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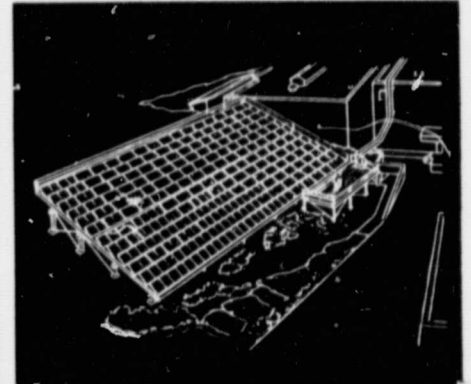
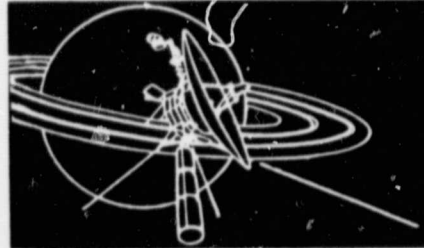
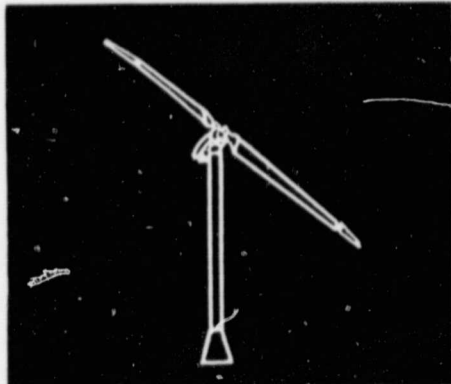
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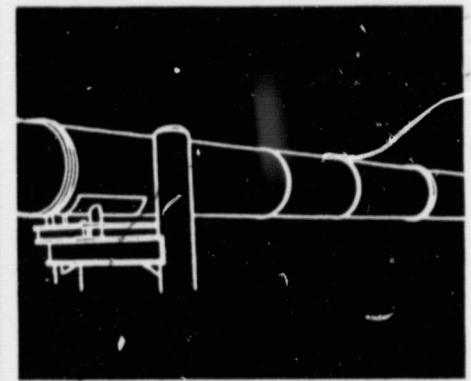
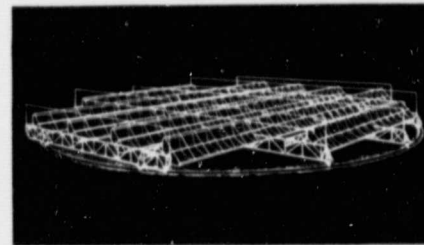
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QUARTERLY REPORT NO. 3 INTEGRATED RESIDENTIAL PHOTOVOLTAIC ARRAY DEVELOPMENT

PREPARED UNDER JPL CONTRACT 955894
REPORT DATE: AUGUST 14, 1981



ADVANCED
ENERGY
PROGRAMS
DEPARTMENT



ENERGY SYSTEMS AND TECHNOLOGY DIVISION

GENERAL  ELECTRIC

DOE/JPL 955894-3
DISTRIBUTION
CATEGORY UC-63

QUARTERLY REPORT NO. 3

INTEGRATED RESIDENTIAL PHOTOVOLTAIC
ARRAY DEVELOPMENT

PREPARED UNDER JPL CONTRACT 955894
REPORT DATA; AUGUST 14, 1981
BY: N.F. SHEPARD, JR.

The JPL Low-Cost 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 low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DOE.

ADVANCED ENERGY PROGRAMS DEPARTMENT
P.O. BOX 8661
PHILADELPHIA, PA 19101

GENERAL  ELECTRIC

ABSTRACT

The design details of an "optimized" integrated residential photovoltaic module/array are presented in this third quarterly report to be published under JPL Contract 955894. This selected design features a unique waterproofing and mounting scheme which was devised to simplify the installation procedures by the avoidance of complex gasketed or caulked joints, while still maintaining a high confidence that the watertight integrity of the integral roofing surface will be achieved for the design lifetime of the system.

The production and installation costs for the selected module/array design are reported for a range of annual production rates as a function of the cost of solar cells.

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SECTION 1
SUMMARY

SECTION 1
SUMMARY

The module design and installation concept depicted in Figure 1-1 was selected and recommended to JPL as the "optimized" design concept to be continued on through the detailed design phase of the program. A complete set of drawings was prepared to describe this selected concept with the characteristics summarized in Table 1-1. This design description was used as the basis of the formulation of a production plan to fabricate the module over a range of annual production rates varying from 10,000 to 500,000 m² of solar cell area. The installation costs for this selected module concept were estimated based on a typical residential array size and configuration.

The module FOB factory price, exclusive of solar cells, was calculated as \$1.18 and \$0.73 per watt at the peak power rating conditions (100 mW/cm² insolation at a cell temperature of 25°C) for production rates of 10,000 and 50,000 m² per year, respectively. The installation cost of these modules, when assembled as a watertight array of 50 modules, was found to vary with the mounting approach used from \$0.33 per watt for the integral mount; to \$0.35 per watt for the direct mount; to \$0.40 per watt for the stand-off mount.

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 By-Pass 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/mm ² insolation and 25°C cell temperature)	97.2 W
Module Efficiency	12.1 percent

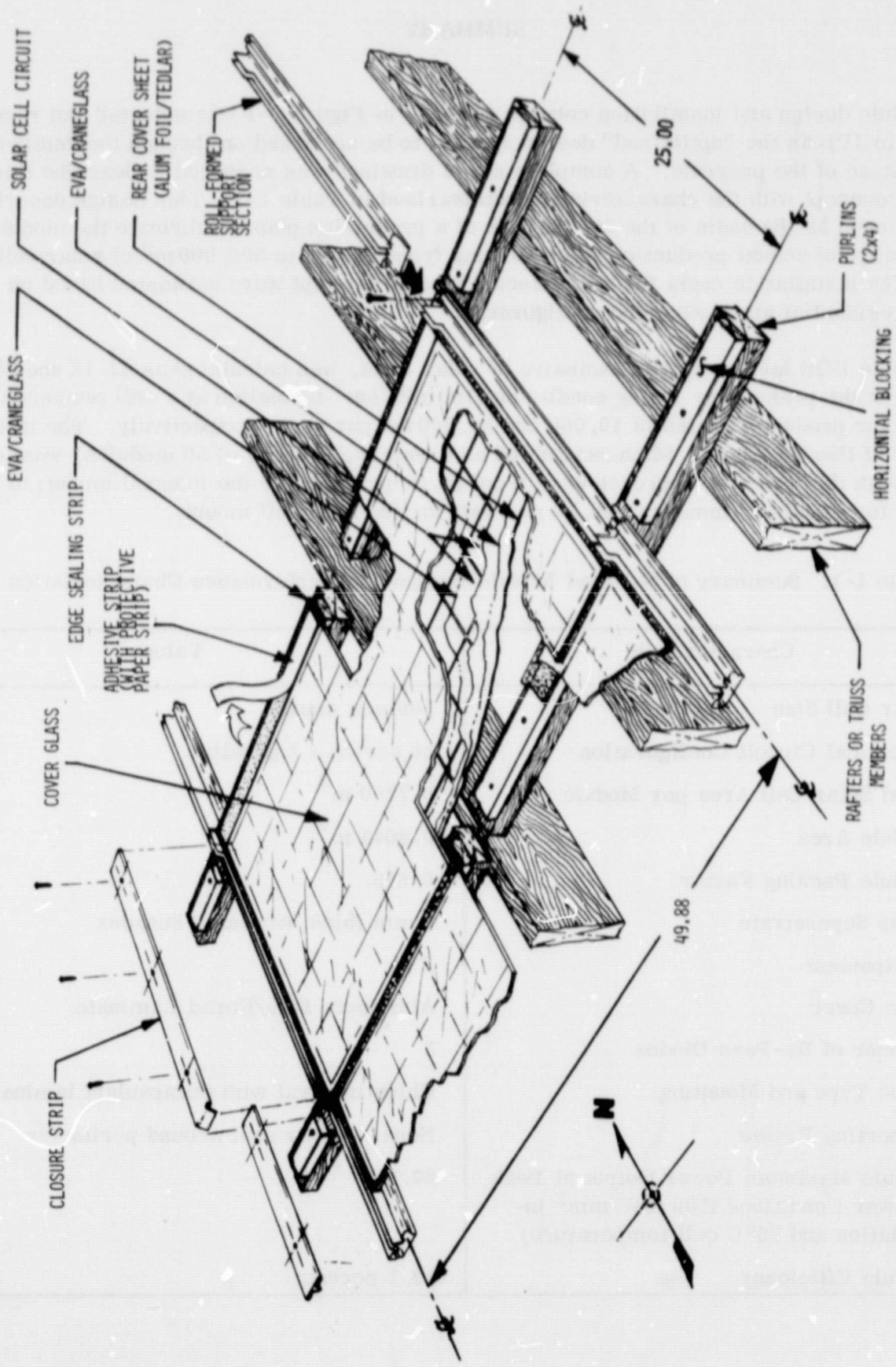


Figure 1-1. Selected Module/Array Design Concept

The design simplicity of this selected module/array concept will be demonstrated by the fabrication and assembly of a full-size six module simulated roof section. This model will illustrate the following unique features of the selected integrated residential array concept:

1. A watertight roofing surface which provides the flexibility to be mounted as either an integral, direct or stand-off installation
2. The watertight integrity of the photovoltaic roof is assured by a simple module perimeter seal which uses the sloping roof surface to the maximum advantage. An overlapping seam is used between modules to shed water which runs down the roof surface. A series of roll-formed steel support channels are nested to provide a continuous trough for the drainage of water which may leak through the clamped joints which run up the roof.

SECTION 2
INTRODUCTION

SECTION 2

INTRODUCTION

The objective of this contract is 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 will be 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 - By-Pass Diode Integration

The fourth task, which is intended to investigate the electrical, mechanical and thermal integration of by-pass diodes within a residential photovoltaic module, was added to the contract work scope as the result of a unilateral modification received on July 23, 1981.

The master program schedule, which includes this new task activity, is reproduced as Figure 2-1. The Task 2 design optimization activity was completed during this period and the detailed design description was presented to JPL at a design review conducted on July 17, 1981. At this time preliminary sketches of the proposed prototype array roof section were reviewed along with the cost estimate for the construction of this simulated roof section.

This report presents the details of the selected module design concept with the associated estimate of the production costs at two levels of annual module factory output. The installation details for a typical residential photovoltaic array which uses this module design in each of three different mounting arrangements are presented. The installation costs associated with each of these mounting approaches is combined with the estimated FOB factory price of the modules to determine the expected total installed cost of the selected photovoltaic array design.

This effort was supported by Kulicke and Soffa Industries, Inc. in the analysis of module production costs and by Massdesign Architects and Planners, Inc. for the development of the array installation details for the various mounting approaches and in the formulation of the installation cost estimates for each approach. Additional technical advice, related to the module-to-module interconnection methods, was supplied by AMP, Inc.

TASKS AND MILESTONES	OCT				NOV				D		
	40	41	42	43	44	45	46	47	48	49	50
CONTRACT START											
TASK 1 - DEVELOPMENT OF CONCEPTUAL ALTERNATIVES											
1(A) SELECT CONCEPTS											
1(A)-1 ESTABLISH CRITERIA											
1(A)-2 IDENTIFY CONCEPTS (EXISTING AND NEW)											
1(A)-3 EVALUATE CONCEPTS AGAINST CRITERIA											
1(A)-4 SELECT THREE CONCEPTS											
1(B) OPTIMIZE THREE CONCEPTS											
1(B)-1 PERFORM INSTALLATION/MASS PROD. ANALYSES											
1(B)-2 PERFORM TRADE-OFF OF FIELD/FACTORY LABOR MIX											
1(B)-3 ESTABLISH OPTIMIZED DESIGNS											
1(B)-4 COST ESTIMATES AND LIFE CYCLE COSTS											
1(C) DOCUMENT RESULTS											
TASK 2 - OPTIMIZE DESIGN OF ONE CONCEPT											
2(A) SELECT AND OPTIMIZE ONE CONCEPT											
2(A)-1 SELECT CONCEPT											
2(A)-2 ENGINEERING AND PRODUCTION ANALYSES											
2(B) DETAILED DESIGN											
2(B)-1 PREPARE DRAWINGS AND SPECIFICATIONS											
2(B)-2 PREPARE DETAILED COST ESTIMATES											
2(B)-3 PROTOTYPE SECTION COST ESTIMATE											
TASK 3 - FABRICATE PROTOTYPE ARRAY/ROOF SECTION											
3(A) PREPARE SKETCHES											
3(B) DEFINE METHODS, PROCEDURES AND SOFT TOOLING											
3(C) BUILD ARRAY/ROOF SECTION											
3(D) FEEDBACK TO PRODUCTION DESIGN											
3(E) DELIVER ROOF SECTION TO JPL											
TASK 4 - BY-PASS DIODE INTEGRATION											
4(A) IDENTIFICATION AND CHARACTERIZATION OF AVAILABLE DIODE TYPES											
4(B) IDENTIFICATION OF DIODE MOUNTING CONFIGURATIONS											
4(C) ANALYSIS OF POWER DISSIPATION AND RESULTING JUNCTION TEMPERATURE											
4(D) DIODE RELIABILITY CONSIDERATIONS											
TASK 5 - PROGRAM MANAGEMENT AND REPORTING											
5(A) CONTRACT REVIEW MEETINGS											
5(B) LSA PROJECT INTEGRATION MEETING											
5(C) GOV'T-SPONSORED MEETINGS											
5(D) PROGRAM PLAN AND BASELINE COST ESTIMATE											
5(E) MONTHLY TECHNICAL AND FINANCIAL MGMT REPORTS											
5(F) QUARTERLY REPORT											
5(G) TASK 1 DOCUMENTATION											
5(H) DESIGN REVIEW DATA PACKAGE											
5(I) ENGINEERING DOCUMENTATION											
5(J) FINAL TECHNICAL REPORT											

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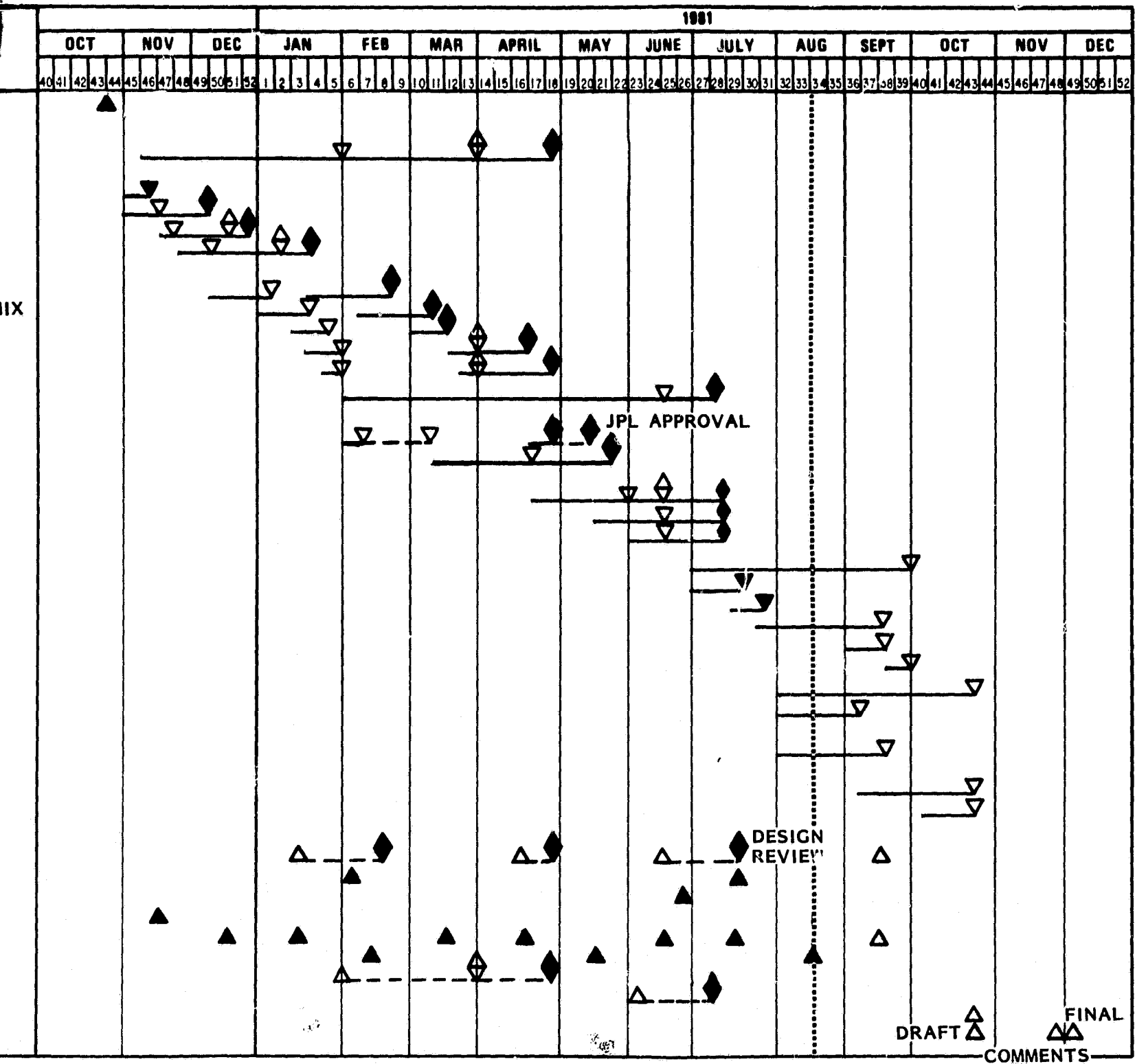


Figure 2-1. Master Program Schedule

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SECTION 3
TECHNICAL DISCUSSION

SECTION 3
TECHNICAL DISCUSSION

3.1 GENERAL DESCRIPTION OF THE SELECTED CONCEPT

The concept shown in Figure 3-1 has 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 the second quarterly report. The selected concept has evolved from these investigations as 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. 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. 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.
2. An integral by-pass diode installation which packages the diode chips within the encapsulant lamination. When combined with the two parallel by 36 series circuit arrangement with a by-pass diode around each 12 series-cell group, the diode junction temperature can be maintained within acceptable limits under worst-case conditions associated with the complete open-circuit failure of a solar cell circuit element.
3. A watertight integral mounting approach which does not rely on gasketed or caulked joints as the primary method of water shedding.

This latter feature is achieved through the use of two watertight joints as shown in Figures 3-2 and 3-3. An overlapped or shingled joint, as shown in Figure 3-2, is provided along the east-west seams at the roof. 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.

The joint along the roof slant height direction is sealed by clamping a "P"-shaped rubber extrusion in a roll-formed steel channel section as shown in Figure 3-3. These channel sections are assembled on the roof in a tongue and groove fashion 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 channel section and the underside of the clamping strip. Any water which leaks past this seal will drain directly into the channel interior where it will flow

