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QUARTERLY REPORT NO. 2
INTEGRATED RESIDENTIAL PHOTOVOLTAIC ARRAY DEVELOPMENT

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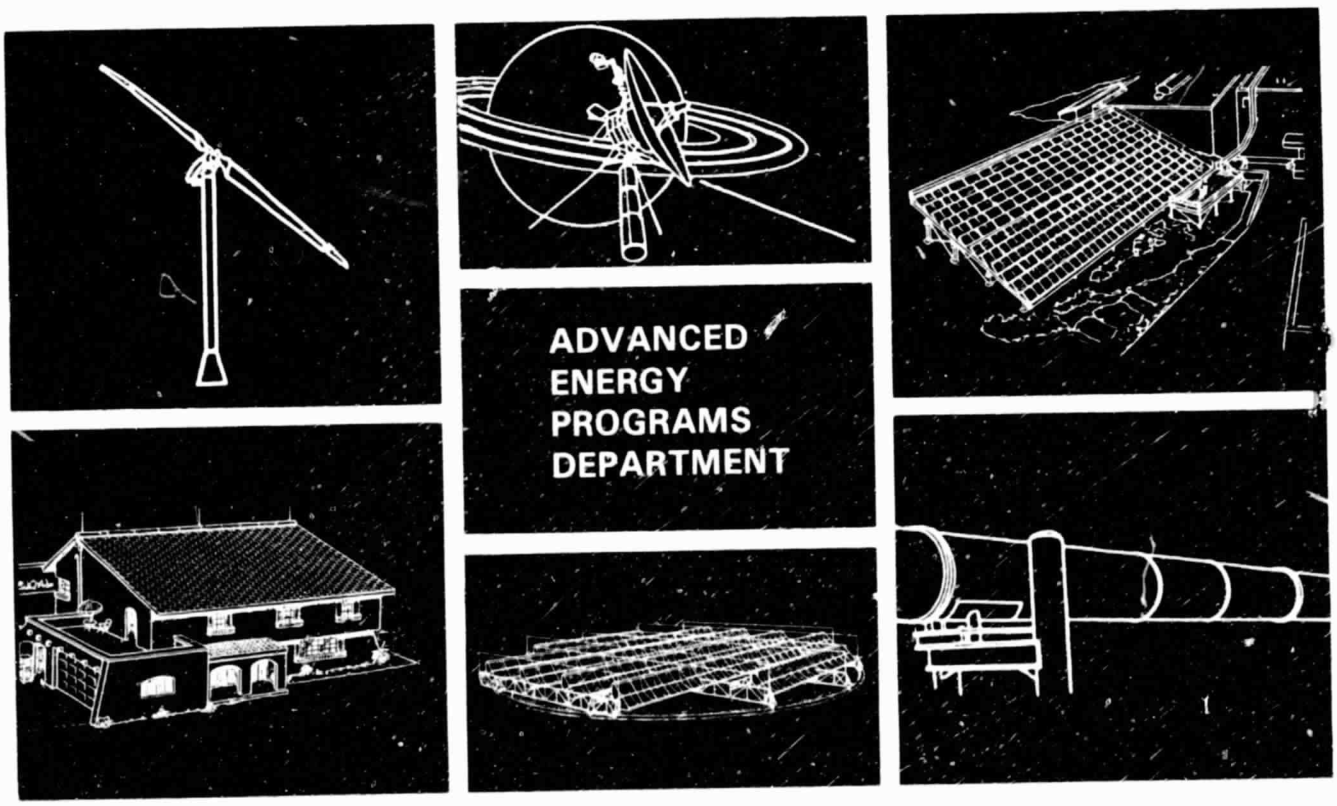
PREPARED UNDER JPL CONTRACT 955894
REPORT DATE: MAY 18, 1981



ENERGY SYSTEMS AND TECHNOLOGY DIVISION

GENERAL ELECTRIC

DOE/JPL 955894-2
DISTRIBUTION
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INTEGRATED RESIDENTIAL PHOTOVOLTAiC ARRAY DEVELOPMENT

PREPARED UNDER JPL CONTRACT 955894

REPORT DATA; MAY 18, 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.

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GENERAL ELECTRIC

PREFACE

The objective of this contract effort is to establish the design definition for an optimum integrated residential photovoltaic array which uses current proven technology to configure a residential array/module concept which is responsive to the longer range DOE cost goals. An important element of the initial phase of this activity consisted of the formulation of a comprehensive set of evaluation criteria which were felt to represent important considerations against which residential design concepts could be ranked and compared. In the first quarterly report (DOE/JPL955894-1), this list was presented along with a ranking and comparison of existing or proposed residential array/module designs. A difficulty with this comparison, which was not successfully overcome, was the total elimination of subjective biases inherent in the attempt to assign values to the areas of strengths and weaknesses of these existing designs. In retrospect the evaluation approach used provides a useful qualitative technique to select what may prove to be an optimum integrated residential array design. At this time, the quantitative results of this evaluation which appeared in the first quarterly report have not proven useful and should be disregarded.

ABSTRACT

The results of a selection process to define the conceptual design of an optimum integrated residential photovoltaic module array are discussed in this report. The three basic module design concepts presented in the first quarterly report have been analyzed with respect to both production and installation costs. The results of this evaluation have been used to synthesize a fourth design which incorporates the best features of these initial concepts to produce a module/array design approach which offers the promise of a substantial reduction in the installed cost of a residential array. A unique waterproofing and mounting scheme has been used to reduce the cost of installing an integral array while still maintaining a high probability that the installed array will be watertight for the design lifetime of the system. This recommended concept will also permit the array to be mounted as a direct or stand-off installation with no changes to the module design.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

SECTION 2

INTRODUCTION

SECTION 2

INTRODUCTION

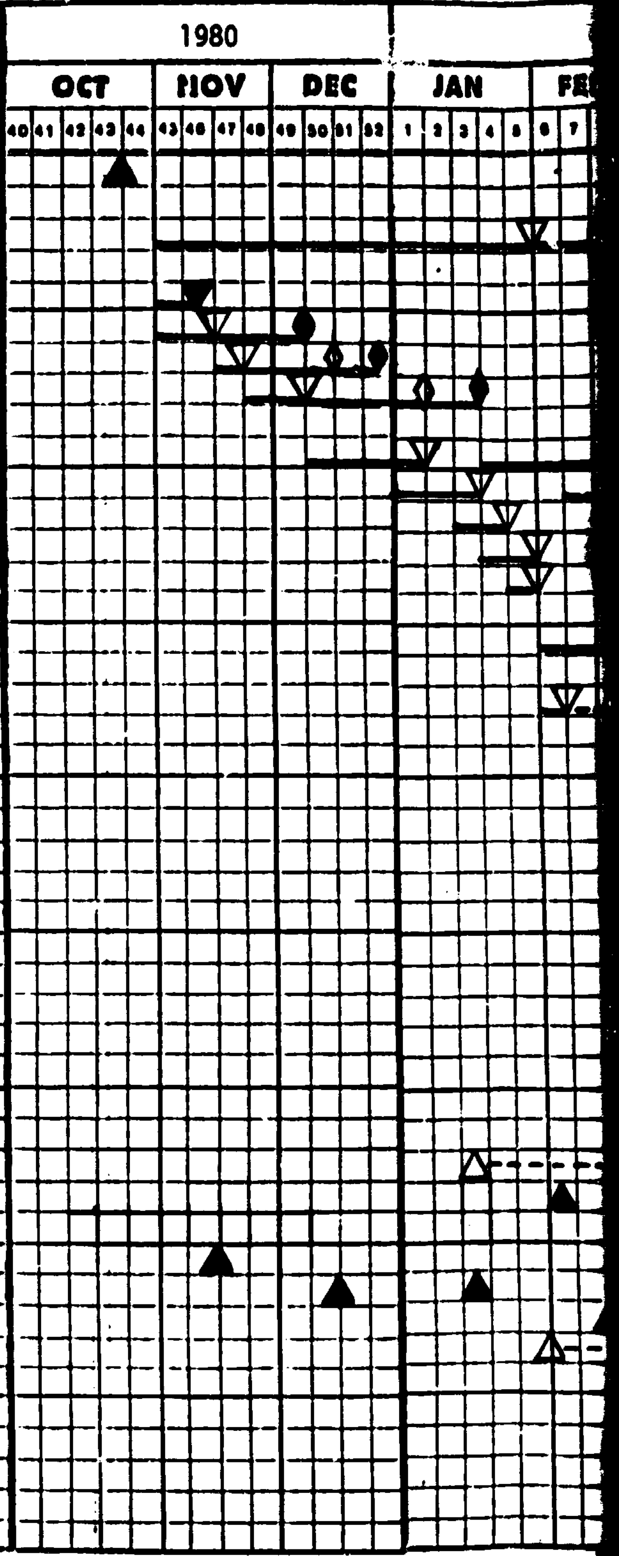
The objective of this contract is to develop an optimized integrated residential photovoltaic array concept and to prepare detailed design definition which includes sufficient information to permit fabrication, assembly, and installation by a competent third-party. A prototypical simulated roof section 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 three 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

The master program schedule for this activity, which is reproduced as Figure 2-1, indicates the status of the effort as of this reporting date. The Task 1 effort was completed during this period and the results were presented to JPL at a contract review meeting held on April 29, 1981. A recommendation regarding the selection of a single concept to be optimized during the Task 2 activity was made at this time. This report presents the results of the Task 1(B) effort which compared the three selected concepts with respect to production and installation costs and led to the recommendation of one concept to be further developed and analyzed during Task 2. 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 module concepts and in the formulation of the installation cost estimates for each approach.

