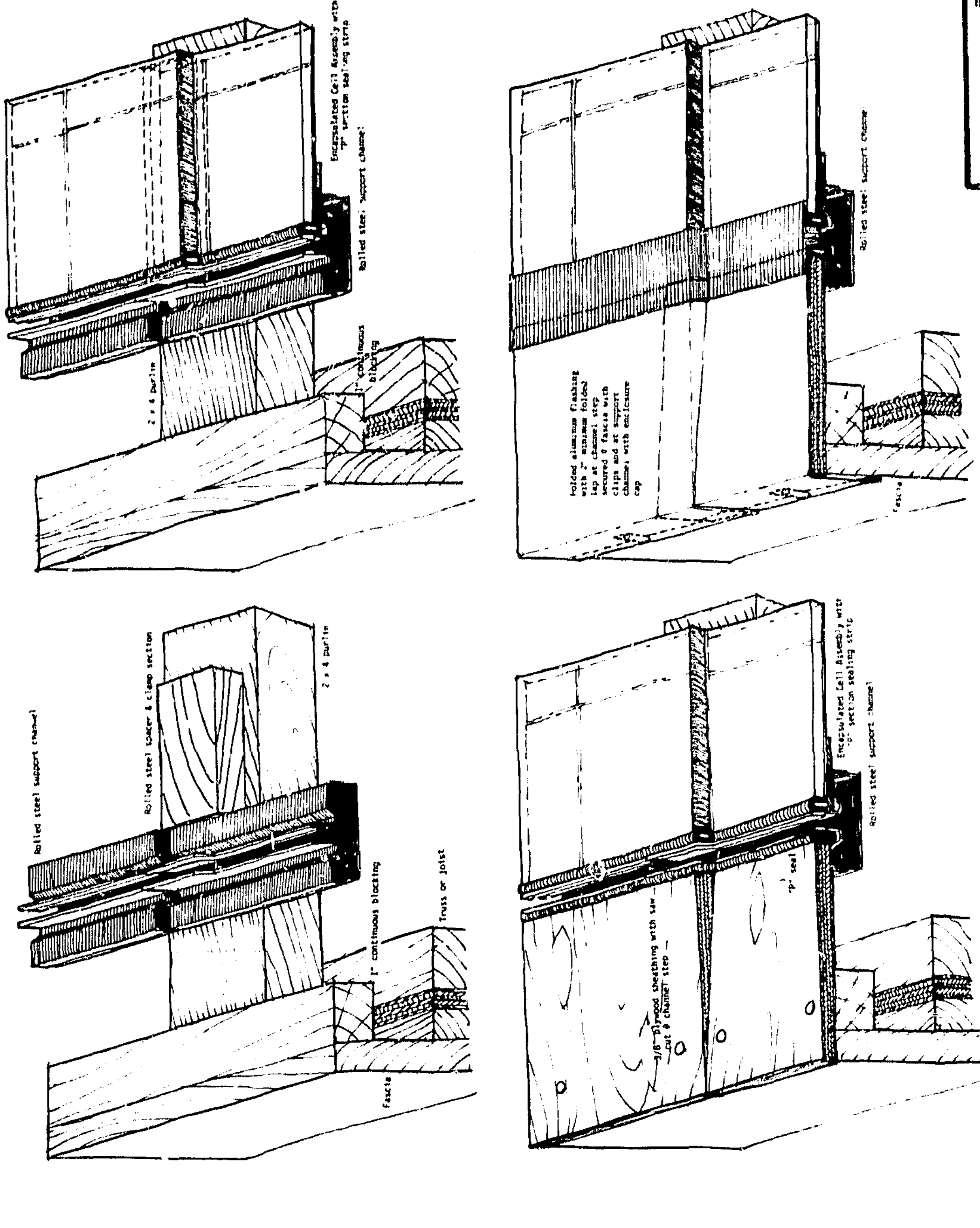


Figure 3-35. Pictorial Views of Installation Sequence at Rake

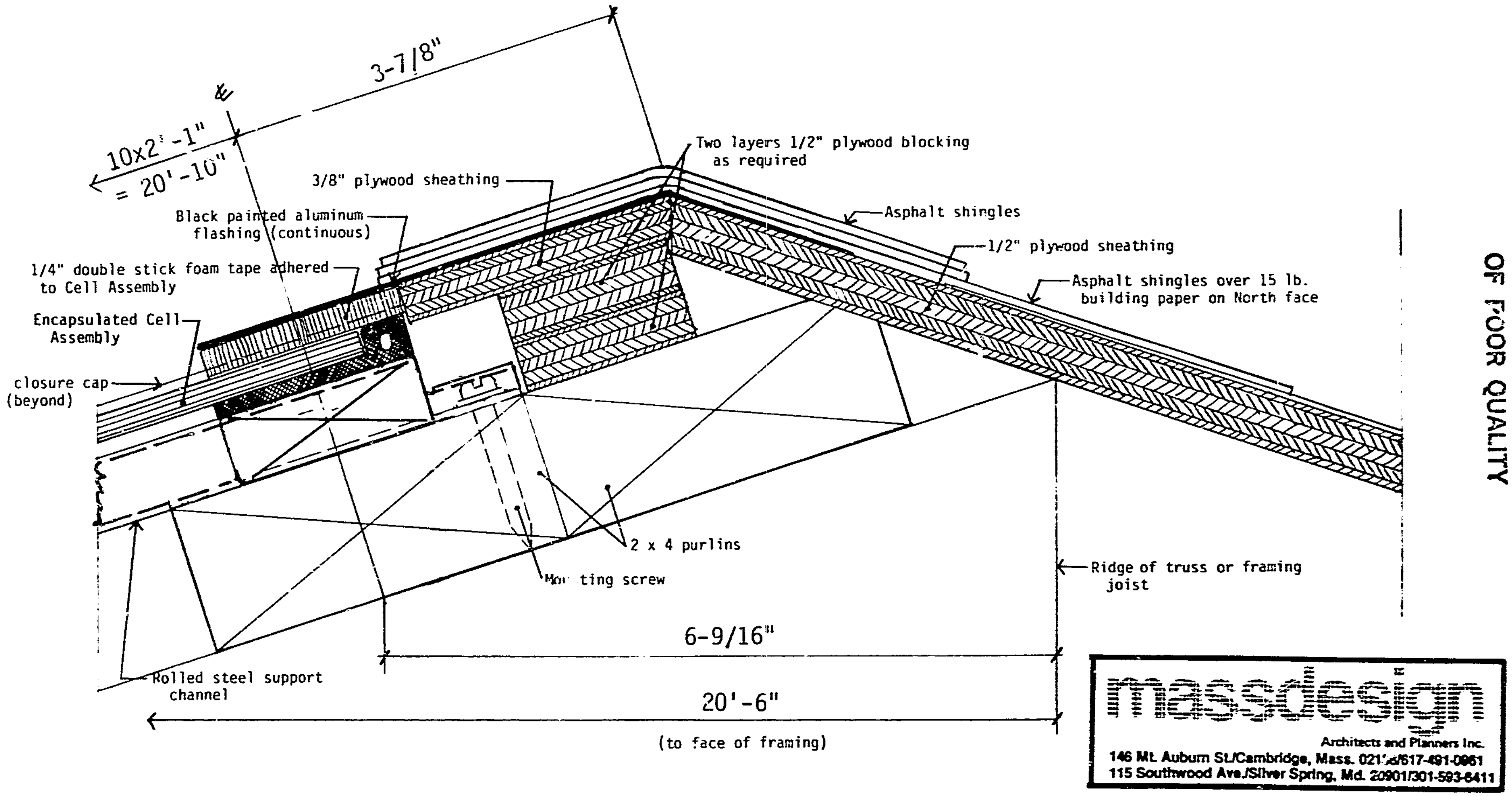


Figure 3-36. Ridge Detail (Integral Mount)

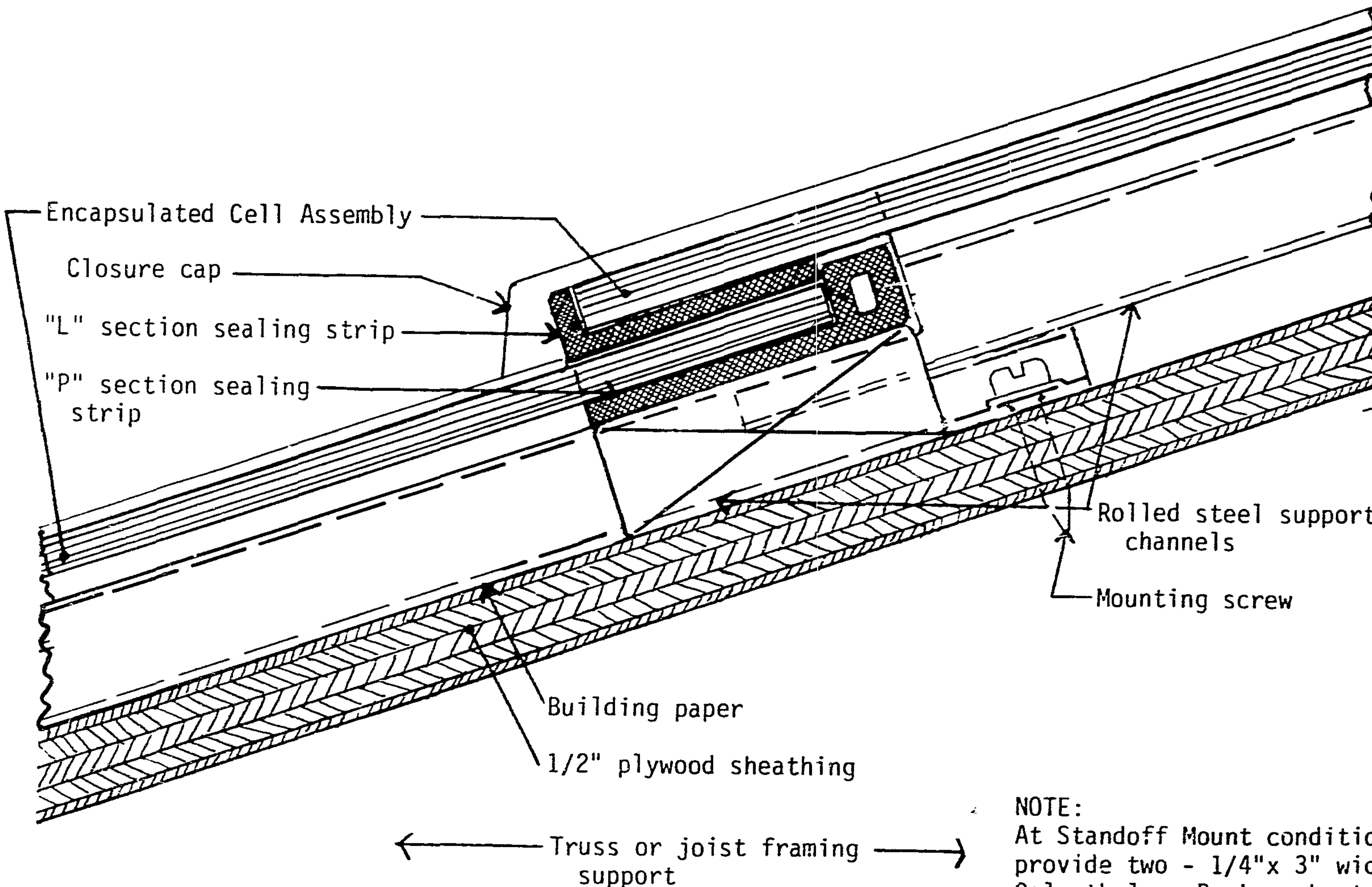
at the ridge is shown to be continued over onto the south side of the ridge line to provide a smooth transition at the increased height of the module installation. Blocking and flashing are used to build-up the roof height at this point and provide a watertight interface with the asphalt shingles.

3.1.3.4 Direct and Stand-off Mount Roof Interface Details

The installation details which pertain to the direct and stand-off mounting approaches are shown in Figures 3-37 through 3-40. These mounting methods are similar to those previously described for the integral array except that the purlin system is replaced by the conventional plywood roof sheathing. Building felt is used as a cover over this sheathing for the direct mount case whereas roll roofing is used as the watertight surface for the stand-off case.

The direct and stand-off installations are nearly identical above the conventional roofing surface, but the stand-off approach, by virtue of its roll roofing surface, gives the builder the option of installing the photovoltaic array long after the building is completed. Both the integral and direct mounting approaches require the timely scheduling of module installation within the overall building construction plan. In all cases the photovoltaic module installation is designed and installed to provide a watertight exposed surface. However, the consequences of a leak through this surface are considerably different among the three mounting configurations considered: varying from, potentially catastrophic, for the integral mount; to, of little concern, for the stand-off mount.

Both the direct and stand-off mounting approaches require the electrical cabling to be positioned prior to the installation of the modules. Cable connectors must be mated with the module-mounted receptacles at the time of module installation since access from the rear side is impossible.



NOTE:
At Standoff Mount condition, provide two - 1/4"x 3" wide Polyethylene Backer sheets on rolled roof @ support channels and one - 1/4"x 3" wide Backer @ mid span (typical)

Figure 3-37. Typical Overlapped Joint (Direct Mount)

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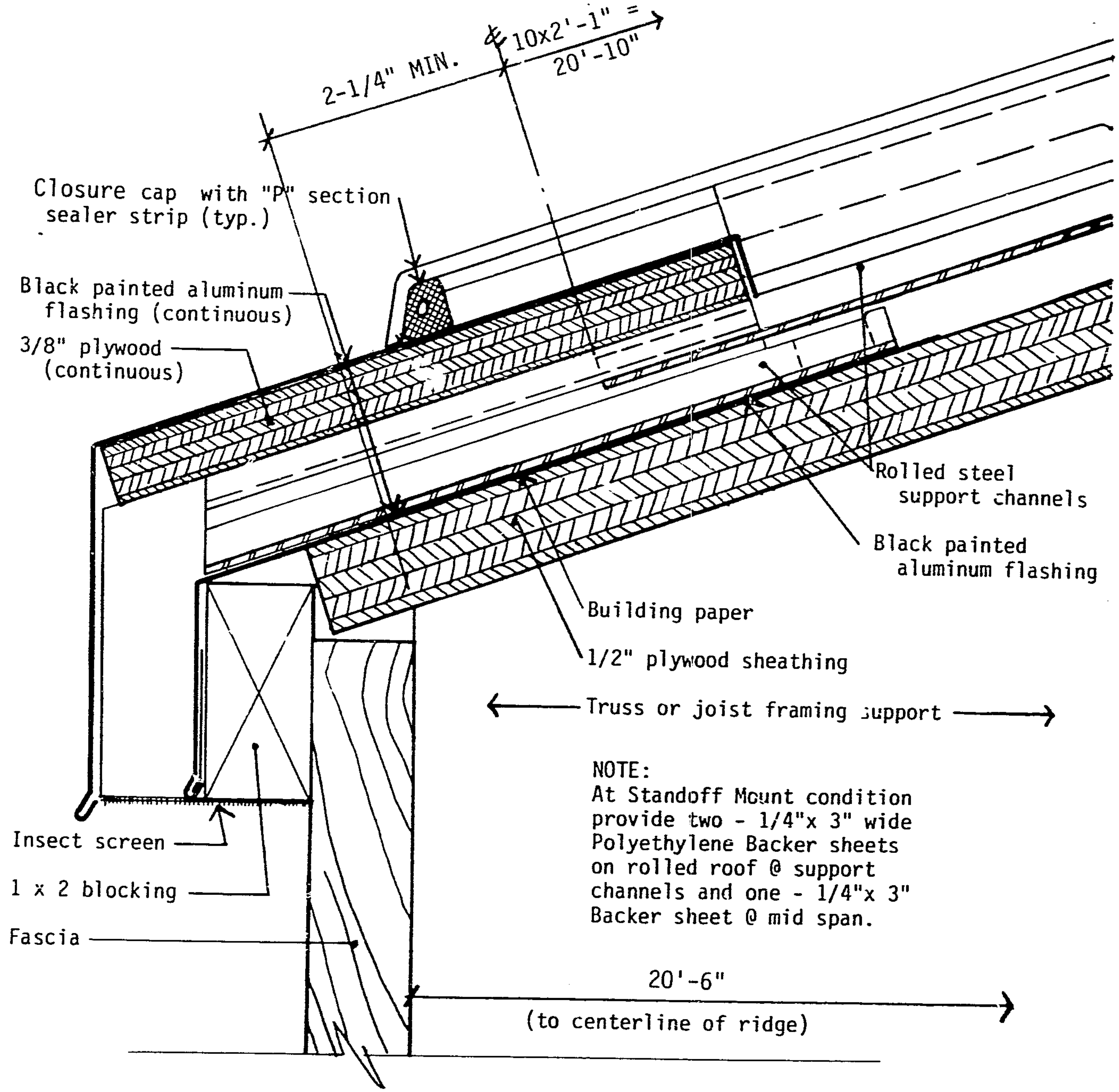

Figure 3-38. Eave Detail at Support Channel (Direct Mount)

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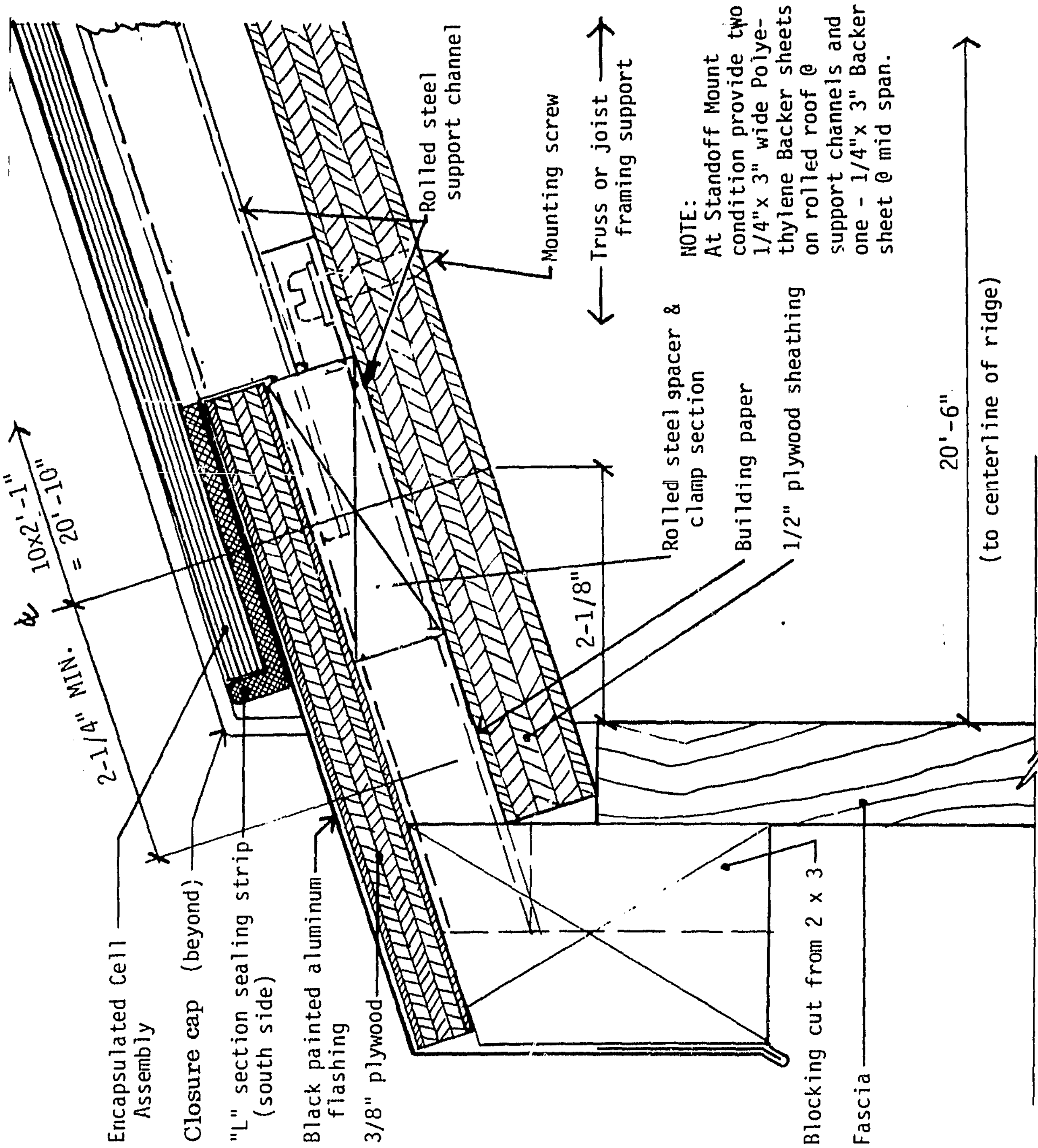


Figure 3-39. Eave Detail Between Support Channels (Direct Mount)