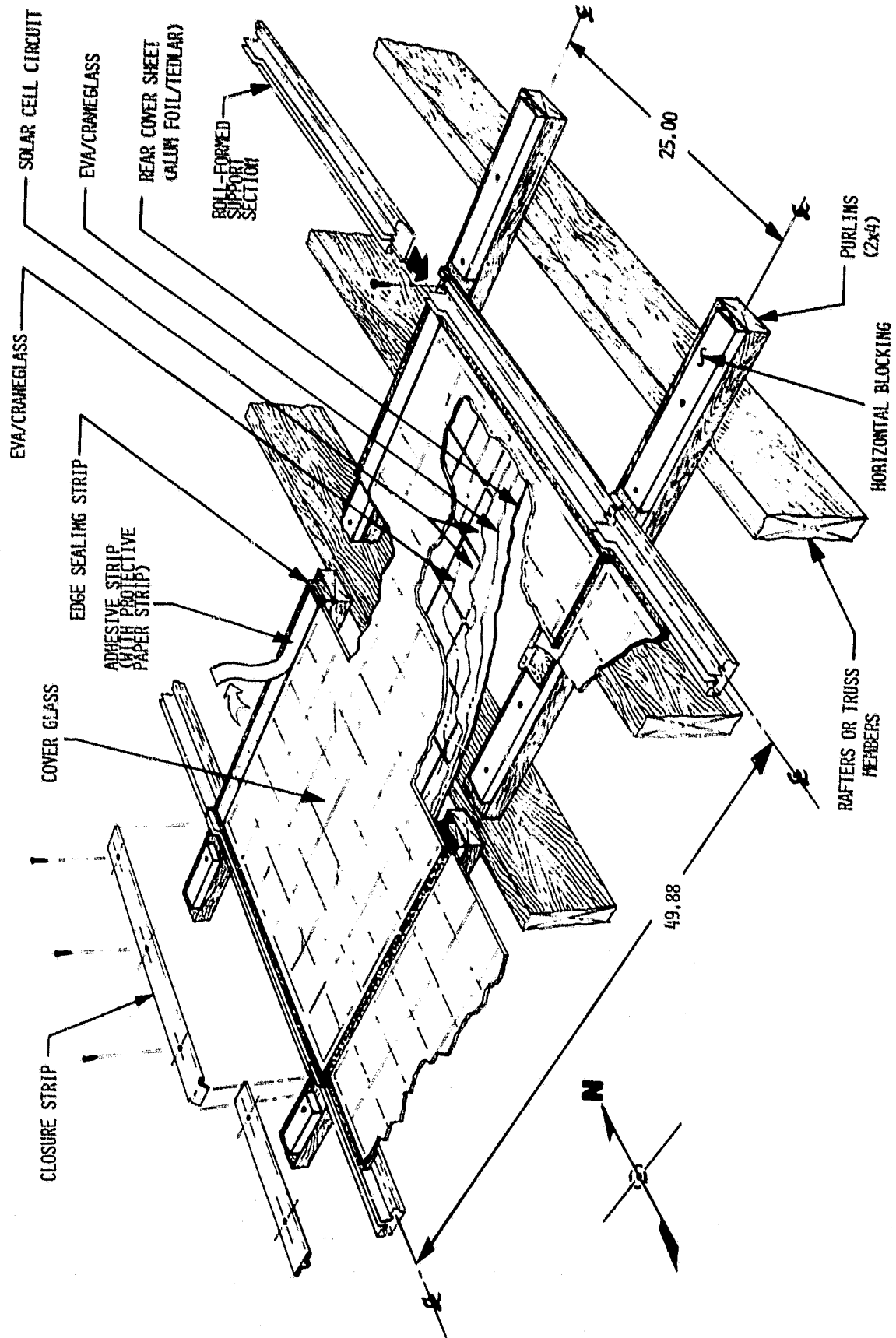
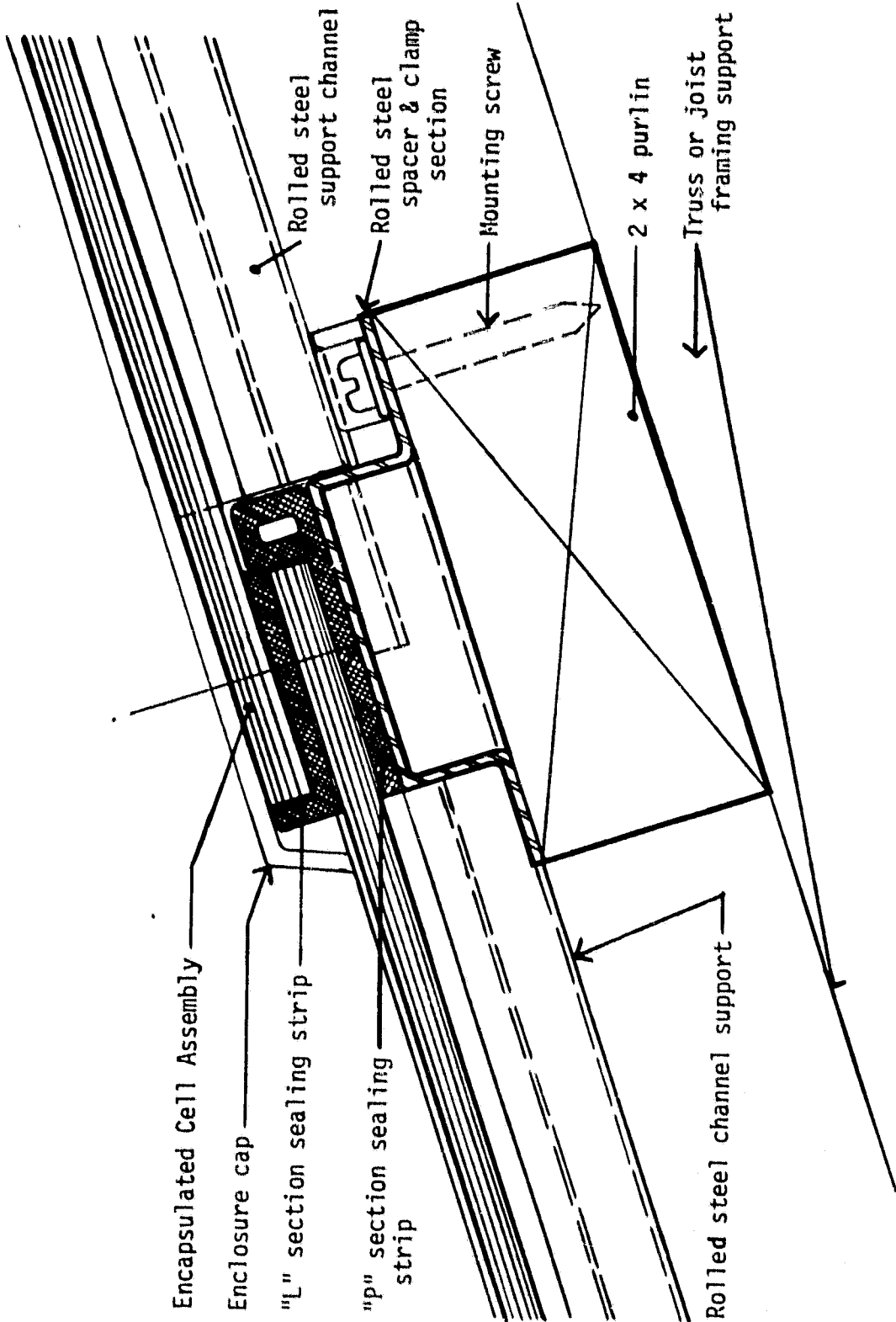


Figure 3-1. Selected Module/Array Concept



Encapsulated Cell Assembly

Enclosure cap

"L" section sealing strip

"P" section sealing strip

Rolled steel support channel

Rolled steel spacer & clamp section

Mounting screw

2 x 4 purlin

Truss or joist framing support

Rolled steel channel support

Figure 3-2. Sectional View Through Overlapping Joint

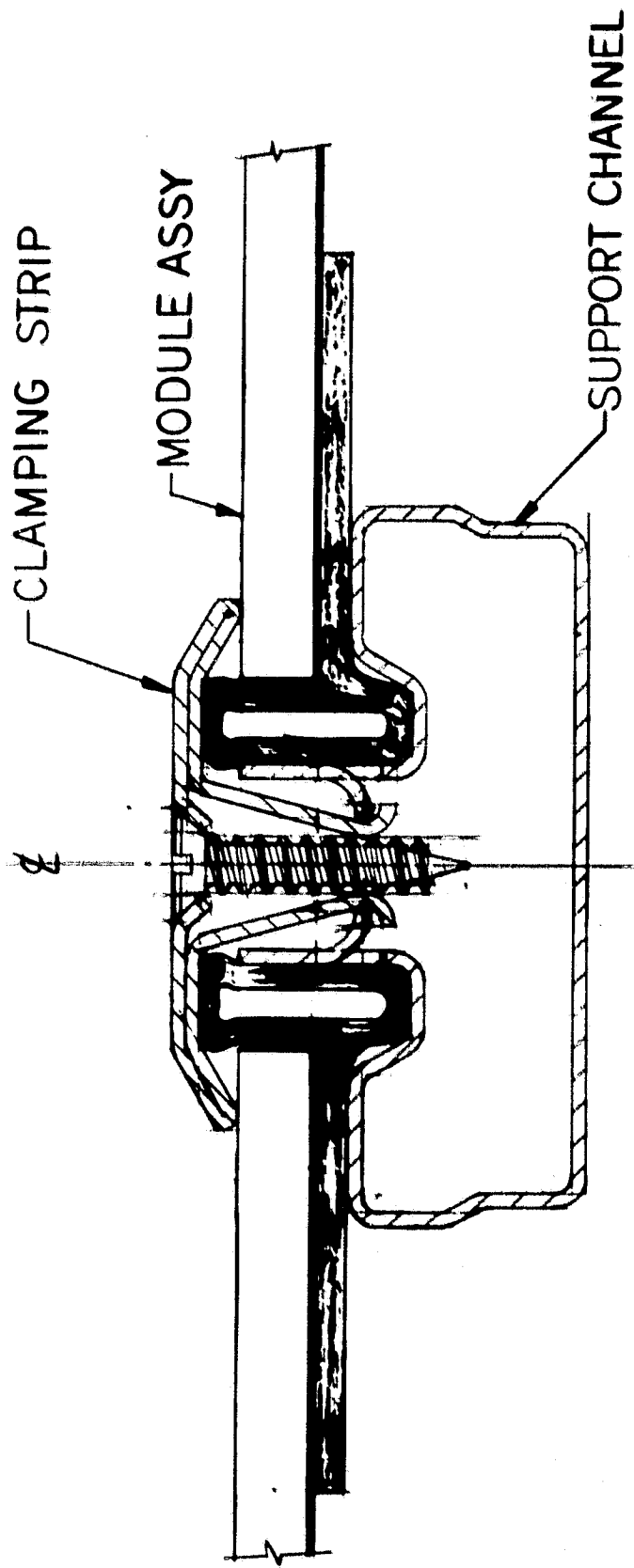


Figure 3-3. Sectional View Through Support Channel Showing Clamping Method

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.

3.2 MODULE DESIGN DESCRIPTION

3.2.1 MODULE ASSEMBLY

The module assembly shown in Figure 3-4 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 3-5, is bonded around the perimeter of the encapsulated cell subassembly on three sides as depicted in Section B-B of Figure 3-4. Figure 3-6 shows the "L" seal which is bonded along the fourth side 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.

Two AMP, Inc. Solarlok bus bar housings are installed by bonding to the rear cover sheet as shown in Section A-A of Figure 3-4.

3.2.2 ENCAPSULATED CELL SUBASSEMBLY

3.2.2.1 General Description

The encapsulated cell subassembly shown in Figure 3-7 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 by-pass diodes are packaged within the laminate under an extended edge of 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 by-pass 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 3-7. 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.

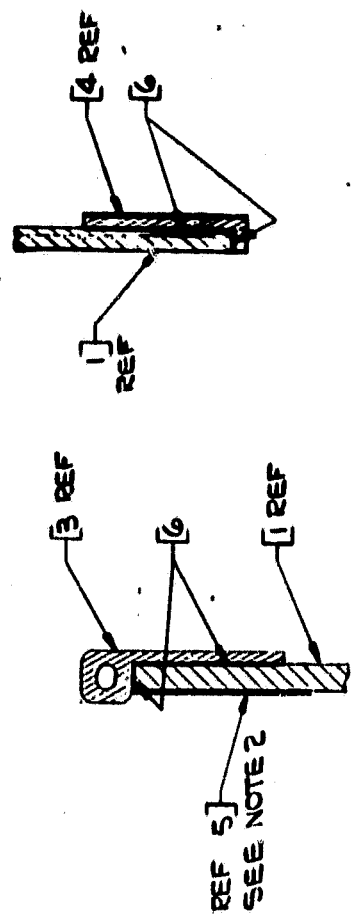
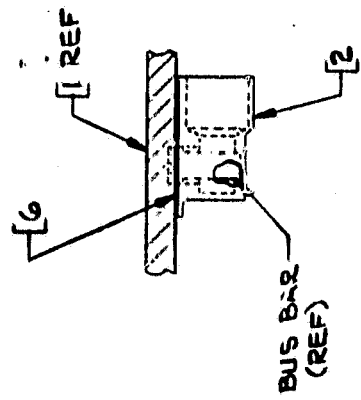
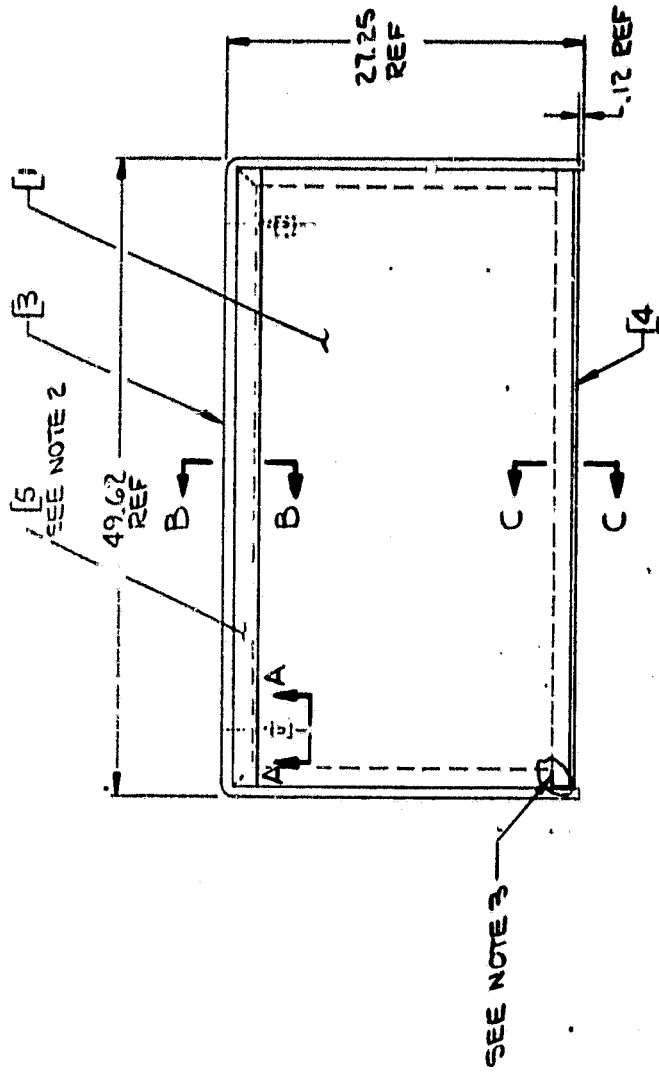
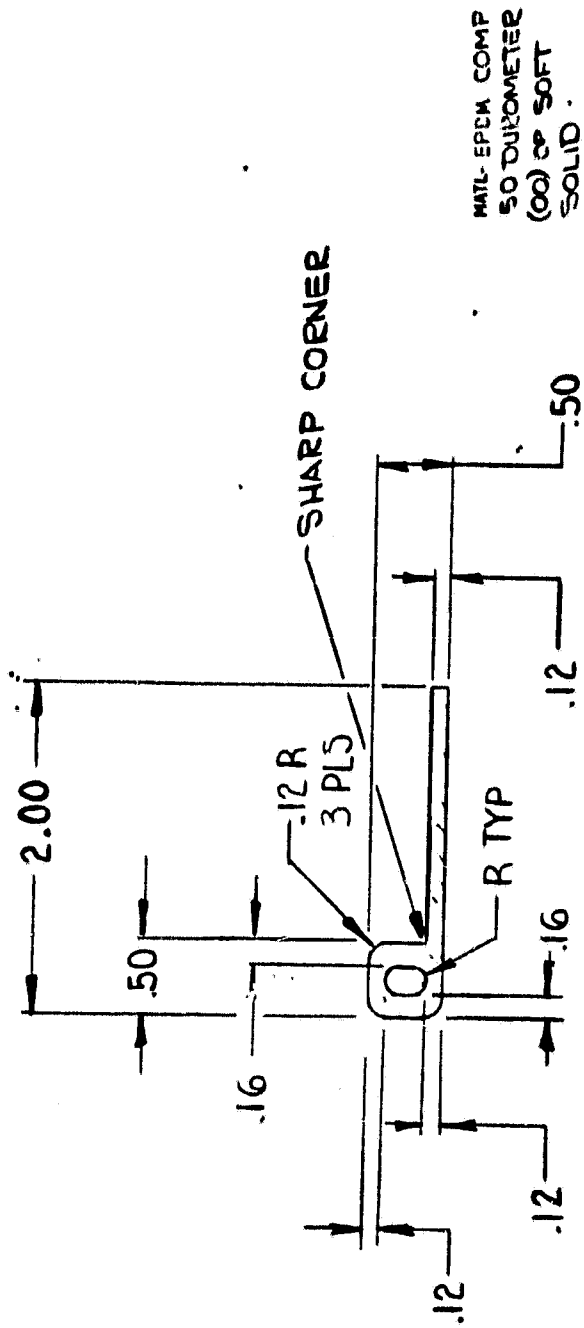
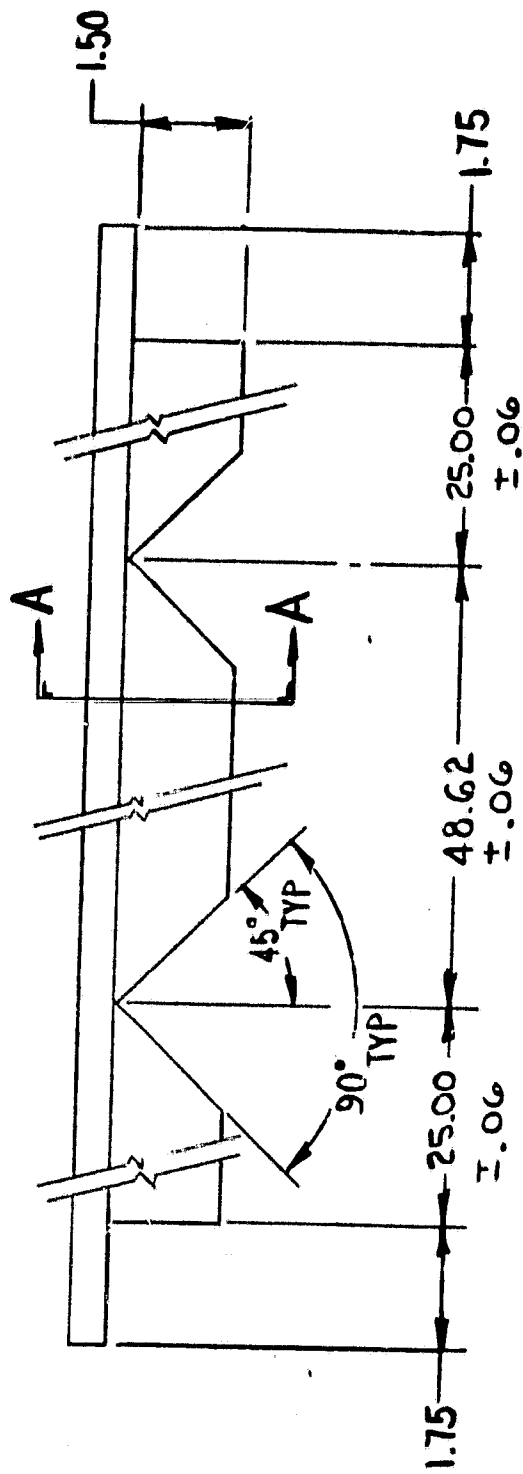
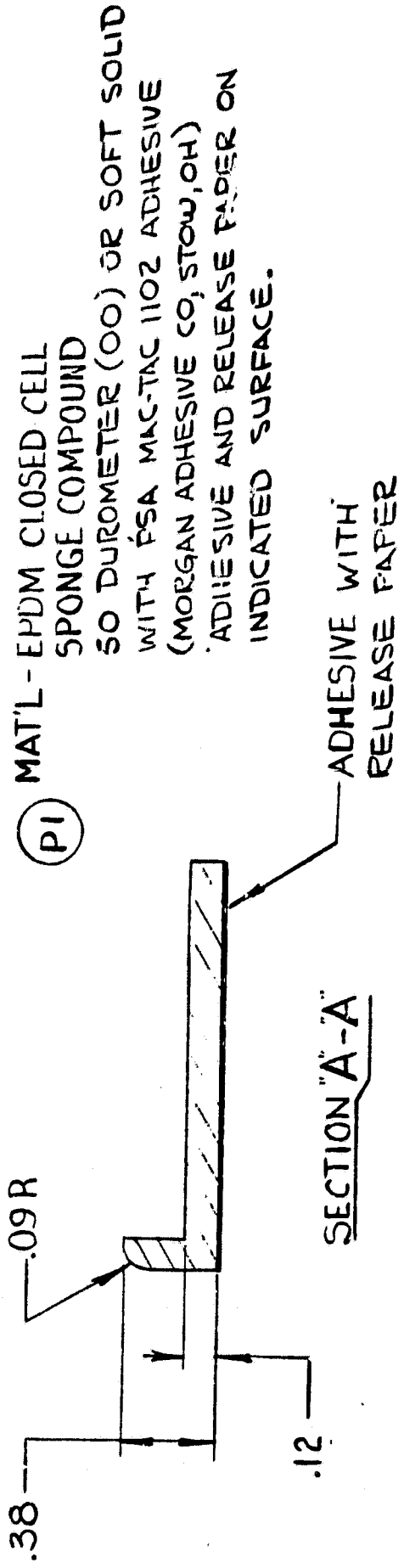
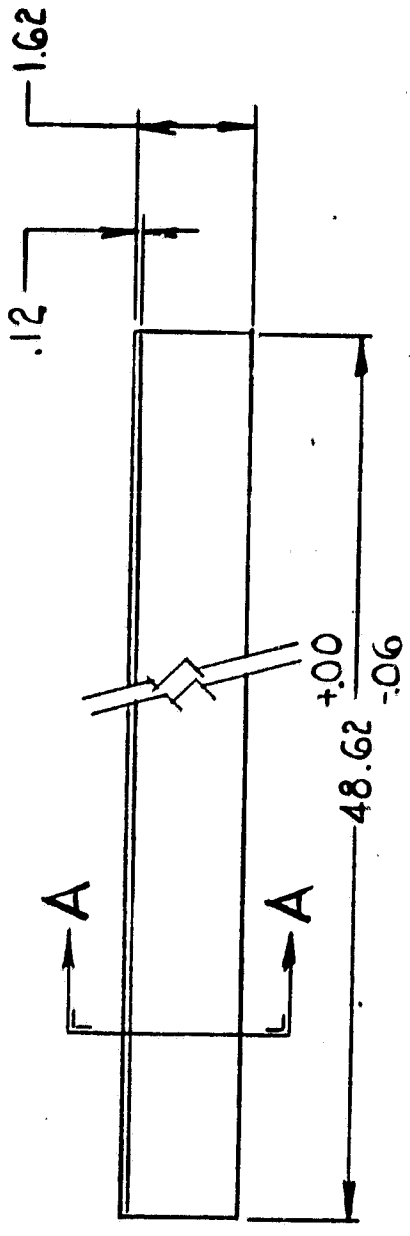


Figure 3-4. Module Assembly Drawing



SECTION A-A

Figure 3-5. "P" Seal Framing Extrusion



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Figure 3-6. "L" Seal Framing Extrusion

3.2.2.2 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. 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 by-pass diodes around each group of twelve series-connected cell pairs as shown in Detail A of Figure 3-7.

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/cm² illumination conditions with a -20°C cell temperature. As shown in Figure 3-8, this circuit arrangement should produce a module maximum power output of 97.2 watts under peak power rating conditions (100 mW/cm² insolation with 25°C cell temperature) with the specified 13.5 percent encapsulated cell efficiency. Under Normal 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. As discussed in Section 3.2.2.5, this current will produce a by-pass diode dissipation of about 4.8 watts under conditions where the solar cell circuit elements have failed as a complete open circuit. This dissipation level is shown to approach the upper limit of by-pass diode junction temperature to assure thermal compatibility with the EVA lamination system.

3.2.2.3 Glass Superstrate

A glass coverplate of 5 mm (0.188 inch) thick annealed Sunadex glass was selected as the superstrate for the module. The structural analysis of this glass coverplate was performed using the method described by Moore in JPL Document No. 5101-148. An array installation in Boston, MA was considered as representative of a realistic worst-case site in terms of combined snow and wind loading. Using the 25 year mean recurrence interval for wind speed and ground snow load at this site, the following design loads are obtained from ANSI A58.1:

- 70 mph basic wind speed
- 26 lb/ft² ground snow load

Assuming an array roof slope of 35 degrees from the horizontal, these design conditions can be translated into loads on the 0.188 inch thick glass coverplate using the methods described in JPL Document No. 5101-148 to yield the values of pressure loading given in Table 3-1. Each of these pressure loadings has been converted into a Load Intensity Factor (LIF) for use in determining the corresponding Stress Intensity Factor (SIF) and resultant maximum positive principal stress in the plate.