Pending JPL approval of the recommended concept, further analysis and evaluation will be performed under Task 2. Detailed design analyses and engineering tradeoff studies will be performed to further optimize the design for minimum life-cycle cost for the installed array. A set of drawings and specifications will be prepared to describe the module and array design. Based on this detailed information, refined life-cycle cost estimates will be generated for annual production levels of 10,000, 50,000 and 500,000 m^2. In addition, a

TASKS AND MILESTONES



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 - Program Management and Reporting
- 4(A) Contract Review Meetings
- 4(B) LSA Project Integration Meeting
- 4(C) Gov't-Sponsored Meetings
- 4(D) Program Plan and Baseline Cost Estimate
- 4(E) Monthly Technical and Financial Mgmt Reports
- 4(F) Quarterly Report
- 4(G) Task 1 Documentation
- 4(H) Design Review Data Package
- 4(I) Engineering Documentation
- 4(J) Final Technical Report

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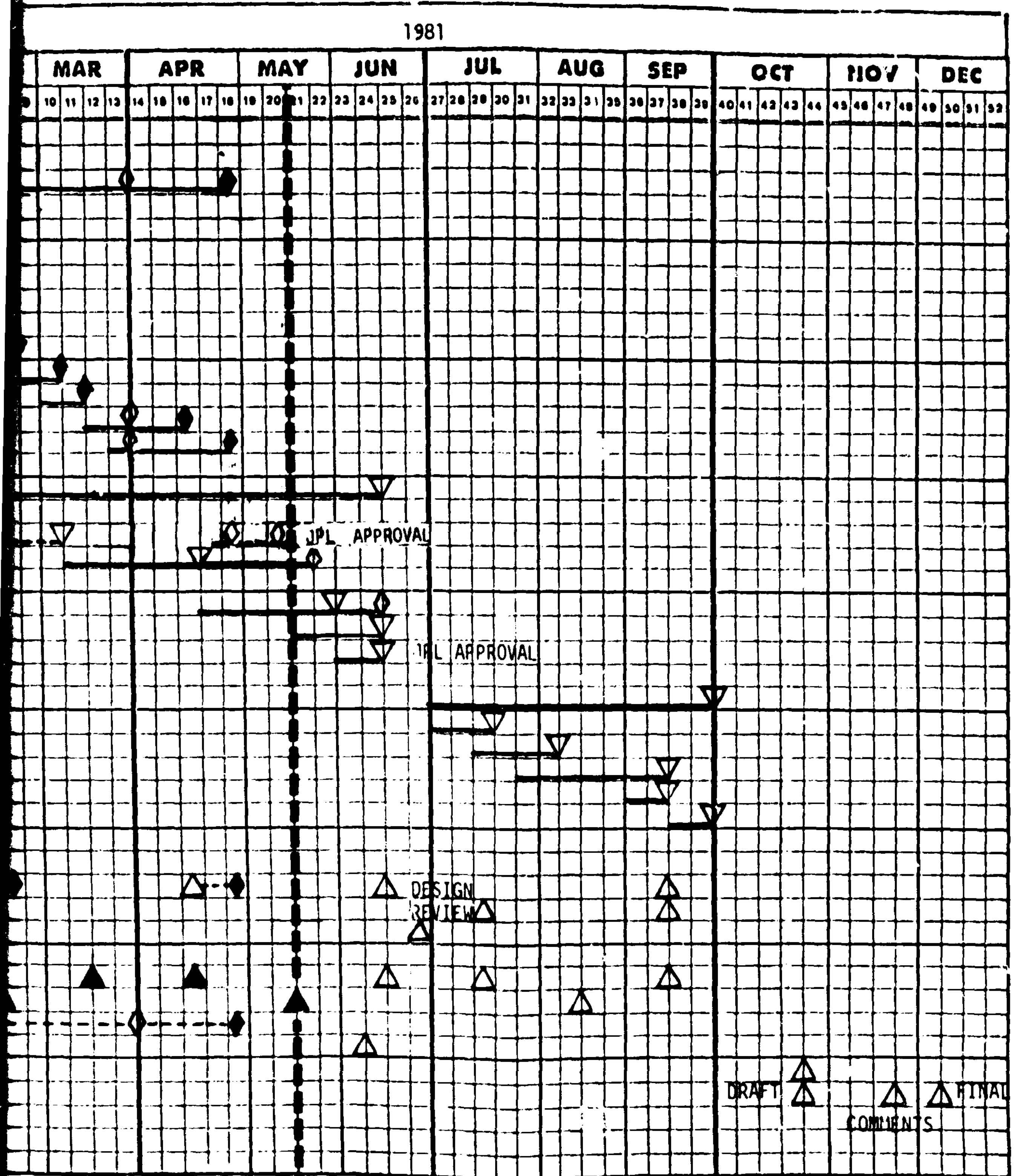

Figure 2-1. Master Program Schedule

full-scale prototype array roof section will be defined and a cost estimate prepared for its fabrication.

The Task 3 activity will include 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 prototype section, which need not be electrically active, will serve as a model in identifying additional manufacturing, installation, maintenance and other interface concerns.

SECTION 3

TECHNICAL DISCUSSION

SECTION 3

TECHNICAL DISCUSSION

3.1 SYNTHESIS OF MODULE DESIGN CONCEPTS

3.1.1 ELECTRICAL CIRCUIT DESIGN

The module electrical circuit, as represented by the schematic diagram in Figure 3-1 and the arrangement drawing of Figure 3-2, was configured to provide a common electrical design for the three module concepts to be evaluated. This circuit design, which consists of nominal 100mm square cells arranged in a 36 series by 2 parallel matrix, provides the following features which integrate well with the three selected concepts.

1. The ability to be configured as a half-width module which generates the same maximum power voltage at half the current of a full-width module. This permits the staggered overlapped shingle concept to fully utilize the available area within a rectangular roofing surface.

2. A by-pass diode installation which is simply packaged within the encapsulant lamination. The power dissipation within an individual forward conducting diode chip during periods of complete cell shadowing can be accommodated with an acceptably low junction temperature.

3. Block V requirements for cell string reliability and hot-spot endurance can be met with dual cell-to-cell interconnector strips which extend across the entire front and back surfaces of the cell with multiple solder joints to provide a crack tolerant design.

4. The open-circuit voltage at 100 mW/cm^2 insolation and at $-20^{\circ}C$ cell temperature is less than 30 vdc.

5. The basic 0.61 x 1.22 m (2x4 ft) module size is a reasonable choice for this application since it offers a wide variety of roof sizes and aspect ratios which can be implemented in conjunction with a nominal 200 vdc inverter input voltage level. This size is also consistent with the current technology base with respect to EVA lamination process 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.

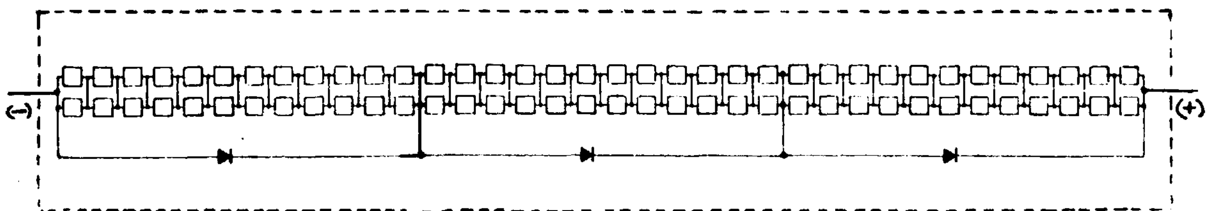

Figure 3-1. Module Electrical Circuit Schematic

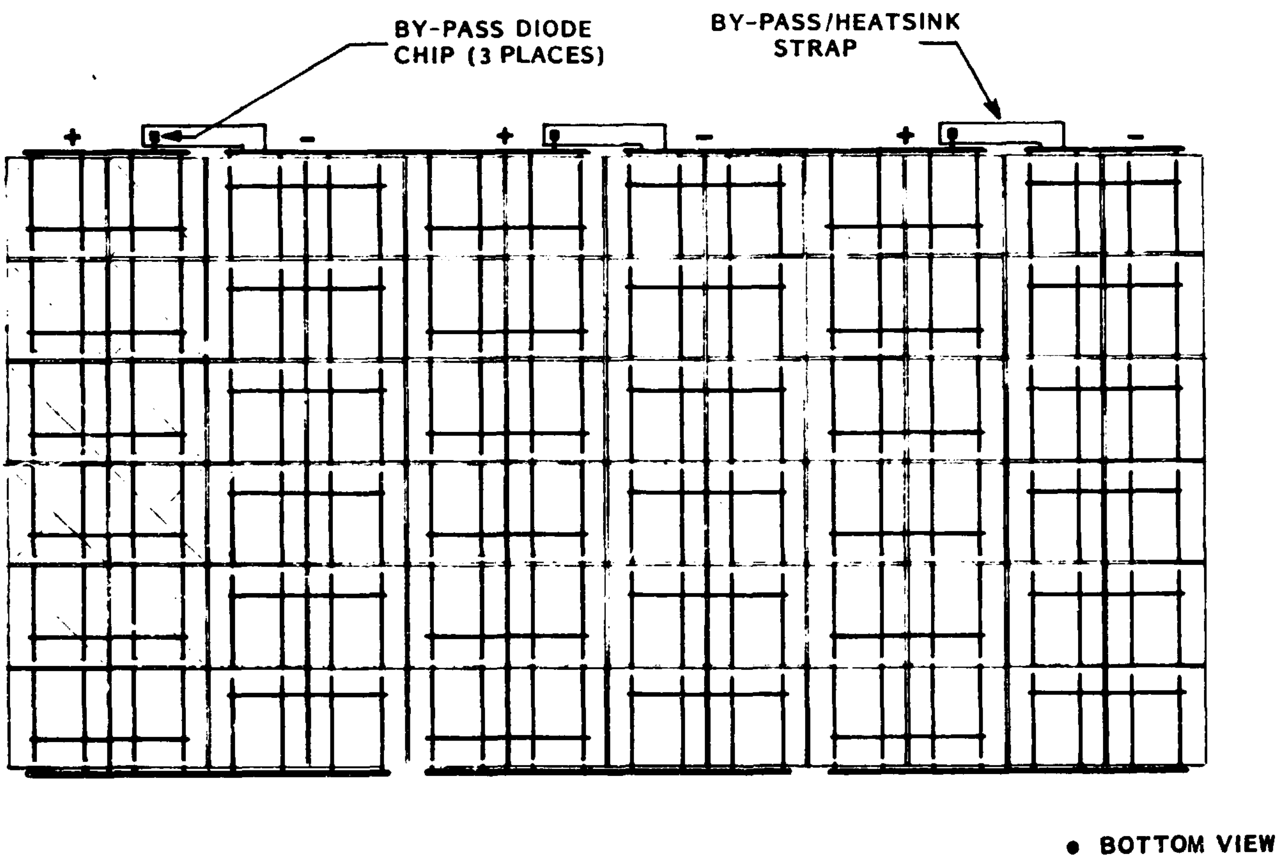

Figure 3-2. Arrangement of Electrical Circuit Elements

The mechanical and electrical integration of the by-pass diode around each 12 series cell group is shown in Figure 3-3. The diode chips can be simply packaged within the encapsulant laminate along side the circuit for Concept No. 1, but must be folded over onto the back of the cell circuit, with an intermediate insulator layer, for the other two module concepts. Unitrode solderable chips will adequately handle the power dissipation associated with the forward conduction of the short-circuit current from two parallel cells when mounted to the copper heat fin strap as shown. This 0.020 in. thick by 1.00 in. wide copper foil heat fin also serves as the lead between the circuit termination and the anode side of the chip. No other length of by-pass conductor is required to complete the installation.