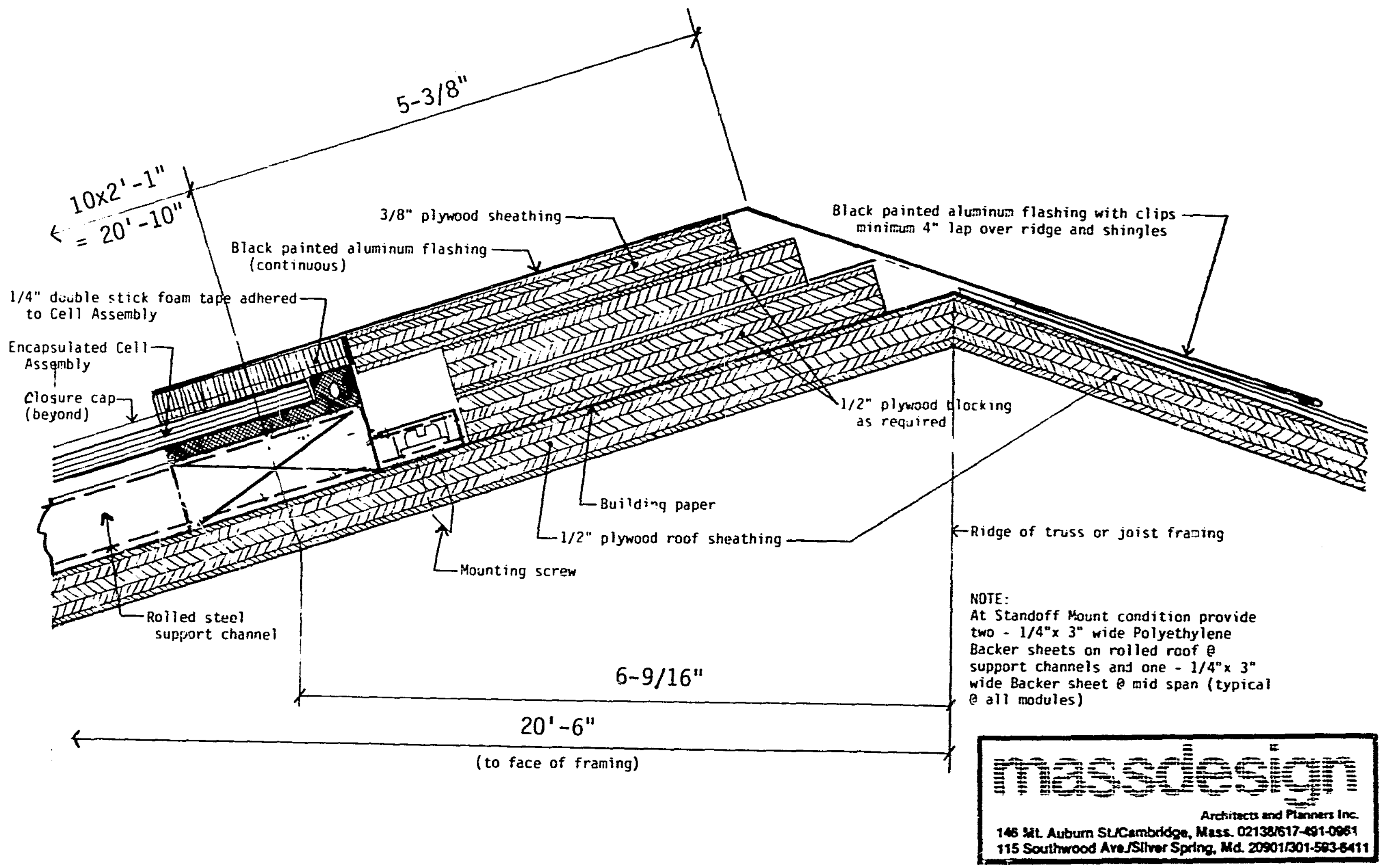


Figure 3-40. Ridge Detail (Direct Mount)

3.1.4 INSTALLATION COST ANALYSIS

3.1.4.1 Assumptions and Constraints

The installation cost for the selected module design was estimated for each of the three mounting approaches described in Section 3.1.3. This estimate was prepared by Massdesign Architects and Planners with the help of an experienced residential general contractor in the Boston, MA area. The following assumptions and constraints are implicit in these cost estimates:

1. The array size is the same for each installation type and consists of 50 modules representing 36 m^2 of solar cell area on each residence. This photovoltaic roof size was felt to be representative of the lower limit of array area which could be practically installed on a single-family residence. Thus the resulting array installation cost, expressed per unit area or per unit of peak power output, should represent the upper limit for that particular module concept and mounting approach.

2. These estimates assume the existence of a specialty photovoltaic installer, having the necessary staff of mechanics, and putting in several hundred systems per year on a one-by-one basis for individual contractors or homeowners.

3. All work is performed by carpenters, electricians, and glaziers. Roofers are not used. Non-union work crews were assumed to permit flexibility in work assignment among the trades.

4. Boston area wage rates, which are usually within 2 percent of the national average were used in the calculation of labor costs. The estimates reflect a 40 percent combined labor burden, which includes a 20 percent mark-up to cover the cost of insurance. The total material and labor cost is further burdened by a 20 percent mark-up to cover overhead and profit.

5. All costs include the labor and materials associated with the installation of the photovoltaic array and roofing surface, if it is required. The interface of the photovoltaic array with the building structure is assumed to be at the roof truss or joist system so that the array installation costs include all materials and labor required to complete the roofing surface including the mounting of the solar cell modules, but not the actual cost of the modules.

The three installation options considered in this analysis (viz., integral, direct and standoff) are similar in many regards, but are notable for the following distinctive differences:

1. <u>Wiring</u>. With the integral mounting approach it will generally be possible to gain access to the underside of the array after installation, whereas with the direct and

stand-off mounting methods, the module-to-module wiring must be done from above at the time of module installation taking care to route the cabling through gaps in the support framing members.

2. Waterproofing. In the integral mount, the roof must be carefully waterproofed, as opposed to the stand-off and direct mounts, where less exacting standards need to be applied. As a result, the integral mount must be installed by a crew which includes a glazier or other mechanic responsible for a watertight job.

3. Substrate. The mounting substrate constitutes the basic distinction among the three installation methods. In the integral mount, purlins are nailed perpendicular to the normal roof trusses to form the supporting surfaces for the module installation. In the direct mount, the purlins are replaced by normal roof sheathing, which is covered with a layer of building paper for added water resistance. In the stand-off mount, the building paper is replaced by a layer of rolled roofing, to increase the water protection beneath the array and to allow the roof to be weatherproofed in case construction must proceed before the modules are delivered.

3.1.4.2 Integral Mount

The installation cost for the integral mounting approach is summarized in Table 3-11. The labor estimate is based on an installation scenario which consists of three separate phases. The first of these employs a crew consisting of a carpenter and a laborer to perform the following tasks:

- Cut purlins, measure roof and install purlins at required centers.
- Cut and install blocking at top, bottom and two sides, to support flashing; and cut and install plywood flashing substrate.
- Cut, bend and install aluminum flashing to required dimensions.

This is followed by a second work phase which requires a crew made-up of a glazier and a carpenter to perform the following tasks:

- Strike perpendicular lines off the purlins, and measure the roof for the array.
- Working off ladders at the roof edge and within the building (since there is no sheathing), set the support channels, horizontal blocking, modules and closure caps either from the eave or from one side, depending upon the circumstances. It should not be necessary to go back onto the array once installed, so no staging is is included in the cost estimate.

Table 3-11. Installation Cost Estimate for the Integral Mount

	Item Description	Quantity	Units	Unit Price (1980 $)	Total Cost (1980 $)
Material	Closure Cap	62*	EA	1.75	109
	Support Channel	70*	EA	3.30	231
	Horizontal Blocking	220	LF	0.38	84
	Mounting Screws	2	LB	0.50	1
	P Seal	50	LF	0.30	15
	Double Sided Foam Tape (1/4" x 2")	24	LF	0.54	13
	AMP Solarlok Harness				
	6' Double End	50	EA	2.50	125
	12' Single End	5	EA	3.00	15
	24' Single End	5	EA	4.25	21
	CDX Plywood 3/8" Thk	2	SHT	10.00	20
	CDX Plywood 1/2" Thk	0.5	SHT	12.50	6
	Purlins (2 x 4 fir)	277	LF	0.24	66
	Flashing - Black Aluminum				
	0.032" x 10" x 50'	2	RL	24.00	48
	0.032" x 14" x 50'	0.5	RL	34.00	17
	Eave Blocking 2" x 3"	22	LF	0.18	4
	Conduit - 1" Dia.	20	LF	0.30	6
	Outlet Box 4" x 4"	2	EA	2.00	4
Labor	Set-up, Purlins, Blocking, Flashing, Plywood Substrate - 10 Hrs. Carpenter and Laborer @ $25.20/hr.				252
	Layout, Set Supports, Lay-in Connectors, Set Panels, Set Closure Caps, Check and Caulk - 4 Hrs. Glazier and Carpenter @ $30.80/hr.				123
	Set Outlet Boxes, Connect Panels and Check - 2 Hrs. Electrician and Helper @ $37.00/hr.				74
				Subtotal	1234
				Overhead and Profit (20%)	247
				Warranty	100
				Total Installation Cost	1581

*Quantities listed include an allowance for spares.

An electrician and helper complete the installation by performing the following tasks:

- Install outlet boxes on the rake at the top and bottom of the array, and connect them by a conduit.
- Install the long cable runs from each branch circuit termination and connect to the junction boxes.
- Working inside the building, interconnect the modules.
- Test to verify that the system is performing as required.

The estimated cost of the integral mount installation has been increased by $100 to account for the increased warranty liability associated with this mounting approach.

3.1.4.3 Direct Mount

The installation cost for the direct mounting approach is summarized in Table 3-12. The work plan for this installation type is similar to that previously described for the integral mount except that the glazier's skills are not reqired since the risk of a water leak is significantly reduced for a direct mount installation with roofing felt. The installation plan calls for the carpenter and laborer crew to perform the majority of the tasks including:

- Install roof sheathing and #15 felt. (Note that the array must be installed promptly after the felt is laid, before the first windstorm).
- Measure the roof and establish the datum line for the installation of the first column of support channels.
- Cut and install blocking and plywood flashing substrate at the four sides of the roof.
- Measure, cut and install aluminum flashing at four sides of the roof.
- Install the support channels, horizontal blocking, modules and closure caps. Work is done from ladders, using the horizontal blocking boards as foot supports for climbing the roof.

During the final stage of module installation it will be necessary to add an electrician and a helper to the work force to complete all electrical tasks including:

- Install outlet boxes and connecting conduit.
- Install branch circuit termination cables runs and connect to boxes.
- Lay in all module interconnections according to the wiring interconnection drawings, ready for module attachment.

Table 3-12. Installation Cost Estimate for Direct Mount

	Item Description	Quantity	Units	Unit Price (1980 $)	Total Cost (1980 $)
Material	Closure Cap	62*	EA	1.75	109
	Support Channel	70*	EA	3.30	231
	Horizontal Blocking	220	LF	0.38	84
	Mounting Screws	2	LB	0.50	1
	P Seal	50	LF	0.30	15
	Double Sided Foam Tape (1/4" x 2")	24	LF	0.54	13
	AMP Solarlok Harness				
	6' Double End	50	EA	2.50	125
	12' Single End	5	EA	3.00	15
	24' Single End	5	EA	4.25	21
	CDX Plywood 3/8" Thk	2	SHT	10.00	20
	CDX Plywood 1/2" Thk	16	SHT	12.50	200
	#15 Bldg. Paper	500	SF	0.03	15
	Flashing - Black Aluminum				
	0.032" x 10" x 50'	2	RL	24.00	48
	0.032" x 14" x 50'	0.5	RL	34.00	17
	Eave Blocking 2" x 3"	22	LF	0.18	4
	Conduit - 1" Dia.	20	LF	0.30	6
	Outlet Box 4" x 4"	2	EA	2.00	4
Labor	Set-up, Sheathing, #15 Felt, Blocking, Layout, Set Supports, Plywood Substrate, Flashing - 14 Hrs. Carpenter and Laborer @ $25.20/hr.				353
	Set Panels and Cap, Make all Connections, Set Boxes and Conduit - 4 Hrs. Electrician and Helper @ $37.00/hr.				148
				Subtotal	1429
				Overhead and Profit (20%)	286
				Total Installation Cost	1715

*Quantities listed include an allowance for spares.

3.1.4.4 Stand-Off Mount

Table 3-13 summarizes the results of the installation cost analysis of the stand-off mounted array. In this case additional effort is required by the carpenter and laborer crew to install the rolled roofing and to install the polyethylene pads under the horizontal blocking to provide the flow path for rain water running down the rolled roofing surface.

Table 3-13. Installation Cost Estimate for Stand-off Mount

	Item Description	Quantity	Units	Unit Price (1980 $)	Total Cost (1980 $)
Material	Closure Cap	62*	EA	1.75	109
	Support Channel	70*	EA	3.30	231
	Horizontal Blocking (Treated)	220	LF	0.45	99
	Mounting Screws	2	LB	0.50	1
	P Seal	50	LF	0.30	15
	Double Sided Foam Tape (1/4" x 2")	24	LF	0.54	13
	AMP Solarlok Harness				
	6' Double End	50	EA	2.50	125
	12' Single End	5	EA	3.00	15
	24' Single End	5	EA	4.25	21
	CDX Plywood 3/8" Thk	2	SHT	10.00	20
	CDX Plywood 1/2" Thick	16	SHT	12.50	200
	Rolled Roofing	500	SF	0.11	55
	Polyethylene Stand-offs 1/4" x 3"	374	LF	0.18	67
	Flashing - Black Aluminum				
	0.032" x 10" x 50'	2	RL	24.00	48
	0.032" x 14" x 50'	0.5	RL	34.00	17
	Eave Blocking 2" x 3"	22	LF	0.18	4
	Conduit - 1" Dia.	20	LF	0.30	6
	Outlet Box - 4" x 4"	2	EA	2.00	4
Labor	Set-up, Sheathing, Rolled Roofing, Blocking, Lay-out, Set Supports, Plywood Substrate, Flashing - 16 Hrs. Carpenter and Laborer @ $25.20/hr.				403
	Set Panels and Caps, Make all Connections, Set Boxes and Conduit - 4 Hrs. Electrician and Helper @ $37.00/hr.				148
				Subtotal	1601
				Overhead and Profit (20%)	320
				Total Installation Cost	1921

*Quantities listed include an allowance for spares.

3.1.5 COST SUMMARY

The installation cost for a typical array of the selected design amounts to \$39.30, \$42.64 and \$47.76 per m^2 of module area for integral, direct and stand-off mounting, respectively. If these installation prices are added to the FOB factory price of the modules it is possible to obtain the curves shown in Figure 3-41 for the median module production rate. It is important to note that these installed price curves do not include any price mark-up for the shipping, handling and distribution of the modules.

At a \$ 3.00 per watt solar cell cost level, which might be typical of 1982 production at the median rate considered, the installed array price can be categorized as shown in Table 3-14.

Table 3-14. Installed Array Price Breakdown at a \$3.00 per Watt Solar Cell Cost

	Price (1980 \$/Watt)	Fraction of Total Installed Price
Solar Cells	3.00	0.61
Balance of Module Assembly	1.57	0.32
Total Module FOB Factory Price	4.57	0.93
Installation Price (Integral Mount)	0.32	0.07
Total Installed Array Price	4.89	1.00

It is apparent from these data that the cell cost is the dominant factor in determining the price of the installed array and that the small differences in the installation cost among the three mounting appraoches considered will have little impact on the resulting cost of the installed residential array.

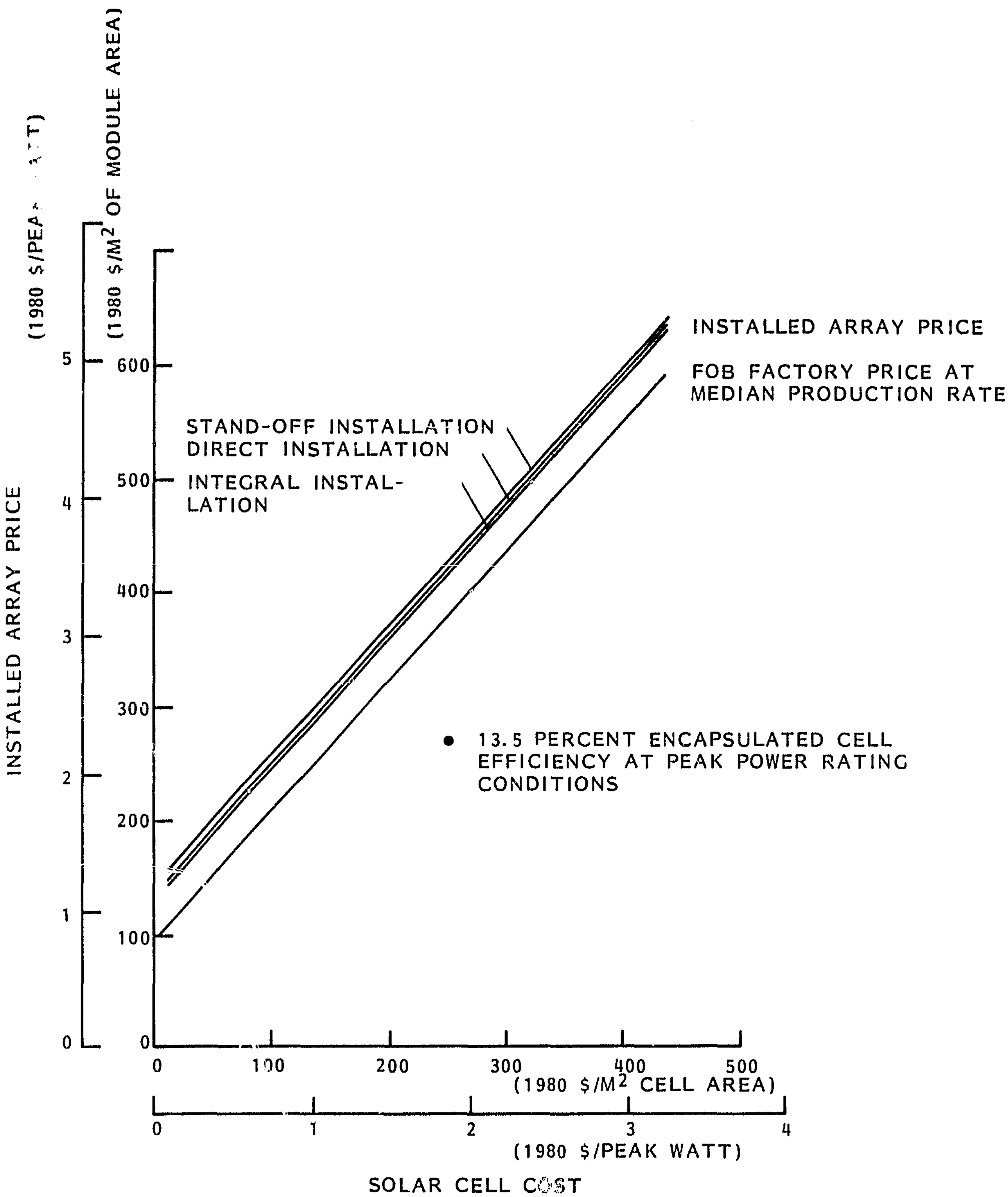


Figure 3-41. Installed Array Price vs. Solar Cell Cost

C-2

3.2 DESIGN AND FABRICATION OF A FULL-SIZE ROOF SECTION MODEL

3.2.1 DESIGN APPROACH

The prototype roof section design approach, shown in Figure 3-42, allows for the installation of six full-size simulated modules of the selected design. The modules were mounted as an integral installation to demonstrate that the selected approach provides the necessary watertight roofing surface. This roof model accurately simulates the actual module mounting interface including the eave, rake and ridge details. The module construction used on this model duplicated the actual module mechanical characteristics and interfaces, except for the active solar cells which were replaced with black and white photographs of solar cells. The electrical connectors and cabling between modules was identical to that proposed for an actual array installation.

It was intended that this model function as a learning tool to aid in the discovery of design problems which surface during the fabrication and assembly. Particular attention was given to the transition details at the eave, rake and ridge since the simplicity, reliability and aesthetics of these interface areas has a significant impact on the cost and acceptance of the installed array.

3.2.2 CONSTRUCTION DETAILS

A sketch of the model was prepared to show the details of the construction of the basic simulated roof structure. A local carpenter was employed to construct the structure shown in Figure 3-43. The model was deliberately made larger than the area required to the six modules to permit the simulation of the transition details between the modules and the conventional roof surface at the rakes and ridge. The purlins were installed normal to the rafters on 25 inches centers as shown in Figure 3-43.

The model was equipped with swivel casters to provide mobility in display areas. Two access doors on the north wall and an interior light were provided to permit the examination of the wiring on the rear of the array installation.