These calculated stress values must be compared to the glass breakage stress to determine the suitability of the selected plate size and thickness when subjected to the anticipated design loads. The glass breakage strength for a 1 m² plate area and a one minute load duration

SEE DETAIL A

12] -
24 PLACES

SEE NOTE 4

10]

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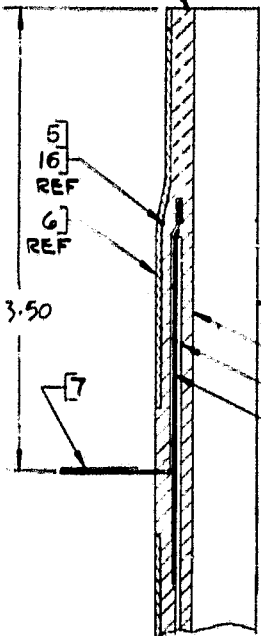
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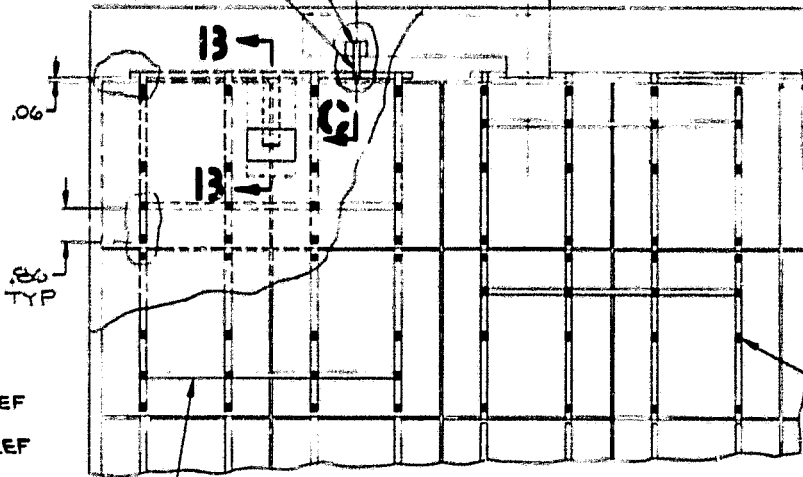
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SECTION 13-13
2 PLACES

FOLDOUT FRAME



13] -
36 PLACES
SEE NOTE 2

DETAIL A

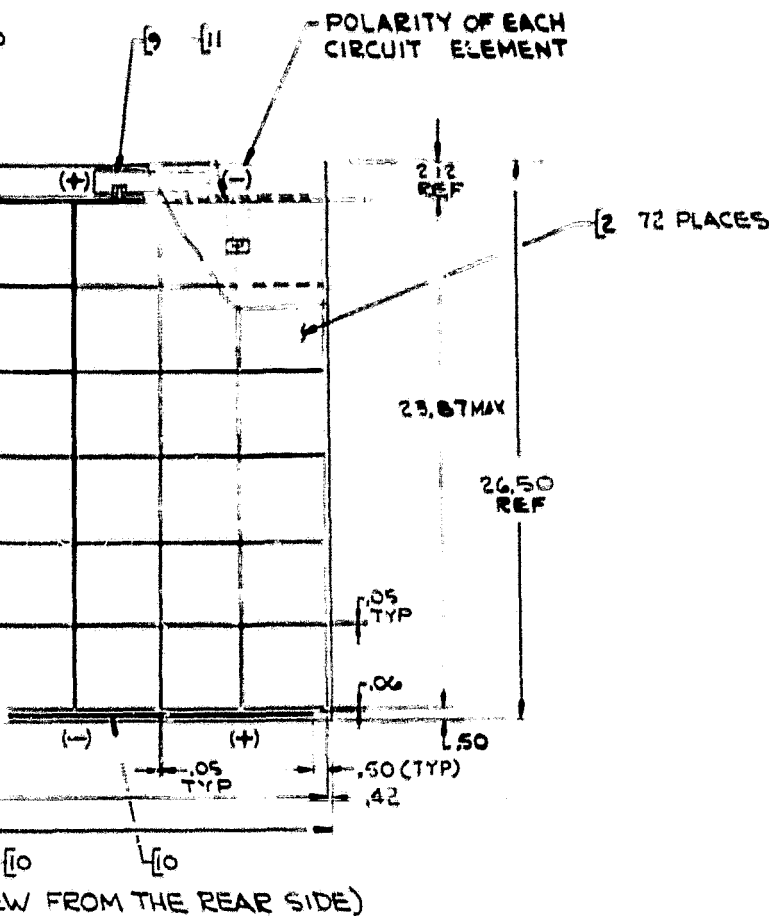
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SEE NOTE 3

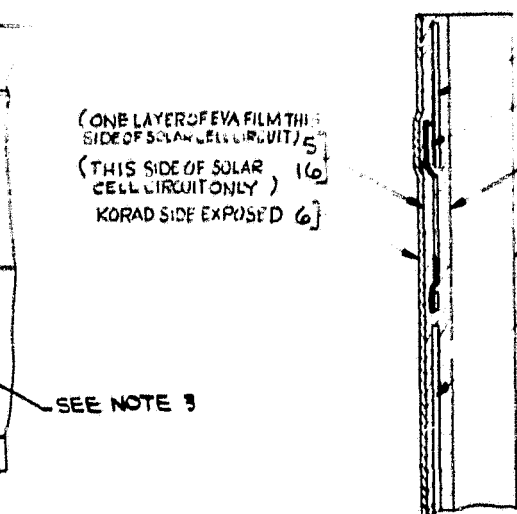
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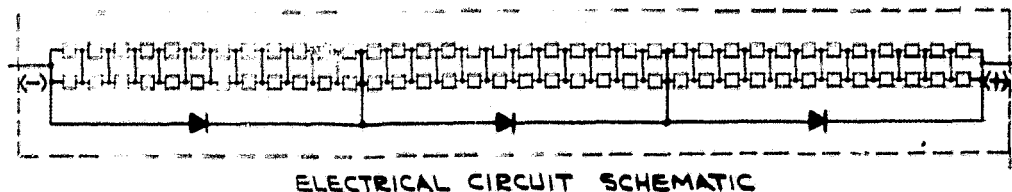


NOTES:

1. DRAWING TERMS AND TOLERANCES PER GE SPEC 5 30009
2. SOLDER PARALLEL CROSS-STRAPPING STRIPS (ITEM 13) TO REAR CELL INTERCONNECTOR STRIPS USING ITEM 3, FOUR PLCS PER CELL PAIR
3. SOLDER INTERCONNECTOR STRIPS TO BACK OF SOLAR CELLS USING ITEM 3, SIX PLACES PER CELL AT APPROXIMATE LOCATIONS SHOWN
4. AFTER FINAL ASSEMBLY, TRIM ALL EXCESS EVA (ITEM 5), CRANE GLASS (ITEM 6) & BACK COVER (ITEM 6) AROUND EDGES OF GLASS
5. APPLY PRIMER (ITEM 17) TO ALL SURFACES TO BE BONDED WITH EVA FILM (ITEM 5) THESE INCLUDE THE INSIDE GLASS SURFACE (1), BOTH SIDES OF THE SOLAR CELL CIRCUIT, THE INSIDE SURFACE OF THE BACK COVER, & ALL COPPER INTERCONNECTOR STRIPS
6. CURE EVA FILM TO AT LEAST 75 PERCENT GEL CONTENT AS DETERMINED BY THE PERCENTAGE OF MAT'L THAT IS INSOLUBLE IN A SOLVENT (TOLUENE)



- 9 REF
- 4 REF (SOLDER WITH ANODE SIDE TO ITEM 9)
- 5 ONE LAYER OF EVA FILM THIS SIDE OF SOLAR CELL CIRCUIT
- 1 REF (LAMINATE WITH ROUGH SURFACE ON THE INSIDE)
- 2 REF



ELECTRICAL CIRCUIT SCHEMATIC

(G1)

SECTION C-C

FOLDOUT FRAME

2

Figure 3-7. Encapsulated Cell Subassembly

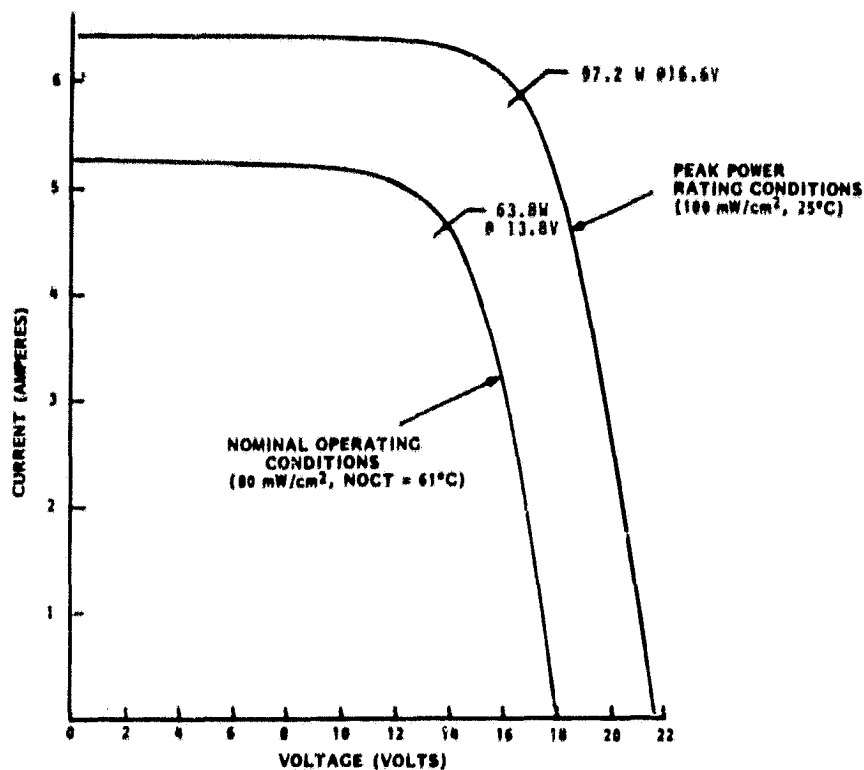


Figure 3-8. Module I-V Characteristics

Table 3-1. Loads and Stresses in Glass Coverplate

Load Description	Pressure (lb/in ²)	LIF*	SIF**	σ (lb/in ²)
Dead Weight (P _D)	0.0164	5.86	4	196
Snow (P _S)	0.1264	45.13	27	1337
Wind (P _W)	0.2404	85.84	50	2476

$$*LIF = \frac{pb^4}{Dt}$$

$$**SIF = \frac{\sigma b^2 t}{D}$$

where

- b = width of glass plate
- t = thickness of glass plate
- D = flexural rigidity of glass plate
- $$= \frac{Et^3}{12(1-\nu^2)}$$
- E = Young's modulus of plate material
- σ = maximum positive principal stress on plate
- ν = Poisson's ratio for glass

(σ_{11}) is plotted in Figure 3-9 as a function of the probability of failure. For annealed glass with a 2 percent probability of failure the resulting value of σ_{11} is 4,200 lb/in². This value must be corrected for plate area and load duration to yield the breakage strength for each of the loading conditions. This corrected breakage strength (σ_B) can be obtained as follows:

$$\sigma_B = f_A f_T \sigma_{11}$$

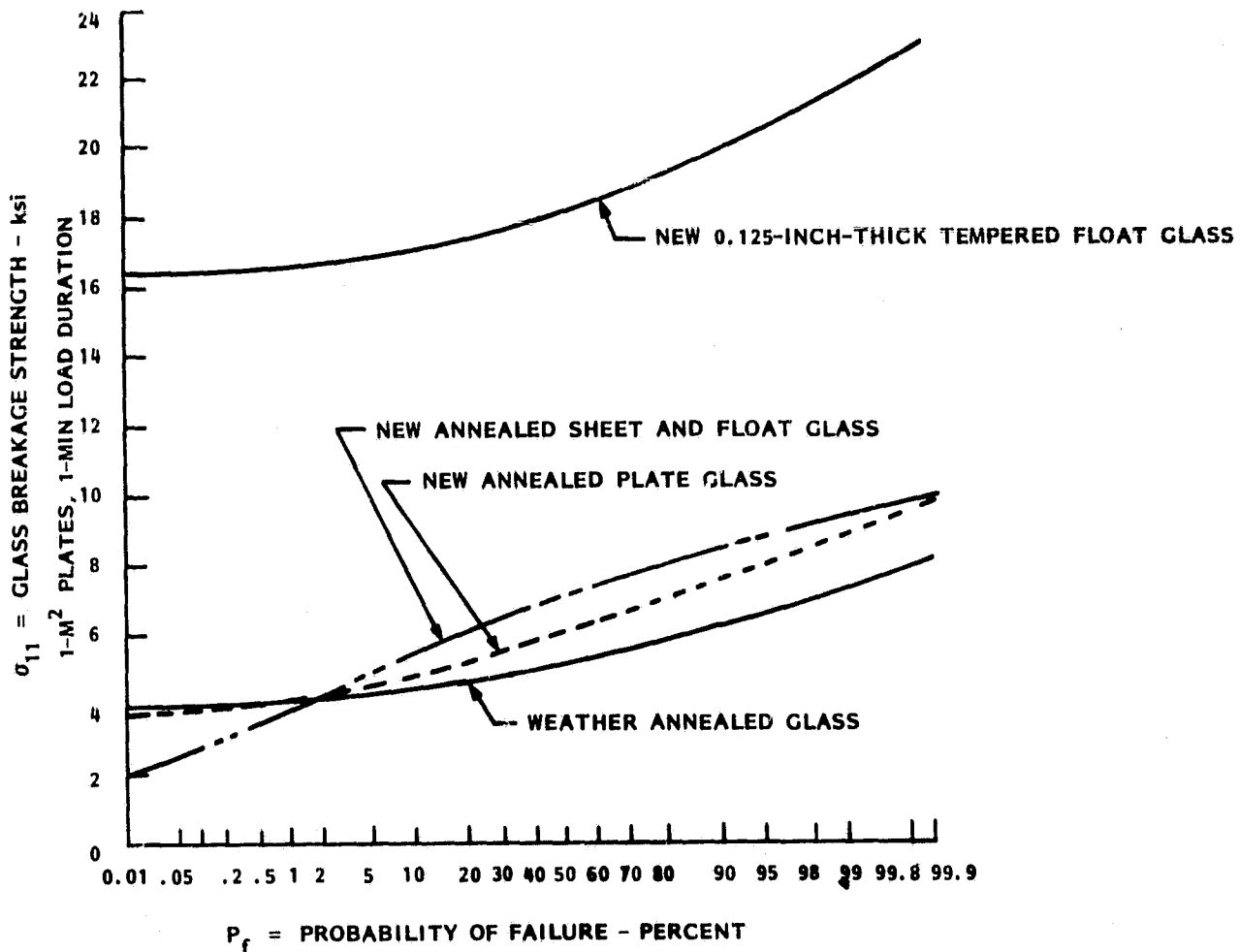


Figure 3-9. Recommended Design Values for Glass Breakage Strength (from JPL Document No. 5101-148)

where

f_A = fraction of breakage stress of a 1 square meter plate

$$f_A = \left(\frac{1}{A}\right)^{\frac{1}{6}}$$

f_T = fraction of 1 minute load duration breakage stress

For the plate size considered in this analysis ($A = 0.80645 \text{ m}^2$), the value of breakage strength can be reduced to

$$\sigma_B = 4368f_T$$

where the f_T values must be determined for each of the loading types considered. Table 3-2 lists this calculated breakage strength for each of the loading conditions analysed based on estimated values for load duration.

Table 3-2. Load Duration and Resulting Breakage Strength for Each Loading Condition

Load Description	Total Load Duration for 20 Yr. Life	f_T for Annealed Glass	σ_B (lb/in ²)
Dead Weight	20 Yrs.	0.51	2230
Snow	3 Days	0.62	2710
Wind	15 Min.	0.82	3580

The stresses due to the applied loads from Table 3-1 must be compared to the glass breakage strength from Table 3-2 to determine if the assumed glass thickness is adequate. ANSI A58.1 was used as a guide in the formulation of the combined loading criteria listed in Table 3-3. In all cases the plate design is considered to be structurally adequate if the numerical value for each criterion is less than one. As shown in Table 3-3, all load combinations considered have shown that the selected 0.188 inch thick annealed glass plate is structurally adequate for this application.

3.2.2.4 Encapsulation System

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 LSA 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 DuPont under the Elyax 150 identification number. The estimated cost of this material as a function of quantity ordered is given in Figure 3-10.

Table 3-3. Comparison of Applied Stress to Glass Breakage Strength

Combined Load Criteria	Value
$\frac{\sigma_D}{\sigma_{BD}}$	0.09
$\frac{\sigma_D + \sigma_S}{\sigma_{BS}}$	0.57
$\frac{\sigma_D + \sigma_W}{\sigma_{BW}}$	0.75
$.75 \left[\frac{\sigma_D + \sigma_S + \sigma_W}{\sigma_{BW}} \right]$	0.84

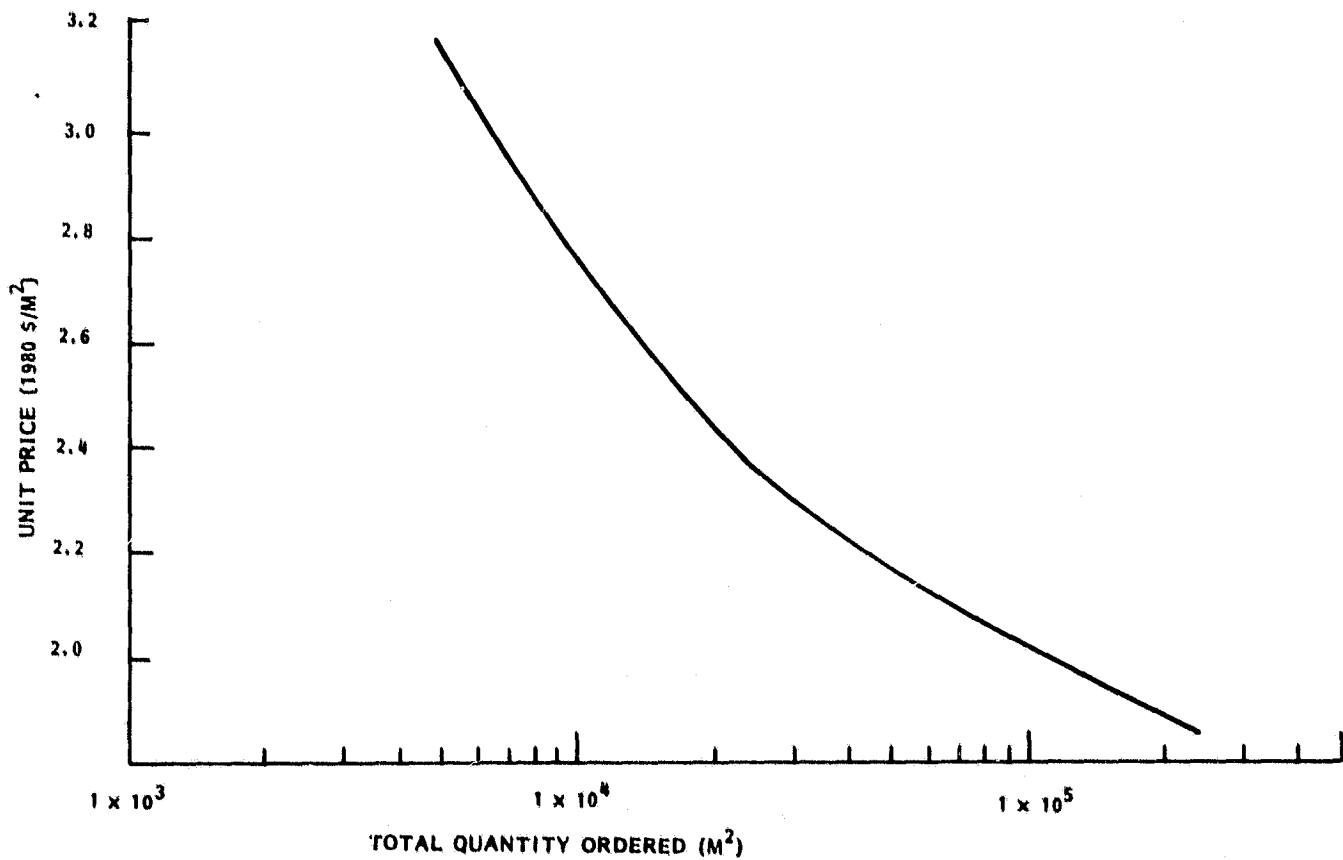


Figure 3-10. Estimated Price of Elvax 150 Sheet Containing the Springborn A9918 Additive Package

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. This rear cover sheet, which is a laminate of 18 μm (0.0007 inch) thick aluminum foil to 76 μm (0.003 inch) thick Korad film, functions as both the rear side vapor barrier and the exposed dielectric layer. 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.

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 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.

Consistent with the ground rules of this contract, the production costing of the encapsulated cell subassembly has reflected current processing technology which includes the application of a primer to all bonded surfaces and a 50 to 60 minute batch lamination/cure cycle in a dual chamber vacuum laminator.

3.2.2.5 By-Pass Diode Installation

Three by-pass diodes are installed as an integral part of each encapsulated cell subassembly as shown in Figure 3-7. As discussed in Section 3.2.2.2, each diode could be required to dissipate 4.8 watts under conditions resulting from the complete open-circuit failure of a parallel-connected cell pair. A steady-state thermal model for the proposed diode chip mounting configuration was formulated as shown in Figure 3-11 and used as 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.

Under these conditions the forward conducting by-pass diode will reach a 120°C junction temperature if the chip is soldered to a 0.020 inch thick copper strap which is 1.00 inch wide by 4.00 inches long.