The calculated I-V characteristics of this module electrical circuit are shown in Figure 3-4 based on the contract statement of work specified 13.5 percent encapsulated cell efficiency at the peak power rating conditions. Under Nominal Operating Conditions (NOC), as defined by the Block V specification, this same module is calculated to produce 63.8 watts of maximum power output with a NOCT which might be typical of a direct or integral mounting approach. Thus, at NOC this module could be expected to be 11.1 percent efficient based on encapsulated cell area.

3.1.2 ENCAPSULATED CELL SUBASSEMBLY

The encapsulated cell subassembly, which is substantially identical among the three module concepts, is configured as shown in Figures 3-5 and 3-6. A low-iron glass coverplate functions as the structural superstrate for the module. The solar cell circuit is laminated to this coverplate with a single layer of clear EVA film used in conjunction with a sheet of Craneglass which functions to vent the gasses during lamination. The rear side of the subassembly is completed by laminating a rear cover sheet with the same encapsulation system. This rear cover sheet functions as a moisture-barrier and also as a secondary dielectric for those module designs which do not have a secondary dielectric installed as part of the final assembly. For Concept Nos. 1 and 2, this rear cover sheet is aluminum foil (0.03 mm thick), whereas for Concept No. 3, which does not have another dielectric layer added during final assembly, this rear cover sheet is a laminate of aluminum foil (0.01 mm thick) and Tedlar (0.10 mm thick). In all cases the rear encapsulation layer of EVA/Craneglass is

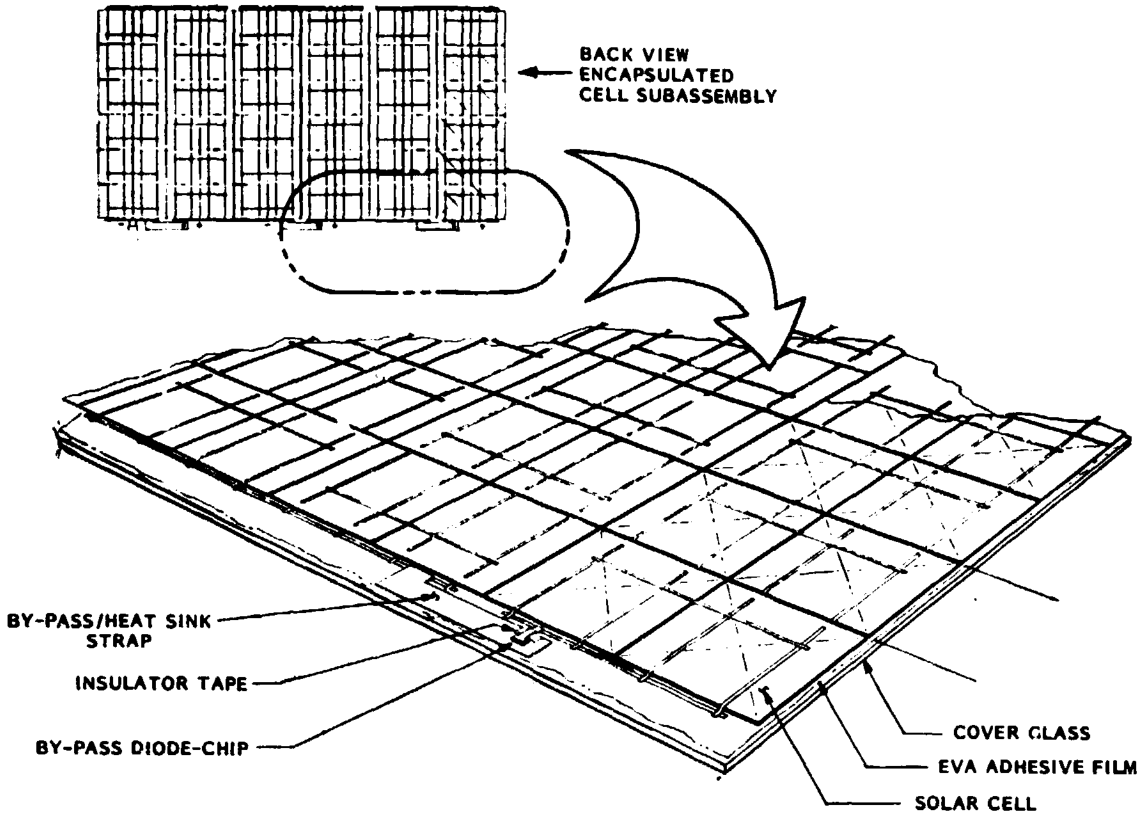

Figure 3-3. By-pass Diode Installation Detail

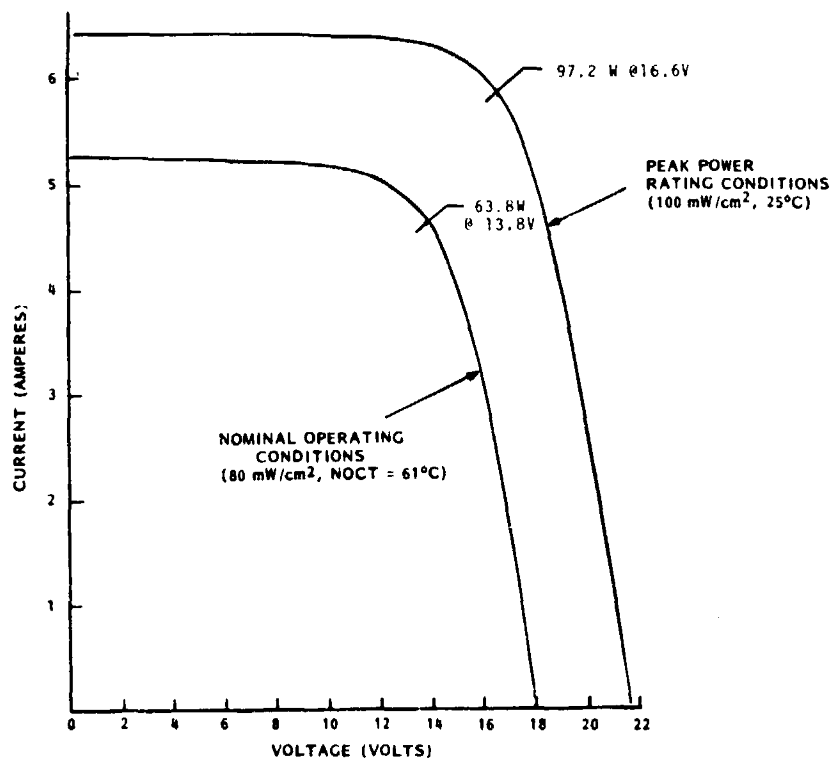

Figure 3-4. Module I-V Characteristics

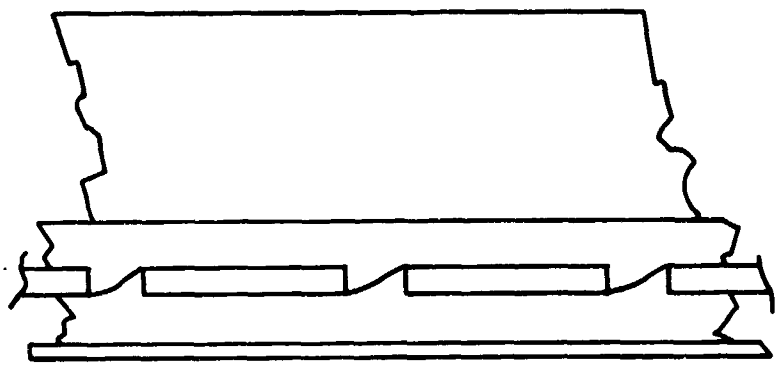

Figure 3-5. Module Encapsulation System

considered to function as the dielectric which supplies the required insulation resistance between the active solar cell circuit components and the exposed module surfaces. Provisions have been made in the processing flow for the application of a suitable primer to all surfaces to be bonded during the lamination step.

3.1.3 MODULE DESIGN CONCEPTS

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

A direct-mounted, overlapping shingle module of the configuration shown in Figure 3-7 has been identified as Concept No. 1 for this evaluation. A comparison of this current configuration with that which appeared in the first quarterly report will reveal that the substrate tab has been reduced in length as a measure to substantially reduce the production cost of the module at the sacrifice of a small increase in the installation cost associated with the addition of a PVC underlayment sheet to form the watertight overlap between shingle courses.