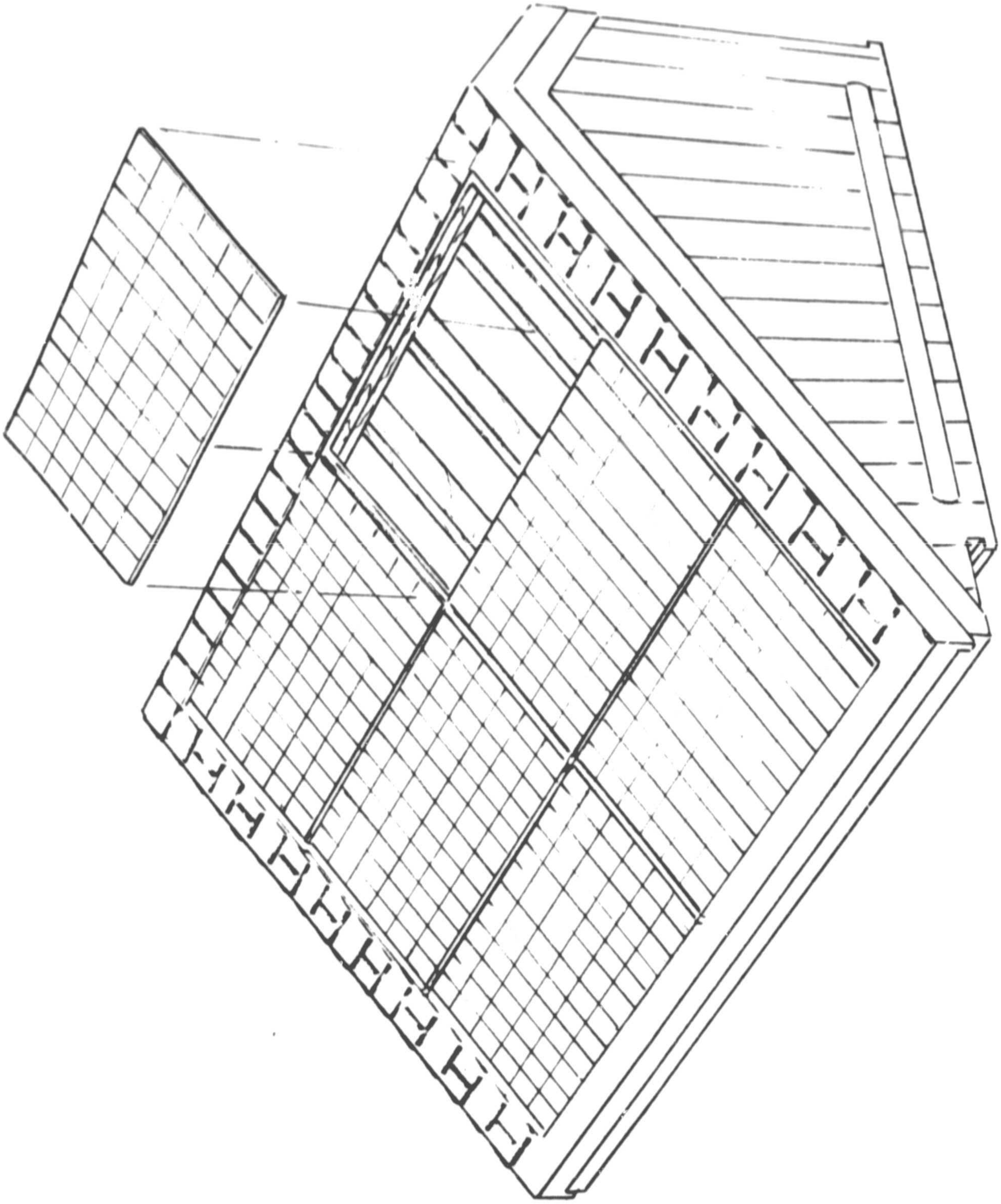
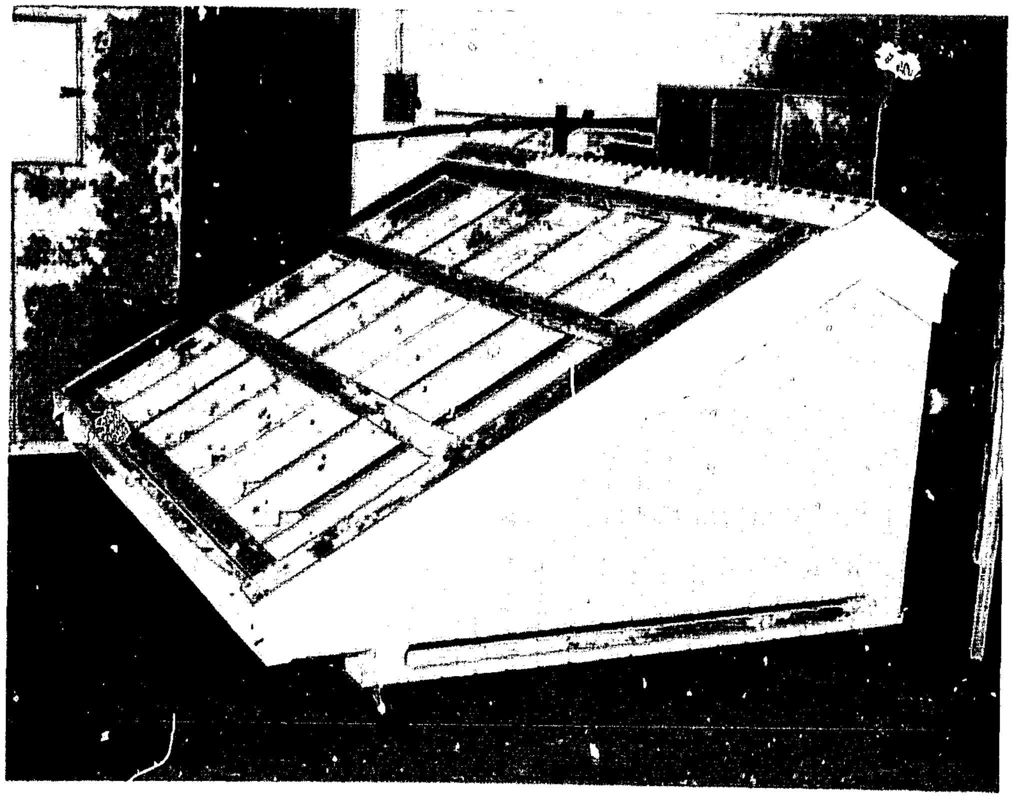


Figure 3-42. Prototype Roof Section



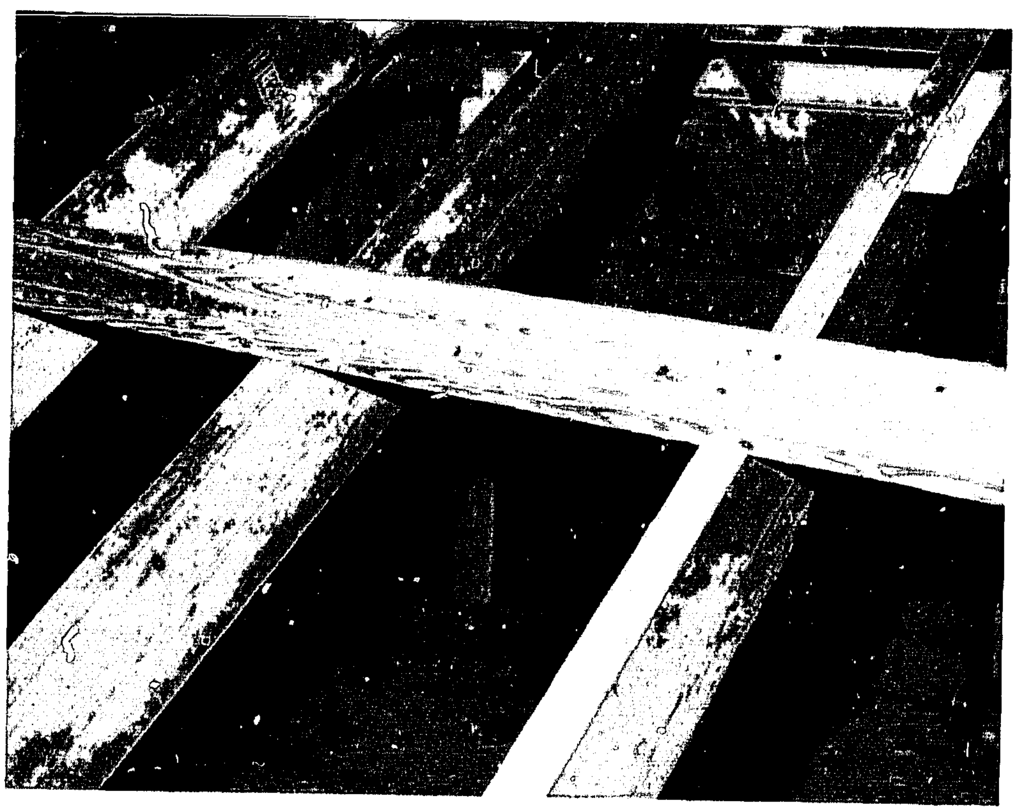


Figure 3-43. Basic Roof Model Structure

BLACK AND WHITE PHOTOGRAPH

The first step in the installation of the simulated modules involves the attachment of the support channels to the purlins as shown in Figure 3-44. One sheet metal screw (#10x1" long) is required for each channel section. The next higher channel section dovetails with the top end of the lower piece as shown in Figure 3-44. This unique design concept provides a drainage channel for any water leakage as illustrated in Figure 3-45. Water which might leak into the channel (top left of Figure 3-45) will run down the trough formed by this channel section and will cascade to the next lower channel (center of Figure 3-45) until it is finally drained over the eave (bottom right of Figure 3-45). The transition at the eave is constructed by cutting a short piece of the top end of a support channel to fit over the eave as shown in Figure 3-33. A continuous piece of formed flashing folds over the fascia to cover this channel drain opening.

The support channels, which were designed to be fabricated as roll formed steel parts, were instead manufactured as a riveted assembly of three brake formed steel parts. This change in part configuration was dictated by the small number of parts required for the model assembly. It was possible to brake form the closure caps in the identical configuration to the roll part design. Galvanized sheet steel was used in each case.

Photographic details of a simulated module and associated support hardware are showing in Figures 3-46 and 3-47. A single module mounted in the lower left corner of the array is depicted in Figure 3-46 along with close-up photographs of the corners showing the interface details with the eave and left side rake. At each rake the transition to the conventional shingle roofing surface was made by fabricating a flashing detail by forming the aluminum flashing over a narrow width of 3/8 inch plywood to duplicate the module interface with the support channel and closure cap (see the lower left photograph of Figure 3-46). No gasket seal is used at this flashing interface with the support channel. The flashing is extended under the conventional roofing shingles for an appropriate distance to assure the watertight integrity of the surface.

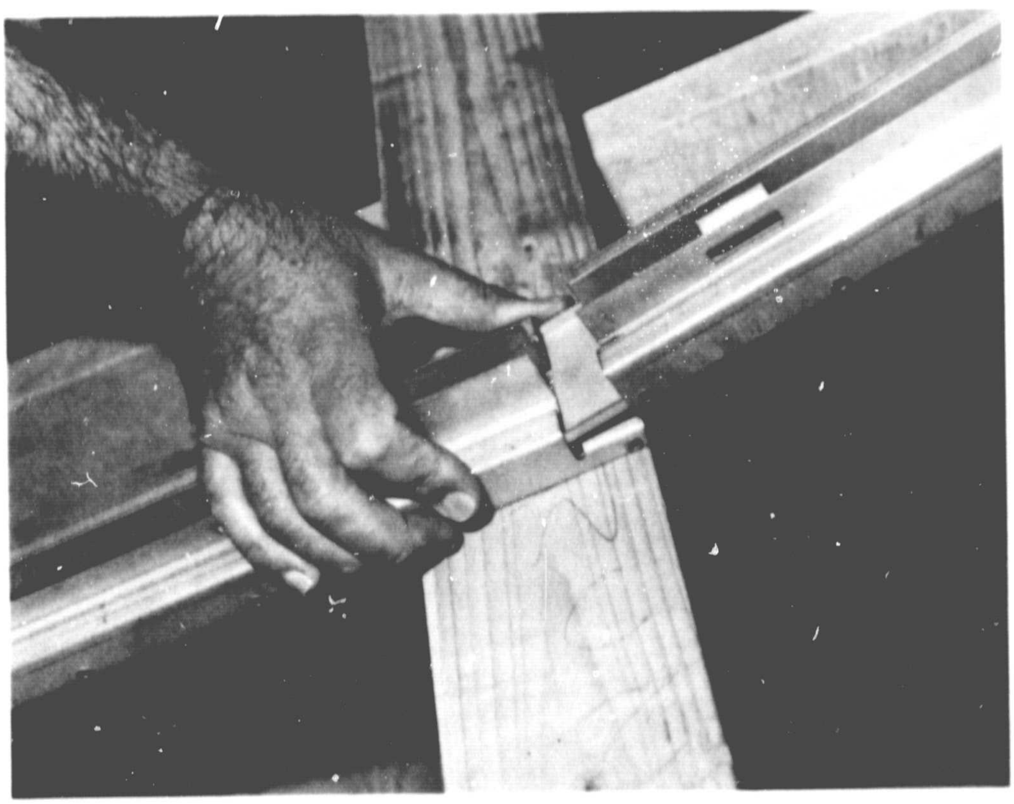


Figure 3-44. Installation of Support Channels

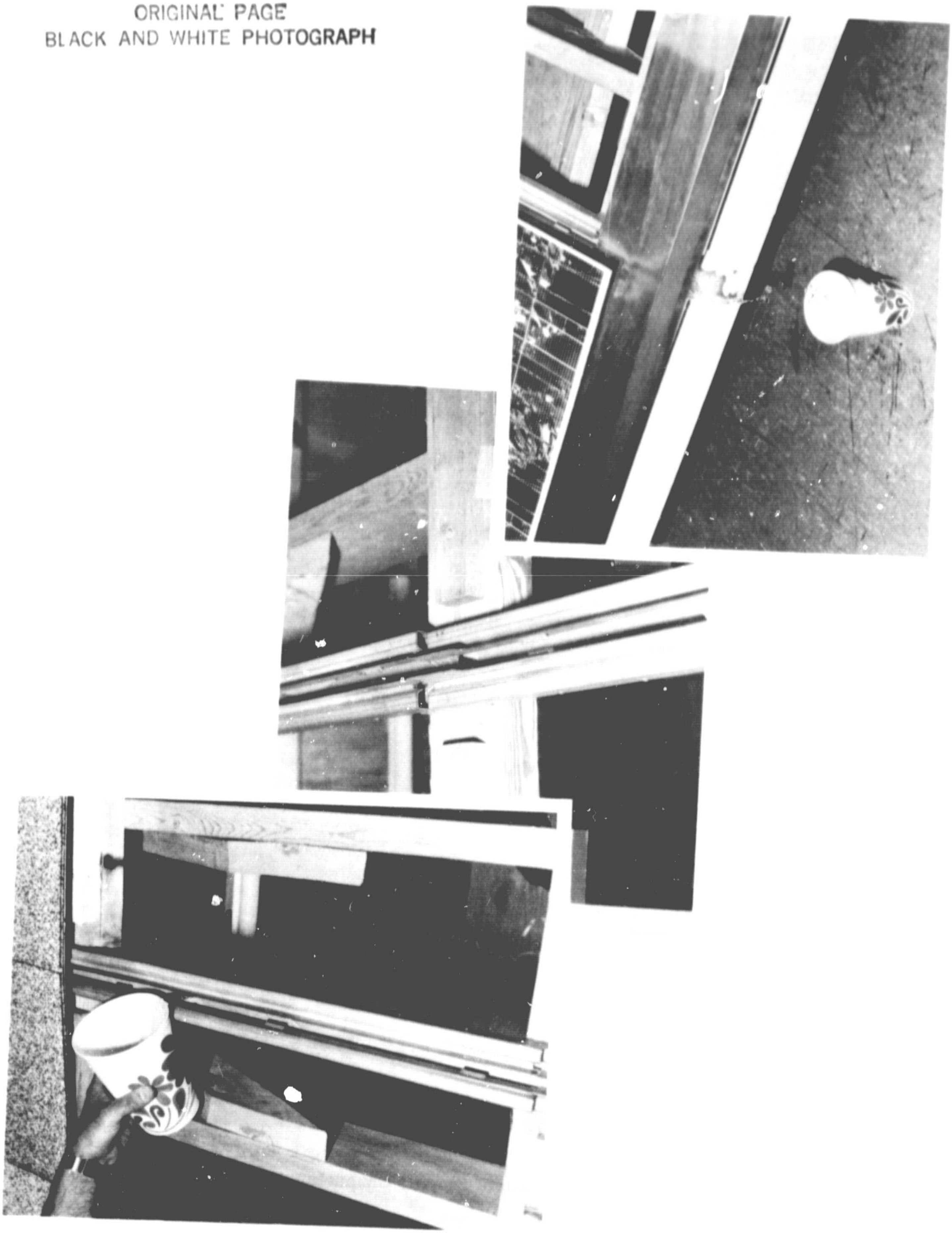


Figure 3-45. Water Drainage in Support Channels

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

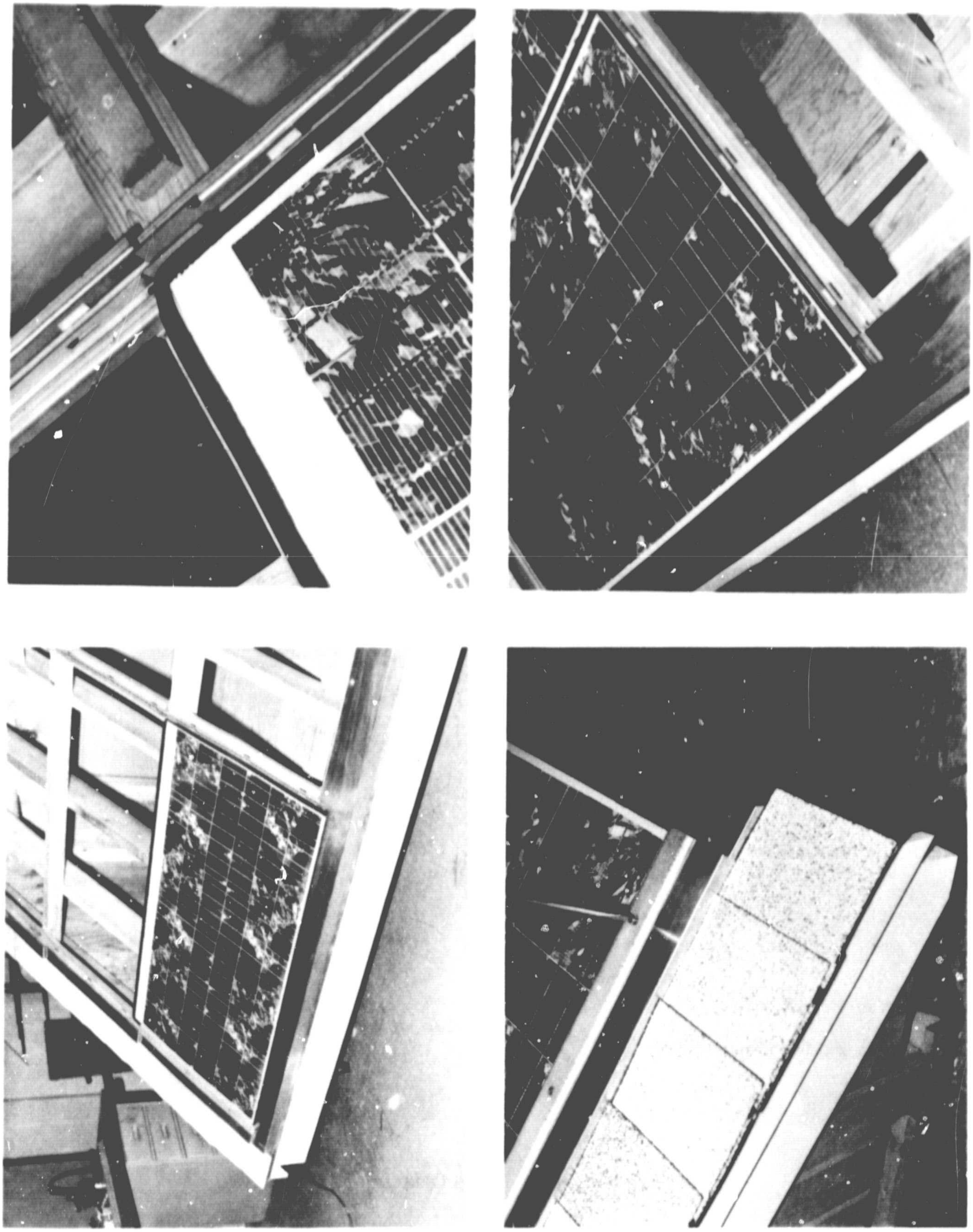
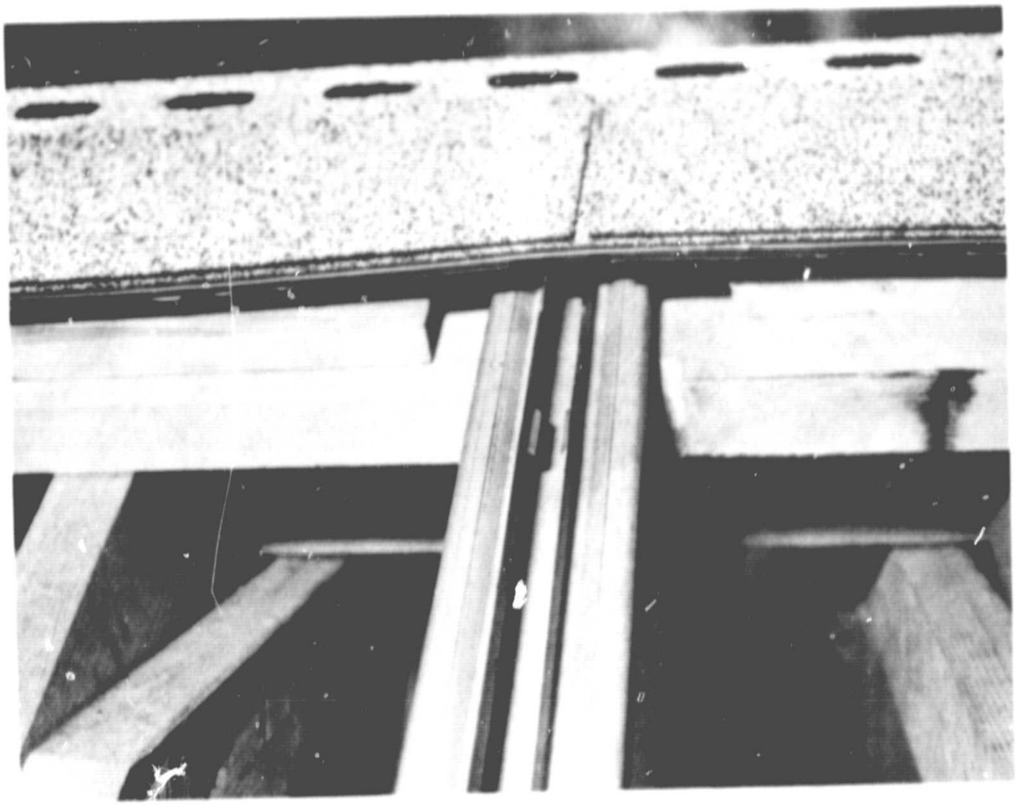


Figure 3-46 Module Interface with Support Hardware at Eave and Rake



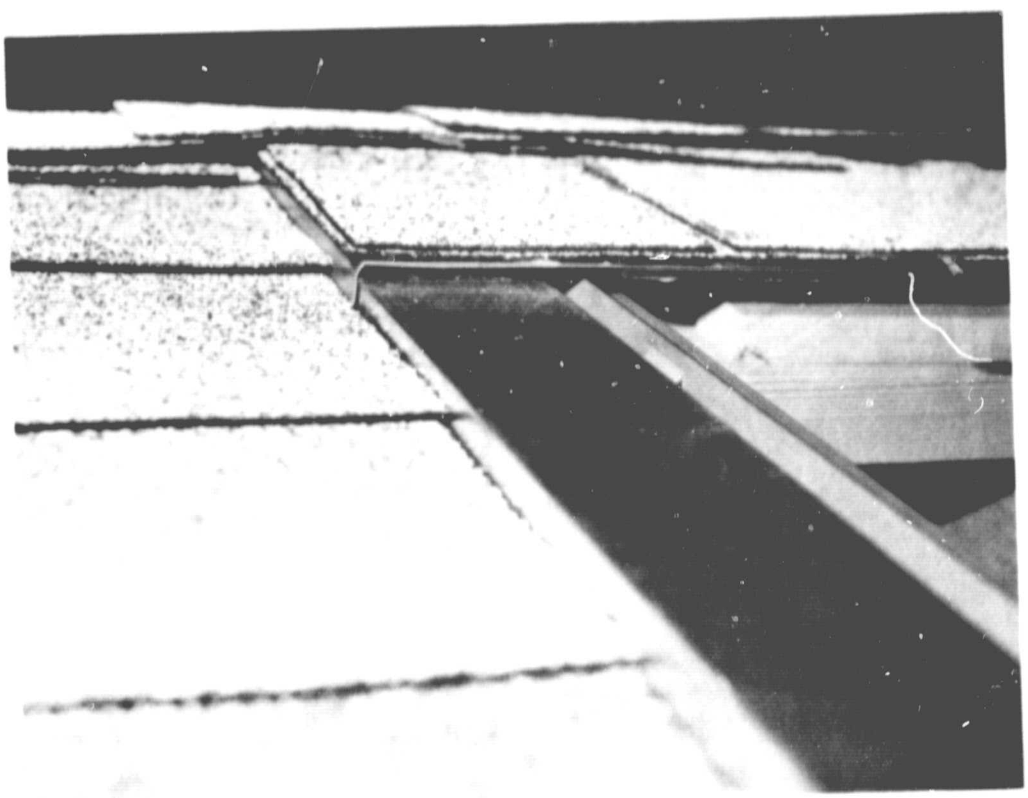


Figure 3-47. Ridge Details

At the top of the module installation a transition to the ridge cap is made as shown in Figure 3-47. A flap of formed aluminum flashing, which is covered with asphalt shingles, overlaps the top edge of the upper row of modules to provide the watertight seal. This flap is hinged up to permit the upper row of modules to be installed. A strip of double-backed foam tape is adhered to the top inactive glass area to prevent this flap from lifting in a wind storm.