3.3 MODULE PRODUCTION COST ANALYSIS

3.3.1 ASSUMPTIONS AND CONSTRAINTS

The selected module design described in Section 3.2 was analyzed with respect to manufacturing costs under two annual production rate scenarios: 10,000 and 50,000 m^2 of solar

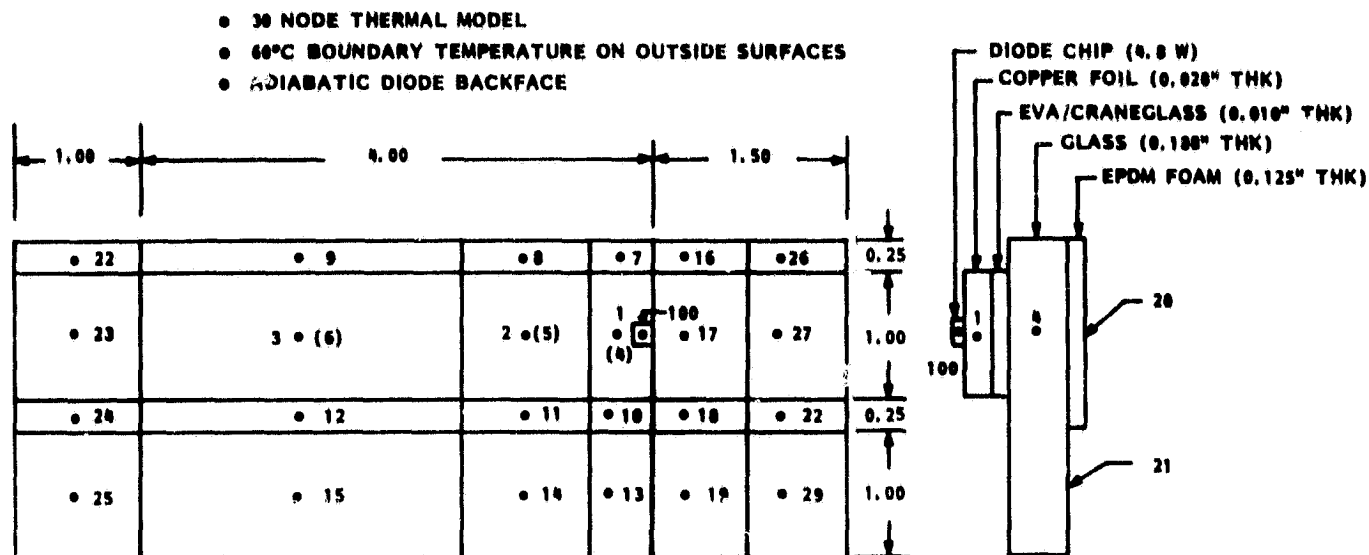


Figure 3-11. Thermal Model for By-Pass Diode Installation

cell area. As shown in Table 3-4, these production rates represent 13,889 and 69,444 modules per year, respectively. The highest production rate to be considered under this contract (viz., 500,000 m² per year) requires a high level of plant automation which is still being analyzed for inclusion in the final report.

Table 3-4. 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 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 m² per year) a minimum of 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:

- a. Optimum unit for handling and storing.
- b. Optimum arrangement of equipment so as to minimize the negative effect to output if a particular machine goes down.
- c. Adequate buffers in production flow.
- d. Functions best accomplished in continuous flow vs. functions best accomplished in batches.
- e. Optimum utilization of manpower.
- f. Achieving output requirements with a balanced line factory based on reasonable projections for output and technological advances for equipment involved.
- g. 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.

3.3.2 PROCESS DESIGN AND PLANT LAYOUT

3.3.2.1 Lowest Production Rate

At the lowest production rate to be considered in this analysis (viz., 10,000 m² 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 3-12 and 3-13, 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.

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:

a. Flux and Load - 10 sec/cell x 12 cells	= 120 sec
b. Place parallel interconnects = 5 sec/cell x 12	= 60 sec
c. Transfer Carrier	= 30 sec
d. Unload and Check	= <u>30 sec</u>
	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.

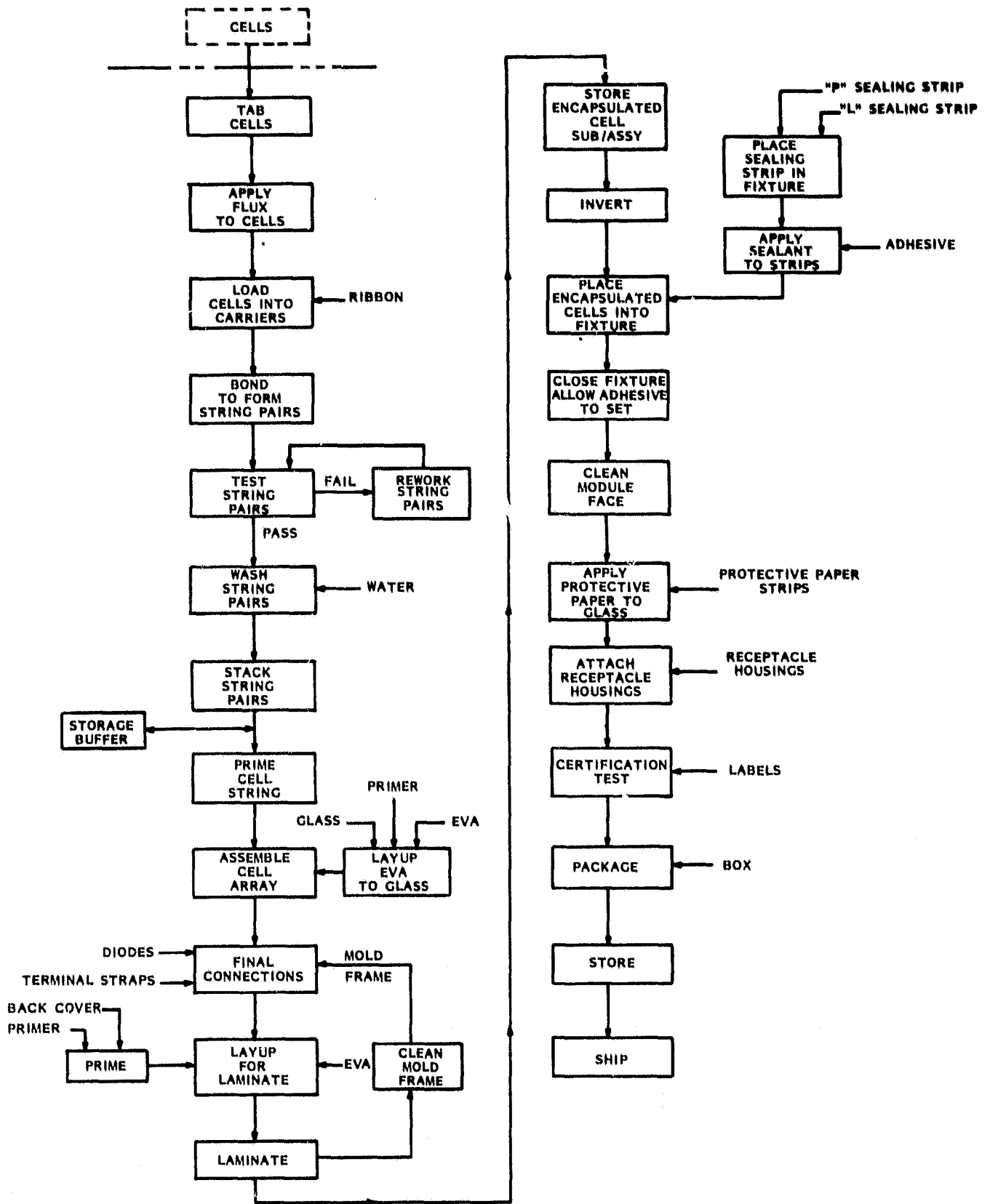


Figure 3-12. Process Flow Diagram for Lowest Production Rate

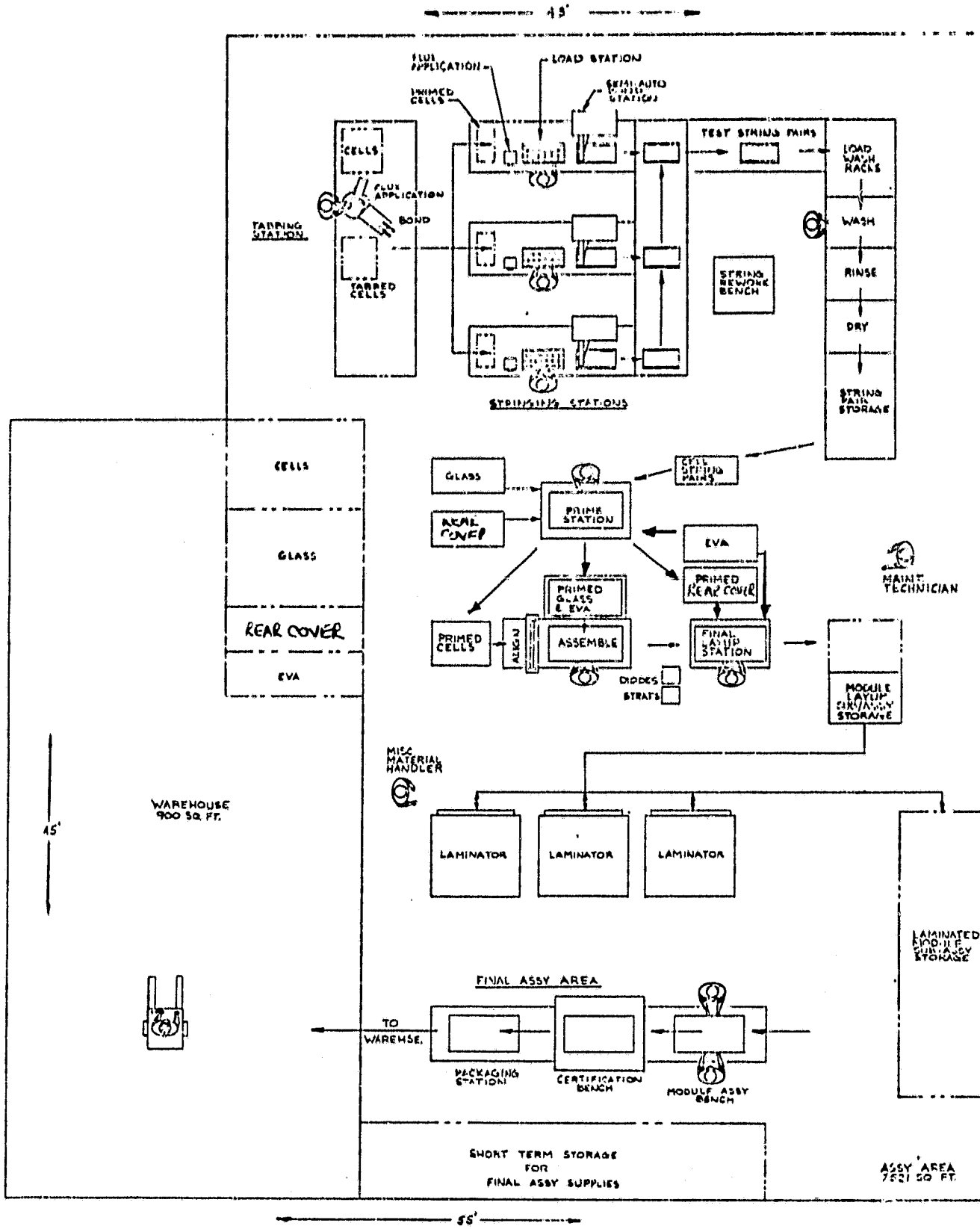


Figure 3-13. Plant Layout for Lowest Production Rate

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 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 3-5 along with the associated utility service requirements. The manpower requirements for the assembly area and warehouse area are enumerated in Table 3-6.

3.3.2.2 Median Production Rate

At the 50,000 m² 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

**Table 3-5. 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 3-6. 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

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 3-14 with the corresponding plant floor layout as depicted in Figure 3-15. 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.

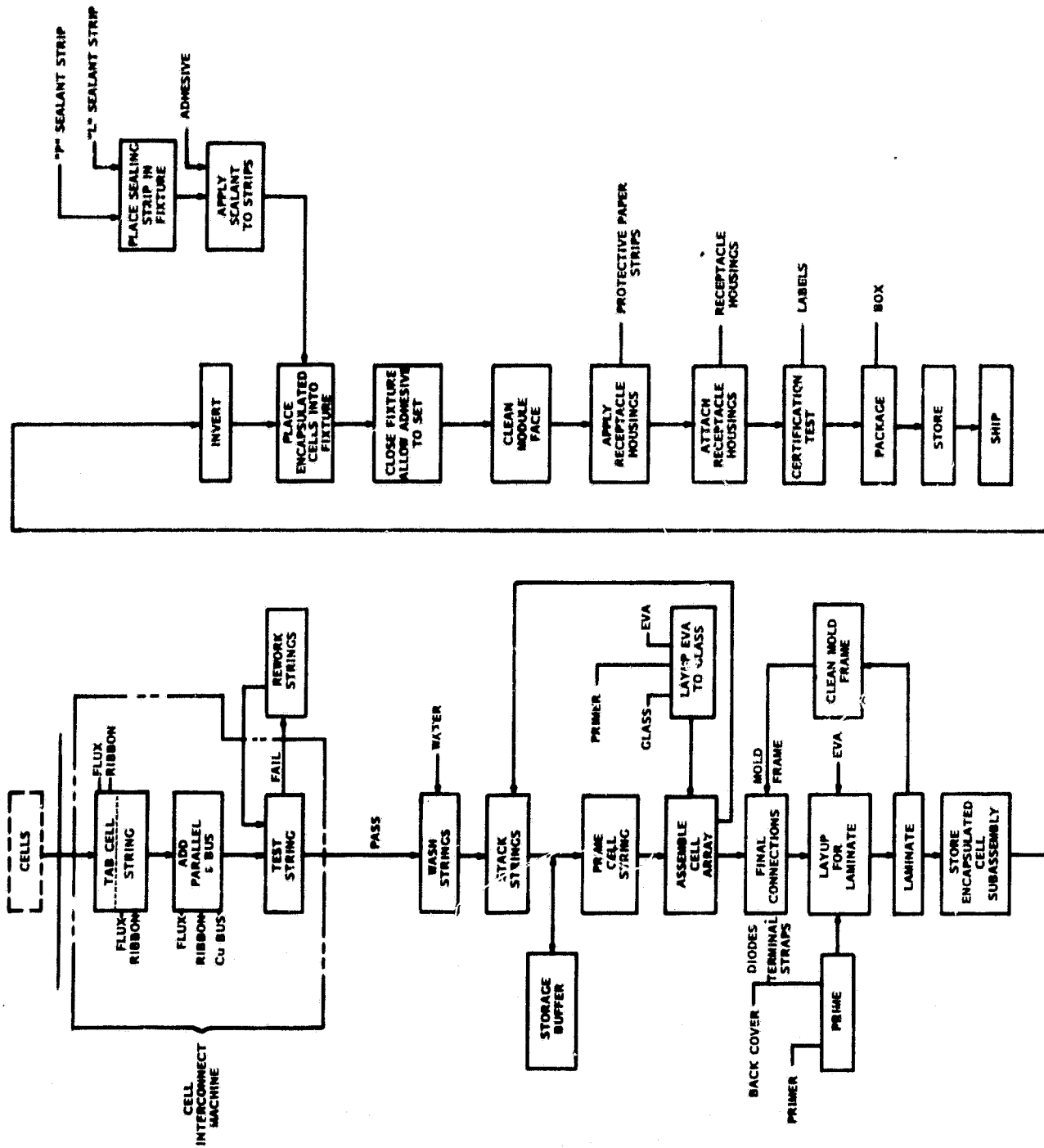
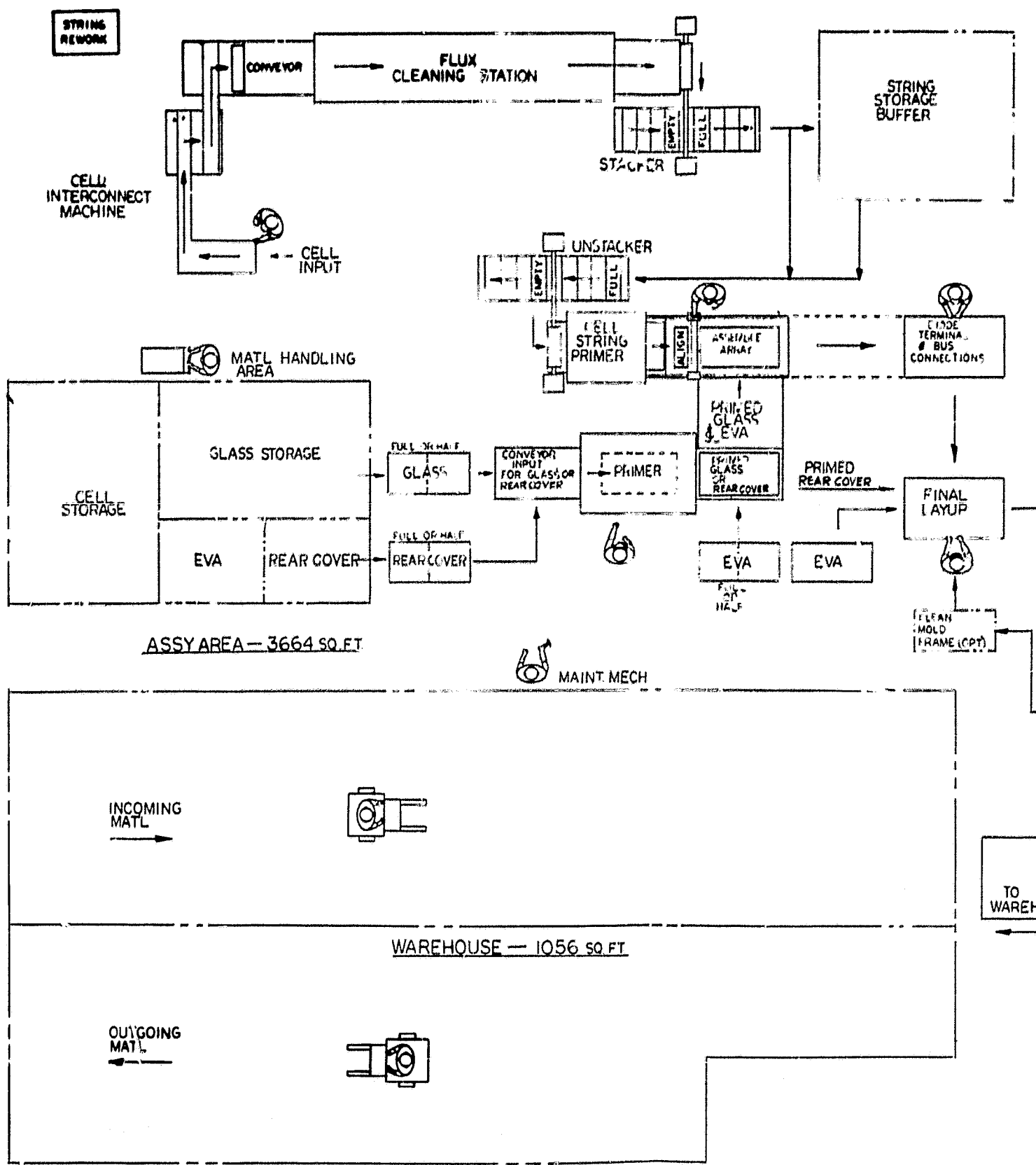


Figure 3-14. Process Flow Diagram for Median Production Rate



FOLDOUT FRAME

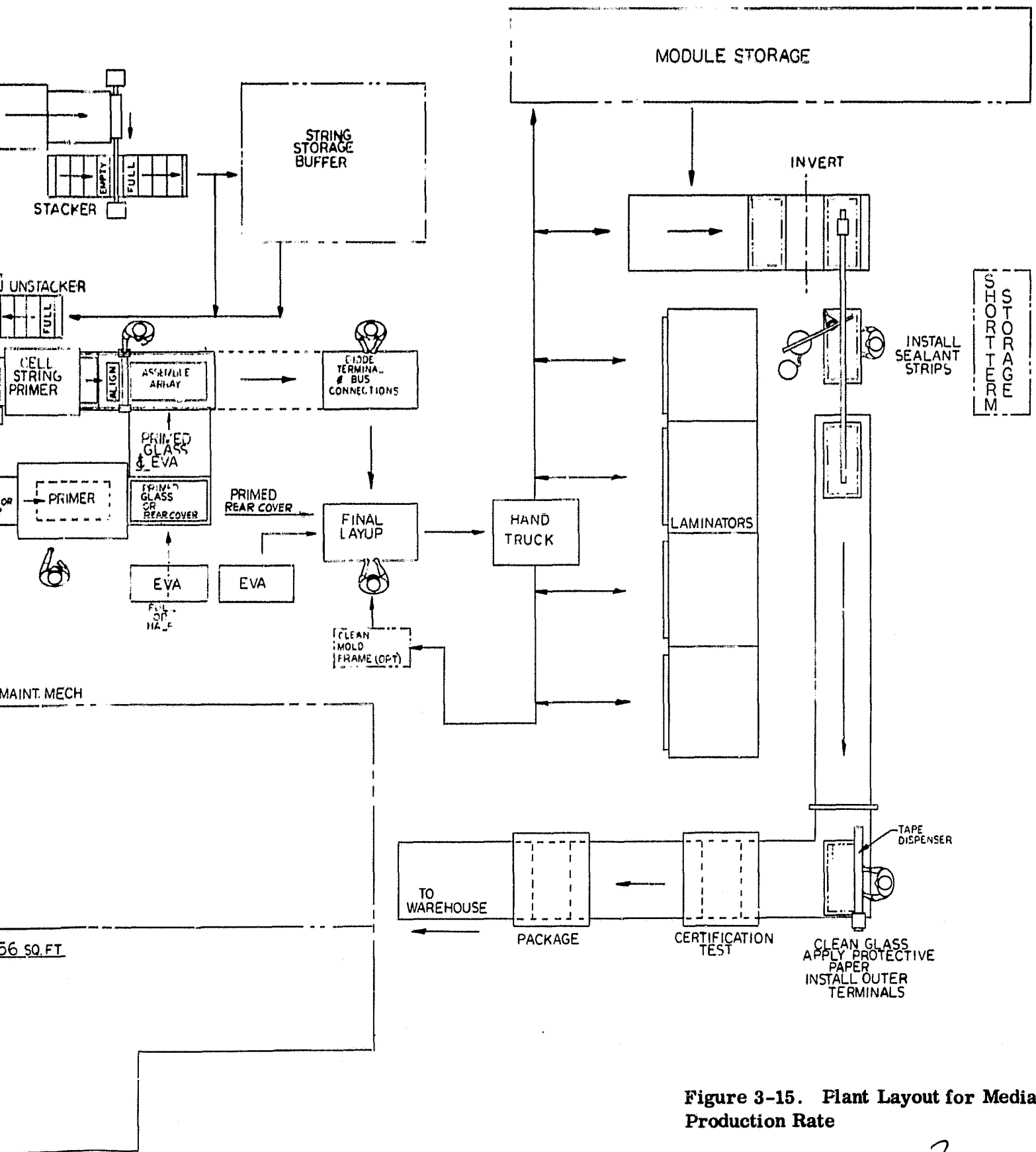


Figure 3-15. Plant Layout for Median Production Rate

FOLDOUT FRAME

In the cleaning station, the cell string pairs are rinsed 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 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 upstream 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 down 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 the 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 in Section 3.3.2.