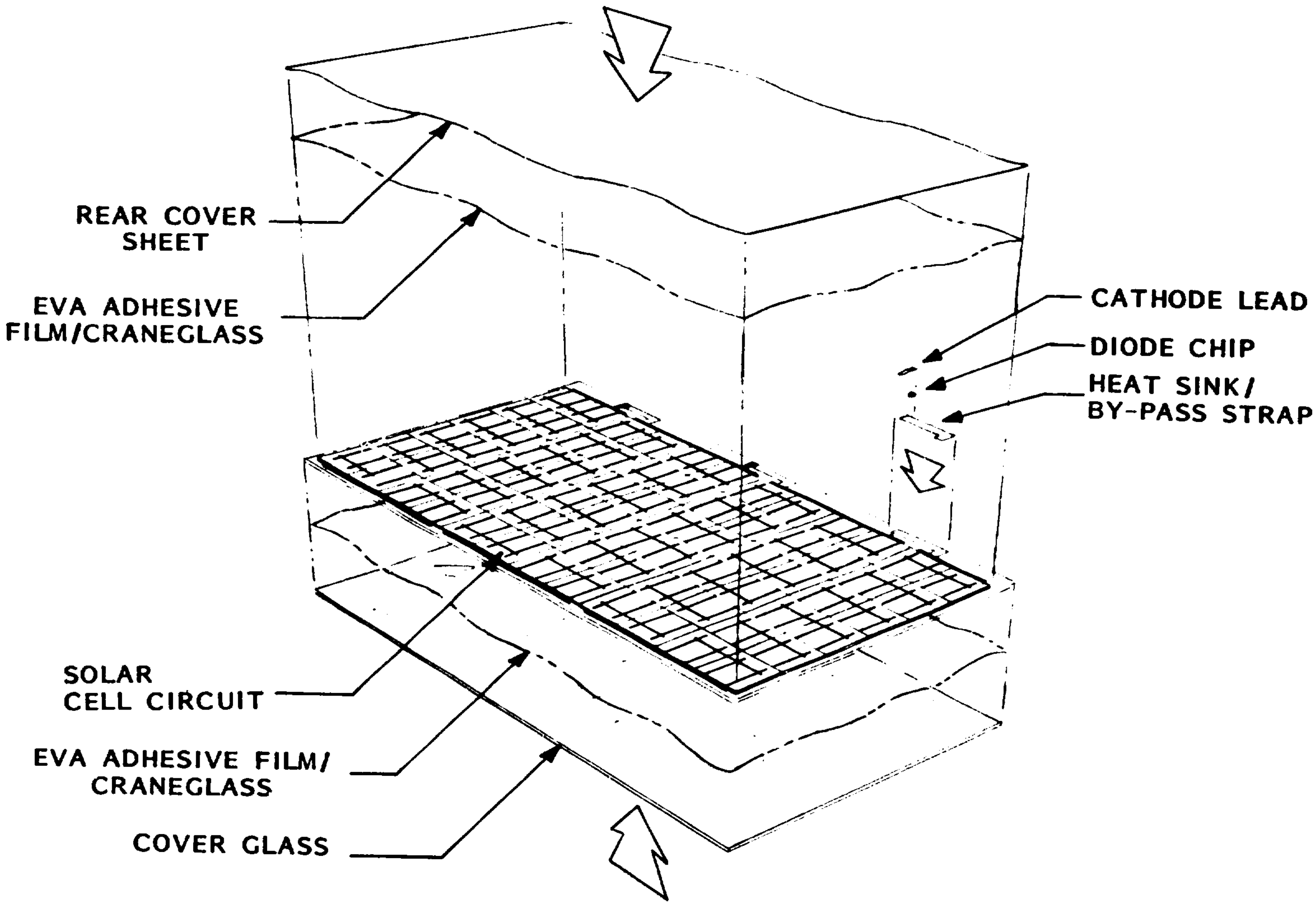

Figure 3-6. Construction of the Encapsulated Cell Subassembly

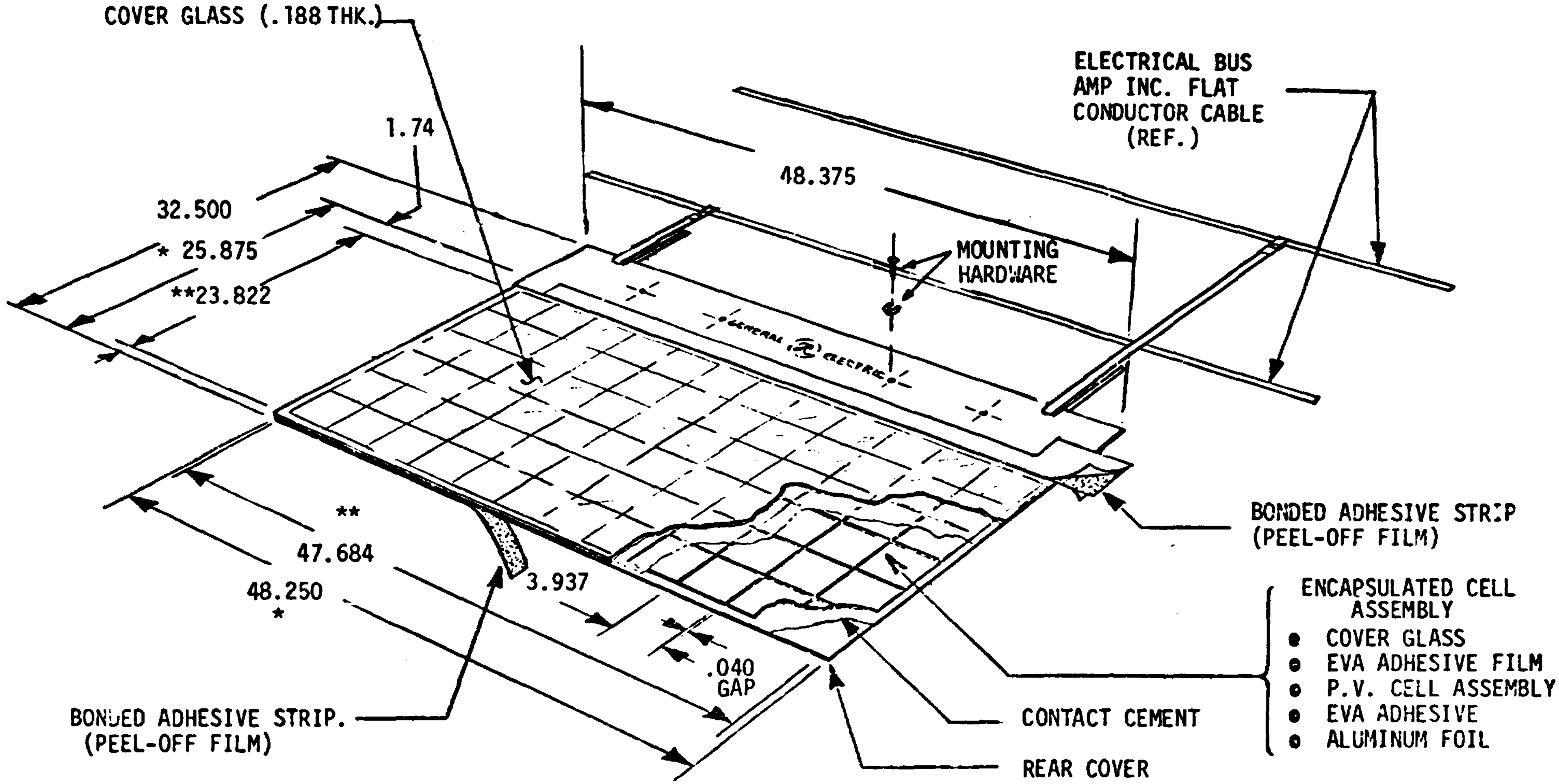

Figure 3-7. Design Concept No. 1 - Direct-Mounted, Overlapping Shingle

As currently configured the 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.

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 produces 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.

3.1.3.2 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 3-8, 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.

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.

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

The stand-off mounted module concept shown in Figure 3-9 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 3-9. 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.

3.2 MODULE PRODUCTION COST ANALYSIS

3.2.1 INTRODUCTION AND ASSUMPTIONS

The three module design concepts described in Section 3.1.3 were analyzed with respect to manufacturing costs assuming an annual production rate of 50,000 m^2 of solar cell area. As