3.2.3 LESSONS LEARNED

This model served as a learning tool to aid in the discovery of design problems which surfaced during the fabrication and assembly. These problems are discussed below in two areas related to the fabrication of parts and the final assembly of the roof.

3.2.3.1 Parts Fabrication

The simulated modules were fabricated with EVA as the encapsulant using a double vacuum chamber laminator in a process which closely duplicates an actual solar cell module laminating procedures. Photographs of solar cell circuits were used in lieu of actual cells to provide a pictorially accurate model without the additional cost associated with real solar cells. Initial attempts were made to perform this lamination with a 0.188 inch thick annealed Sunadex glass plate as the module superstrate since the structural analysis had shown that annealed glass of this thickness was adequate to meet the loading requirements for this application. However, these lamination trials using annealed glass resulted in several cases of glass breakage within the laminator. Thus it appears that, in some cases, the loading imposed during module lamination may be the limiting design condition. In this case a switch to thermally-tempered glass of the same thickness was adequate to eliminate this breakage problem.

The fabrication of the support channels resulted in the recommendations of several changes to improve and simplify the design. The tabs which are bent in to catch the expanded wings of the clamping strip were changed from a curved section to a straight profile as shown in Figure 3-48. The drainage slots at the lower end of the support channel were changed to holes as shown in Figure 3-49. The width of the tabs was also changed to 1.00 inch to correspond to the width of an available punch.

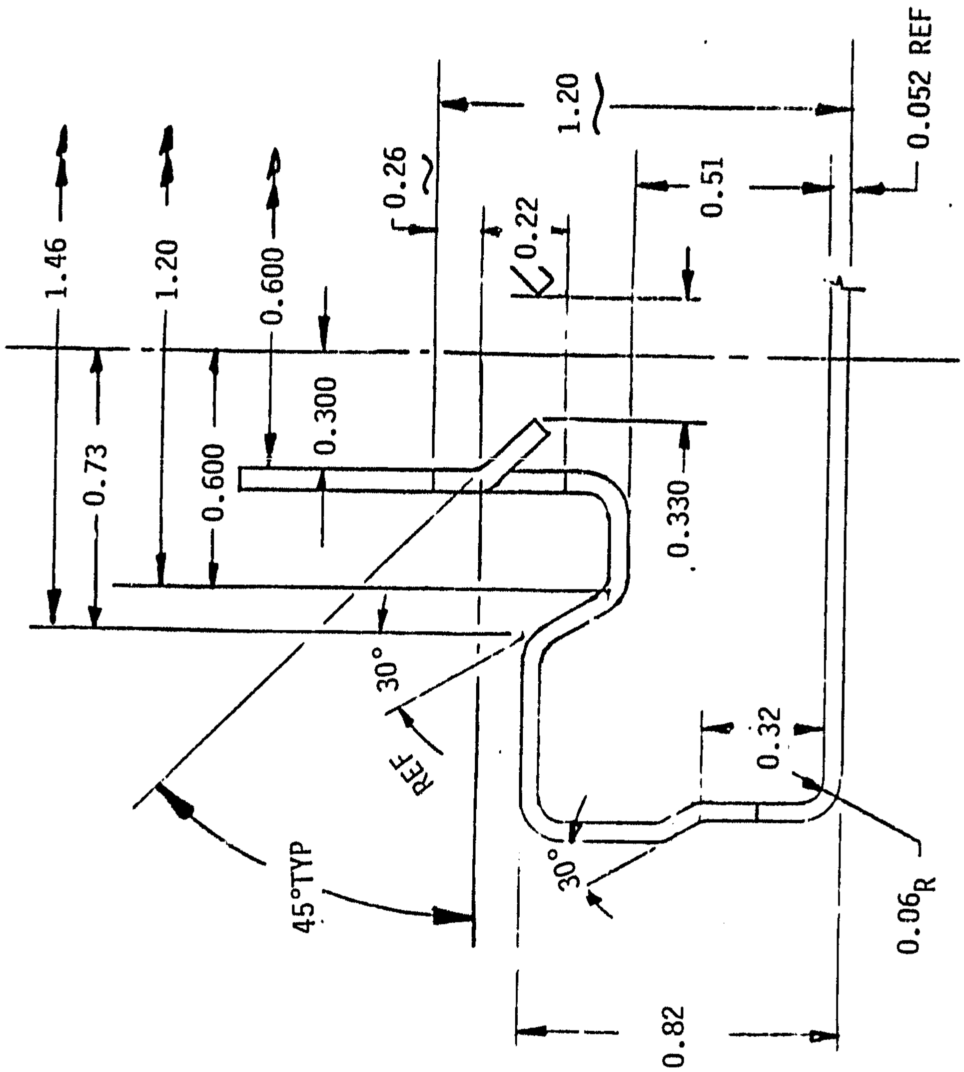


Figure 3-48. Support Channel Design Modifications (Straight Tabs)

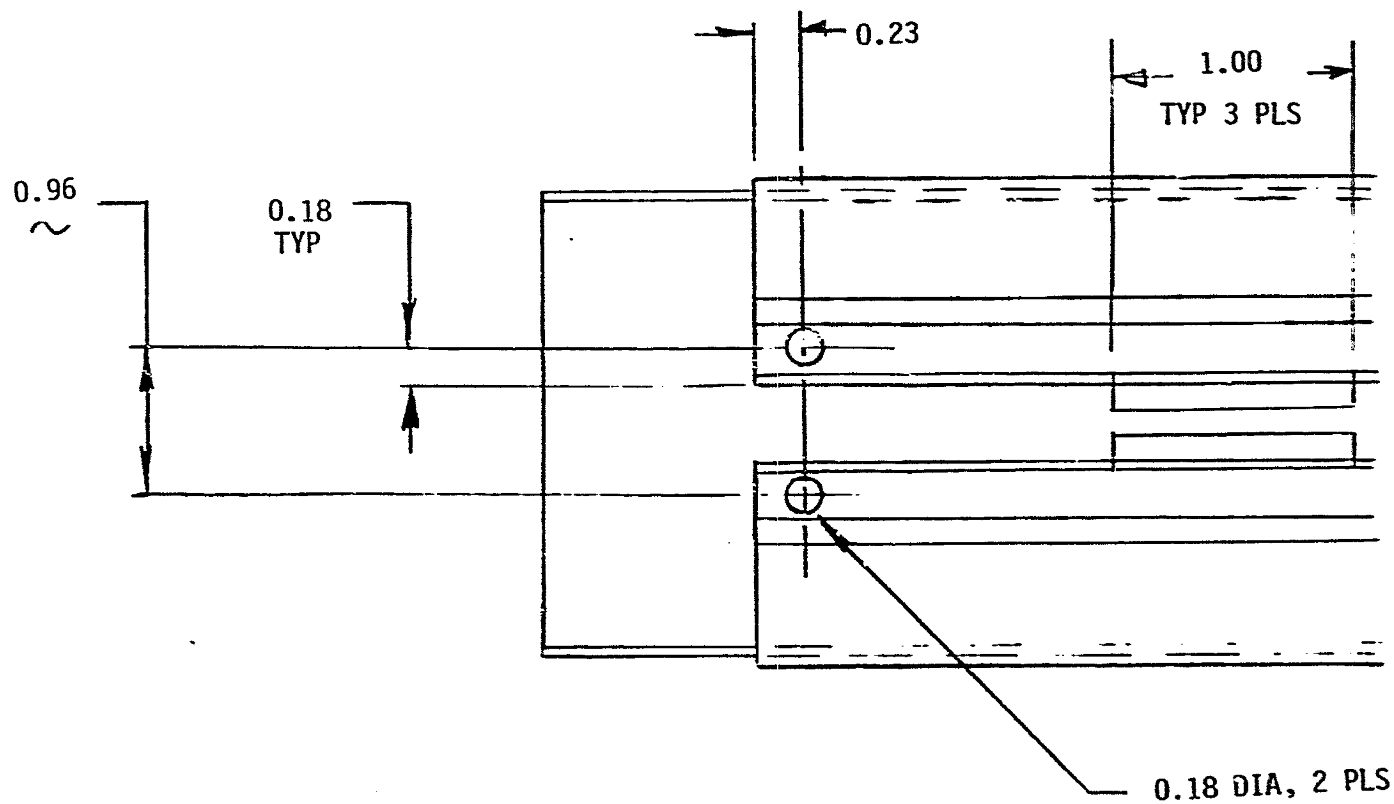


Figure 3-49. Support Channel Design Modifications (Drain Holes)

During the fabrication of the closure caps it became apparent that the wings would have to be slotted on both sides of each screw hole, as shown in Figure 3-50, to provide increased flexibility in the local areas where the wing is required to expand outward.

3.2.3.2 Model Final Assembly

The support channels were installed with 49.88 inches between centers in the horizontal direction. With this spacing the installation of the modules was difficult due to the frictional load of the compressed gaskets against the steel side walls of the support channel. An increase in channel spacing to 50.00 inches would reduce the force required to insert the modules between the channel walls.

At several screw locations it was noted that the expanding closure cap wing were not engaging the tabs in the support channel. A slight increase in the wing depth would probably correct this condition.

3.3 DEVELOPMENT OF CONCEPTUAL ALTERNATIVES

3.3.1 DEFINITION OF EVALUATION CRITERIA

The criteria to be used in the evaluation of the various existing or proposed residential array installations were formulated as the first step of the evaluation process which ultimately led to the selection of three array/module concepts as described in Section 3.4 of this report. These criteria, as identified in Table 3-15, encompass the gamut of technical, economic and institutional concerns associated with a residential photovoltaic array installation. The 39 criteria have been organized and grouped into seven broader categories as shown in the table. It was felt that such a grouping would provide a visualization of the relative strengths and weaknesses of the various concepts with respect to a given area of concern such as "Compatibility with Residential Construction," which is considered as being represented by five criterion.

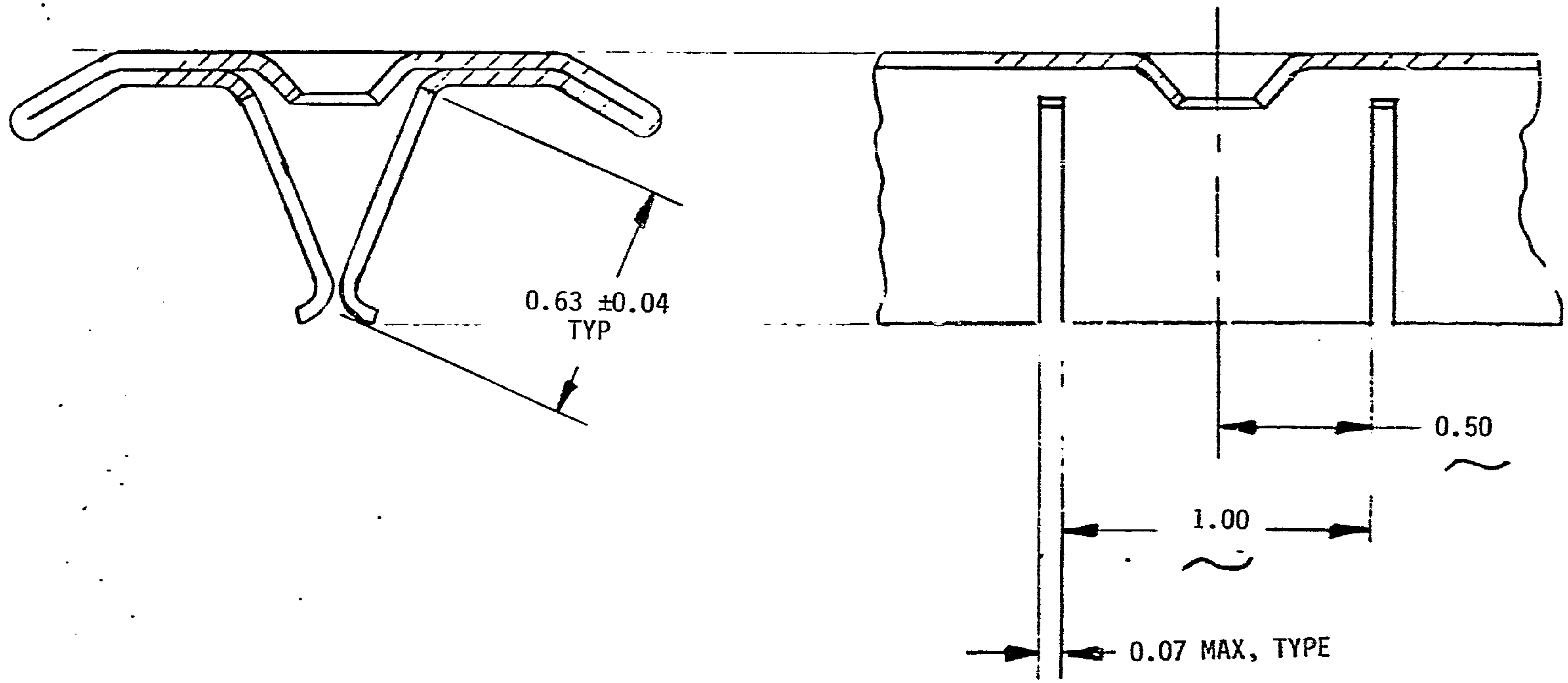


Figure 3-50. Closure Cap Design Modifications (Slotted Wings)

Table 3-15. Criteria for Residential Array Concepts Evaluation

A. Pre Installation Factors
- Module Factory Cost
- Ease of Storage, Shipping and Handling
- Product Maturity
- Shipping Weight per Unit Area
- Shipping Volume per Unit Area
- Shipping and Handling Durability

B. Compatibility with Residential Construction
- Compatible with Standard Construction Practice
- Standard Tools and Equipment
- Minimum Risk to Normal Building Function
- Structural Compatibility with Building
- Construction Trade Compatibility

C. Installation
- Need for additional or special weatherproofing
- Minimum Added Structure
- Electrical Connections per Unit Area
- Mechanical Attachments per Unit Area
- Ease of Handling
- Installation Handling and Durability
- Field Cabling Required
- Ease of Grounding

D. Maintenance and Warranty
- Maintenance Frequency
- Ease of Module Replacement
- Overlap of Warranty Responsibility
- Interference with Normal Building Maintenance
- Susceptible to Vandalism
- Safety
- Product Life

E. Operation
- Array Efficiency at NOC
- Operating DC Voltage Compatible with Existing Inverter Requirements
- Reliability
- Weatherability
- Safety

F. Potential for Code Compliance
- Potential to Meet UL 790 Class B (Fire)
- Potential to Meet National Electric Code Requirements
- Capability with Existing Building Codes

G. Acceptance
- Aesthetics
- Insurability
- Application Flexibility
- Builder/Architect Acceptance
- Homeowner/Community Acceptance

An explanation and amplification of each criterion is given below:

A. Pre-installation factors

1. Module factory cost
   Module factory cost is evaluated as the cost per rated watt at NOC for a baseline production rate.

2. Ease of storage, shipping and handling
   This criterion encompasses those modules characteristics that impact on storage, shipping, and handling functions, including:

   - The number of modules which can be stacked together as a unit for shipment, storage and handling

- The need and extent of packaging
- The need and extent for special precautions such as protection from the weather during storage
- The need for special equipment such as a fork lift truck

3. Product maturity
Product maturity relates to the status of product development and potential or capability for manufacture at the baseline production rate.

4. Shipping weight and volume per unit area
The areal shipping weight and volume describe the bulk packaging characteristics of the module, and when coupled with stackability, are the major factors influencing the cost for shipping and storage.

5. Shipping and handling durability
This criterion addresses the vulnerability of the module to damage or deterioration during pre-installation phases of shipping and handling, and reflects both the durability enhancement provided by any required packaging, and normal shipping and handling practice. Items considered in this category include:

   - Overall potential for damage to module
   - Potential for interconnect damage
   - Potential for cell breakage due to flexure of the substrate or superstrate

B. Compatibility with residential construction

1. Compatible with standard construction practice
The installation of some modules may require the development and implementation of methods of roof construction that are not currently considered as standard practice. Factors to be considered here include:

   - Module configuration impact on spacing of roof structural elements (e.g., rafters, purlins)
   - Array conflict with other roof features (e.g., vent pipe, chimney)
   - Need for tolerances tighter than standard carpentry practice
   - Need for roof modification (e.g., removal of plywood, reinforcement of standard rafters, addition of purlins, rafter crossbracing)
   - Need for non-standard flashing and sealants

2. Standard tools and equipment
The installation of some modules may require special tools or may require special material handling equipment (e.g., cranes, ladders, hoist, etc.)

3. Minimum risk to normal building function
Some modules may exhibit characteristics or involve installation features that adversely impact on the normal functions of the building, including:

- Module increases risk for rain leakage
- Module encourages nesting of squirrels, birds, vermin, or accumulation of debris

4. Module structural compatibility with supporting structure
Depending on the type of installation, some modules may be required to withstand structural loads imposed by wind, snow, and their own dead weight. In meeting this requirement, it may be necessary to provide additional structural support to the module. Modules must not reduce overall structural integrity of building.

5. Construction trades compatibility
Building construction particularly within a trade union context, is performed in accordance with a rigidly defined demarcation between job function. For example, electrical work is performed exclusively by electricians while roofing is performed only by members of roofers union. PV modules by their very nature appear to fall within the domain of electrician: however, their installation and maintenance might also involve other trades such as carpenters and roofers. This potential for multi-involvement of trades is not necessarily detrimental unless ambiguity of responsibility, or a conflict between construction trades, or a redundancy of manpower results.

C. Installation

1. Need for additional or special weatherproofing
Additional or special weatherproofing to protect either the module or the build- beneath it may be required for permanent protection; or for temporary protection during periods when installation is interrupted by weather or end-of-day.

2. Minimum added structure
Some module installations may require supporting structural elements which would not otherwise be required for the residence if it did not have a photovoltaic array. This criterion also applies to required increases in the size or quantity of standard residential structural elements which are dictated by the types of photovoltaic installation and/or the interaction of the array and the building. For example, roof mounted arrays (integral, direct, stand-off, rack) may require additional roof structure to meet any increase in loads caused by the presence of the modules, or to accommodate a separate module support structure.

3. Electrical connections per unit area
The cost and complexity of installation tends to increase with the number of electrical connections between modules, and is greater for the traditional J-box wiring connections than for modular quick-connect terminations.

4. Mechanical connections per unit area
The cost and complexity of installation tends to increase with the number and type of mechanical connections between adjacent modules, and between module and support structure. Simple accessible connections (e.g., nailing or stapling) are preferred over those which add to installation time.

5. Ease of handling (by one or two persons)
Module size and weight contribute to the ease of handling during installation. Most residential tasks are accomplished by one or two persons, each with a hand-to-hand comfortable grip span of 36 to 40 inches and an individual lifting capacity of 50 to 60 lbs. Modules with size and weight which exceed the physical limitation of two persons will generally require the use of special mechanical lifting or positioning equipment.

6. Installation handling durability
During installation, modules may be exposed to unevenly distributed loads, such as bending or flexure, arising from workmen standing on modules or from other typical manual handling practices. Modules designed to withstand or accommodate these handling loads will facilitate the installation without jeopardizing operational performance.

7. Field cabling required
Field installed cabling will be required on any photovoltaic array, but the extent of such wiring is a function of the specific module design and array layout. The placement of the field wiring within a sheltered environment can be expected to reduce the labor cost when compared to an equivalent installation which requires the electrician to work outdoors.