The estimated cost of the equipment required for this plant is listed in Table 3-7 along with the associated utility service requirements. The direct plant labor requirements for the assembly and warehouse areas are enumerated in Table 3-8.

**Table 3-7. 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 K	
String Rinsing Machine	60 K	1.0 kW 10 gpm water
String Stacker	8 K	0.2 kW
String Storage and Buffer Area (500 Boxes @ \$2)	1 K	
Unstacker	8 K	0.2 kW
Cell Priming Machine	30 K	0.5 kW
Array Assembly Station	12 K	0.2 kW
Diode, Terminal and Bus Connections (Including 2 Weld Heads, Fixturing Automatic Feed Mechanism)	35 K	0.5 kW
Final Layup	2 K	
Primer Dispensing Station	15 K	
Laminators (4 @ \$60 K)	240 K	24.0 kW 0.04 cfm air 1.6 gpm water
Conveyors and Misc. Handling Aids	53 K	0.5 kW
Module Invert	3 K	
Robotic Arm (Includes Sealant Dispenser)	20 K	0.8 kW
Assembly Fixture	10 K	0.3 kW
Overhead Vacuum Transfer	5 K	0.2 kW
Roller Conveyors	3 K	
Terminal Bench (Tilt Table)	1 K	0.1 kW
Test Station	50 K	0.5 kW
Box Station	1 K	
Totals	943 K	31.5 kW 6 cfm air 13.1 gpm water

**Table 3-8. 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	1
Load, unload laminator	
Deliver modules to output conveyor and buffer Storage	
General material handling and relief	1
Move module laminate assembly to assembly bench	1
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	
Install outer terminal covers	1
Perform certification test	
Place module in carton	
Move packaged modules into warehouse	
Bring cartons to short term storage area	
Plant and machine maintenance technician	1
Warehousing, shipping and receiving	2
Total	11

3.3.3 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 3-9 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 volume required for the lowest production rate would result in a 20 percent increase in the total material cost per module.

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.

Table 3-9. Direct Material Inventory

Item Description	Part Number	Quantity Required Per Module	Estimated Cost Per Module (1980 \$)
Solar Cell	SVS10161	72	--
Glass Coverplate	47B258419P1	1	8.60
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			27.50

3.3.4 SUMMARY OF PROCESS AND COST PARAMETERS

Table 3-10 summarizes the production parameters which contribute to the determination of the factory FOB price of the module for the two production rates considered in this analysis. These production parameters were used along with the direct material cost to determine the total module cost in accordance with the methodology outlined in Table 3-11. 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 3-10. Summary of Production Parameters

Parameter	Value	
	Lowest Production Rate	Median Production Rate
Manpower (No. of Employees)	13	11
Floor Space (ft ²)	3421	4720
Utility Services		
Electricity (kW)	23.0	31.5
Air (cfm)	2.3	6.0
Water (gpm)	12.7	13.1
Equipment Cost (1980 \$)	465,500	943,000
Process Yield (%)		
Lamination	98	98
Final Assembly	99.5	99.5
Plant Operating Hours per Year	2376	7128
Annual Production Rate (Modules)	13,889	69,444

The direct labor costs, which were calculated as outlined in Item 1 of Table 3-11, were burdened at the rate of 170 percent as a labor overhead to account for indirect labor-related expenses, including salaries for plant management and supervision, company Social Security payments, holiday and vacation pay, plant maintenance, and other general utility services, such as telephones, lighting, heating and air-conditioning.

The cost of the direct material inventory in each module design concept was burdened at a 3 percent rate to account for the cost of purchasing and expediting functions.

The estimated cost of the process capital equipment was amortized over a five-year period and prorated on a per-module basis as shown in Item 5 of Table 3-11. Similarly, the factory floor space was rented at an annual rate of \$5.50 per square foot and prorated on a per-module basis.

Table 3-11. 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 = $\frac{(\text{Power} - \text{kW}) (\text{Plant Oper. Hrs. per Yr.}) (0.04)}{(\text{Annual Production Rate})}$

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

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

The expenses associated with process related utility services were accounted for as shown in Item 7 of Table 3-11. The most significant of these is the charge for electricity which is prorated over the annual production rate at \$0.04 per kWh.

Table 3-12 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 \$114.60 per module for the lowest production rate to \$70.62 per module for the median rate.

The module FOB factory price is presented in Figure 3-16 as a function of the cost of the solar cells. Both parameters are expressed in 1980 dollars per unit area, where 0.8045 m² is used as the module area. The price per unit area values, which correspond to the DOE Commercial Readiness Price Goals for 1982 and 1986 with a 13.5 percent encapsulated cell efficiency, have been indicated on this figure as reference points for comparison purposes.

The 1982 goal of \$2.80 per watt can be achieved with this design if cells are available in the \$170 to \$220 per m² (or \$1.26 to \$1.68 per watt) price range depending on the production rate selected. The \$0.70 per watt price level cannot be achieved at the production rates considered.

Table 3-12. Production Cost Summary

Cost Category	1980 \$ per Module	
	Lowest Production Rate	Median Production Rate
Direct Labor	19.46	9.88
Labor Overhead	33.08	16.80
Cost of Capital Equipment	6.70	2.71
Cost of Utility Services	0.16	0.13
Floor Space Rental	1.35	0.37
Direct Material *	33.74	28.12
Material Overhead	1.01	0.84
Subtotal	95.50	58.85
Profit and Warranty (20%)	19.10	11.77
Total Factory FOB Price	114.60	70.62

* Does not include the cost of solar cells.

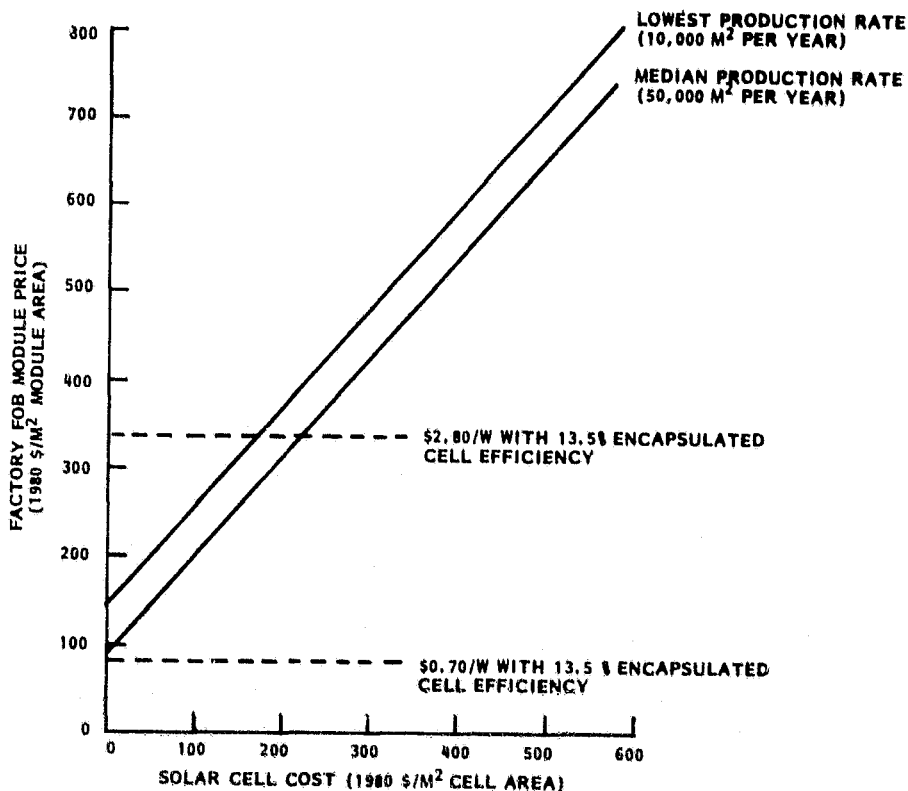


Figure 3-16. Module Production Cost as a Function of Solar Cell Cost

3.4 ARRAY INSTALLATION DETAILS

3.4.1 ARRAY LAYOUT AND ELECTRICAL INTERCONNECTION

A roof-mounted, residential photovoltaic installation consisting of 50 modules, arranged as shown in Figure 3-17, 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/cm² 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 3-17 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 3-17 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 3-17 and enlarged in Figure 3-18 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 3-18, 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.

3.4.2 ROOF INTERFACE AND CLAMPING HARDWARE

The selected module design, as described in Section 3.2, 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 section shown in Figure 3-19. 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 channel sections 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.

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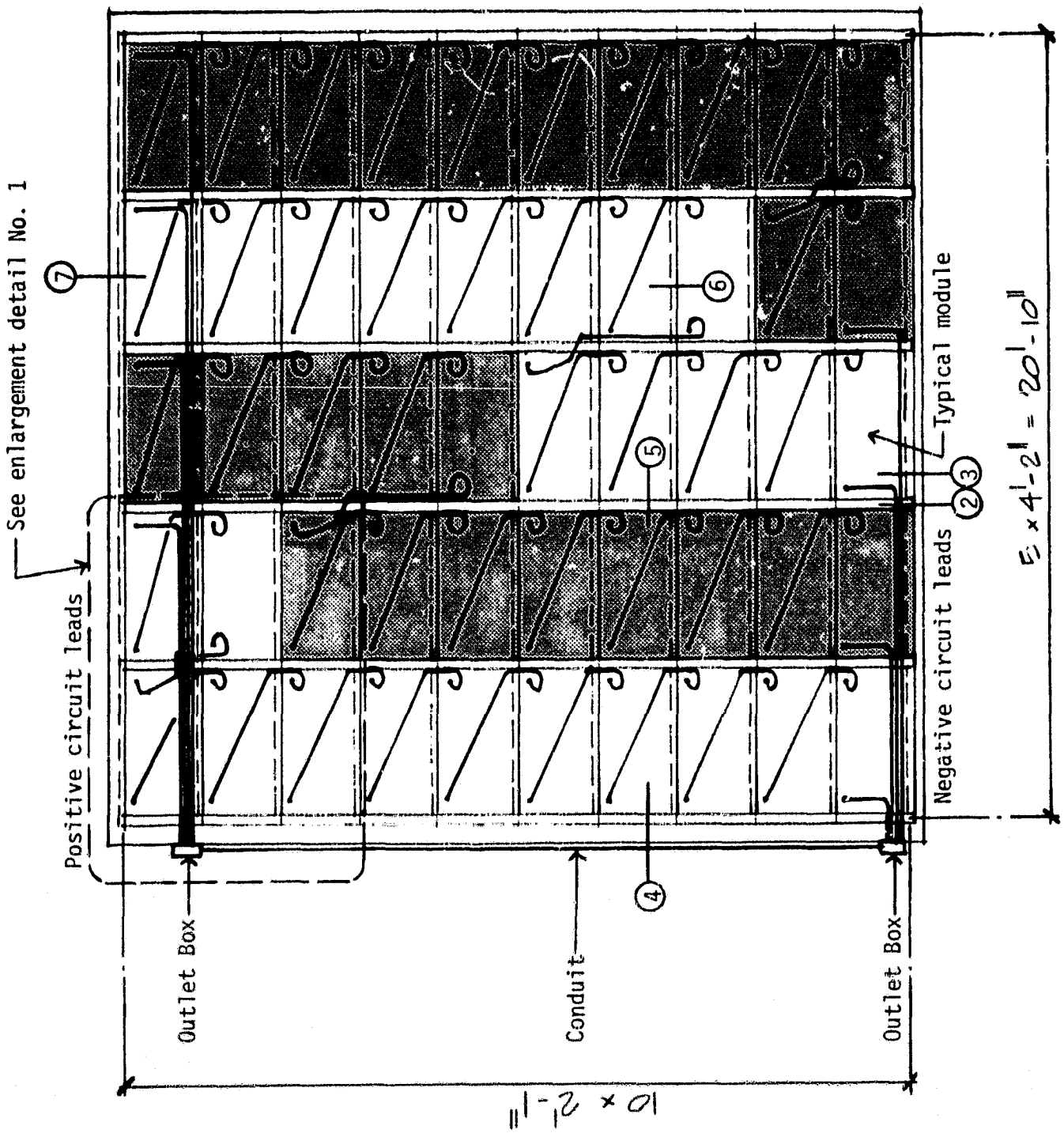


Figure 3-17. Array Layout and Wire Routing

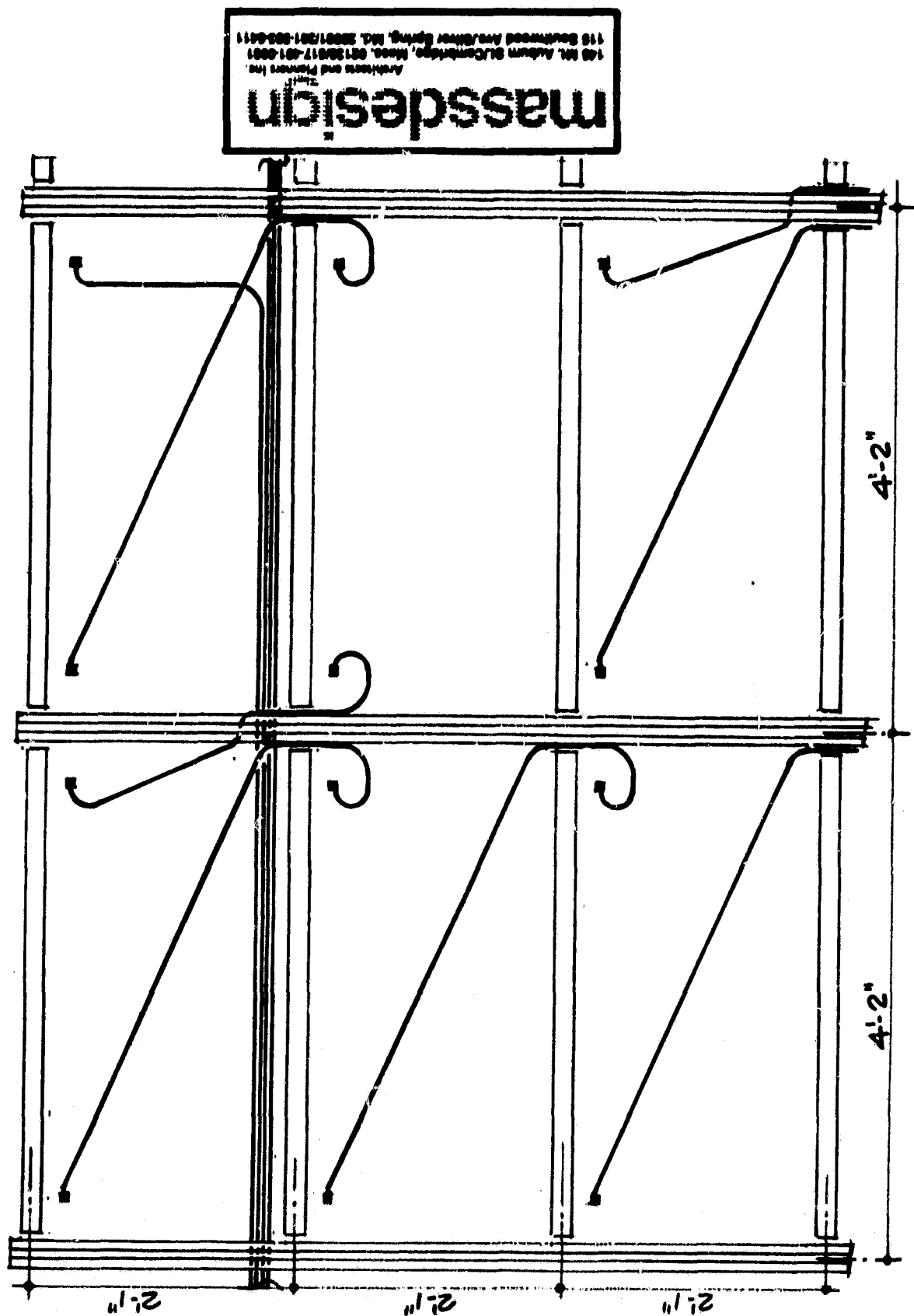
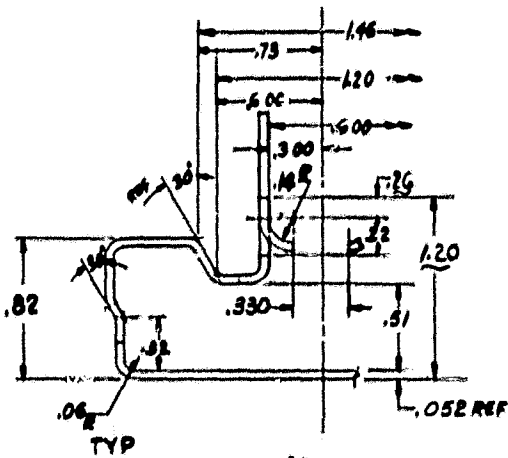
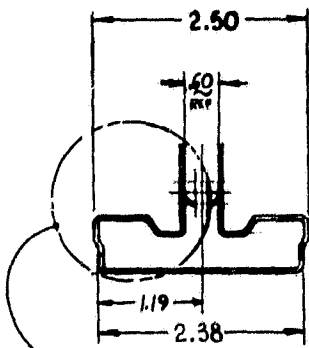
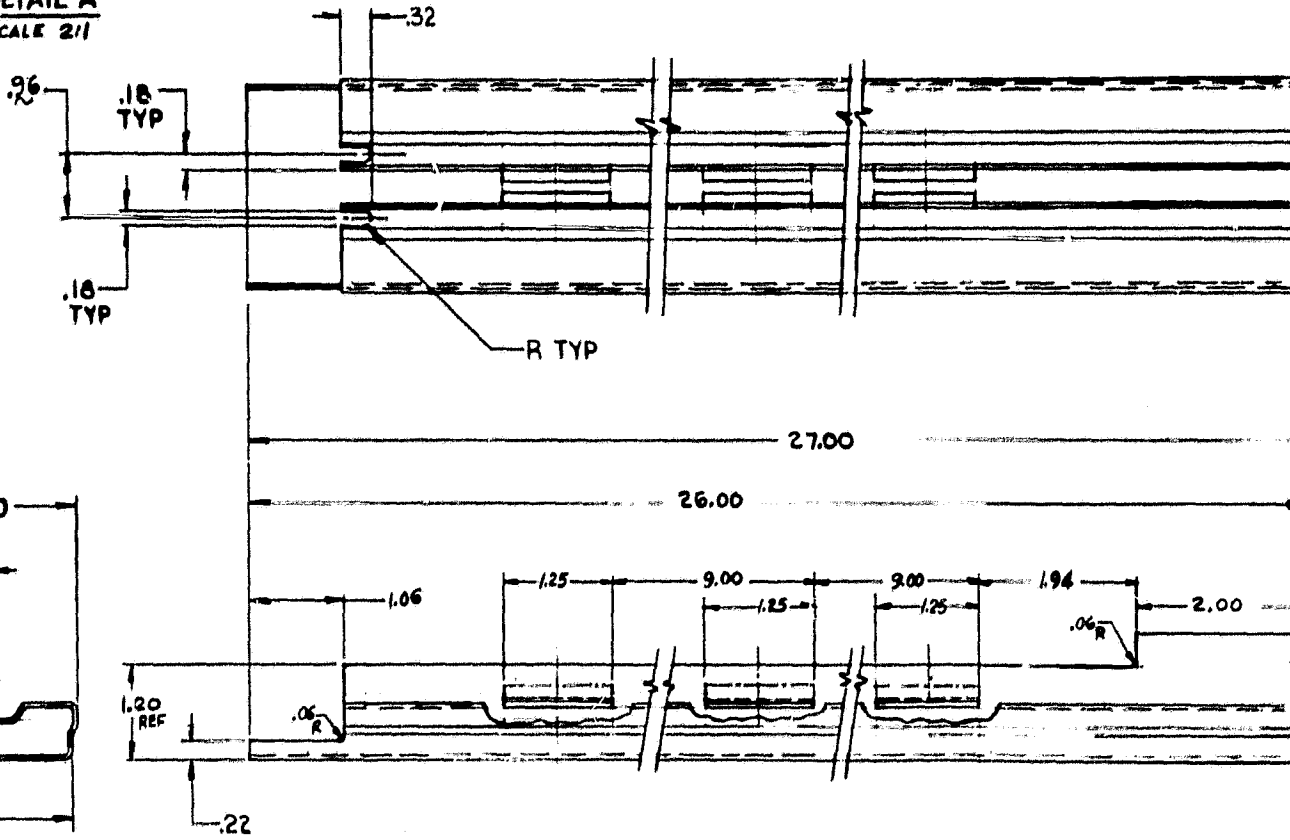


Figure 3-18. Module-to-Module Wiring Detail (Array Upper-left Corner)



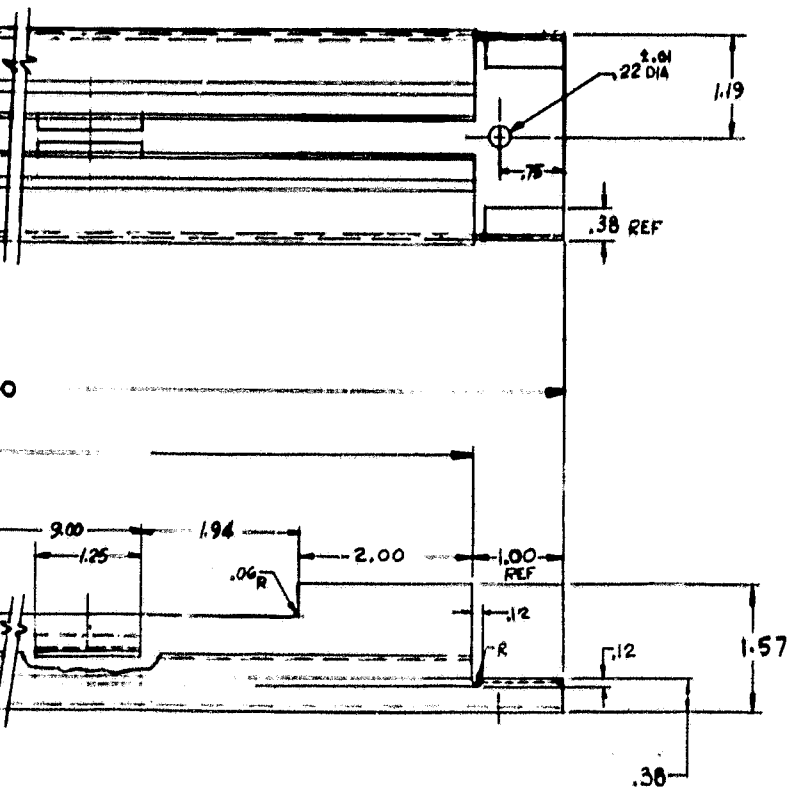
DETAIL A
SCALE 2:1



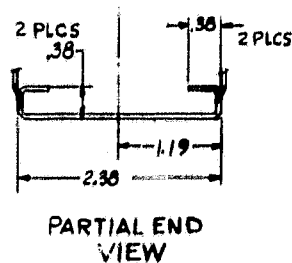
SEE DETAIL A

(PI) MAT'L - LOW CARBON STEEL
18 GAUGE (.052 THK), GALVANIZED

FOLDOUT FRAME



NOTES:-
 1.- DRAWING TERMS AND TOLERANCES PER
 ANSI Y 14.5



CARBON STEEL
 (.052 THK), GALVANIZED

2
 BOLDOUT FRAME

Figure 3-19. Support Channel

The roll-formed clamping strip shown in Figure 3-20 interfaces with the support channel and module to complete the joint as shown in Figure 3-21. Sheet metal screws inserted through holes in this clamping strip, 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 clamping strip 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 nested 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.