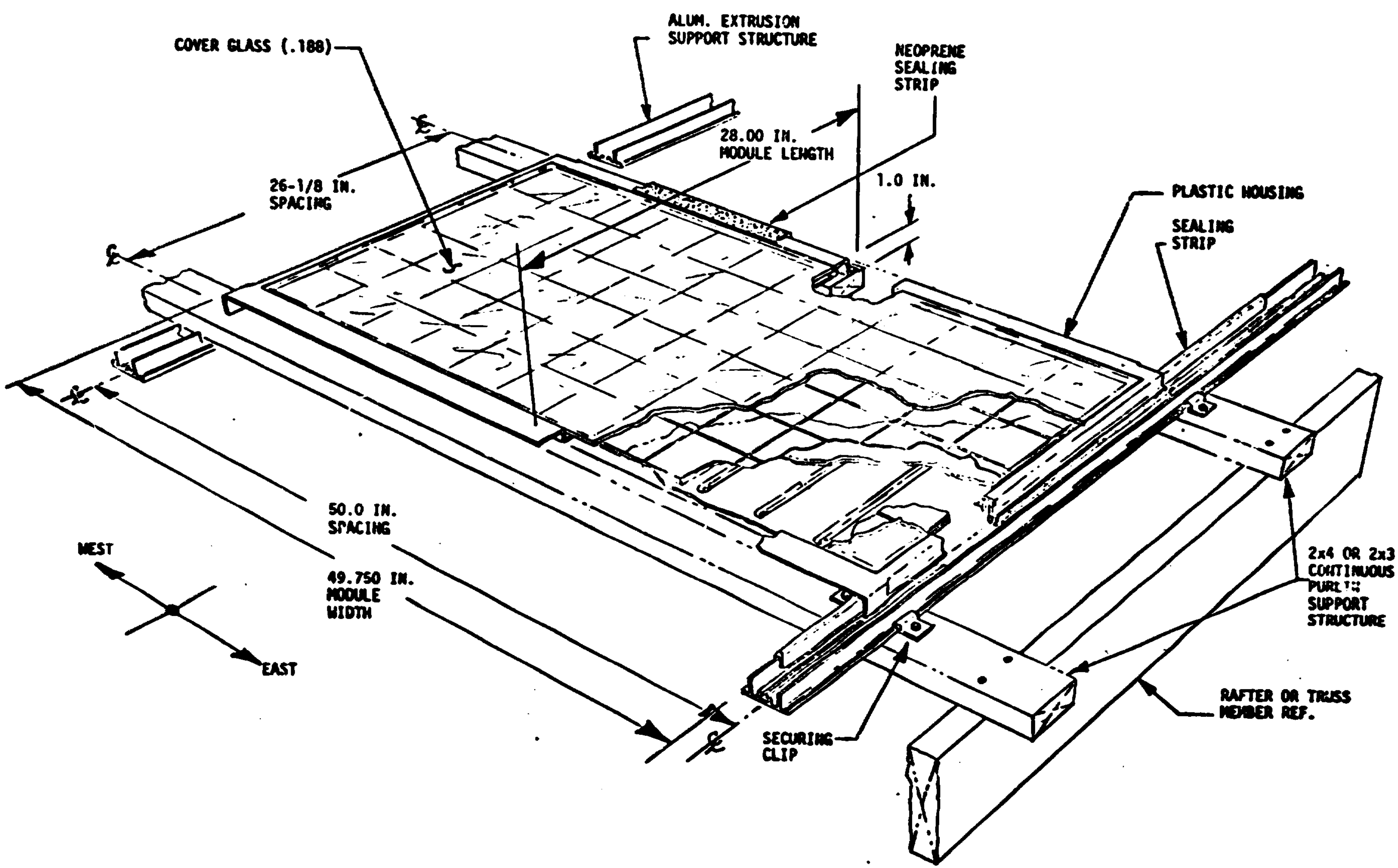

Figure 3-8. Design Concept No. 2 - Integrally-Mounted with Plastic Tray

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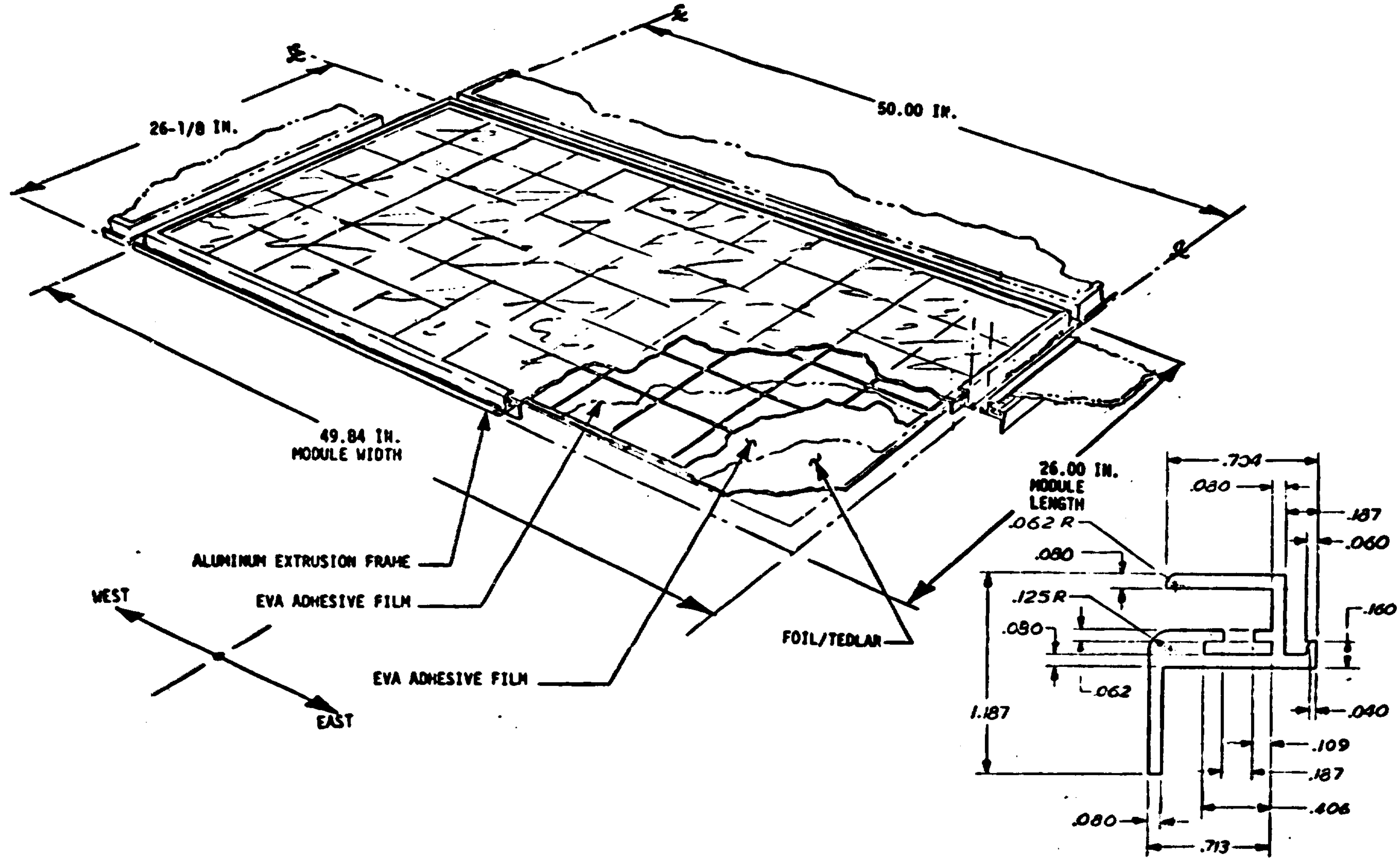

Figure 3-9. Design Concept No. 3 - Stand-off Mounted with Aluminum Frame

shown in Table 3-1 this production rate is equivalent to 69,444 modules per year or 6.75 MW of annual plant capacity assuming a 13.5 percent encapsulated cell efficiency at 25°C. The manufacturing facility required to produce this annual throughput is assumed to operate 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. A production rate of 9.74 completed modules per working hour is required to meet the required annual throughput.

Table 3-1. 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
Number of Residences	180	902	9,019
Power Output at Peak Power Rating Conditions (MW)	1.35	6.75	67.5

Use for Task 1 Evaluations

The approach taken by K&S in the formulation of the basic production plan attempts to anticipate problems that could take place on a normal plant operation of this type and to set forth a realistic building block approach which can minimize the effects of these potential problems. The following factors have been considered in the configuration of the production facility for each module concept:

1. Subassembly size and configuration for optimum handling and storage
2. Arrangement of equipment to minimize the negative impact on plant throughput in the event of equipment failure
3. Adequate buffers in production flow

4. Tradeoff of continuous vs batch processing for each functional operation

5. Optimum utilization of manpower

6. Achievement of output requirements with a balanced line factory based on reasonable projections for cycle times and the technological status of the equipment involved

As shown in Figure 3-10, the factory layout is centered around a basic production line which assembles the encapsulated cell subassembly as the common element among the three module design concepts. Except for small differences in the size of the glass coverplate, in the placement of the by-pass diodes, and in the material used for the rear insulation layer, this same basic subassembly will be employed for each design. The final assembly and warehouse areas of the plant will vary with the concept being considered as described later.

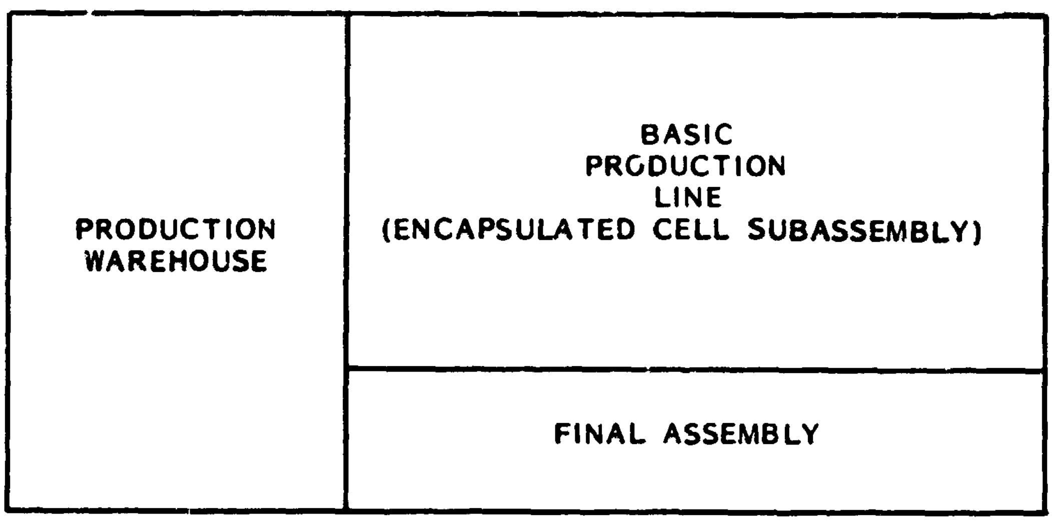

Figure 3-10. Production Plant Layout

3.2.2 BASIC PRODUCTION LINE

The process flow diagram for the basic production line which produces the encapsulated cell subassembly is shown in Figure 3-11. This portion of the plant is virtually identical for all three concepts and includes the cell soldering and stringing machinery as well as the lamination equipment. This basic production line accepts 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 strings to the 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 rinsed to remove any flux residue and dried. As shown in Figure 3-12, the cleaned strings are then automatically picked up by a transfer mechanism and delivered to a stacker where the strings are stacked in carriers. This stacker station represents the basic inventory unit within the production line. The strings, which are the handling unit from this point through the laminating stations, 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 strings 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 to an aligning fixture. An operator at this station actuates the pick-up system to pick-up a cell string and deposit it in the module array assembly area.