8. Ease of grounding
The JPL specifications defining the requirements for flat-panel terrestrial photovoltaic modules have historically included the requirement for grounding of exposed external conductive surfaces. A terminal or stud must be provided to serve as a common grounding point for exposed conductive surface. A grounding connection is not required for modules without exposed conductive surfaces. The need for grounding, which is not present on modules of the latter type, has an obvious negative impact on the field wiring cost and on the overall safety and reliability of the array.

D. Maintenance and Warranty

1. Maintenance frequency
Some modules, by the very nature of their design, increase the need for maintenance. Factors to be considered include:

- Dirt or debris accumulation, which is caused by module surface features, and which must be removed to prevent a performance reduction. For stand-off modules debris may also accumulate under the modules, thereby insulating the back face and resulting in higher cell temperatures and lower output.
- Susceptability of exposed parts to rust and corrosion.
- Wooden components requiring periodic painting.
- Gasketed joints requiring replacement for leak-free performance over the array design lifetime.

2. Ease of module replacement
This criterion reflects the difficulty, cost or time involved in the identification of failed modules and in the removal and replacement of these failed modules. Specific items which may be considered include:

- Accessibility of module. Can modules be walked on or is special equipment necessary to reach module?
- Can module removal and replacement be performed in the daytime?
- Can the module be removed from the array without disturbing adjacent modules?
- Is there a simple procedure for the location of failed modules?

3. Overlap of warranty responsibility
A module or array warranty, when offered, may be invalidated or compromised by the need to remove stand-off mounted modules when repair of the underlying roof is necessary. Similarly the warranty on a conventional asphalt shingle roof may be of little value if the surface is penetrated by the brackets required to support a stand-off array installation.

4. Interference with normal building maintenance
Normal building maintenance, such as roof repair, gutter cleaning, and painting around eaves, may become more difficult due to the presence of roof mounted arrays. Assessment of this category should reflect the degree of difficulty imposed on normal building maintenance.

5. Susceptibility to vandalism
The threat of vandalism to PV arrays will probably be proportional to the accessibility of the array, with the greatest threat to ground mounted arrays. Assessment of this category should account for both accessibility and vulnerability of modules to thrown objects. Annealed glass covered modules are more susceptible to damage from thrown objects than are tempered glass covered modules.

6. Safety
Safety refers to those module features which tend to increase the risk to personal safety or property during installation and maintenance, and include:

- Weight and size of modules to be lifted to point of installation at the same time
- Potential for accidental shock
- Restrictive installation procedure requiring awkward or unstable workmen positioning

7. Product life
Some modules may incorporate materials or design features that tend to limit product life. For example, the use of a polymeric outer cover should result in a useful product life which is less than a comparable glass-covered modules.

E. Operation

1. Array efficiency at NOC
The array efficiency at NOC is defined by the following ratio:

$$\frac{\text{Array Maximum Power Output}}{(\text{Gross Array Area, m}^2)\ (800)}$$

The array maximum power output (watts) is measured or referenced to Normal Operating Conditions (NOC) which reflect an ambient temperature of 20°C, a wind speed of 1 m/s and an insolation of 800 w/m^2.

2. Operating DC voltage compatible with existing inverter requirements
Available inverters have an input voltage range which must be maintained for satisfactory operation. The size and output of the module, and type and location of the electrical connectors should not constrain the array layout so that the resultant circuit does not meet this voltage requirement for typical residential roof sizes and aspect ratios.

3. Reliability
Per JPL module design and test specifications, module reliability is related to module circuit redundancy features, which may include, but are not limited to the following:

- Redundant interconnections between solar cells, including redundant cell attachment points
- Series/parallel interconnection of cells within the module
- Integral bypass diodes within each module

The decision to incorporate redundancy features shall be based on the expected percent improvement in lifetime/yield and replacement cost as contrasted with the percent increase in module cost/watt. Series/parallel circuit arrangements, when used, shall be designed so that "hot-spot" cell heating does not lead to further module degradation under worst-case-single-cell-failure conditions defined as follows:

- The module output is short-circuited
- A single representative solar cell is open-circuited to represent a single cell failure
- The incident irradiance is 100 mW/cm^2, AM1.5
- The thermal boundary conditions are adjusted so that the equilibrium solar cell temperature outside of the hot-spot region is equal to NOCT +20°C

4. Weatherability
Weatherability refers to the module's ability to withstand the deleterious effects of the environment while maintaining the as-installed appearance and performance characteristics. For instance, plastic cover materials generally exhibit a photo-degration of optical transmission which is not present with a glass cover. Other features that are related to weatherability include the ability of the module surface to shed dust and dirt, as well as the potential for mildew, corrosion, rot, and decay.

5. Safety
Under this category safety refers to the degree of hazard imposed by the operation of the array, and may include:

- Increased fire hazard to roof
- The generation of high voltage, particularly if this occurs near the eave of the roof

F. Potential for code compliance

The three criterion under this category address the potential for module code compliance which can be estimated on the basis of existing requirements for residential construction and electrical elements which are functionally similar to the module. The more widely recognized building codes will be used in this evaluation and include:

1. UL 790 (Fire)

2. National Electric Code (NEC)

3. Regional building codes

- Building Officials and Code Administrators (BOCA) Basic Building Code
- Southern Building Code Congress (SBCC) Standard Building Code
- International Conference of Building Officials (ICBO) Uniform Building Code

G. Acceptance

1. Aesthetics
The appearance of a house is very important to the buyer. The house market tends to be conservative, reflecting the tastes of the average buyer and his concern for resale. The PV module/array should conform to this conservative aesthetic, blending in with the surroundings and not drawing attention. Module/ array characteristics that impact on aesthetics include:

- Size
- Shape
- Color
- Texture
- Pattern

2. Insurability
While insurance companies do not currently have provisions covering the application of photovoltaic arrays to residential dwellings, the question of insurability is of concern since it might ultimately have a significant impact on the acceptance of the technology for privately-owned residential installations. At present it can be assumed that the array would be treated as part of the dwelling, and its value incorporated in the total replacement value upon which the insurance premium is based. The durability of the module will probably be the most important factor in the establishment of insurance rates, and includes resistance to damage from natural causes, accidents, and vandalism. It is likely that array installations which are divorced from the normal building functional elements will be looked upon with favor by the insurance underwriters.

3. Application flexibility
This criterion addresses the ability of a given module/array concept to be adapted to a variety of residential architectural styles. For example, a rack-mounted array can be integrated well with a flat-roof dwelling, but can not be easily adapted to a sloping gable roof. On the other hand, a direct-mounted, overlapping shingle module is ideally suited for such a sloping roof and loses many of the advantages when considered for installation on a flat-roof building.

4. Builder/architect acceptance
Acceptance by the builder/architect community includes many factors which are enumerated elsewhere in this list but its inclusion within this category is intended to emphasize the importance of this aspect of the array design. Factors such as compatibility with standard construction practice, aesthetics, potential for code compliance, and construction trades compatibility contribute to the acceptance of a given concept by the builder/architect.

5. Homeowner/community acceptance
This criteria also encompasses many of the items previously discussed, but these are not necessarily the same concerns which could contribute to builder/architect acceptance. It is expected that the lay person, who is a potential owner of a photovoltaic-powered house, would consider factors such as cost, product maturity, maintenance frequency, reliability, insurability, and aesthetics before making the decision to purchase.

3.3.2 DESCRIPTION OF EXISTING OR PROPOSED RESIDENTIAL ARRAY DESIGNS

The four array designs which were developed as part of the effort under Sandia Contract 13-8779 are considered to represent the existing state-of-the-technology relative to array designs for residential installations. For each of these point design studies, a detailed system design has been completed and architectural and engineering drawings have been developed to permit the construction of the photovoltaic installation. Actual array installations, which are similar to three of these four point designs, have been constructed at the Northeast and Southwest Residential Experiment Stations. Table 3-16 summarizes the pertinent characteristics of each of these four arrays. Further details are contained in Document Numbers SAND 79-7056, SAND 80-7148, SAND 80-7170, and SAND 80-7171, for each of these four systems, respectively.

Thirteen prototype residential array systems, which are also representative of the existing state-of-the-technology, are currently under test at the two Residential Experiment Stations (RES). The characteristics of these array systems are summarized in Tables 3-17 and 3-18 for the Northeast and Southwest installations, respectively. An aerial view of the NE RES, showing the five prototype arrays, is included as Figure 3-51.

Table 3-16. Summary of Existing or Proposed Residential Array Systems

Application Description	Module Supplier	Module Development Status	Module Mounting Approach	Brief Module Description	Array Electrical Circuit Configuration
1) First Preferred Design Study [3]	GE	BIV [1]	Direct	Overlapping hexagon shingle, 19 series-connected, 4 inch diameter cells	One branch circuit consisting of 25 series x 19 parallel modules. No bypass diodes.
2) Second Preferred Design Study	ARCO-Solar	BIV+ [2]	Direct	Batten/metal roofing panel, 100mm sq. cells, 16 series by 7 parallel connected cells	Four branch circuits each consisting of 28 series-connected modules. One bypass diode per module
3) Third Preferred Design Study	Solarex	BIV	Stand-off	Intermediate BIV module, 95mm square semi-crystalline cells, 72 cells connected 36 series by 2 parallel, 36 bypass diodes	Ten branch circuits each consisting of ten series-connected modules. 36 bypass diodes per module
4) Fourth Preferred Design Study	GE	New	Direct	Overlapping rectangular shingle, 95mm square cells, 96 cells for full-size module, 48 cells for half-size module	One branch circuit consisting of 8 series x 7 parallel full-size modules

(1) Module developed under the Block IV procurement

(2) Modification of a Block IV module design

(3) Represent detailed photovoltaic system designs performed under Sandia Contract No. 13-8779

Table 3-17. Features of the Solar Arrays on the NE RES Prototype Systems

System Contractor	Module Supplier	Array Area (m^2)	Array Peak Power (kWp)*	Mounting Method
General Electric	General Electric	73.4	6.8	Direct
MIT LL	Solarex	87.4	7.0	Standoff
Solarex	Solarex	71.5	5.3	Standoff
TriSolarCorp	Applied Solar	47.8	4.8	Integral
Westinghouse	ARCO Solar	74.9	5.2	Integral

*at 100 mW/cm^2 and 25°C

Table 3-18. Features of the Solar Arrays on the SW RES Prototype Systems

System Contractor	Module Supplier	Array Area (m^2)	Array Peak Power (kWp)*	Mounting Method
ARCO Solar	ARCO Solar Batten/Seam	87.8	7.4	Direct
ARTU	ARCO 16-2300	53.5	4.9	Standoff
BDM	Motorola	54.0	4.4	Standoff
General Electric	General Electric	74.3	6.7	Direct
Solarex	Solarex	67.8	4.6	Standoff
TEA	Motorola	49.4	4.2	Rack
TriSolarCorp	ASEC	58.0	5.2	Integral
Westinghouse	ARCO 16-2300	70.8	5.5	Integral

*at 100 mW/cm^2 and 25°C

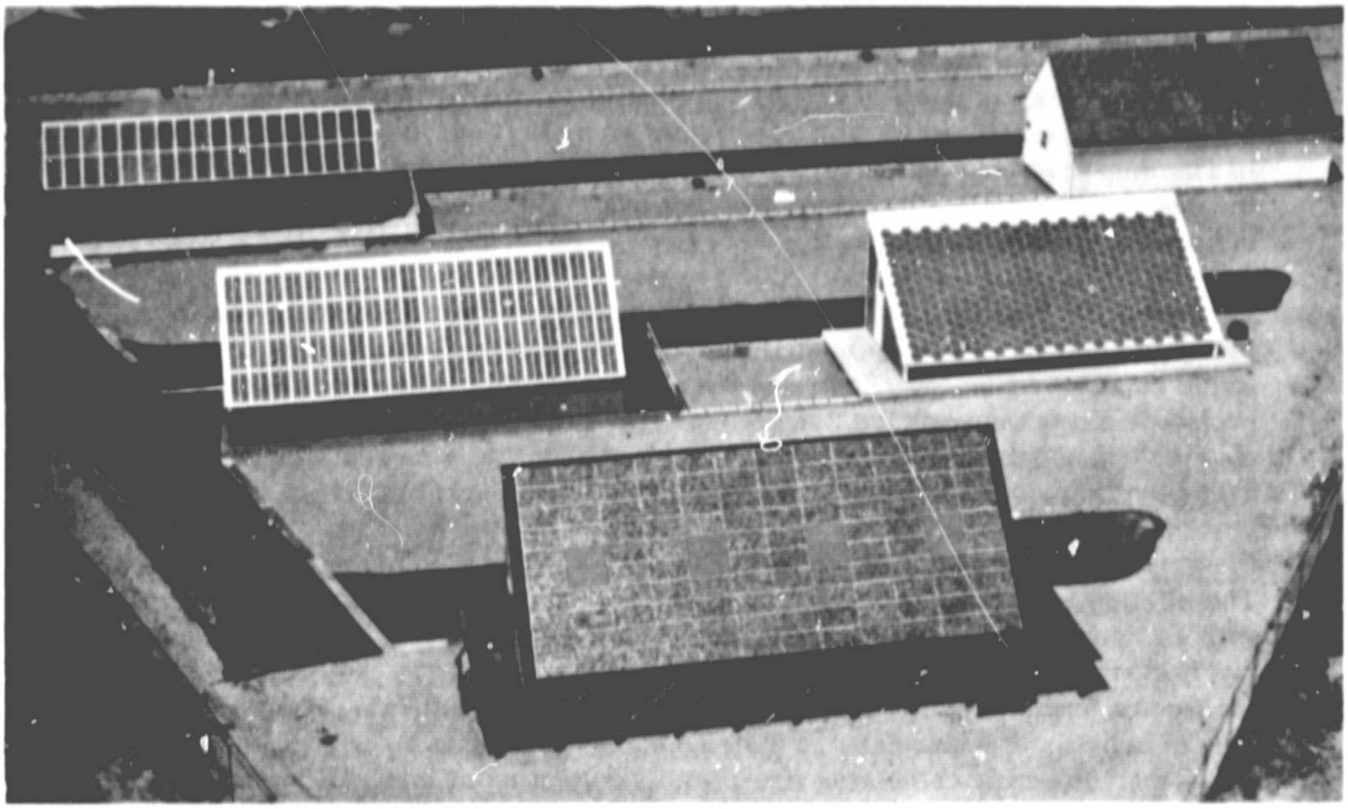


Figure 3-51. Aerial View of the NE RES

3.3.3 LESSONS LEARNED FROM EXISTING APPROACHES

A subjective evaluation of the existing or proposed residential array installations with respect to the criteria discussed in Section 3.3.1 has served to highlight several areas of concern which could have a potentially fatal impact on the acceptance or satisfactory long term performance of these arrays in a residential application. In particular, the following concerns are worthy of further consideration in the formulation of the three module/array design approaches to be evaluated as part of the Task 1 activity:

1. Metal substrates lead to reliability and safety problems. Many instances of short-to-substrate failures with associated arcing have been experienced in modules with metal substrates.

2. Polymeric outer covers have questionable long-term weatherability and fire resistance. There is a considerable uncertainty regarding the ability of polymeric outer covers to adequately protect the encapsulated cell assembly and transmit the incident illumination without significant degradation over the 20 year design lifetime of residential modules. In addition, it is doubtful that a plastic film-covered module could successfully pass the tests specified in UL790, "Tests for Fire Resistance of Roof-Covering Materials."

3. Small module size leads to higher installation cost. The installation cost of a residential array is roughly proportional to the number of modules which must be separately attached and wired to complete the array installation. In this regard it is also important to consider the planar size and weight limitations associated with the convenient handling by one or two persons. This aspect of the module size consideration is discussed in Section 3.3.4.

4. Large module size leads to high replacement cost. The replacement cost of a broken or defective module is approximately proportional to the area of the unit which must be replaced. The replacement of a single broken module on a NE RES prototype array represented 2.7 percent of the total installed array area. It is obvious that the breakage of an installed module of this size represents a significant penalty with respect to the life-cycle cost of the system.

5. Integrally mounted arrays have increased risk of water leaks and spread of fire. The elimination of the roof sheathing and under-layment felt, which is implicit with an integral array installation, leads to an increased risk of water leaks since two back-up waterproofing systems have been removed from the roof. The availability and prompt replacement of a broken integral module also represents the risk of significant water damage that the homeowner or insuror may not be willing to accept. Recently completed fire resistance testing of integrally mounted modules has shown an increased vulnerability to the burning brand test exposure when compared to a direct mounted module installation. The presence of the roof sheathing represents an additional fire resistance barrier.

6. Exposed conductive elements require grounding with associated cost. In conformance with currently accepted practice, all exposed conductive elements of the modules and array must be electrical bonded and grounded for personnel safety. The field installed wiring associated with this grounding network can constitute a significant faction of the total installation cost of the array.

7. Safety is a critical design concern. Personnel safety is perhaps the most important concern facing the module/array designer and system installer. The recently published preliminary module construction requirements (JPL Document 5101-164) defines many of the design features required to produce the necessary level of product safety for the module. However, to-date little attention has been given to the over-all safety aspects of the installed solar array. Electrical safety during both the installation and operational periods is important since the generated voltage levels at the dc bus will typically exceed 200 volts above ground potential. The use of aluminum ladders during module installation is not a wise practice. It was also noted that several of the existing array installations are configured to have high voltage levels along the eave within easy access from the ground level. Excessive leakage current to ground, which has been experienced on at least one prototype array installation, could lead to an electrical safety hazard.

3.3.4 MODULE SIZE CONSIDERATIONS

The selection of an appropriate module size is one of the basic issues which must be addressed in the formulation of candidate residential module designs. This is a complex question since its resolution involves the consideration of numerous factors such as: (1) module production cost; (2) array installation cost; (3) cost of defective module removal and replacement; (4) residential roof size constraints; (5) individual module open-circuit voltage limitations for electrical safety; (6) input voltage constraints for inverters which operate into a residential 240-volt single phase ac line; (7) the structural constraints imposed on the installed modules by wind, snow, and dead weight loads; (8) the structural implications associated with handling and shipping loads; (9) the building structural modifications required to accommodate the loading due to the photovoltaic array; and (10) the ability of one or two persons to handle and install the module without the use of mechanical lifting or positioning devices.

The physical size of the module has a significant impact on its production cost. Many of the costs associated with module production are relatively independent of the module size (e.g., the connectors, wiring and illumination testing costs), so that with increased size, these factors become a smaller fraction of the total cost. On the other hand, increased module size increases the relative cost of handling the module within the plant. The cost of the vacuum lamination equipment required to encapsulate a module should increase at a rate which is more than proportional to the size. The cost associated with the in-process breakage of a glass coverplate can have a significant impact on the production costs if this loss occurs after lamination.

To a certain degree this argument also applies to the array installation costs. As the module size increases, fewer units must be installed to meet a specified peak power output and the installation cost should decrease. However, the physical size and weight of the module play a more significant role in this evaluation since during installation the mechanics are required to lift and position the modules on a sloping roof. Figure 3-52 illustrates the probable ways that one person would carry a photovoltaic module of various sizes. In all cases, the glass cover plate was assumed to be 5 mm (0.188 inches) thick. It is apparent

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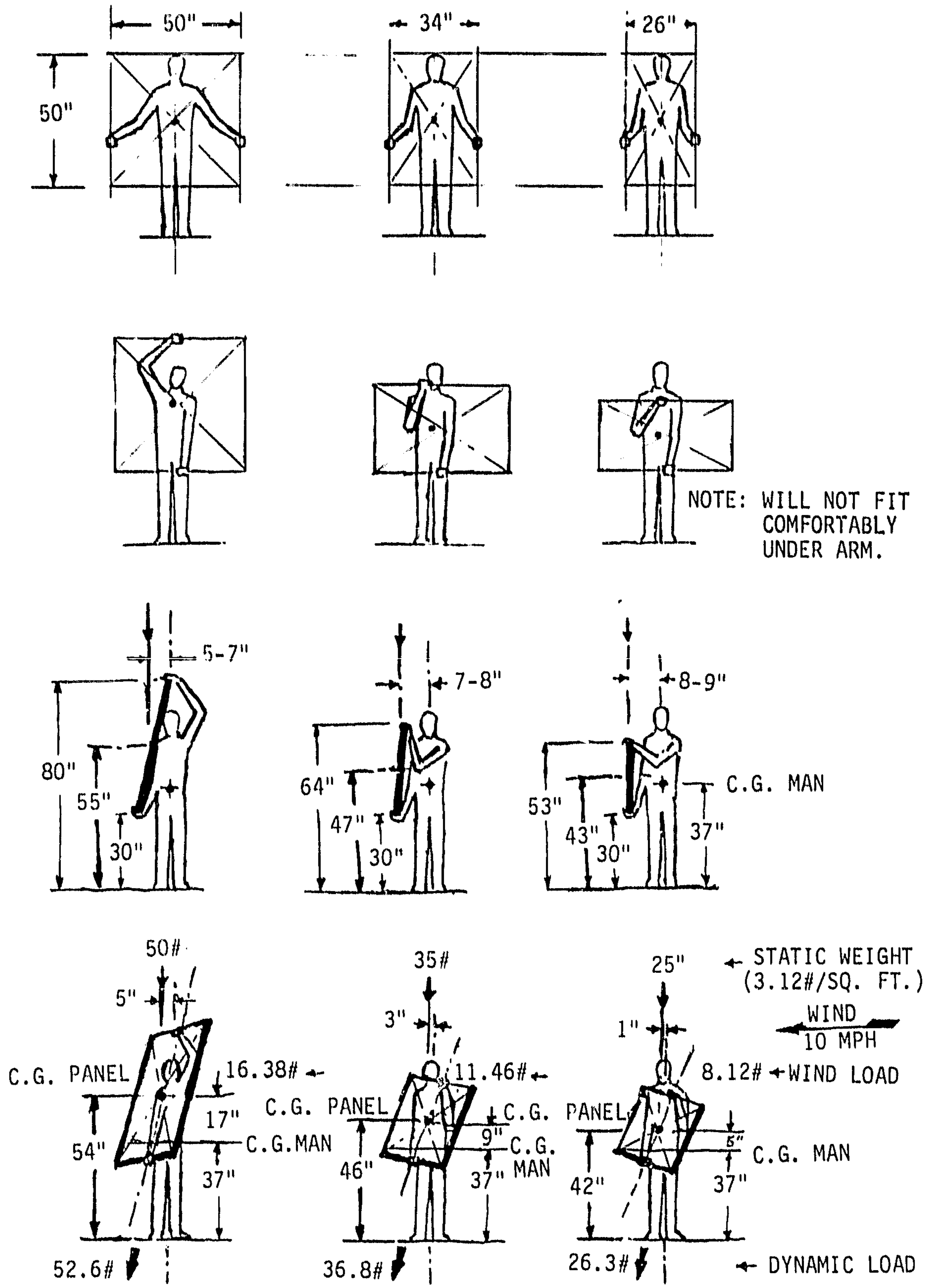

Figure 3-52. Probable One-Man Carrying and Handling Modes
for Photovoltaic Modules of Various Sizes

that a basic module size of 2 by 4 feet represents a practical upper limit for handling by one person. It is probable that the lifting of the modules from the ground level to the roof would be accomplished with a mechanical lift, but it is equally probable that one or two men would be required to remove the modules from the lift for positioning and installation on the roof.