3.4.3 INTEGRAL MOUNT ROOF INTERFACE DETAILS

Figures 3-22 through 3-26 show the installation details which pertain to the integral mounting approach. As depicted in Figure 3-22 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.

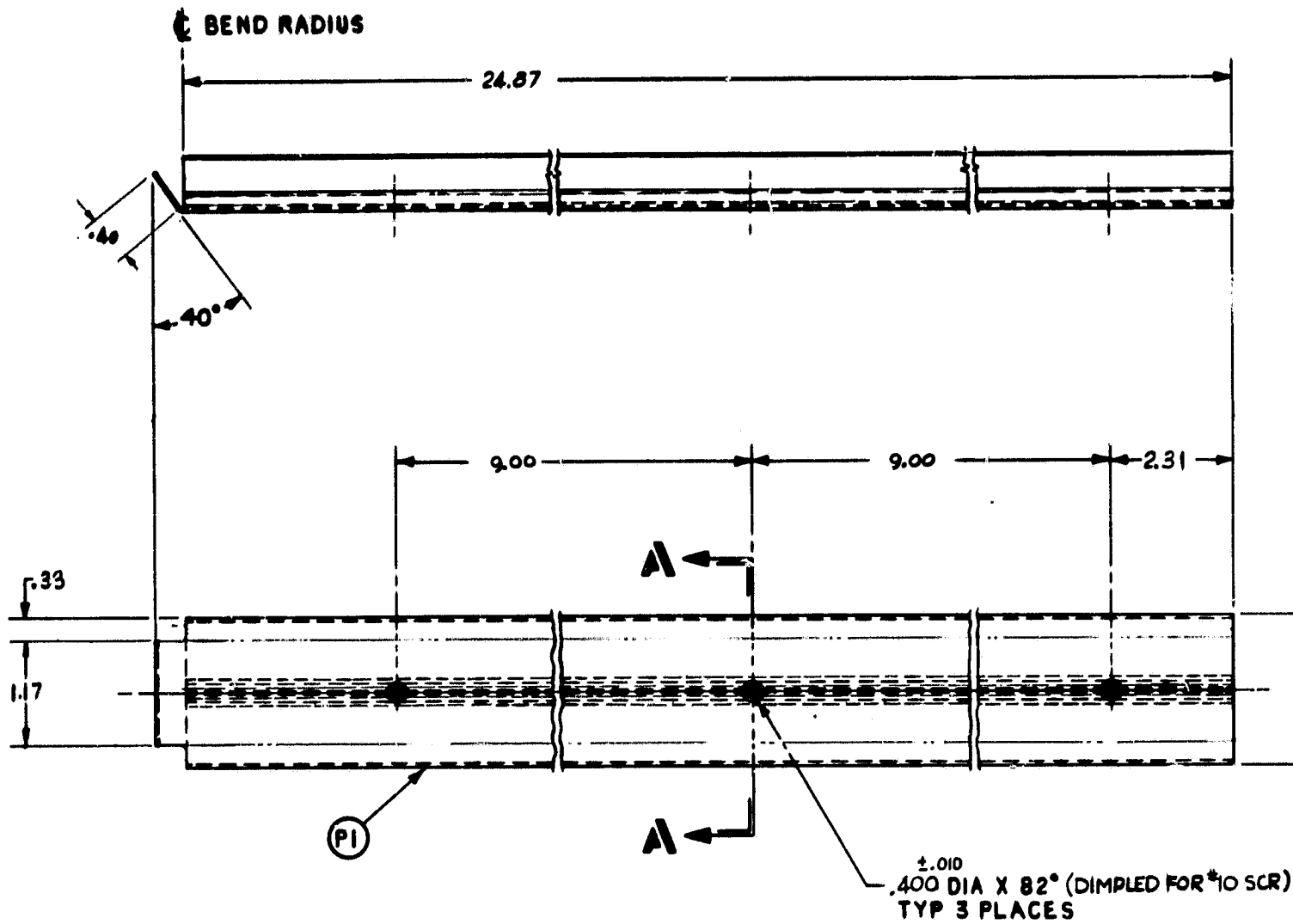
The eave details shown in Figures 3-23 and 3-24, reveal the method used to allow leakage water from the support channel trough to drop over the fascia. A short piece of the top section of support channel is cut to fit over the eave so that any water dripping down the trough formed by these nested channels 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 clamping strips as shown in Figure 3-25. Folded flashing which fits under the clamping strips continues the watertight surface over the fascia at the rake.

Figure 3-26 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 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.

3.4.4 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 3-27 through 3-30. 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.

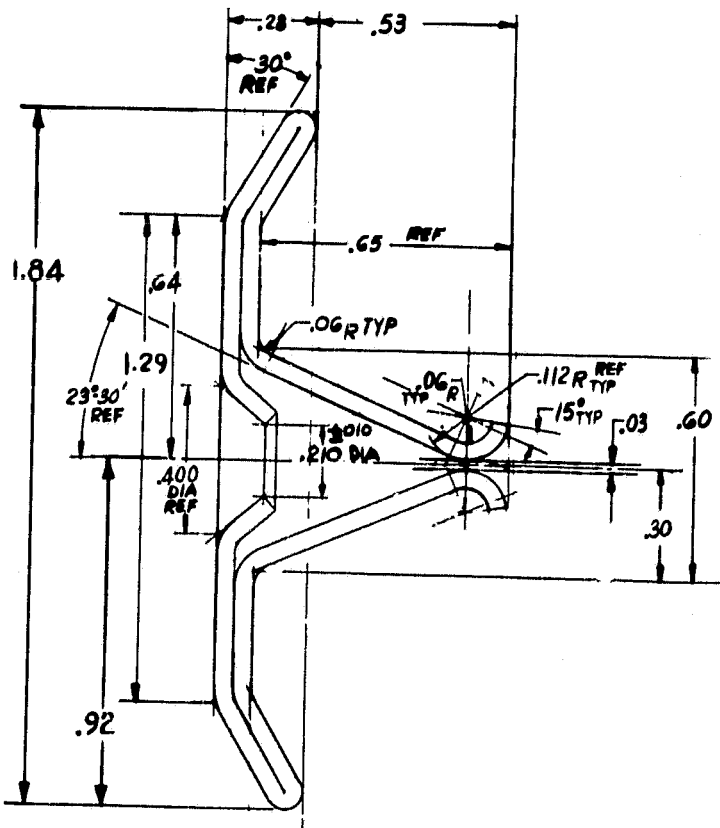


(PI) MAT'L - LOW CARBON STEEL
 18 GAUGE (.052 THK), GALVANIZED

FOLDOUT FRAME

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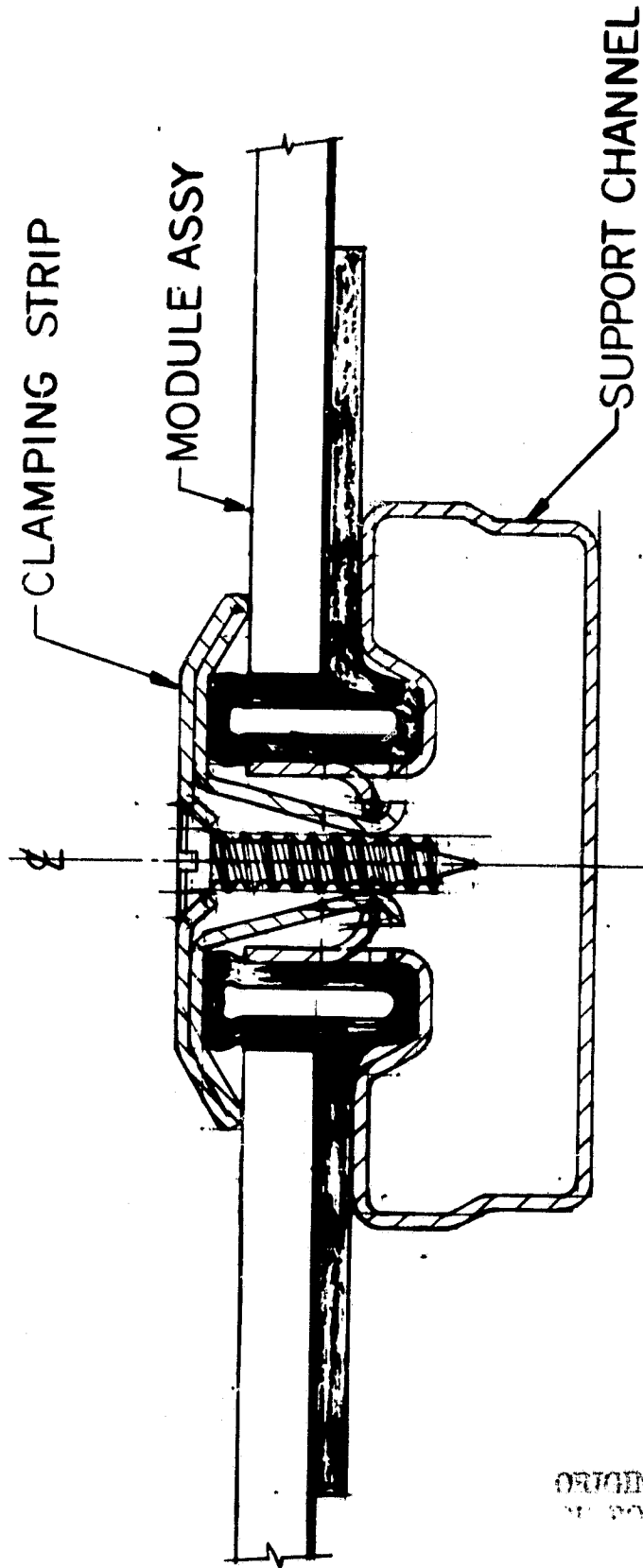
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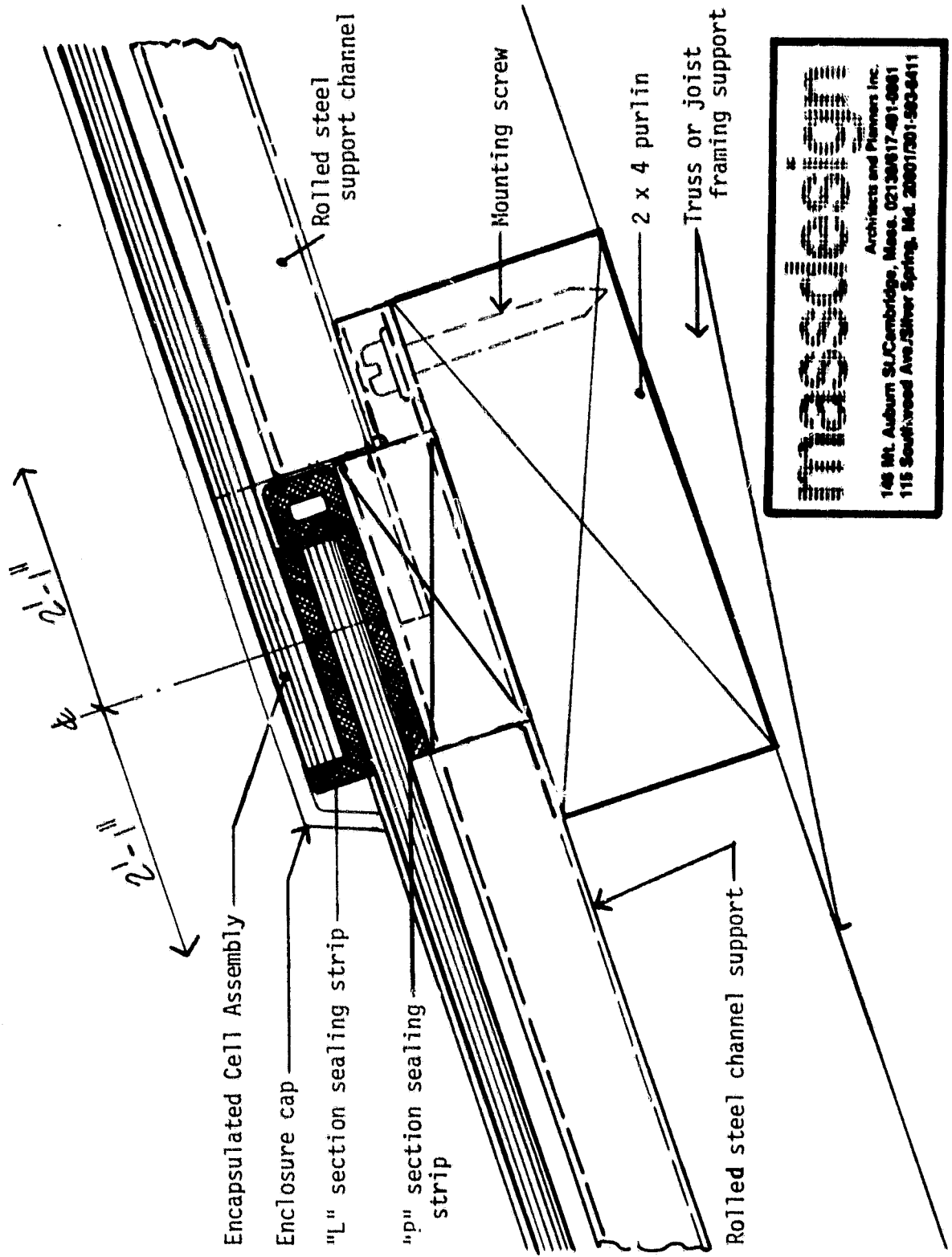
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Figure 3-20. Clamping Strip



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Figure 3-21. Module Clamping and Sealing Detail



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Figure 3-22. Typical Overlapped Joint (Integral Mount)

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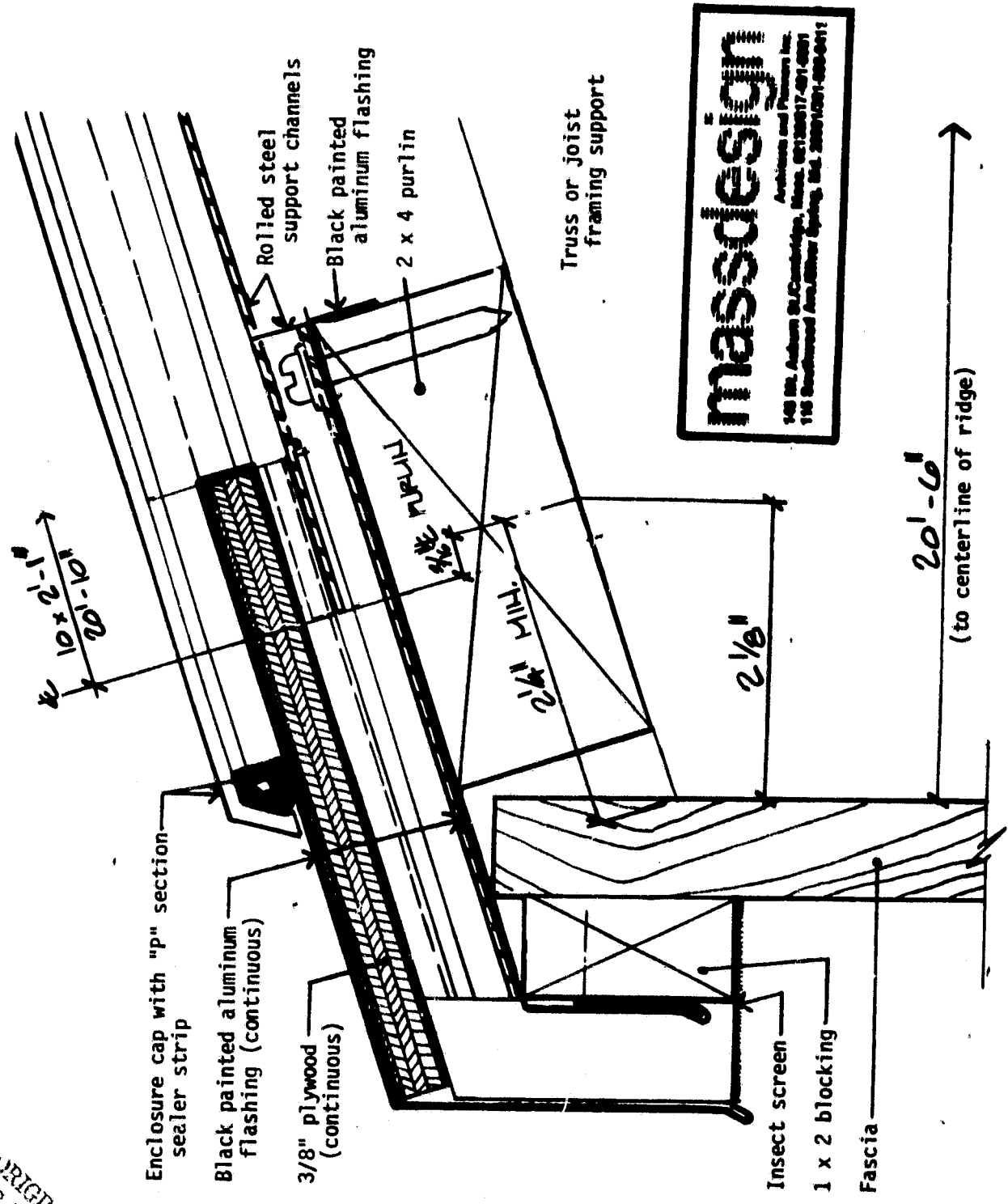


Figure 3-23. Eave Detail at Support Channel (Integral Mount)