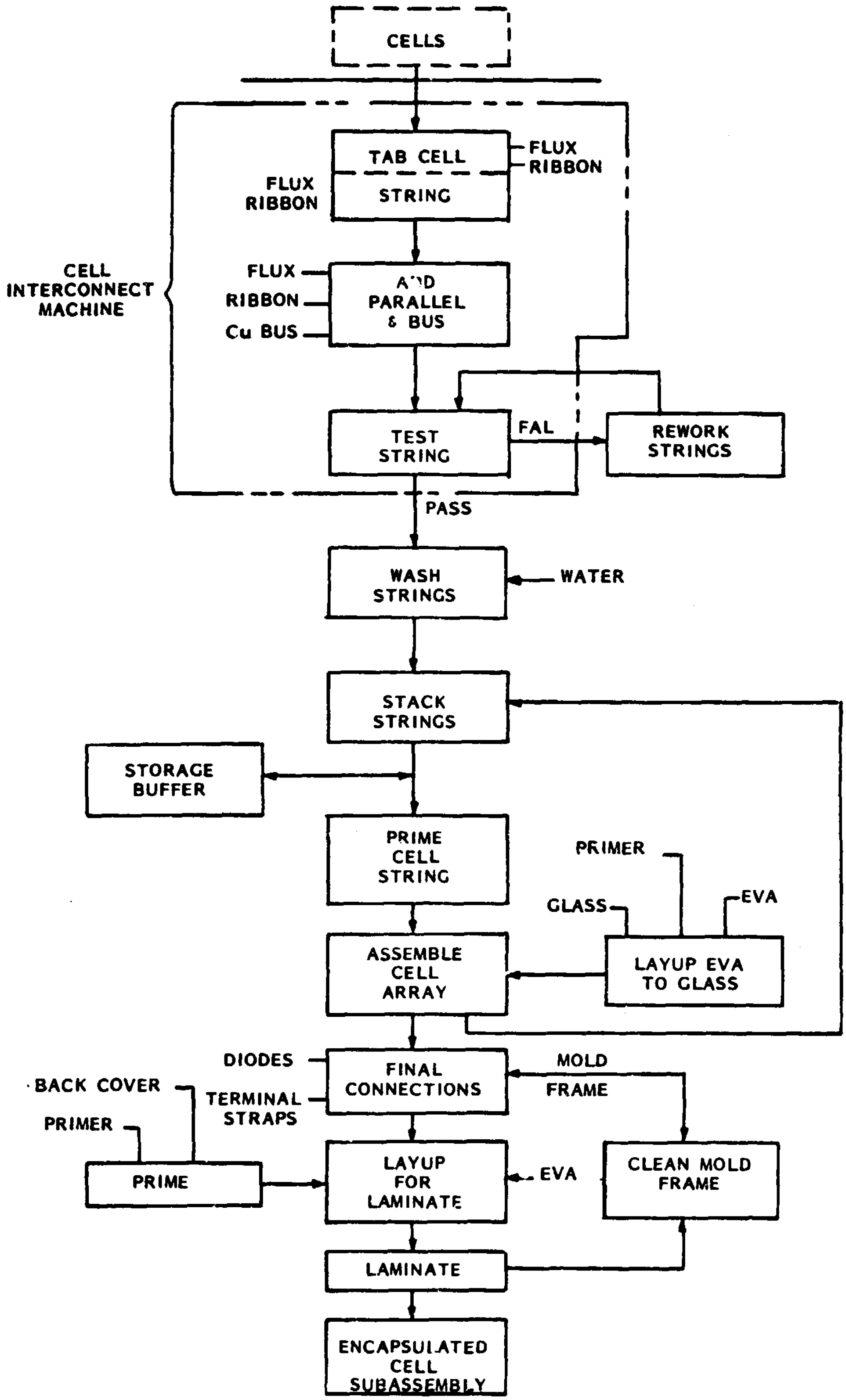

Figure 3-11. Process Flow Diagram for the Basic Production Line

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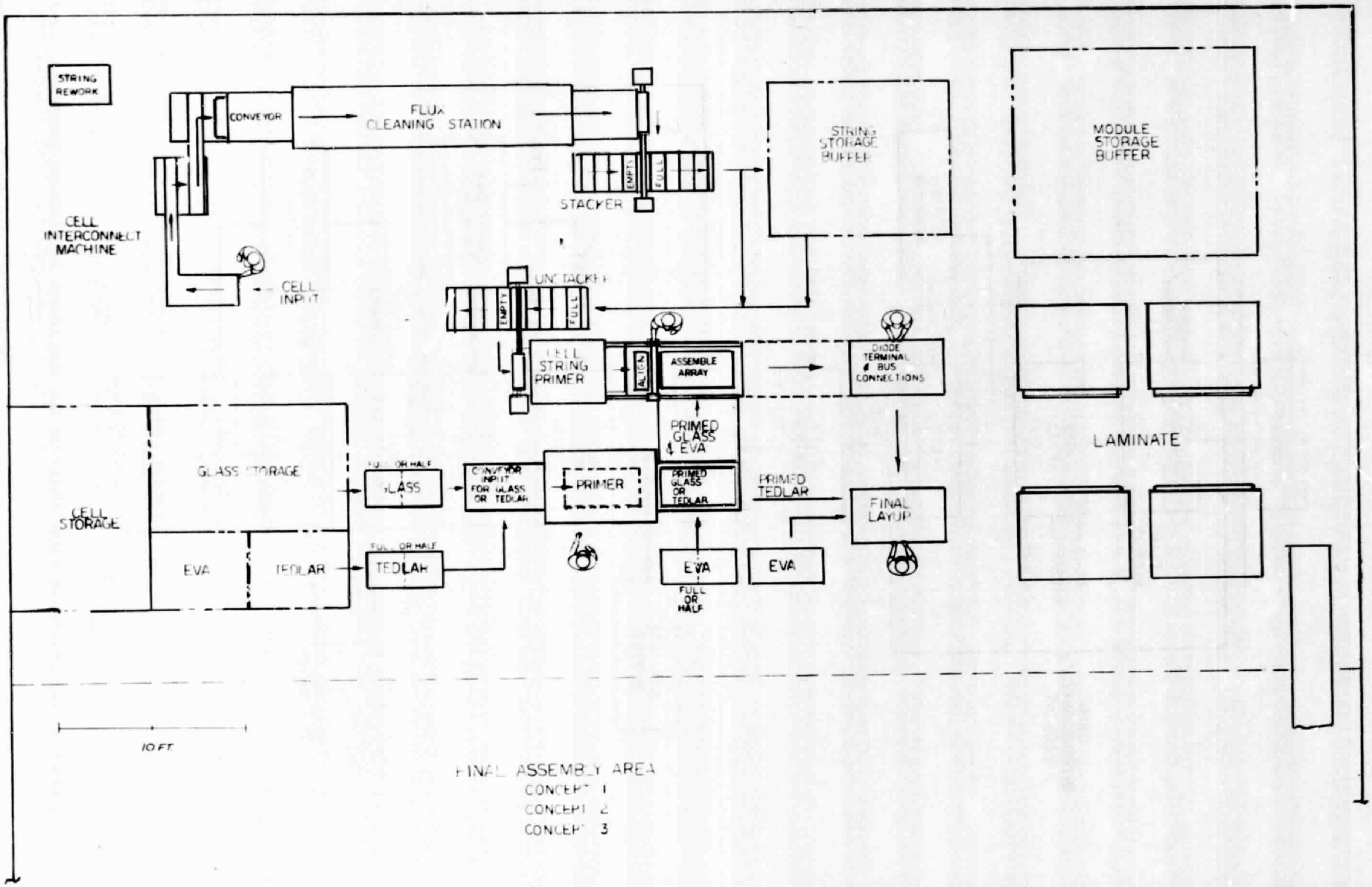

Figure 3-12. Floor Layout for the Basic Production Line

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/ Craneglass encapsulant. As it comes out of the primer area, sheets of EVA/ Craneglass 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 array has been completed. Also, at the primer station, the rear cover sheet, which may be either aluminum foil or an aluminum foil/ Tedlar laminate, 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 accummulated, 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 90-minute cycle to accomplish the laminating with adequate curing time, four laminators are needed to keep pace with rest of the production. This would result in a laminator throughput rate of a module every 4.25 minutes which is slightly less than the basic production line speed. This means that in normal operation, the laminator should not cause any production bottle-necks, and even provides a little 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, which is different for each module concept. Description of the final assembly operations for each module concept as well as other comments on their production flow are discussed in the following sections.

The estimated cost of the equipment within the basic production line is tabulated in Table 3-2 along with the estimated consumption of utility services.

Table 3-2. Equipment and Utility Requirements for the Basic Production Line

Item	Estimated Cost (1980$'s)	Utility Services
Cell Interconnect and String	$375K	2.5 kW 6 cfm air 1.5 gpm water
Cassettes (2000 Boxes@$5)	10K	
String Rinsing Machine	60K	1.0 kW 10 gpm water
String Stacker	8K	0.2 kW
String Storage and Buffer Area (500 Boxes@$2)	1K	
Unstacker	8K	0.2 kW
Cell Priming Machine	30K	0.5 kW
Array Assembly Station	12K	0.2 kW
Diode, Terminal and Bus Connections (Including 2 Weld Heads, Fixturing Automatic Feed Mechanism)	35K	0.5 kW
Final Layup	2K	
Primer Dispensing Station	15K	
Laminators (4 $60K)	240K	24.0 kW 0.04 cfm air 1.6 gpm water
Conveyors and Misc. Handling Aids		0.5 kW
Totals	846K	29.6 kW 6 cfm air 13.1 gpm water

3.2.3 FINAL ASSEMBLY

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

The final assembly of this module concept includes the installation of the inactive tab of the shingle as well as the rear cover which is laminated over the entire bottom surface of the module. The flat-conductor cable terminations are also added as part of the final assembly operation which is completed with an illumination test using a pulsed xenon simulator.

The staggered overlapped nature of this module installation concept involves the use of half-width modules on alternating courses at the gables of the roof. It is estimated that this will require the manufacture of two half-size modules for every 13 full-size modules. This relationship causes some extra logistical considerations that are not involved in the other two concepts to be considered. The production line which produces the encapsulated cell assembly is basically cell limited; i.e., the line output is a function of the cells or strings required per module. This means that, for all practical purposes, two half-size modules can be made in the time it takes to assembly one full-size module. The cell interconnect and stringing machinery is envisioned as being able to perform its functions on the half-size module in the same manner as it does for the full-size module. In the former case the machines would process two single six-cell simultaneously instead of a parallel inter-connected pair of six-cell strings.

However, the final assembly operations, as shown in Figure 3-13 are function limited. In this area of the production plant, which is represented by the floor layout shown in Figure 3-14, it would take just as long to complete a half-size module as it would a full-size module. This means that while it would take the basic production line one shift to produce the amount of units to balance 13 shifts of production of full size modules, the half-size modules would accumulate twice as fast as the full size modules and would back up going into the final assembly area. The accumulated encapsulated cell subassemblies would be placed in the buffer area until required in the final assembly area. The accumulated modules would be assembled and the production flow balance restored over the 14 shift cycle since the final assembly throughput is 5.07 minutes/modules (11.84 modules/hr) and the basic production line time is 6.16 minutes/module (9.74 modules/hr).