The size of a simply supported glass superstrate module was investigated from the standpoint of installed structural loading using the nonlinear techniques reported by Moore in JPL Document No. 5101-148. The results summarized in Table 3-19 were obtained for a combined load consisting of the module dead weight, a 70 mph wind and a 52 lb/ft^2 snow load. This analysis shows that a 2 by 4 foot annealed glass plate size is the upper limit allowable by a worst case combination of operational loads. A plate thickness of 0.188 inches (5 mm) was selected for this analysis since it represents the maximum thickness available for high transmission, low-iron, soda-lime glass. The areal density of this glass plate thickness will yield a total array installed weight which is compatible with typical residential construction. The use of a significantly thicker glass superstrate, which constitutes the major fraction of the array installed weight, will probably require a structural analysis with possible modifications to what would normally be specified for the residence without a photovoltaic installation. The use of a thermally-tempered glass superstrate would increase the breakage stress and permit a larger module size under these loading conditions, but careful consideration should be given to the coverplate deflections under both installed and handling loads to determine if these deflections will fracture the solar cells within the laminate.

The interaction between module size and internal module electrical circuit design was investigated with the results as summarized in Table 3-20. This analysis includes basic module sizes which range from 2 by 4 feet to 4 by 8 feet. In all cases, the use of 100 mm square solar cells was assumed. A maximum module open-circuit voltage limitation of 30 volts at 100 mW/cm^2 insolation and -20°C cell temperature was imposed on the module circuit design. This establishes 40 series-connected cells as the maximum within a module. Bypass diodes were then assigned to each module electrical configuration based upon the upper limit of one diode across 12 series-connected cells. A cell short-circuit current of 3 amperes was used in conjunction with the number of parallel-connected cells within the module to determine the required diode forward current carrying capacity.

Table 3-19. Results of the Structural Analysis for Various Sizes of 5 mm Thick Annealed Glass Plates

GLASS SIZE (FT x FT)	PREDICTED STRESS / BREAKAGE STRESS	CONCLUSIONS
4 x 8	> 1	Unacceptable
4 x 4	~ 1	Marginal
2 x 4	< 1	Acceptable
2 x 2	< 1	Acceptable
1 x 2	< 1	Acceptable
1 x 1	< 1	Acceptable

The number of bypass diodes will vary from one to three depending on the cell electrical interconnection matrix selected for a particular module size. Required diode current carrying capacities vary from a low of 6 amperes to a high of 72 amperes. It should be noted that for all the modules and electrical arrangments considered, except one electrical configuration, in each of the 4 by 6 and 4 by 8 foot modules, the maximum required diode current carrying capacity does not exceed 36 amperes.

A further investigation of the basic 2 by 4 foot module size was performed to assess the array design flexibility which is possible for the set of array physical and electrical constraints listed below:

- 2 by 4 foot nominal module size
- 2 to 10 kW array peak power rating
- 12 to 22 foot roof slant height ("H" dimension in Figure 3-53)
- 0.50 to 1.50 roof aspect ratio ("H/W" from Figure 3-53)
- 160 to 240 Vdc inverter input voltage

Table 3-20. Interaction of Module Size and Electrical Circuit Design

MODULE SIZE (FTxFT)	MODULE AREA(FT^2)	NO. OF CELLS	MAX. MODULE POWER @ 100 MW/CM^2 AND 25°C (WATTS)	MODULE CELL ELECTRICAL MATRIX*	MODULE OPEN CIRCUIT VOLTAGE (V)	REQUIRED NO. OF BYPASS DIODES	REQUIRED DIODE CURRENT CARRYING CAPACITY (AMPS)
2 x 4	8	72 (6x12)	97.2	$36_S \times 2_P$ (2 Config)	27	3	6
			97.2	$24_S \times 3_P$ (2 Config)	18	2	9
			97.2	$18_S \times 4_P$	13.5	2	12
			97.2	$12_S \times 6_P$	9	1	18
2 x 5	10	90 (6x15)	121.5	$30_S \times 3_P$ (2 Config)	22.5	3	9
			121.5	$18_S \times 3_P$	13.5	2	15
			121.5	$15_S \times 6_P$	12.75	2	18
3 x 4	12	108 (9x12)	145.8	$36_S \times 3_P$ (2 Config)	27	3	9
			145.8	$27_S \times 4_P$ (2 Config)	20.25	3	12
			145.8	$18_S \times 6_P$	13.5	2	18
			145.8	$12_S \times 9_P$ (2 Config)	9	1	27

* S = Series Cells
P = Parallel Cells

Table 3-20. Interaction of Module Size and Electrical Circuit Design (Cont'd)

MODULE SIZE (FTxFT)	MODULE AREA(FT^2)	NO. OF CELLS	MAX. MODULE POWER @ 100 MW/CM^2 AND 25°C (WATTS)	MODULE CELL ELECTRICAL MATRIX	MODULE OPEN CIRCUIT VOLTAGE (V)	REQUIRED NO. OF BYPASS DIODES	REQUIRED DIODE CURRENT CARRYING CAPACITY (AMPS)
3 x 5	15	135 (9x15)	182.3	$15_S \times 9_P$	12.75	2	27
3 x 6	18	162 (9x18)	218.7	$27_S \times 6_P$	20.25	3	18
				$18_S \times 9_P$	13.5	2	27
2.66 x 4	10.64	96 (8x12)	129.3	$32_S \times 3_P$	24	3	9
			129.3	$24_S \times 4_P$ (2 Config)	18	2	12
			129.3	$16_S \times 6_P$	12	2	18
			129.3	$12_S \times 8_P$	9	1	24
2.66 x 5	13.3	120 (8x15)	161.6	$30_S \times 4_P$	22.5	3	12
			161.6	$24_S \times 5_P$	18	2	15
			161.6	$15_S \times 8_P$	12.75	2	24
2.66 x 6	15.96	144 (8x18)	193.9	$24_S \times 6_P$	18	2	18
			193.9	$18_S \times 8_P$	13.5	2	24

Table 3-20. Interaction of Module Size and Electrical Circuit Design (Cont'd)

MODULE SIZE (FTxFT)	MODULE AREA(FT^2)	NO. OF CELLS	MAX. MODULE POWER @ 100 MW/CM^2 AND 25°C (WATTS)	MODULE CELL ELECTRICAL MATRIX	MODULE OPEN CIRCUIT VOLTAGE (V)	REQUIRED NO. OF BYPASS DIODES	REQUIRED DIODE CURRENT CARRYING CAPACITY (AMPS)
4 x 4	16	144 (12x12)	194.4	$36_S \times 4_P$	27	3	12
			194.4	$24_S \times 6_P$	18	2	18
			194.4	$12_S \times 12_P$	9	1	36
4 x 6	24	216 (12x18)	291.6	$36_S \times 6_P$ (2 Config)	27	3	18
			291.6	$24_S \times 9_P$	18	2	27
			291.6	$18_S \times 12_S$	13.5	2	36
			291.6	$12_S \times 18_P$	9	1	54
4 x 8	32	288 (12x24)	388.8	$36_S \times 8_P$	27	3	24
			388.8	$24_S \times 12_P$ (2 Config)	18	2	36
			388.8	$12_S \times 24_P$	9	1	72

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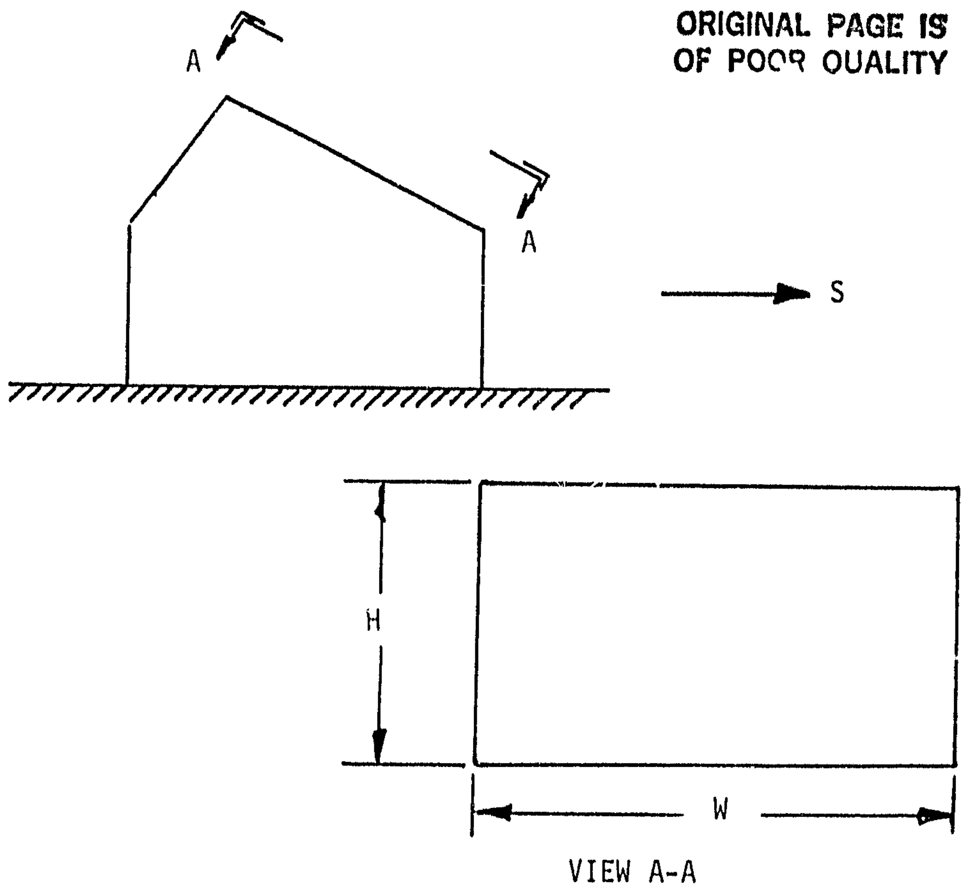

Figure 3-53. South Facing Roof Dimensions

The array peak power rating was limited to the range of 2 to 10 kW to be consistent with a typical residential application. A roof slant height dimension, as measured from the eave to the ridge, was constrained to be in the range of 12 to 22 feet to assure compatibility with typical single family residence building envelopes. Similarly, the roof aspect ratio, which is defined here as H/W, was restricted to be within the limits of 0.50 to 1.50.

When these roof geometry constraints are coupled with the inverter input voltage requirements and the module electrical circuit configuration within the 2 by 4 foot (0.61 x 1.22m) module, it is possible to formulate a matrix of possible roof layouts which simultaneously meet all constraints.

Available inverters require solar array output voltages which are at a nominal 200 Vdc level. In particular, the Abacus Sunverter Model No. 763-4-200 excepts a dc input voltage within the range of 160 to 240 Vdc. The calculated integral distribution of the solar cell maximum power point voltage for four site locations is presented in Figure 3-54 for a direct-mounted array installation. Hourly meteorological and insolation data from SOLMET TMY tapes was used with appropriate module thermal and electrical performance models to obtain the corresponding maximum power point output power and voltage. These voltage distribution curves show that the actual operating voltage range for the installed array is above the value of V_{no} at the Nominal Operating Conditions (NOC) as indicated on Figure 3-54. The allowable inverter input voltage range has been identified at the top of this figure for four specific values for the number of series-connected solar cells. Two specific module electrical design configurations have been considered as possible implementation approaches, viz., a 36 series by 2 parallel circuit and a 12 series by 6 parallel circuit. Each of these array series configurations, which is identified by the number of series-connected modules of each type, will yield an operating maximum power voltage distribution which is generally compatible with the inverter input voltage requirements for each of the site locations considered. However, it should be emphasized that the fraction of the potential maximum power power point energy which is converted to ac will differ slightly for a given array series configuration when sited at the extremes of the climates represented by the locations considered. For example, a direct-mounted array consisting of 396 series solar cells (11 series-connected modules with 36 series cells each or 33 series-connected modules with 12 series cells each) will fail to convert a larger fraction of the available energy when located in Phoenix than this same configuration which is sited in Boston. Conversely, an array of 504 series cells is a better choice for a Phoenix location but will give somewhat lower, but satisfactory, performance in Boston.

When these electrical circuit constraints are coupled with the roof geometric considerations described earlier, it is possible to identify only a relatively small number of module arrangements on the roof which meet all mechanical and electrical requirements. Figure 3-55 depicts these possible arrangements for a module configured with 36 series cells while Figure 3-56 applies for the 12 series cells per module case. The roof sizes and array peak output rating is given for each of these possible configurations. The electrical circuit layout on the roof which gives the minimum value of array open-circuit voltage (at 100 mW/cm^2 and -20°C) along the eave of the roof has been determined and the corresponding value for this voltage

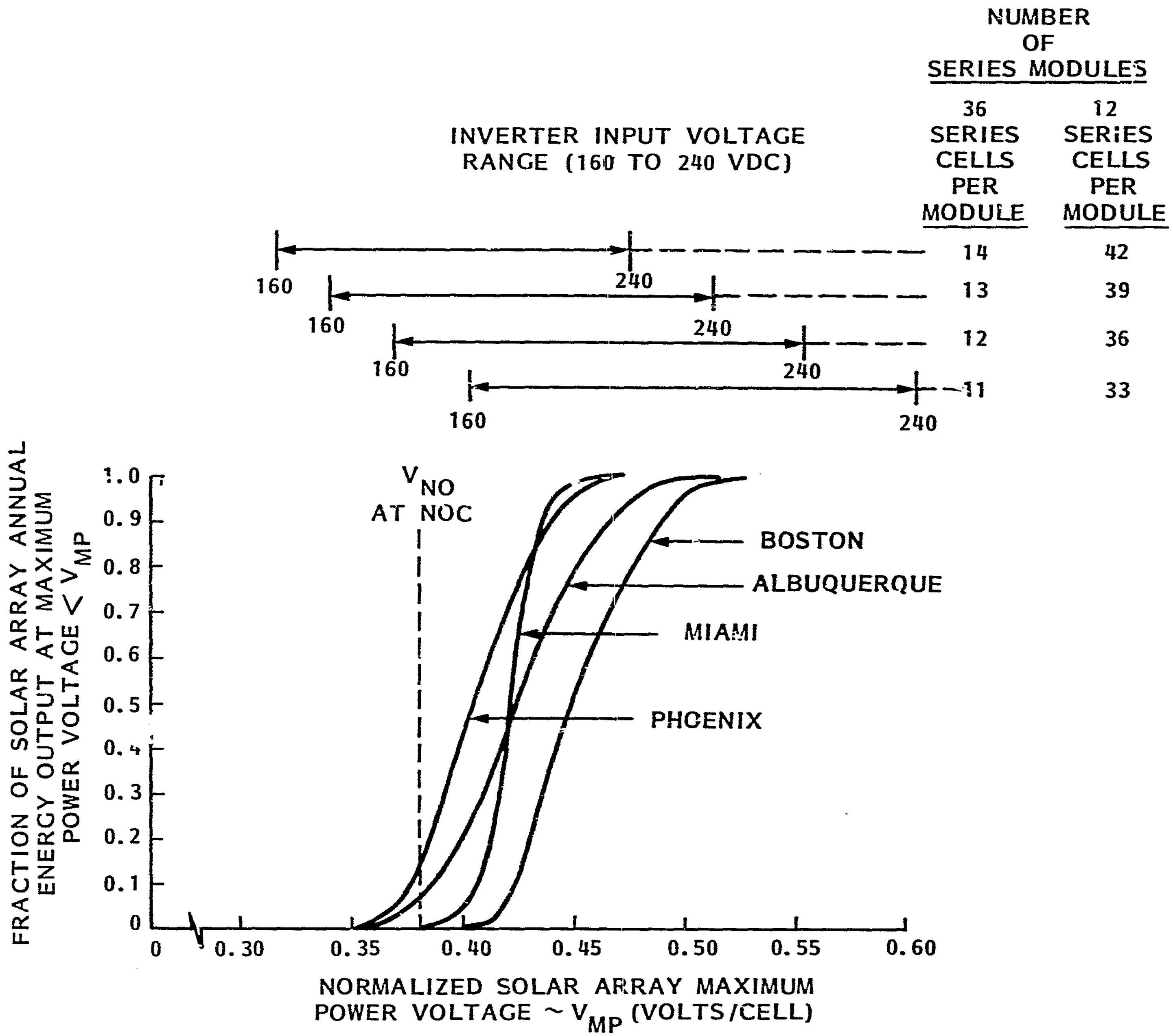

Figure 3-54. Integral Distribution of Solar Cell Maximum Power Point Voltage for a Direct-Mounted Installation at Four Site Locations

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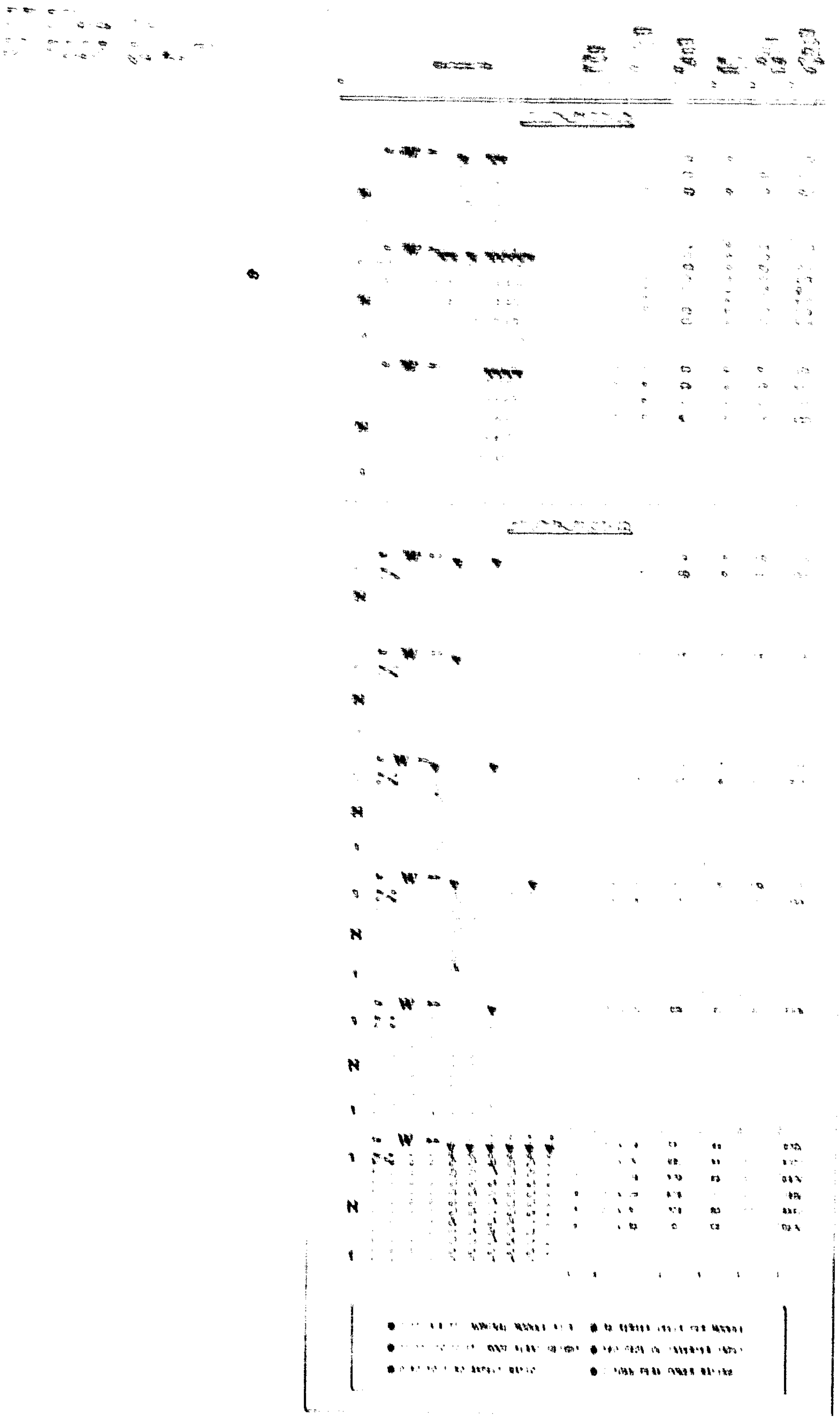
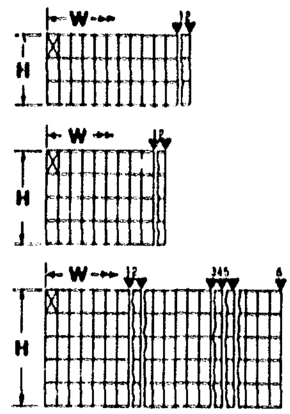