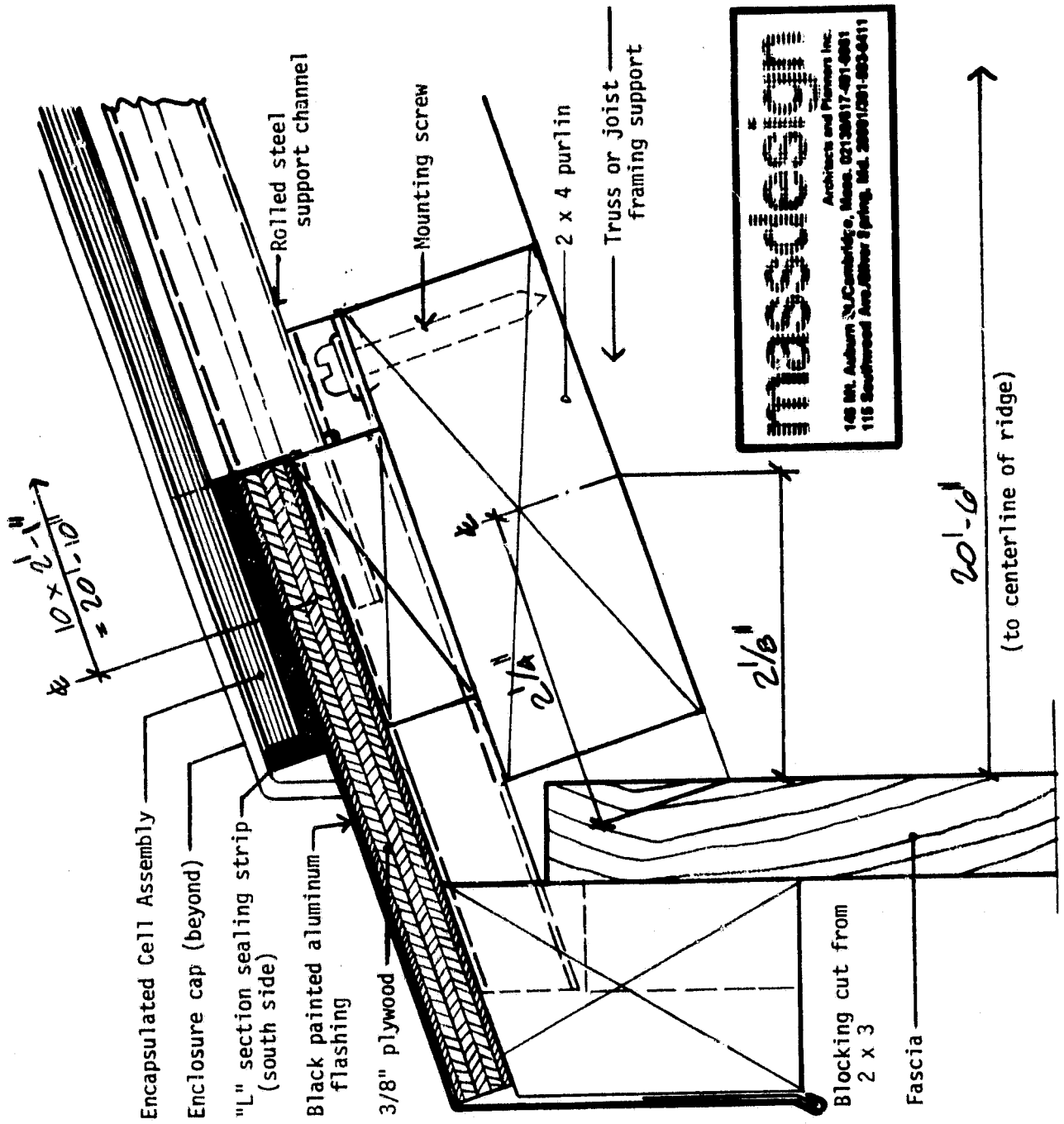
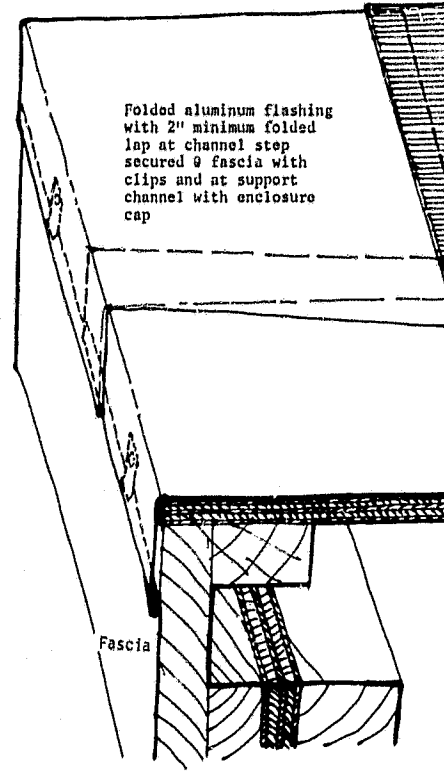
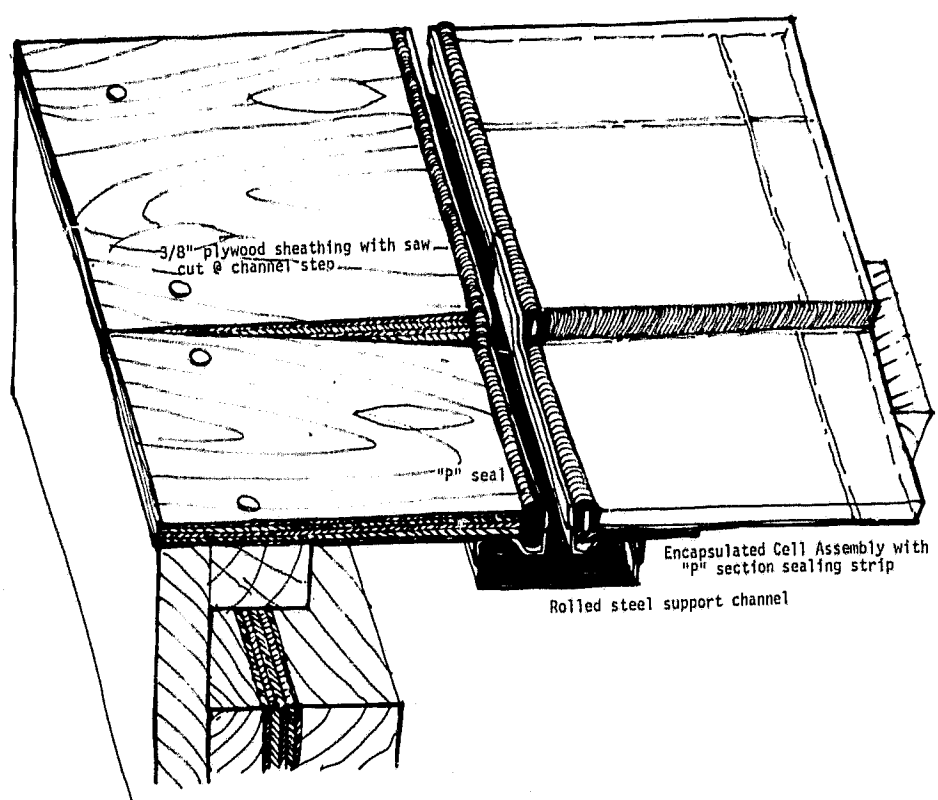
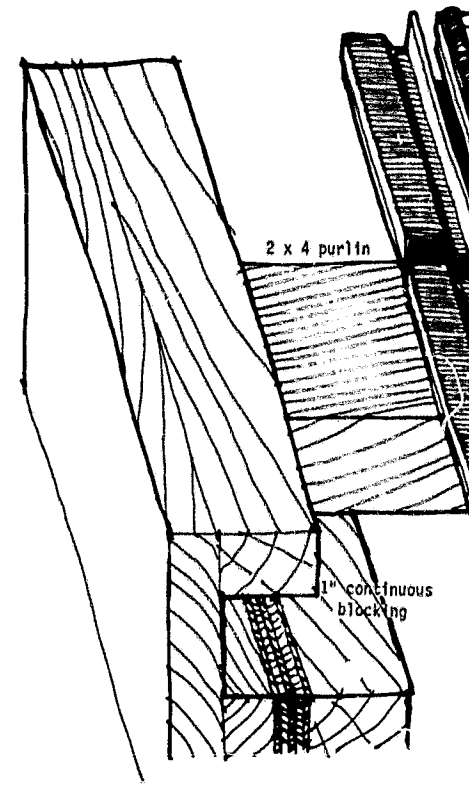
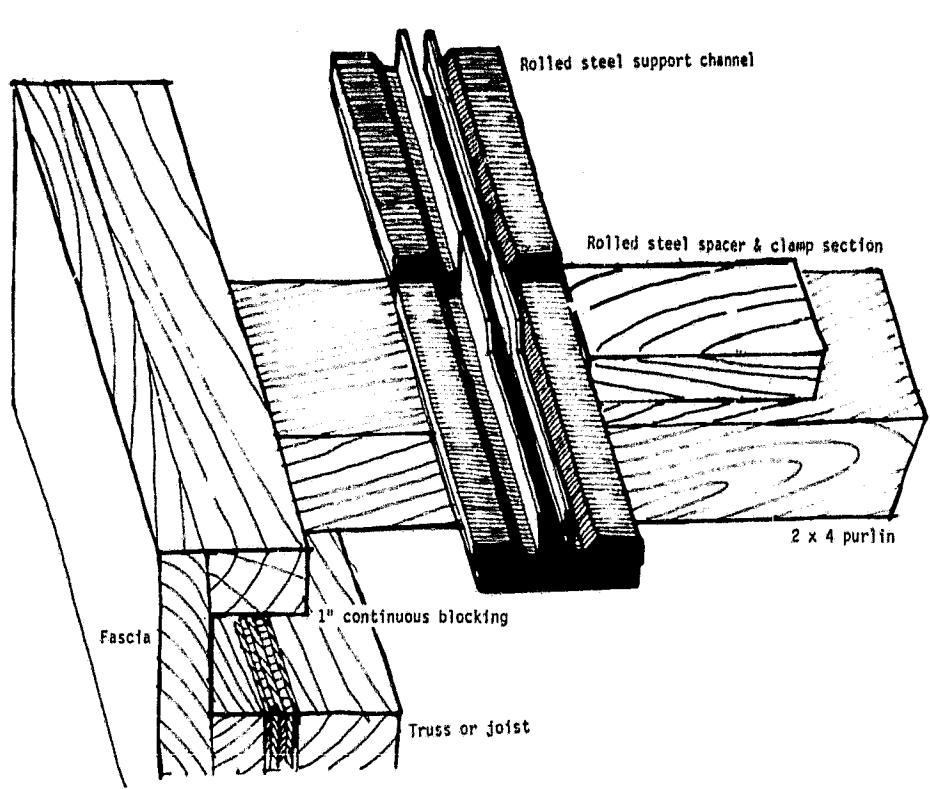


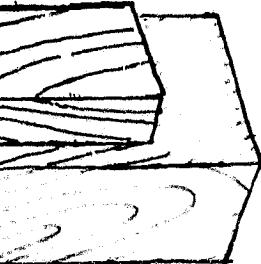
Figure 3-24. Eave Detail Between Support Channels (Integral Mount)



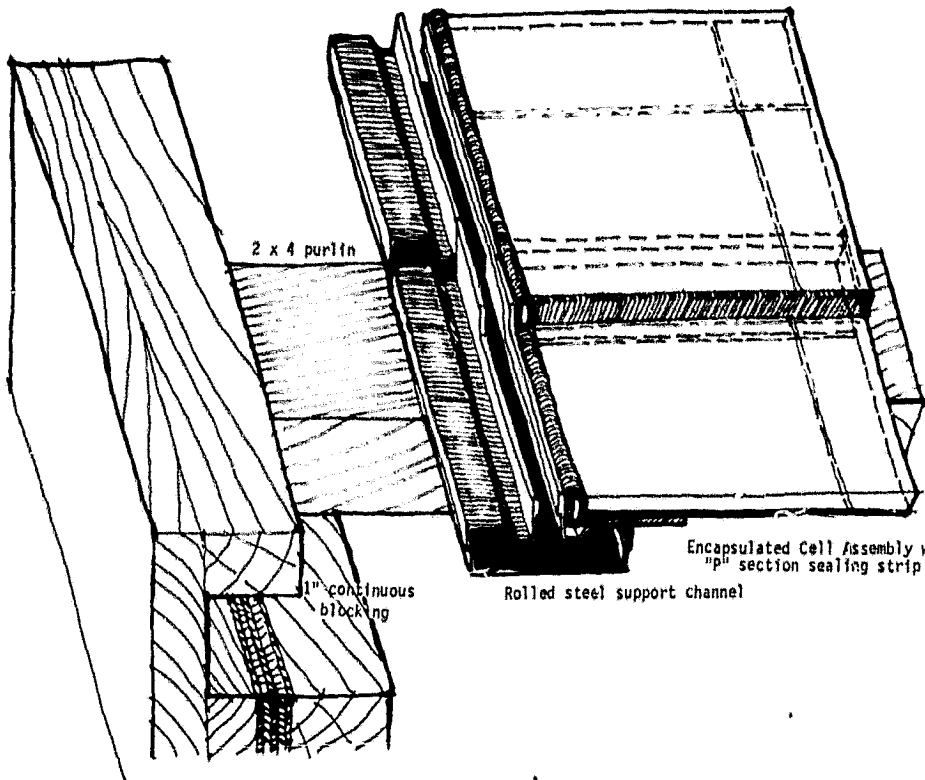
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port channel

eel spacer & clamp section



2 x 4 purlin

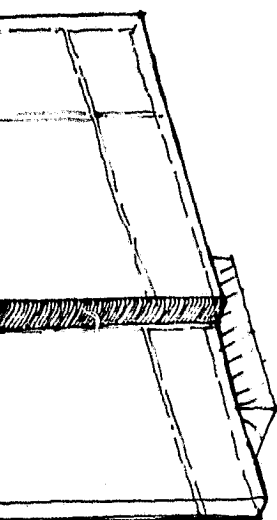


2 x 4 purlin

1" continuous blocking

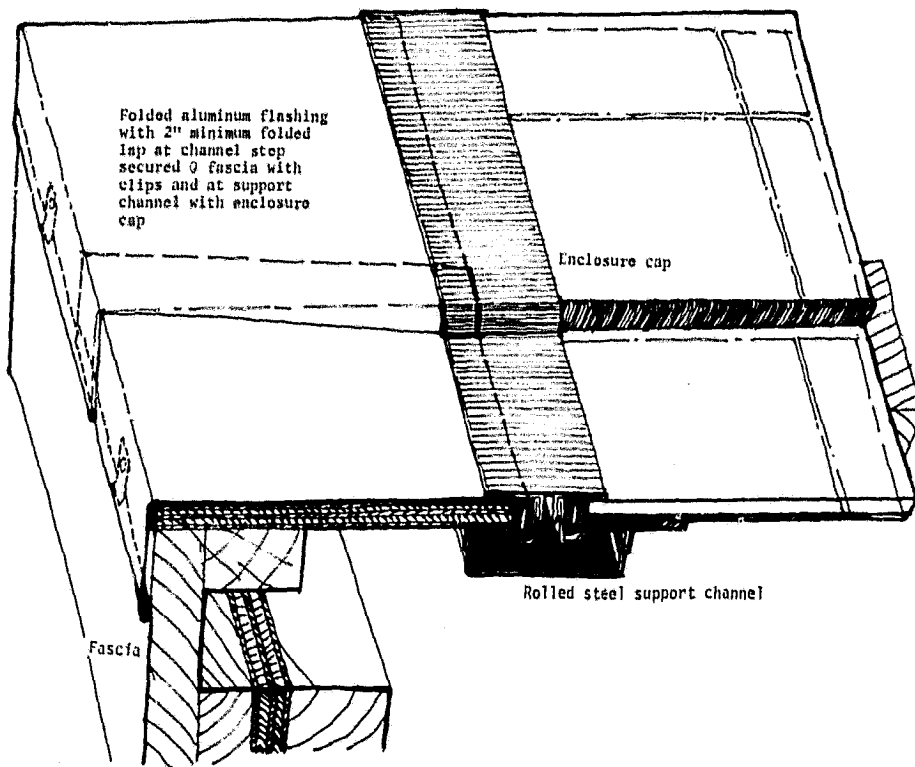
Encapsulated Cell Assembly with "P" section sealing strip

Rolled steel support channel



Encapsulated Cell Assembly with "P" section sealing strip

support channel



Folded aluminum flashing with 2" minimum folded lap at channel step secured O fascia with clips and at support channel with enclosure cap

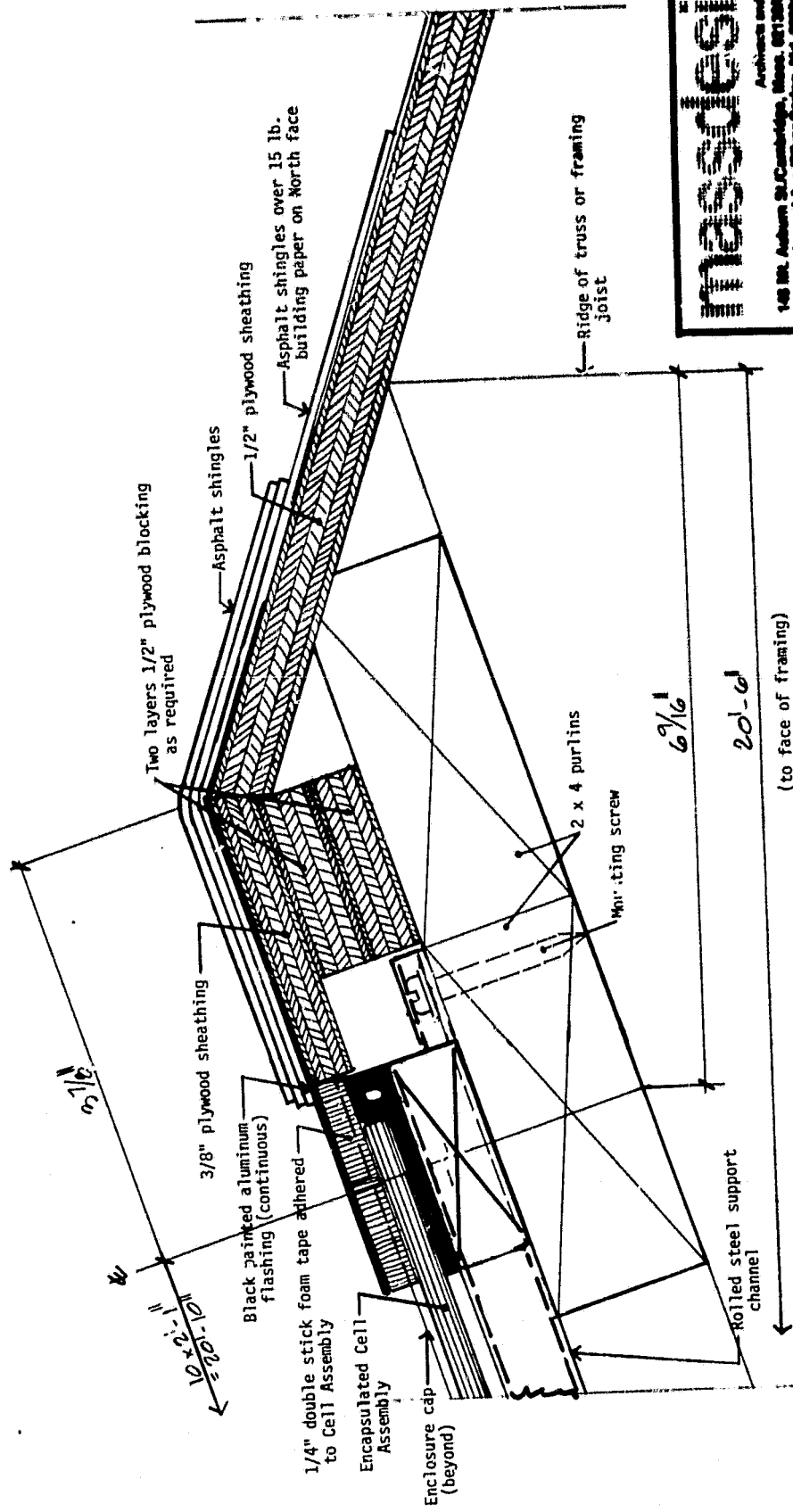
Enclosure cap

Rolled steel support channel

Fascia

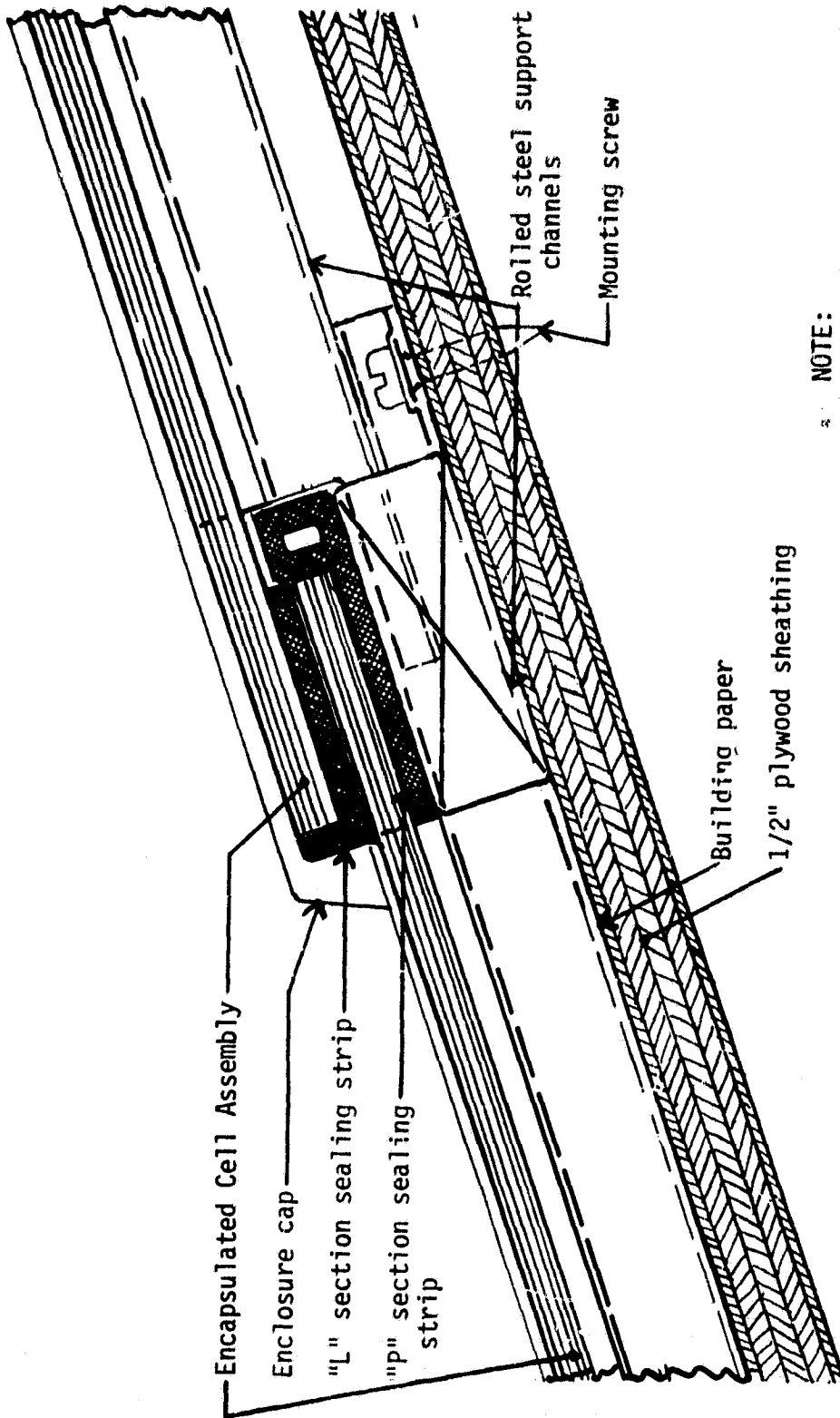
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Figure 3-25. Pictorial Views of Installation Sequence at Rake



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Figure 3-26. Ridge Detail (Integral Mount)



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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)

← Truss or joist support →

Figure 3-27. Typical Overlapped Joint (Direct Mount)