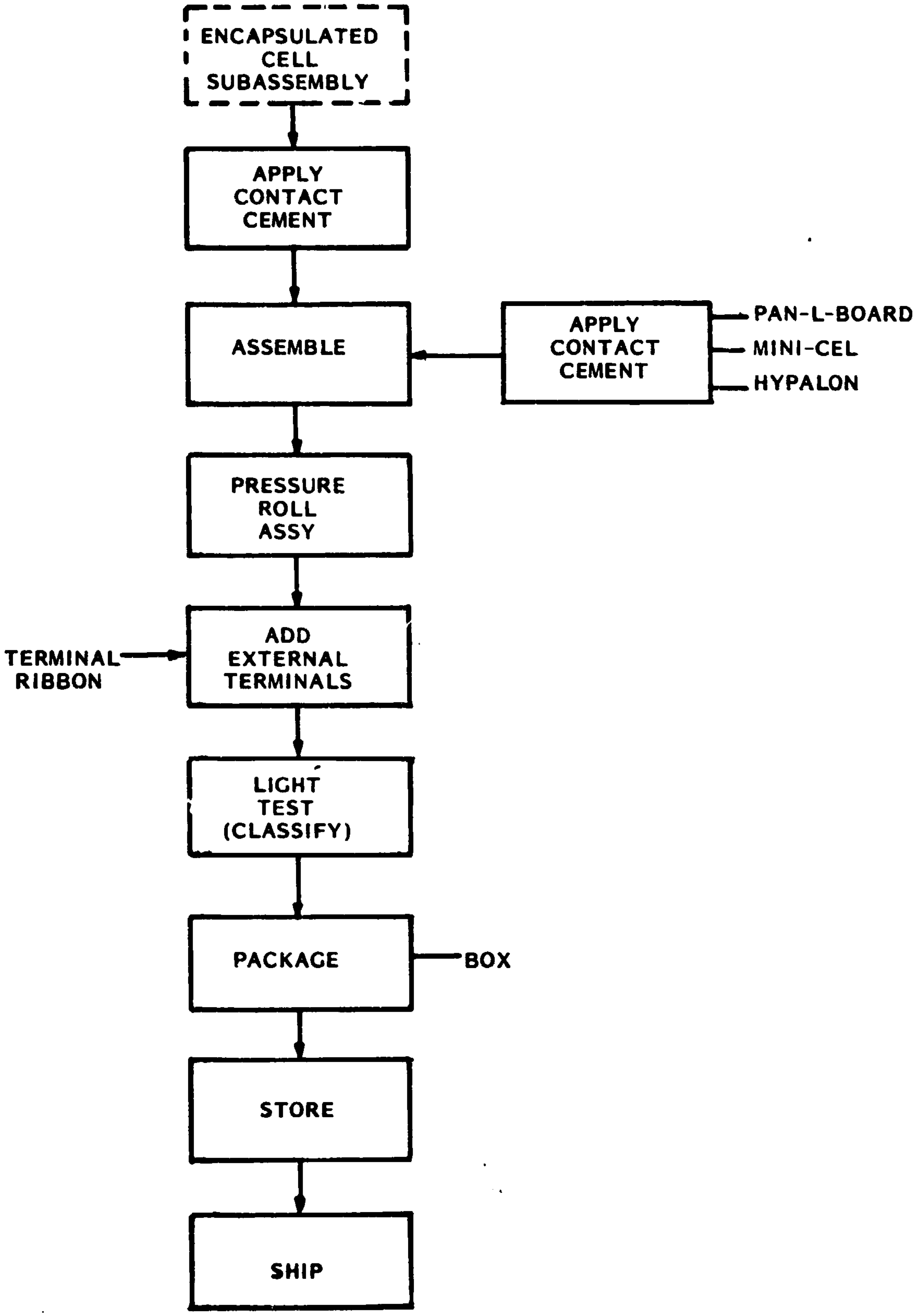

Figure 3-13. Process Flow Diagram for the Final Assembly of Concept No. 1

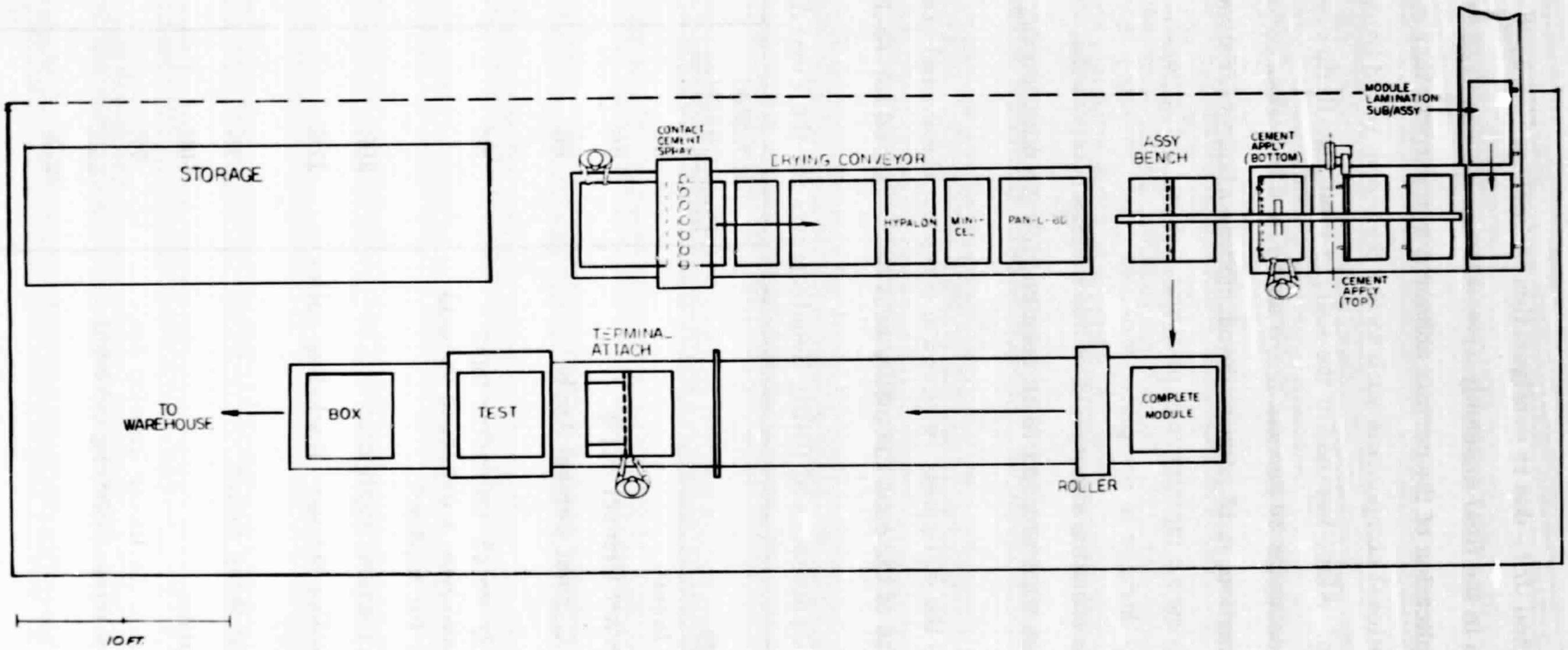

Figure 3-14. Floor Layout for the Final Assembly of Concept No. 1

It should be noted that, due to configuration of Concept No. 1, there are many functions that take place in the final assembly area that are not required in the other concepts. These include the application of the contact adhesive to the areas that must be cemented together, the use of additional components such as the Sunstrom board backing, foam core, and the Flex-seal outer skin. Also, because of the shingle-type installation requirements, each Concept No. 1 module occupies 30 percent more space than the other concepts. In addition, because of the spray function, a 10 percent downtime was allowed for clean-up tasks as part of a production preventive maintenance program. Also, a one percent loss was allowed to account for any damage to completed modules going through pressure roll equipment to accomplish the adhesive attachment of the various components. These negative allowances are greater than what was felt to be required for the other concepts.

Table 3-3 lists the equipment required to complete these final assembly operations, along with an estimate of the cost and utility services required for each item.

Table 3-3. Equipment and Utility Requirements for the Final Assembly of Concept No. 1

Item	Estimated Cost (1980$'s)	Utility Services
Module Invert	3K	
Top Contact Cement Apply	3K	0.2 kW
Bottom Contact Cement Apply	8K	0.3 kW 3 cfm air
Assembly Bench (including input roller conveyor & overhead vacuum transfer for module)	8K	0.2 kW
Contact Cement Applicator	30K	0.5 kW
Pinch Roller Station (including roller conveyor)	17K	0.1 kW
Terminal Strap Attach	1K	0.1 kW
Test Station	50K	0.5 kW
Box Station (including interim conveyors & misc. handling devices)	7K	
Totals	127K	1.9 kW 6 cfm air

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

This concept would also use the basic production line to supply the encapsulated cell subassembly as described in Section 3.2.2. The final assembly process flow diagram and schematic layout of the area are shown in Figures 3-15 and 3-16, respectively. In this case the final assembly operations require the application of a bead of sealant around the plastic tray 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. With fewer operations and pieces that have to be assembled together, the final assembly operations would require less floor space and manpower than Concept No. 1.