Figure 3-55. Possible Arrangements for a Residential Array with 36 Series Cells per Module

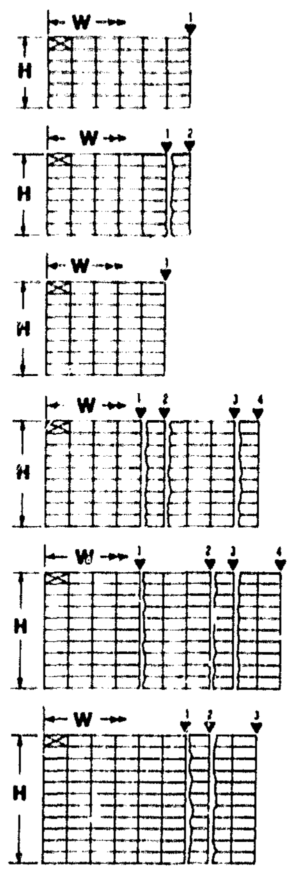
— CONFIGURATION —

— VERTICAL ORIENTATION —



ARRAY CONFIG. CHOICE	ARRAY SIZE (H-FT.) x (W-FT.)	ARRAY AREA REQ (SQ FT.)	NO OF MODULES	OPEN CIRCUIT VOLTAGE AT EAVE	ARRAY PEAK POWER RATING (W)
1	12 x 22	264	33	99	3210
2	12 x 24	288	36	108	3500
1	16 x 18	288	36	81	3500
2	16 x 20	320	90	90	3890
1	20 x 14	280	35	63	3400
2	20 x 16	320	40	72	3890
3	20 x 28	560	70	126	6800
4	20 x 30	600	75	135	7290
5	20 x 32	640	80	144	7780
6	20 x 40	800	100	180	9720

— HORIZONTAL ORIENTATION —



ARRAY CONFIG. CHOICE	ARRAY SIZE (H-FT.) x (W-FT.)	ARRAY AREA REQ (SQ FT.)	NO OF MODULES	OPEN CIRCUIT VOLTAGE AT EAVE	ARRAY PEAK POWER RATING (W)
1	12 x 24	288	36	54	3500
1	14 x 20	280	36	45	3400
2	14 x 24	336	42	54	4080
1	16 x 20	320	40	45	3890
1	18 x 16	288	36	36	3500
2	18 x 20	360	45	45	4370
3	18 x 32	576	72	72	7000
4	18 x 36	648	81	81	7870
1	20 x 16	320	40	36	3890
2	20 x 28	560	70	63	6800
3	20 x 32	640	80	72	7780
4	20 x 40	800	100	90	9720
1	22 x 24	528	66	54	6420
2	22 x 28	616	77	63	7480
3	22 x 36	792	99	81	9620

- 2 FT. x 4 FT. NOMINAL MODULE SIZE
- 12 FT. TO 22 FT. ROOF SLANT HEIGHT
- 0.50 TO 1.50 ASPECT RATIO
- 12 SERIES CELLS PER MODULE
- 160-240V DC INVERTER INPUT
- 2-10KW PEAK POWER RATING

Figure 3-56. Possible Arrangements for a Residential Array with 12 Series Cell per Module has been tabulated in these figures. Each 36 series cell module is expected to have an open-circuit voltage of 27 Vdc under these conditions while the 12 series cell option will reduce this voltage to 9 Vdc.

3.4 SYNTHESIS OF THREE DESIGN CONCEPTS

3.4.1 CANDIDATE MODULE DESIGN DESCRIPTIONS

The evaluation of the existing and proposed residential array designs, as discussed in Section 3.3, led to the formulation of three candidates module/array designs which were felt to be representative of generically different approaches. These candidate designs encompass the three mounting methods that have been widely used for residential installations, viz., integral, direct and stand-off. A common electrical circuit configuration was used for each design concept to eliminate this variable from consideration in the comparative evaluation.

3.4.1.1 Concept No. 1 - Direct-Mounted, Overlapping Shingle

The direct-mounted, overlapping shingle module configuration shown in Figure 3-57 was identified as the first concept to be considered in this evaluation. This shingle module assembly consists of the lamination of the encapsulated cell subassembly to the rear cover and to the substrate form core and outer skin. A double-backed adhesive bonding strip is used as shown to provide the sealant during module installation to prevent the wind uplift forces from separating the installed shingle layers. Mead Sunstorm board, which a 2.0 mm thick weather-resistant solid fiberboard material, is proposed as the rear cover of the module. This material is of a laminated construction with the core composed of highly sized, reclaimed kraft fibers. All glue lines are bonded with waterproof PVA adhesive. Both outer facings of Sunstorm board are white-wet strength beached virgin kraft lining paper. This liner has a mold inhibitor added to reduce the possibility of mildew in exterior applications. Also, a clay coating is applied to facilitate high quality silk screen printing and various modes of paint application. The outer facings are secured to the core with a film of polyethylene. This film serves as a barrier, retarding water and moisture absorption, while giving added dimensional stability to the overall product.

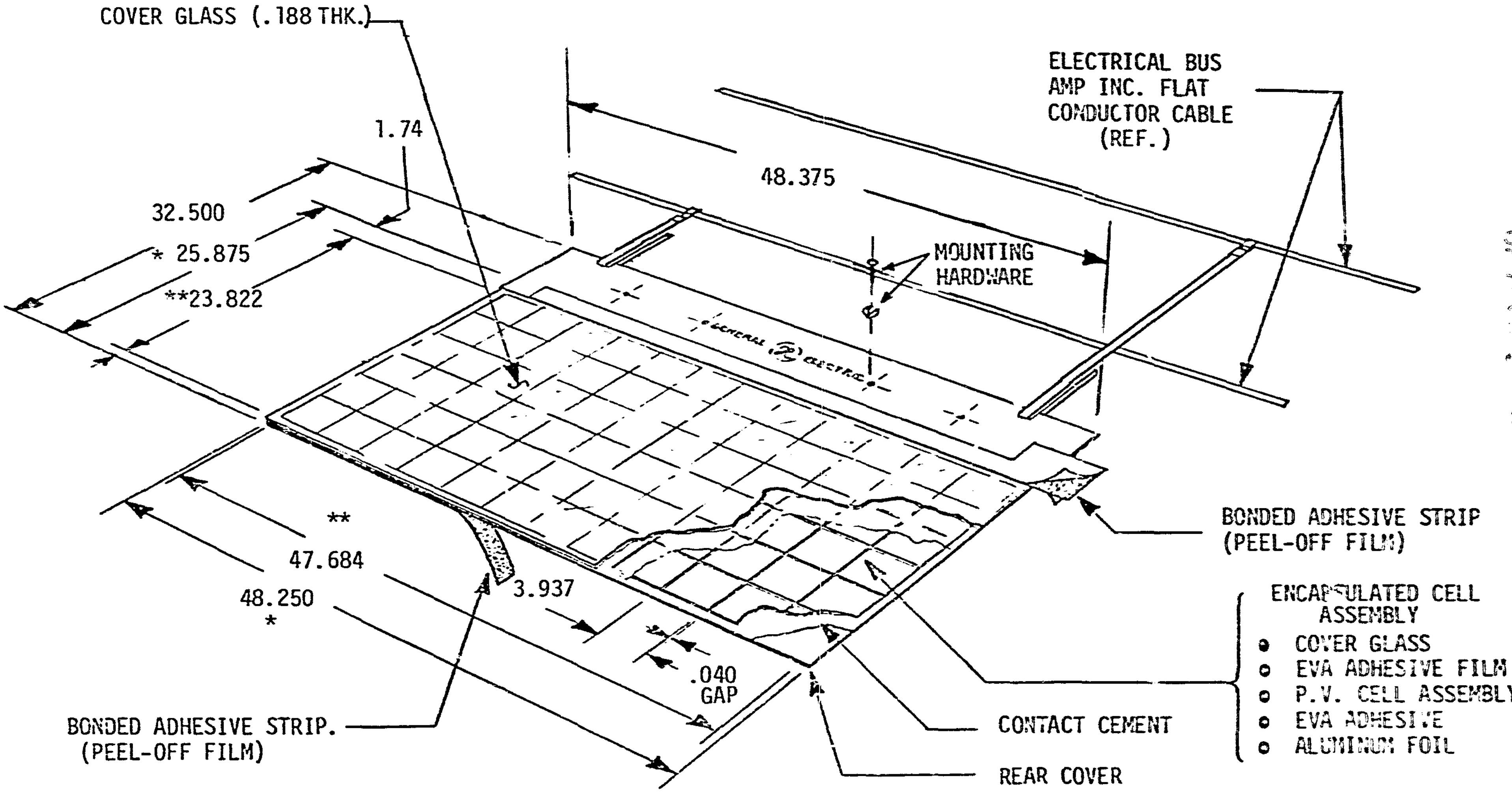


Figure 3-57. Design Concept No. 1 - Direct-Mounted, Overlapping Shingle

The substrate tab is a laminate of B.F. Goodrich scrim reinforced Flexseal as the outer skin and a closed-cell polyethylene foam core. A contact cement is proposed as the laminating adhesive for this assembly and is used to bond the aluminum foil rear sheet of the encapsulated cell subassembly to the rear cover, the rear cover to the foam core, the foam core to the Flexseal skin and the Flexseal skin to the glass coverplate. Scotch-Grid Adhesive 4230 (3M Co.) appears to be an excellent candidate for this application. It is an economical, water-dispersed adhesive offering excellent wet strength, and resistance to temperatures as high as 325°F, and to high humidity and aging effects. This adhesive can be applied easily with low pressure spray equipment, and procedures no toxic or flammable noxious fumes. One gallon covers about 600-800 ft^2. It is primarily used for bonding fiber glass to sheet metal in heating and air conditioning equipment, and also for felt, cardboard, cork, sponge and foam rubber to metal and other surfaces.

3.4.1.2 Concept No. 2 - Integrally-Mounted with Plastic Tray

The second module design concept selected for evaluation represents an integrally-mounted approach which uses a plastic tray as the protective rear substrate and secondary insulation system as well as providing the mounting flanges and lips needed to maintain the watertight integrity of the integral mount. As shown in Figure 3-58 this design approach places the encapsulated cell subassembly within a vacuum-formed polypropylene plastic tray which provides the mounting interface with specially-designed, U-shaped channels which run vertically up the roof to form both the watertight seal along these joints as well as the mechanical attachment or clamping interface. An overlapping lip on the other two edges of the module form the watertight seal for rain water which runs down the roof.

The encapsulated cell subassembly is bonded and sealed within this tray by applying an appropriate butyl sealant around the perimeter of the recessed area of the tray.

This plastic tray substrate presents a non-conductive exposed surface to the external environment and provides the outer layer of a module dual insulation system.

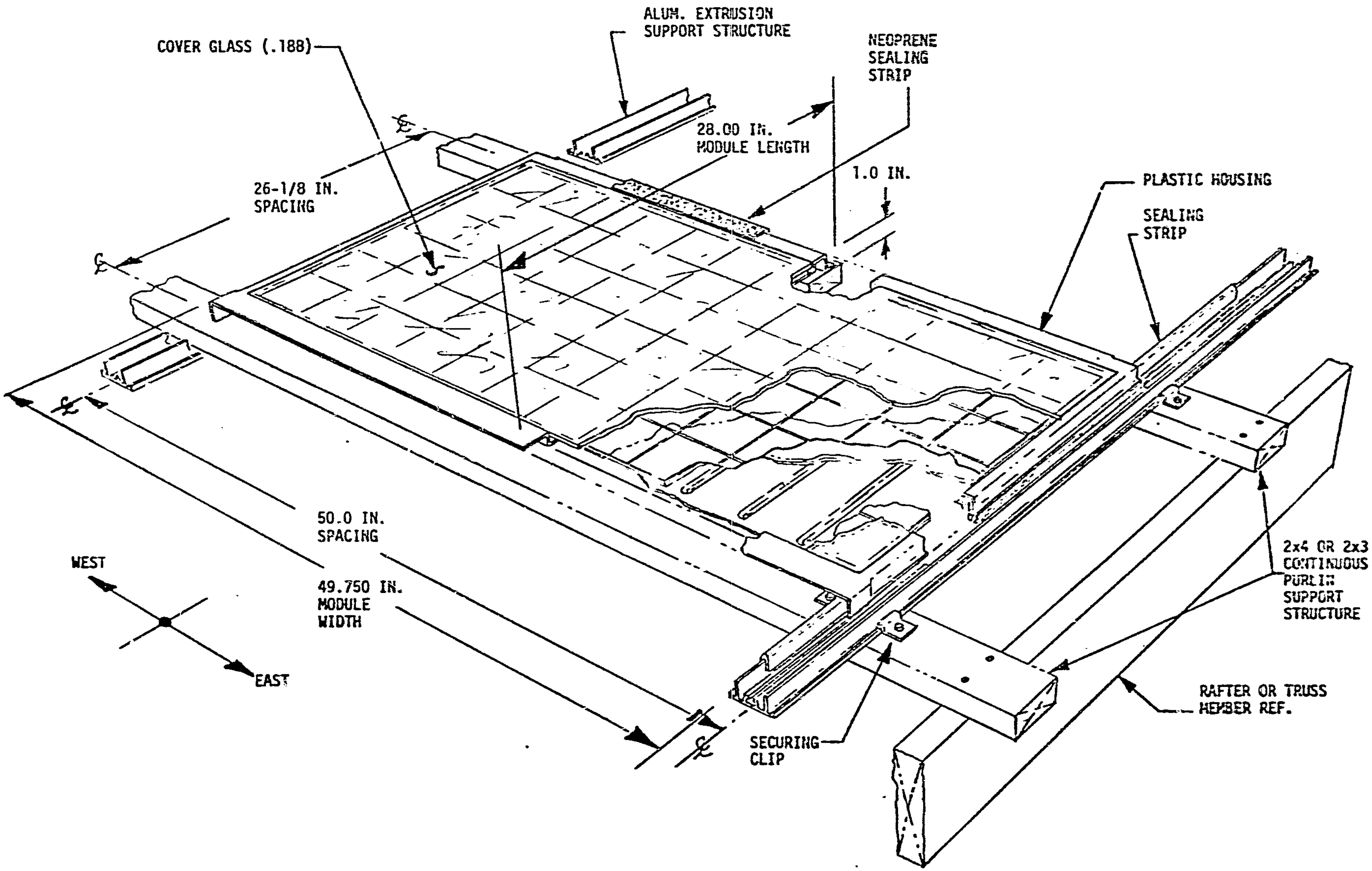


Figure 3-58. Design Concept No. 2 - Integrally-Mounted with Plastic Tray

These design features address the electrical safety issues and may eliminate the requirement to ground the conductive elements which are part of completed array installation.

3.4.1.3 Concept No. 3 - Stand-off Mounted with Aluminum Frame

The stand-off mounted module concept shown in Figure 3-59 uses a more traditional aluminum framing approach to module design. The encapsulated cell subassembly, which is provided with a rear cover sheet of aluminum foil/Tedlar, is framed with the aluminum extrusion shape shown on the righthand side of Figure 3-59. A U-shaped EPDM gasket is bonded around the perimeter of the encapsulated cell subassembly prior to insertion into the track of the extrusion. The frame is mitered and joined at each corner with a bracket which fits into the slot provided in the extrusion.

3.4.2 RESULTS OF MODULE PRODUCTION COST ANALYSIS

The cost of producing each of the three module design concepts was analyzed using an annual production rate of 50,000 m^2 of solar cell area. The manufacturing planning approach described in Section 3.1.2 was applied to each of the three candidate module designs with the results as summarized in Table 3-21. The basic production line, which produces the encapsulated cell subassembly, is nearly identical for each of the three cases considered.

The final assembly portion of the module production cycle yields significant differences in resource requirements among the three concepts considered. The application of the contact cement to the various components which form the overlapped tab of the shingle concept result in more labor, equipment, and floor space than the other two approaches. Concept No. 2, with its plastic tray substrate, is potentially the less labor intensive final assembly operation, but it does require slightly more floor space due to the size of plastic tray. The assembly of the aluminum extrusion frames on Concept No. 3 requires slightly more labor than comparable operations on Concept No. 2, but the floor space required is slightly less because there is no need to store and handle the large plastic trays.

The total production requirements for each of the module design concepts, as summarized at the bottom of Table 3-21 include a total work force which ranges from 12.3 persons for

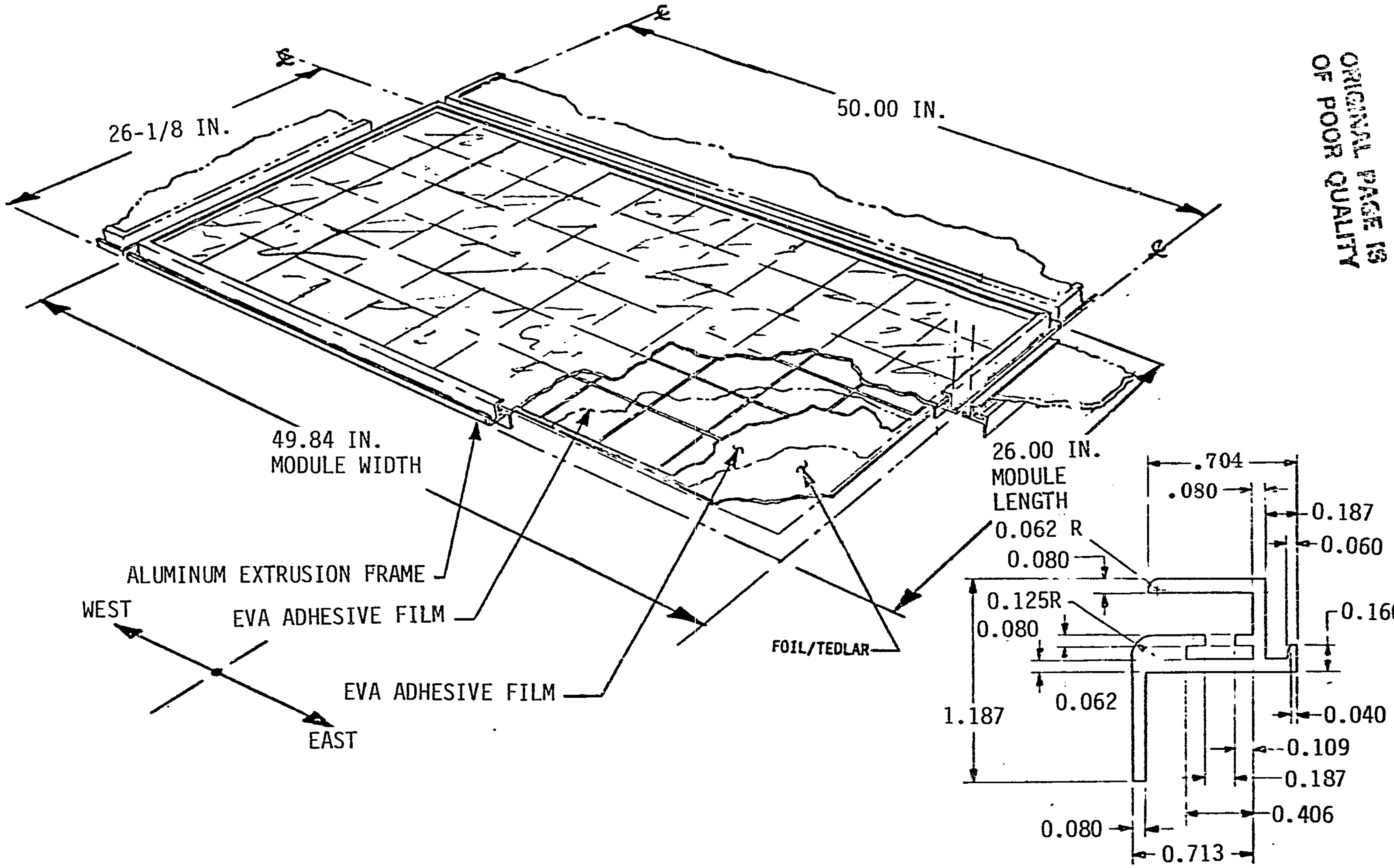


Figure 3-59. Design Concept No. 3 - Stand-off Mounted with Aluminum Frame

Table 3-21. Summary of Production Parameters

	Concept No.		
	1	2	3
Basic Production Area			
Process Yield (%)	99	99	99
Equipment Cost (1980$)	846,000	846,000	846,000
Manpower (No of Employees / Shift)	7.0	7.0	7.0
Floor Space (ft^2)	2,664	2,664	2,664
Utilities			
Electricity (kW)	29.6	29.6	29.6
Air (cfm)	6.0	6.0	6.0
Water (gpm)	13.1	13.1	13.1
Final Assembly Area			
Process Yield (%)	99	100	100
Equipment Cost (1980$)	127,000	88,000	111,000
Manpower (No of Employees / Shift)	4.5	2.3	3.0
Floor Space (ft^2)	1,656	1,152	1,070
Utilities			
Electricity (kW)	1.9	1.6	2.5
Air (cfm)	6.0	-	-
Production Warehouse Area			
Equipment Cost (1980$)	30,000	30,000	30,000
Manpower (No of Employees/ Shift)	3.0	3.0	2.5
Floor Space (ft^2)	1,620	1,272	1,272
Totals			
Equipment Cost (1980$)	1,003,000	964,000	987,000
Manpower (No. of Employees/ Shift)	14.5	12.3	12.5
Floor Space (ft^2)	5,940	5,088	5,006
Utilities			
Electricity (kW)	31.5	31.2	32.1
Air (cfm)	12.0	6.0	6.0
Water (gpm)	13.1	13.1	13.1

Concept No. 2 to 14.5 persons for Concept No. 1. Similar variations in equipment cost, floor space requirements and utility services, while not as significant, do contribute to the overall production cost differences among the three approaches.

Using the production costing methodology described in Section 3.1.2 it is possible to calculate the cost of producing each of these module designs as summarized in Table 3-22.