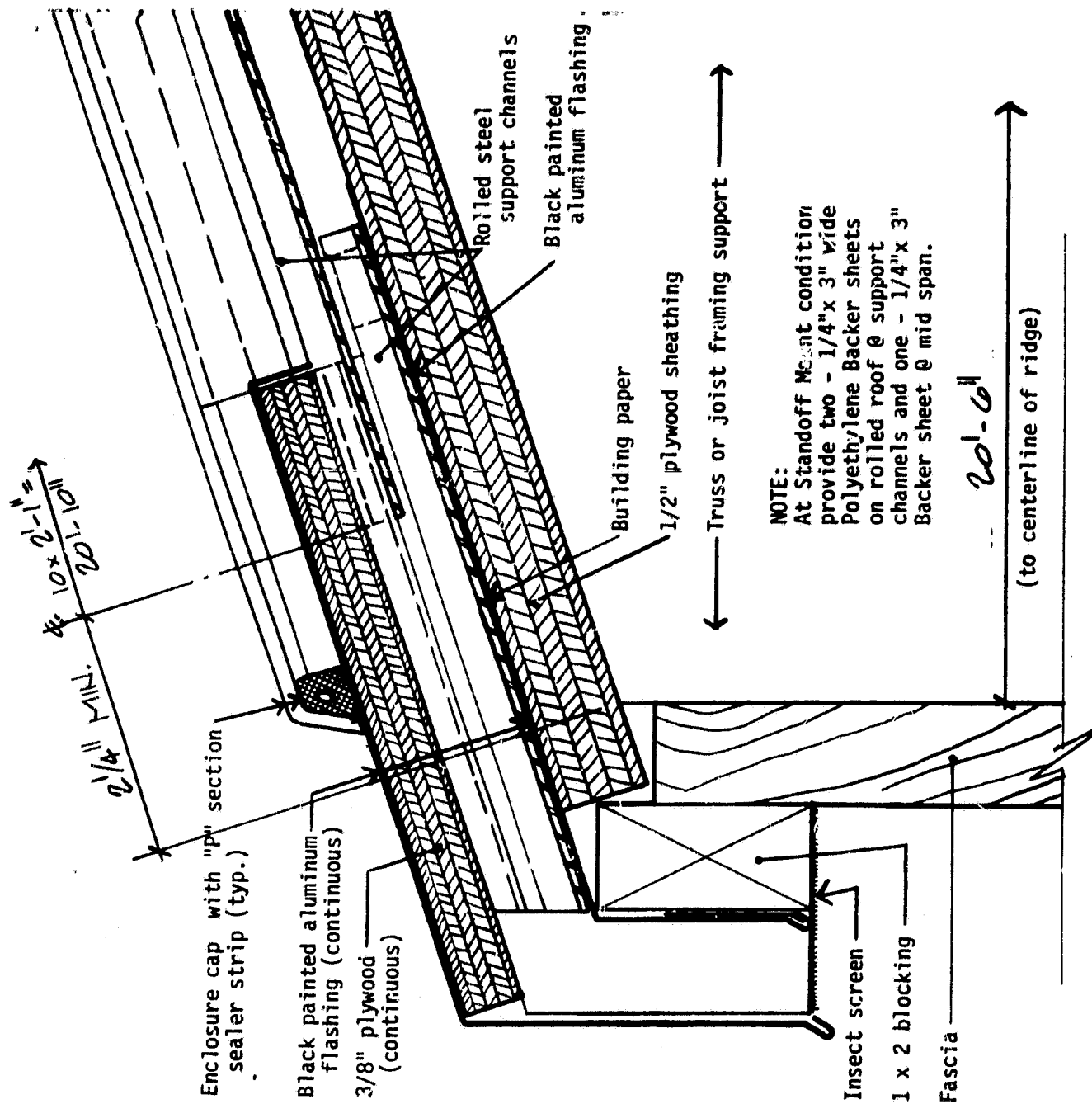


Figure 3-28. Eave Detail at Support Channel (Direct Mount)

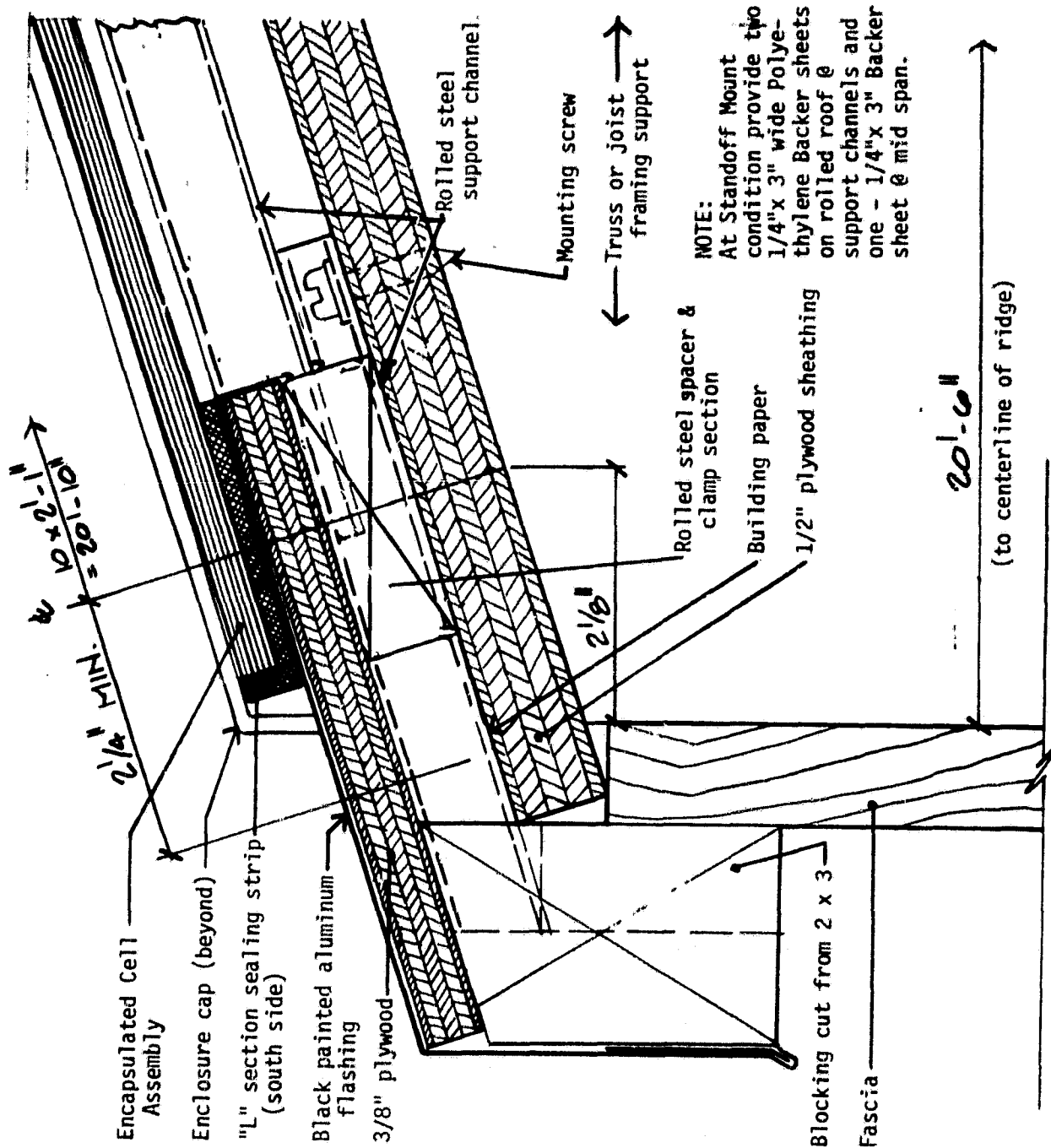
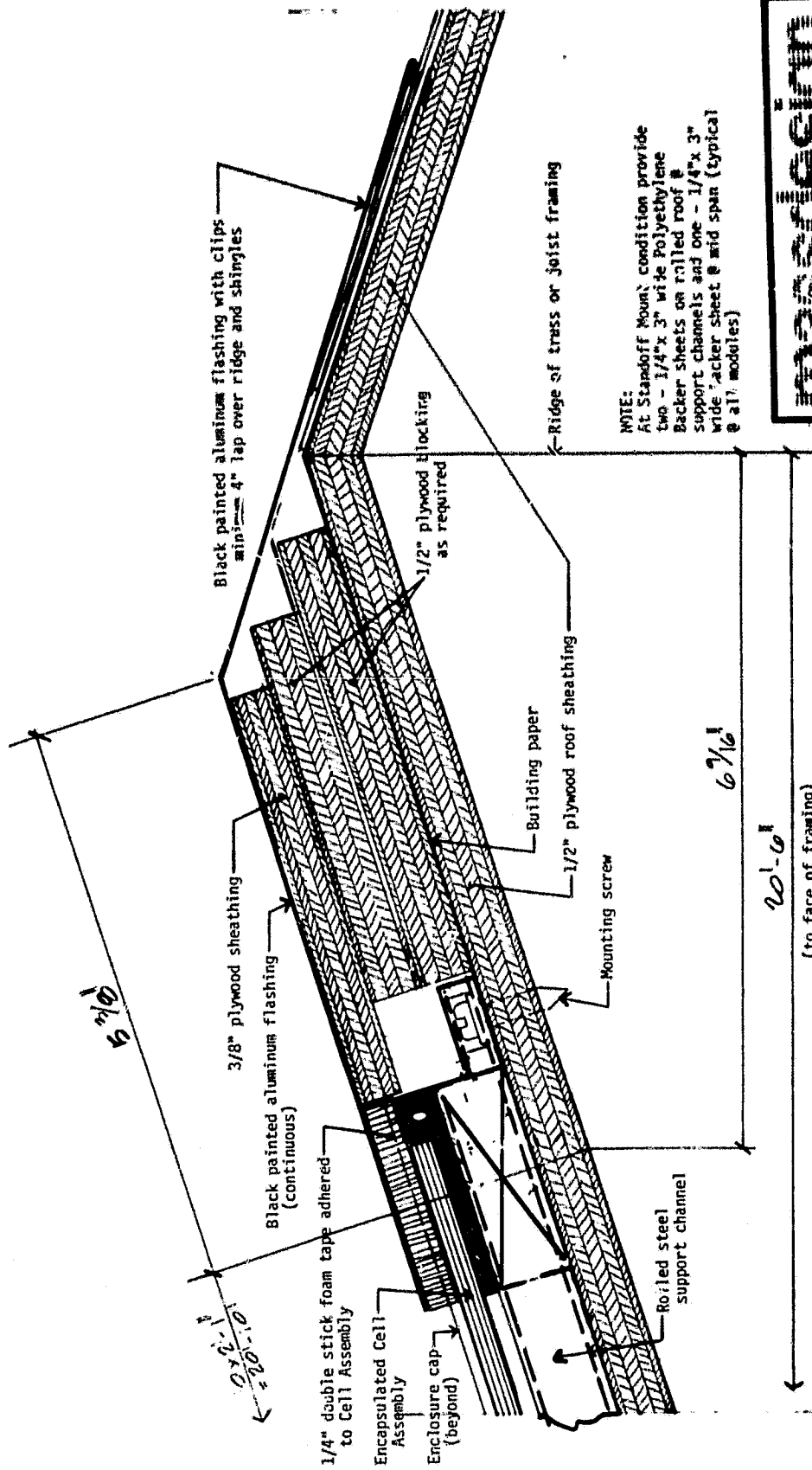


Figure 3-29. Eave Detail Between Support Channels (Direct Mount)



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 sheet @ mid span (typical @ all modules)

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Figure 3-30. Ridge Detail (Direct Mount)

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.

3.5 INSTALLATION COST ANALYSIS

3.5.1 ASSUMPTIONS AND CONSTRAINTS

The installation cost for the selected module design was estimated for each of the three mounting approaches described in Section 3.4. 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 m² 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 stand-off) are similar in many regards, but are notable for the following distinctive differences:

1. Wiring. 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 weather-proofed in case construction must proceed before the modules are delivered.

3.5.2 INTEGRAL MOUNT

The installation cost for the integral mounting approach is summarized in Table 3-13. 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 channel supports, horizontal blocking, modules and closure strips 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 included in the cost estimate.

Table 3-13. Installation Cost Estimate for the Integral Mount

	Item Description	Quantity	Units	Unit Price (1980 \$)	Total Cost (1980 \$)
Material	Closure Strip	62	EA	1.75	109
	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 Ha. Boss				
	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 Covers, 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				<u>100</u>	
Total Installation Cost				1581	

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.

3.5.3 DIRECT MOUNT

The installation cost for the direct mounting approach is summarized in Table 3-14. 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 required 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 strips. 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 3-14. Installation Cost Estimate for Direct Mount

	Item Description	Quantity	Units	Unit Price (1980 \$)	Total Cost (1980 \$)
Material	Closure Strip	62	EA	1.75	109
	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.			
Set Panels and Covers, Make all Connections, Set Boxes and Conduit - 4 Hrs. Electrician and Helper @ \$37.00/hr.				148	
Subtotal				1429	
Overhead and Profit (20%)				<u>286</u>	
Total Installation Cost				1715	

3.5.4 STAND-OFF MOUNT

Table 3-15 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 3-15. Installation Cost Estimate for Stand-off Mount

	Item Description	Quantity	Units	Unit Price (1980 \$)	Total Cost (1980 \$)
Material	Closure Strip	62	EA	1.75	109
	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
	Folyethylene 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 Covers, Make all Connections, Set Boxes and Conduit - 4 Hrs. Electrician and Helper @ \$37.00/hr.				148
Subtotal					1601
Overhead and Profit (20%)					<u>320</u>
Total Installation Cost					1921

3.6 COST SUMMARY

At the median module production rate considered in this analysis (viz., 50,000 m² of cell area per year), the FOB factory price of the selected module design is estimated to be \$88/m² of module area, exclusive of the price of the solar cells. Using the module electrical performance specified in the contract, this areal price can be transformed into \$0.73 per watt of module output under peak power rating conditions (100 mW/cm² insolation and a cell temperature of 25°C). The cost of the solar cells can be added to this module production price to yield the bottom curve in Figure 3-31.

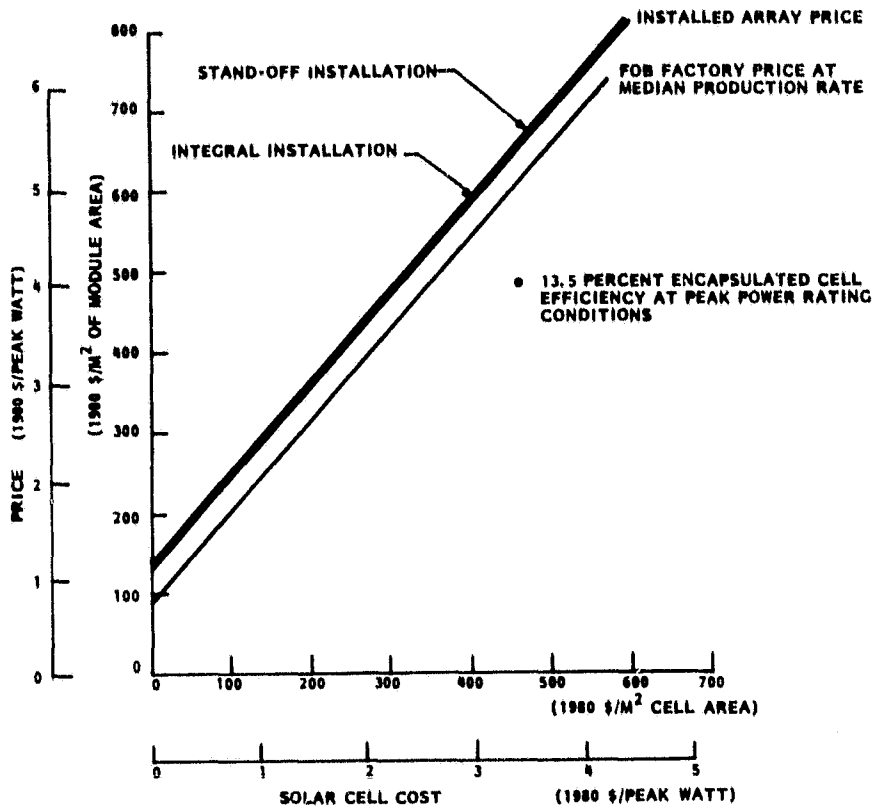


Figure 3-31. Installed Array Price vs. Solar Cell Cost

The installation cost for a typical array of modules of the selected design has been found to range from \$39 to \$48 per m² of module area depending on the mounting approach used, with the integral configuration yielding the lowest cost, and the stand-off approach yielding the highest cost. If these installation price extremes are added to the FOB factory price of the modules the upper curves of Figure 3-31 should represent the estimated installed array areal price. It is important to note that this price does not include any price mark-up for the shipping, handling and distribution of the modules.

At a \$2.00 per watt solar cell cost, which might be typical of 1982 production at the median rate considered, the installed array price can be categorized as follows based on the data from Figure 3-31.

Item	Price (1980 \$/watt)	Fraction of Total Installed Price
Solar Cells	2.00	0.56
Balance of Module Assembly	1.26	0.35
Total Module FOB Factory Price	3.26	0.91
Installation Price (Integral Mount)	0.32	0.09
Total Installed Array Price	3.58	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 approaches considered will have little impact on the resulting cost of the installed residential array.

3.7 PROTOTYPE ROOF SECTION

The proposed configuration of the prototype roof section, as shown in Figure 3-32, allows for the installation of six full-size simulated modules of the selected design. These modules will be mounted as an integral installation to demonstrate that the selected approach provides the necessary watertight roofing surface. This prototype roof section will accurately simulate the actual module mounting interfaces including the eave, rake and ridge details. The proposed module construction for this model will duplicate the actual module mechanical characteristics and interfaces, but the active solar cells will be replaced with photographs of solar cells. The electrical connectors and cabling between modules will be identical to that proposed for an actual array installation.

Any problems encountered in the fabrication and assembly of the simulated roof section will be fed back into the detailed design of the module and/or module mounting components. Particular attention will be 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.

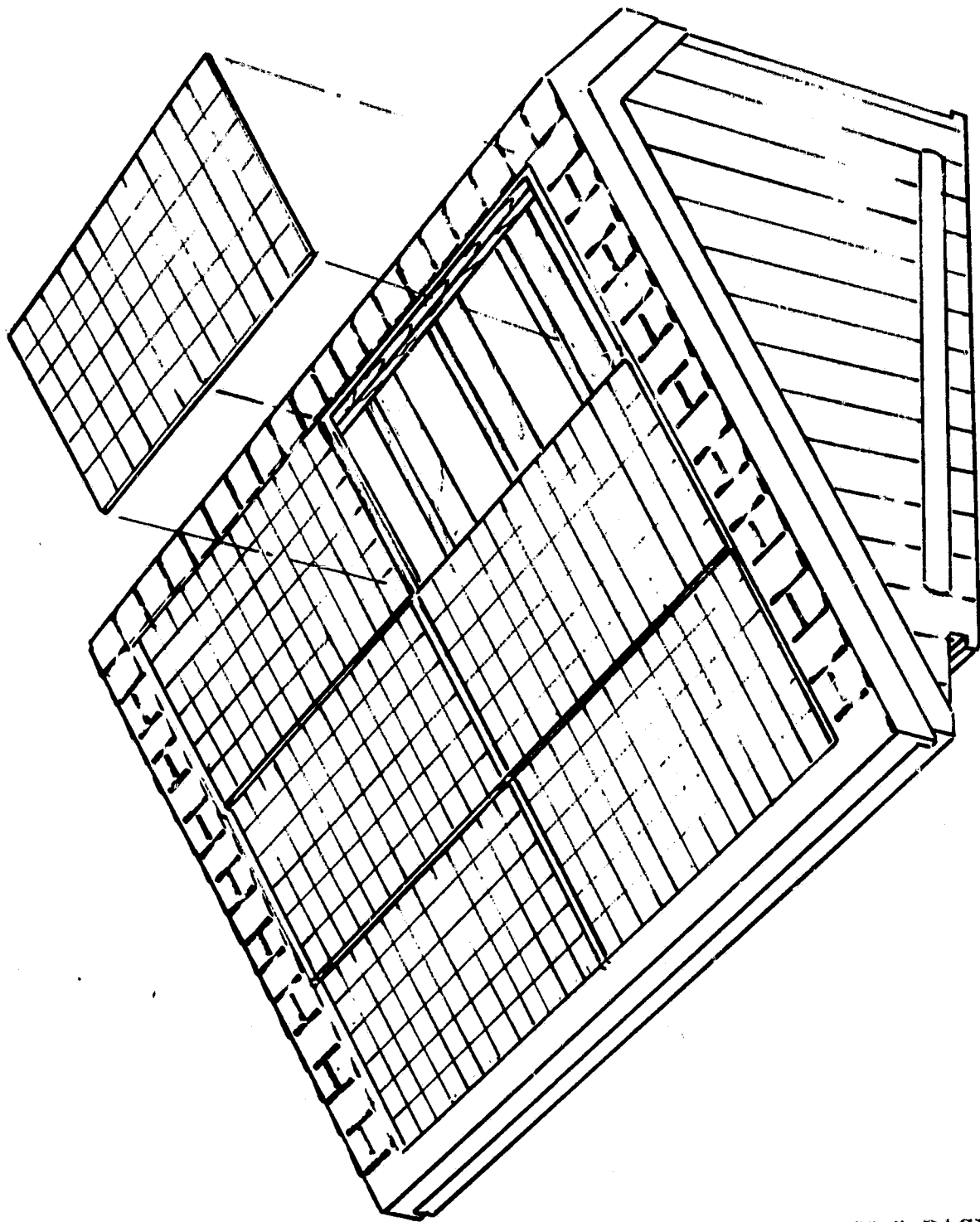


Figure 3-32. Prototype Roof Section

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SECTION 4
CONCLUSIONS AND RECOMMENDATIONS

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

The selected module/array design concept has been optimized to reduce the production costs and provide a simple installation procedure which minimizes the field labor necessary to create the reliable watertight joints required for an integrally-mounted array. It is apparent from the price analyses summarized in Section 3.6 that the solar cell cost is the dominant factor contributing to the total installed cost of a residential photovoltaic array. The installation cost of an array of this type represents only a small fraction of the total installed price. For the example case considered in Section 3.6 only 9 percent of the total installed price can be attributed to the field installation of the modules to form an integrated, watertight roof surface. The mounting scheme used for this roof installation, whether integral, direct or stand-off, has a relatively small effect on the total installed cost of the array. Other considerations such as the ability to completely enclose the building, independent of the photovoltaic array installation, and the reduction of risk associated with the use of conventional building materials as the watertight roof surface may override the relatively small cost advantage associated with the installation of the array as an integral mount.

It is also apparent that the near-term cost reduction efforts for residential photovoltaic arrays should emphasize the reduction in the cost of the area-dependent elements of the module design such as the solar cells and encapsulant materials.