Table 3-22. Module Production Cost Summary (1980$'s Per Module)

	Concept No.		
	1	2	3
Direct Labor	13.02	11.05	11.23
Labor Overhead (170%)	22.13	18.79	19.09
Cost Of Capital Equipment	2.89	2.78	2.84
Cost Of Utility Services	0.13	0.13	0.13
Rent For Floor Space	0.47	0.40	0.40
Direct Material	33.97	37.41	34.66
Material Overhead (3%)	1.02	1.12	1.04
Subtotal	73.63	71.68	69.39
Profit and Warranty Service (20%)	14.73	14.34	13.88
Total Factory FOB Price	88.36	86.02	83.27

It should be emphasized that the direct material cost for each module does not include the cost of the solar cells. The estimated FOB factory price, which includes a 20 percent mark-up for profit and warranty service, is lowest for module design concept No. 3 with the simple aluminum extrusion frame. However, the magnitude of the range of these total prices represents only 6 percent of the lowest value for the case where the solar cell cost is not included in the module prices.

Further details of the analysis are contained in the second quarterly report (Document No. DOE/JPL 955894-2).

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3.4.3 ARRAY INSTALLATION APPROACHES

3.4.3.1 Concept No. 1 - Direct-Mounted Overlapping Shingle

The installation of the direct-mounted, overlapping shingle module is depicted in Figure 3-60. Modules are arranged across the roof surface with two half-width modules being used in alternating courses to provide the staggered overlapped pattern. A PVC underlayment sheet is used between overlapped shingle courses to maintain the watertight integrity of the roof, which could not otherwise be achieved with the shortened module substrate tab. A EPDM roofing membrane is shingled at the rake to transition from the photovoltaic module installation to the edge of the roofing surface, which will generally be wider than required to exactly accommodate the array. Intermediate horizontal FCC runs are placed at every course to perform this cross-strapping by crimp connection with the FCC terminations for each module.

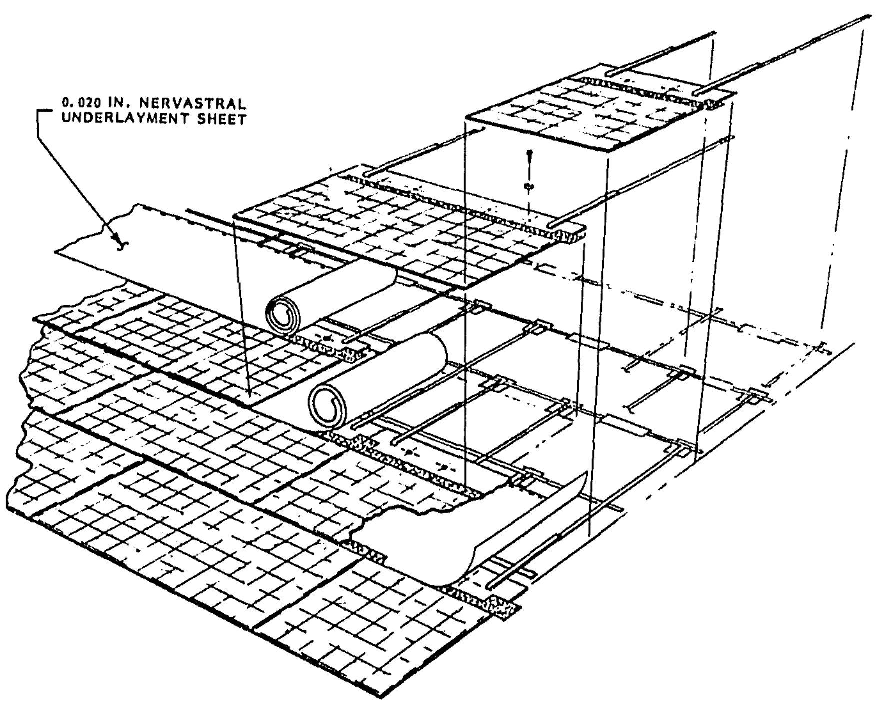


Figure 3-60. Installation Details for Concept No. 1 (Pictorial View of Overlapped Arrangement)

3.4.3.2 Concept No. 2 - Integrally-Mounted with Plastic Tray

Figure 3-61 illustrates the installation approach to be used with the integrally-mounted configuration with the plastic tray substrate. This system mounts to a 2x4 lattice of purlins which are nailed to the roof joists at the proper spacing to support the overlapped seam between modules. The U-shaped aluminum extrusions run normal to these purlins and form the watertight seal with the east-west edges of the modules. Any water leakage through the clamping strip will run down the extruded channel and drip off the eave. The gaskets which cap the legs of the U-shaped channel are supplied to the job site in coils and pressed in place immediately prior to the module installation.

The AMP Solarlok interconnection system is employed for the series wiring of each branch circuit. The integral mounting scheme used for this installation will place all these electrical connections and harnesses in the attic space for easy access.

3.4.3.3 Concept No. 3 - Stand-Off Mounted with Aluminum Frame

The installation of the stand-off mounted array of modules with aluminum frames is illustrated in Figure 3-62. The array mounts above the normal asphalt roofing surface. Vertical runs of pressure-treated 2x4 longerons are nailed to the roof joists through contour conforming Neoprene pads. A system of 2x2 purlins are nailed to the longerons to form a lattice structure for the mounting of the module frames by clamping.

The ridge detail is completed by flashing over onto the north-facing roof surface. This built-up area provides an ideal mounting location for the junction boxes required to terminate the positive bus for each of branch circuits. The AMP Solarlok system of connectors and harnesses is used for all the wiring between modules. The space between the roofing surface and the rear of the array installation is sealed at the ridge and along the rake with a screen at the eave to prevent the entrance of insects, birds and rodents.

3.4.4 RESULTS OF INSTALLATION COST ANALYSIS

The installation cost of each of these module design concepts was estimated using the assumption discussed in Section 3.1.4.1. The details of this analysis are combined in the

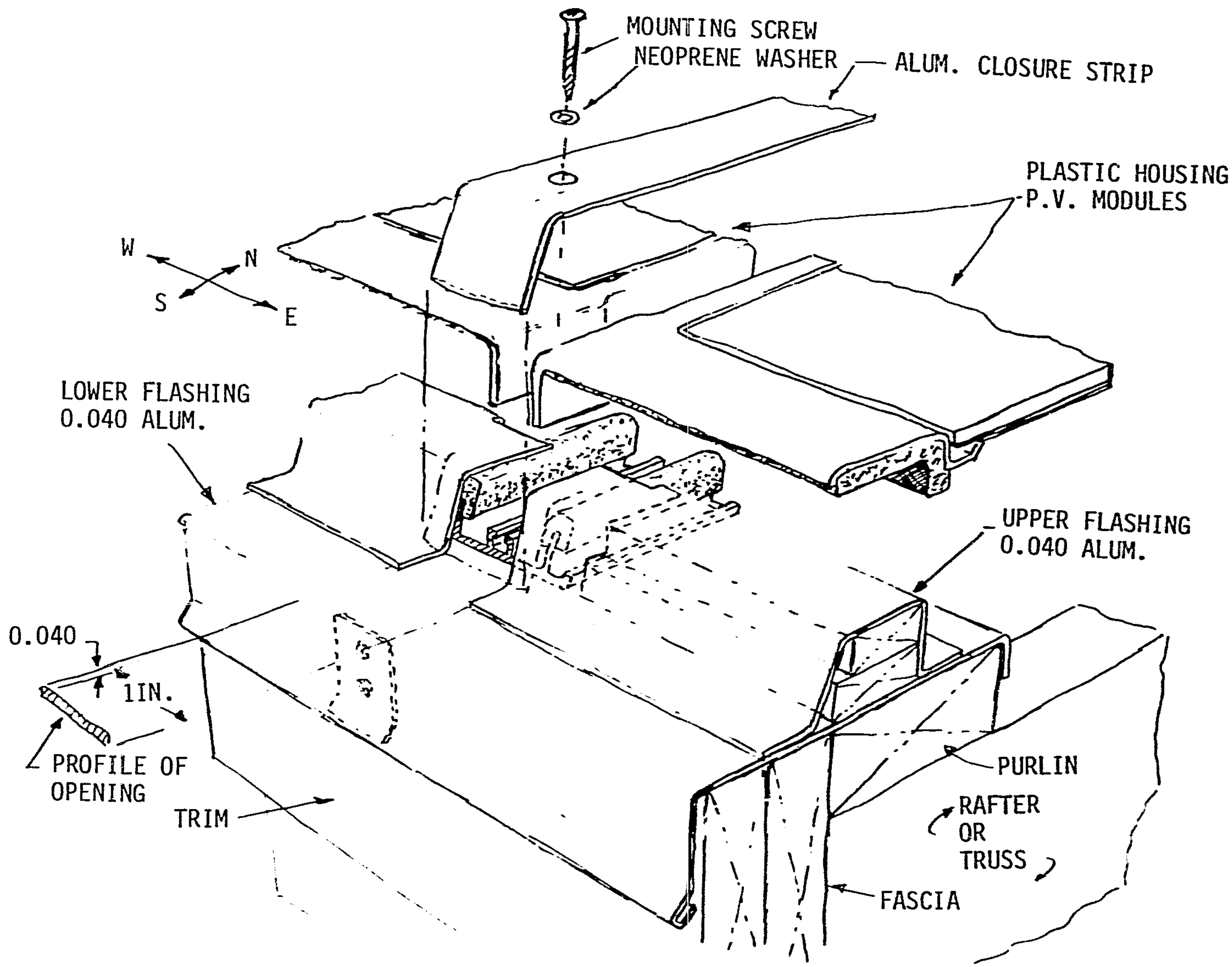
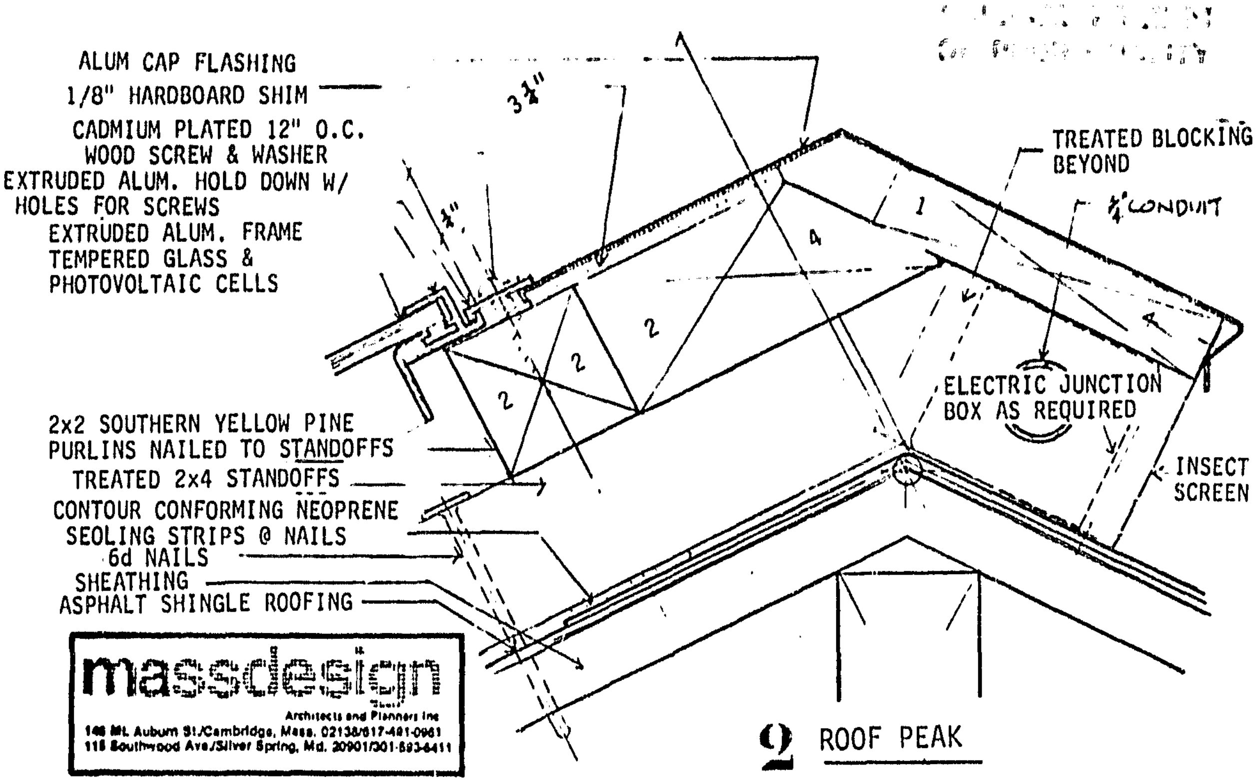


Figure 3-61. Installation Details for Concept No. 2 (Pictorial View at Eave)



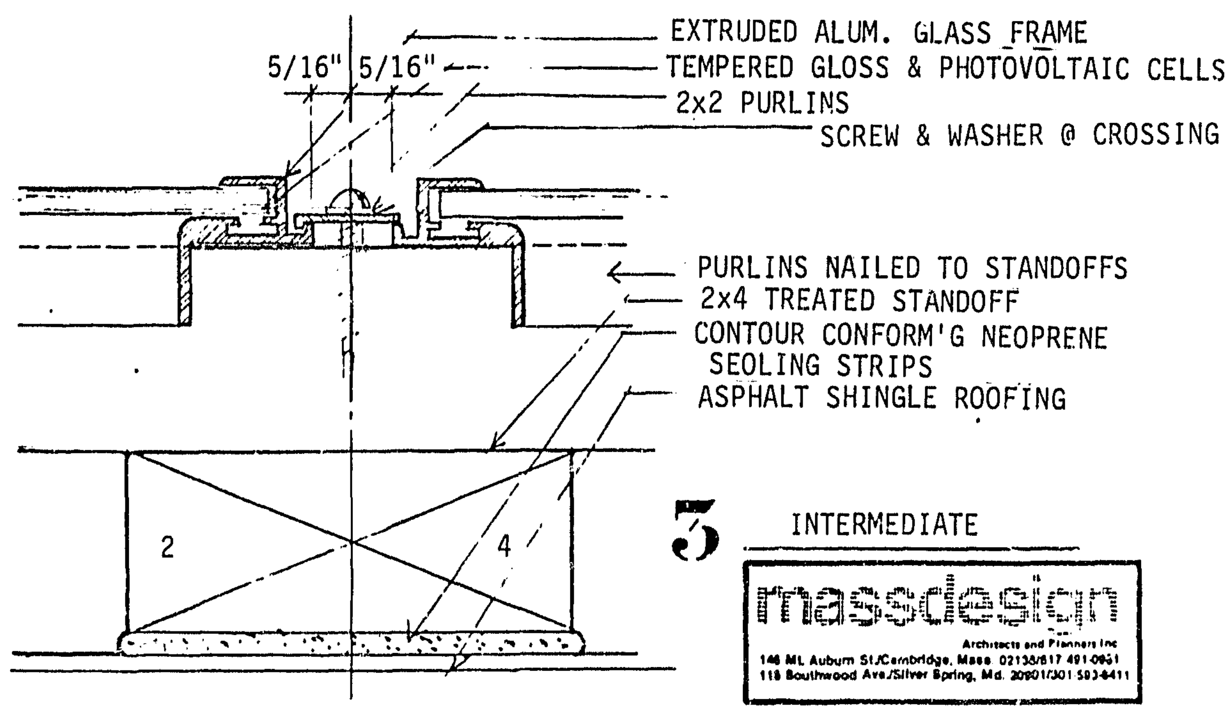


Figure 3-62. Installation Details for Concept No. 3

second quarterly report (DOE/JPL 955894-2) and the results are summarized in Table 3-23. The installation cost savings associated with the elimination of the conventional roofing surface is apparent from these results. The integrally-mounted concept is shown to yield a $6 to $7 per module saving for installation when compared to either of the other two approaches which have nearly identical installation costs. This is enough of a saving to offset the slightly higher production price of the integral module design so that the total installed price for this concept is lower than the stand-off design which yielded the lowest FOB factory price.

Table 3-23. Installation Cost Comparison Among the Three Candidate Array Configurations

Concept No.	Array Installation Cost	
	1980 $/Module	1980 $/Peak Watt at 100 mW/cm^2 and 25°C
1	39.91	0.411
2	33.26	0.342
3	39.75	0.409

3.4.5 DESIRABLE FEATURES OF AN OPTIMIZED MODULE/ARRAY DESIGN

From the results of the previous analyses, it is apparent that further improvements in the module design are possible to take advantage of the best features of the various concepts which are considered in this evaluation. In particular, it would seem desirable to design an "optimized" module with the following features:

1. Simple module edge framing. Every attempt should be made to reduce the cost of the material content of a module while still maintaining the ability to survive in the specified environmental exposures. A simple edge framing gasket which is bonded in place as part of the production process might meet these requirements, while still providing the low installation cost associated with an integral mounting approach.

2. No exposed conductive parts. The inclusion of exposed conductive parts in the module design leads to additional testing requirements, with associated cost implications, which can be avoided with non-conductive exposed parts and components.

3. Dual insulation system for electrical safety. A module design which incorporates a functionally redundant, dual insulation system might eliminate the requirement for the electrical grounding of conductive elements of the array installation.

4. Universally Mountable - When compared with other possible mounting approaches, the integral method, where the photovoltaic array replaces both the roof sheathing and the watertight roofing surface, has been shown to yield substantially lower installation cost. Thus, it would appear desirable to design a module/array installation with the necessary features to permit the integral mounting to be used. Notwithstanding the apparent cost benefits associated with the dual function of the integrally-mounted array, viz, the functional replacement of the conventional roof sheathing and watertight covering, it appears desirable to develop a design approach which also has the flexibility to be mounted as a direct or stand-off installation. There seems to be a considerable body of opinion among architects and builders that the integral mounting approach for residential photovoltaic installations has a low probability of maintaining its watertight integrity for the system design lifetime. There is also concern that the risk of water damage due to the breakage of an installed module may be greater than that which would be tolerated by a typical homeowner.

5. A basic 2 by 4 ft module size offers a reasonable choice for residential-size installations. This basic module size provides the flexibility to accommodate a wide variety of roof sizes and aspect ratios while maintaining a nominal 200 Vdc inverter input voltage level. This size is also consistent with the current technology base with respect to EVA lamination equipment and represents a reasonable compromise between the installation cost, which may be lower for a larger module, and the replacement cost which will be higher for a larger module.

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

SECTION 4
CONCLUSIONS AND RECOMMENDATIONS

The selected module/array concept has been successfully implemented in a full-size demonstration model. The unique module mounting scheme, which uses a series of dove-tailed roll-formed steel support channels as a water drainage trough, minimizes the field labor required to create reliable watertight joints. The overlapped horizontal joint between modules improves the aesthetics of the array while taking advantage of the sloping roof to improve the watertight integrity of the photovoltaic roof surface. This selected design permits installation as either an integral mount without roof sheathing, above the roof sheathing as a direct mount, or over an existing watertight roofing surface as a stand-off mount.

The installation cost of the integral mounting method is somewhat less than either of the two mounting schemes, but there are other important factors which must be evaluated in the selection of a mounting method. The integral mount, which affects its cost saving by the elimination of the roof sheathing and underlayment felt, is more vulnerable to the consequences of water leaks in the photovoltaic array. There is no back-up line of defense to reduce or prevent the entrance of water into the living space of the resistance. This is a risk that many homeowners and insurers may not be willing to take. The vulnerability of this installation method to water leaks is further increased if the consequences of breakage are considered. What is the lead time required to secure a replacement module? How will the roof be made watertight during this time?

Fire safety is another issue which has a profound impact on the mounting method selected for a photovoltaic array. Recent testing to the requirements of UL 790 have revealed that integrally mounted residential modules have an increased risk of fire spread into the dwelling due to the entrance of flaming encapsulant as a result of a burning brand on the roof surface. Direct mounted modules, with the roof sheathing underlayment, have demonstrated a significantly better performance under these conditions. Stand-off mounting schemes, which have clearance space between the conventional roofing surface at the underside of the array, will decrease the spread-of-flame rating of the conventional roof if the flame is permitted to enter and propagate in this clearance space.

A basic 2 by 4 foot module size is a reasonable choice for residential applications. It is near optimum from a production standpoint if current manufacturing processes are utilized. As the film lamination process is further developed, it may become practical to encapsulate larger modules with the extremely high yields which would be required to avoid the loss associated with a non-reworkable defect at this point. However, for residential applications, the field installation is the predominant concern which influences the selection of module size. A 2 by 4 foot module is at the upper limit of size and weight that can be practically handled by one person. If it is assumed that lifting to the roof surface is performed mechanically, the mechanics are still required to lift and position the modules on the sloping roof. A complete array installation of 2 by 4 foot modules could be accomplished with a two-man crew. A larger module would require a larger crew for handling. This larger crew would not be effectively used during the other phases of the installation. This module size also provides considerable design flexibility to accommodate a wide range of residential roof sizes within the constraints imposed by inverter input voltage and maximum individual module open-circuit voltage.

The cost of producing a photovoltaic module at the highest rate considered in this analysis (viz., 500,000 m^2 of cell area per year) is almost completely determined by the cost of the parts and materials within the module. The cost of the solar cells, which are considered to be a purchased commodity for this study, is the predominant factor influencing FOB module price. Near-term cost reduction efforts for residential modules should emphasize the reduction in cost of solar cells as well as other high cost, area-related elements such as encapsulant materials.

In the near-term, the cost of installing a residential array, regardless of the mounting scheme used, is only a small fraction of the total system cost, which is dominated by the cost of the solar cells. Institutional factors such as insurability, fire safety and risk of water damage will have a significant impact on the selection of a residential array mounting method.

The distribution costs associated with getting the modules from the factory to the job site have not been included in the study. If this distribution is handled through regional warehouses, each supplying a number of independent photovoltaic array installers, it is possible for this mark-up to represent a significant fraction of the total installed price for the array.