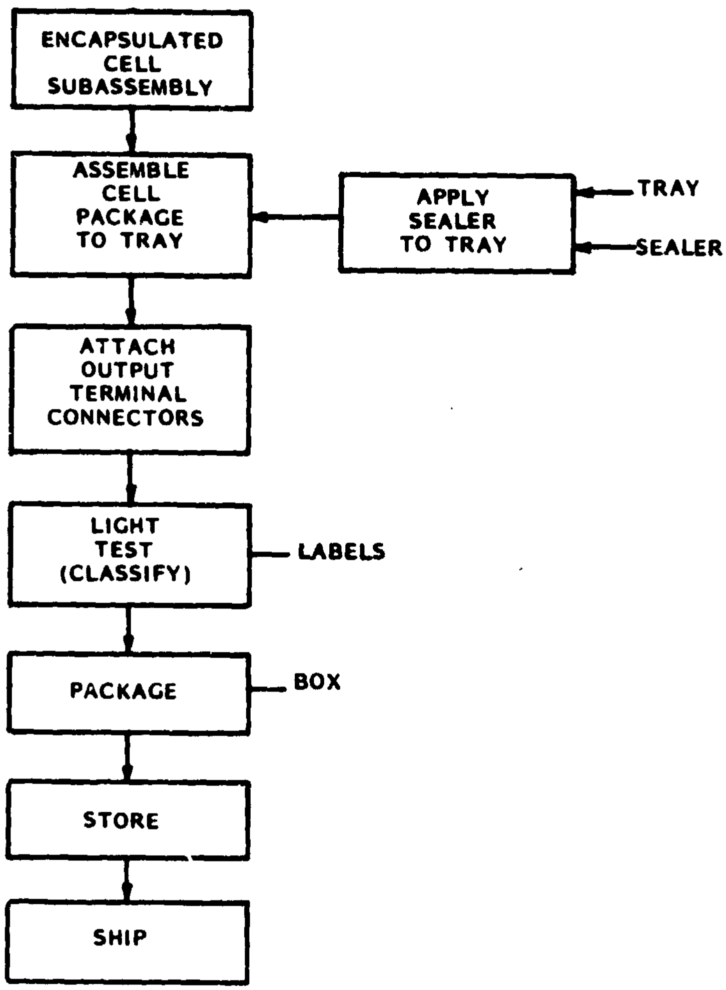

Figure 3-15. Process Flow Diagram for The Final Assembly of Concept No. 2

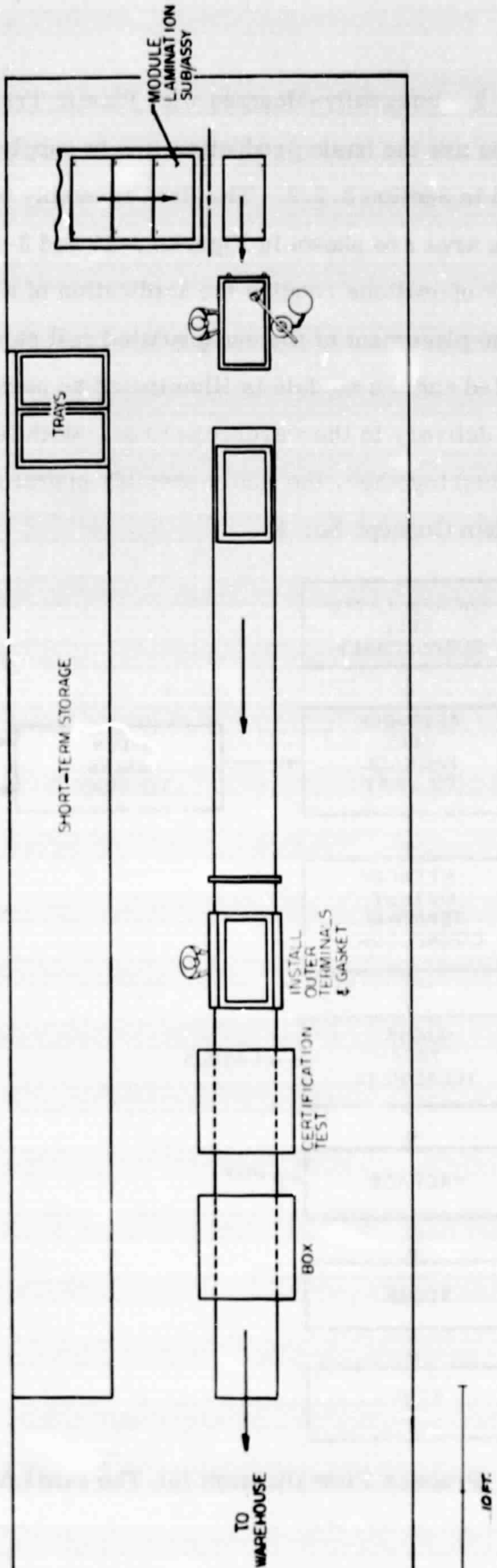

Figure 3-16. Floor Layout for the Final Assembly of Concept No. 2

The estimated cost of the equipment required for this final assembly portion of the plant is listed in Table 3-4 along with the associated utility services required.

Table 3-4. Equipment and Utility Requirements for the Final Assembly of Concept No. 2

Item	Estimated Cost (1980$'s)	Utility Services
Module Invert	3K	
Robotic Arm (includes sealant dispenser)	20K	0.8 kW
Assembly Bench	2K	
Overhead Vacuum Transfer	5K	0.2 kW
Roller Conveyor	2K	
Terminal Bench (tilt table)	2K	0.1 kW
Test Station	50K	0.5 kW
Box Station	1K	
Interim Conveyor	1K	
Misc. Handling Devices	2K	
Totals	88K	1.6 kW

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

As shown in Figure 3-17, the final assembly of this module concept is also fairly simple when compared to the first concept considered. A U-shaped EPDM gasket is bonded around the perimeter of the encapsulated cell subassembly prior to insertion into the mounting track of the framing extrusion. This extrusion is pre-assembled as two side pieces with a mounting clips in the mitered corners. The final fasteners are installed, the Solarlok receptacles mounted, and the finished module is tested, certification label applied, and packaged from delivery to the warehouse area. The floor layout of the final assembly area is shown in Figure 3-18 and the corresponding equipment cost estimate is given in Table 3-5.

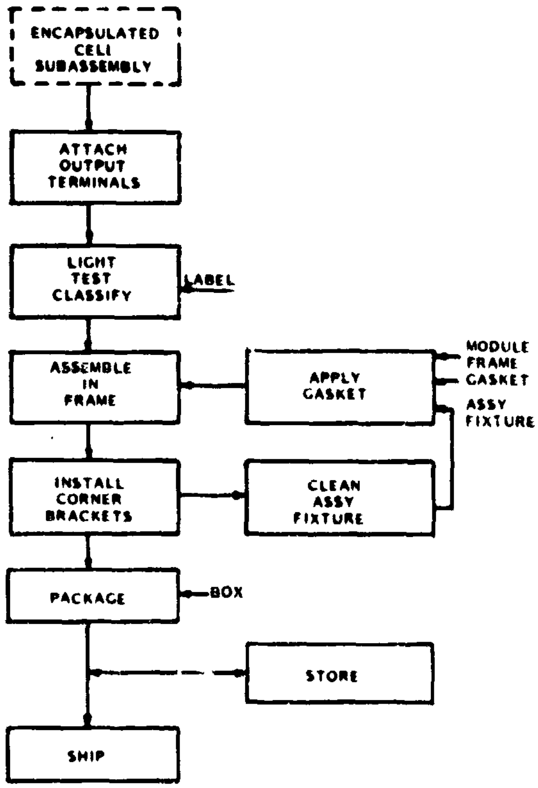

Figure 3-17. Process Flow Diagram for the Final Assembly of Concept No. 3

3.2.4 DIRECT MATERIAL COSTS

The direct material costs were estimated for each of the three concepts by identifying each component within the module and calculating the quantity of each material or part required to complete the assembly. The unit cost associated with each material was obtained by the solicitation of firm quotations for the major cost items such as the glass coverplate, plastic tray substrate, and aluminum extrusions. In each of these cases, a detailed drawing was prepared to support a request for quotation in the quantities required for the 69,444 module annual production rate. Multiple responses were received in all cases and the median unit cost was used to prepare the estimates presented in Tables 3-6, 3-7, and 3-8 for each of the three concepts, respectively. 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.

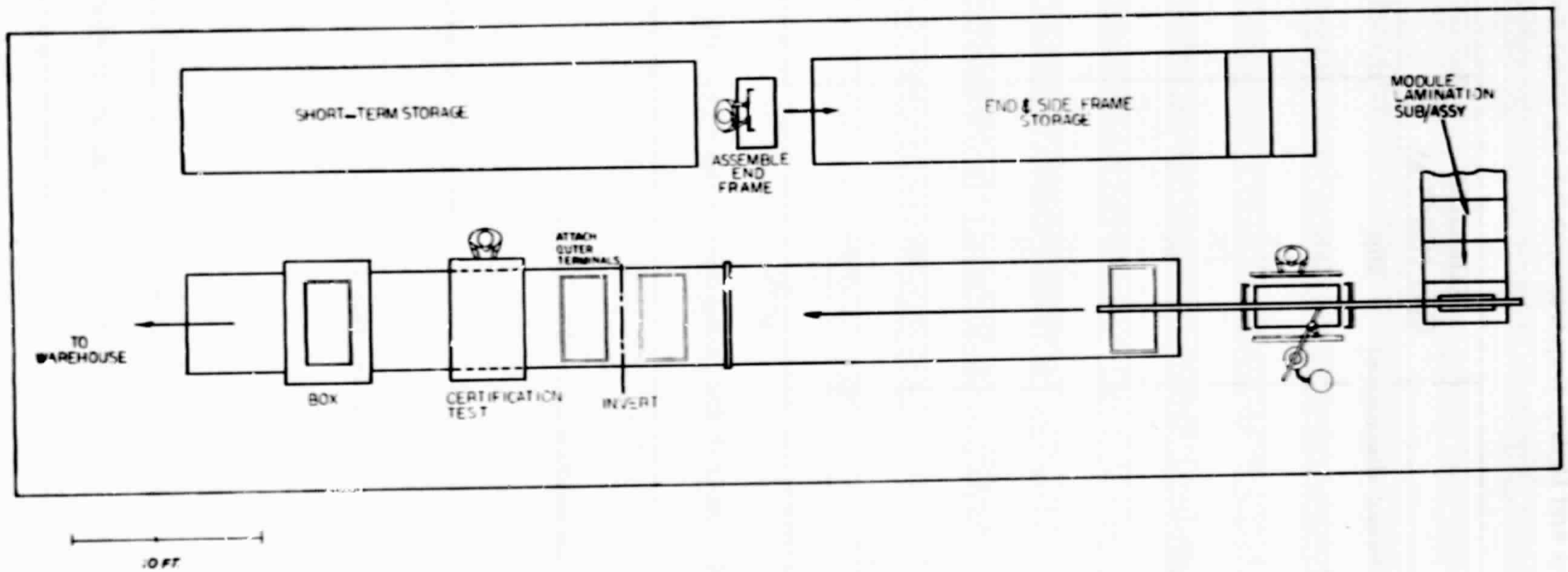

Figure 3-18. Floor Layout for the Final Assembly of Concept No. 3

Table 3-5. Equipment and Utility Requirements for the Final Assembly of Concept No. 3

Item	Estimated Cost (1980$'s)	Utility Services
Robotic Arm (includes sealant dispenser)	20K	0.8 kW
Frame Assembly Bench	15K	0.6 kW
Rivet or Screw Gun	10K	0.3 kW
Roller Conveyor	2K	
Terminal Bench (tilt table)	2K	0.1 kW
Module Inve	3K	
Test Station	50K	0.5 kW
Box Station	1K	
Interim Conveyor	1K	
Misc. Handling Devices	2K	
Overhead Vacuum Transfer	5K	0.2 kW
Totals	111K	2.5 kW

Freight charges have not been included in the cost of the materials listed, but these charges can represent a significant expense which should be reflected in the cost of the material. The magnitude of this cost factor is largely a function of the distance between the glass manufacturing plant and the module assembly factory.

The cost of the solar cells has not been included in any of these direct material tabulations, since data are not available to support a price for this item which is consistent with the basic costing ground rules established for this study.

3.2.5 SUMMARY OF COST PARAMETERS

The production parameters, which contribute to the determination of the FOB factory cost of the module, are summarized on Table 3-9 for each of the three concepts considered. These production parameters are grouped by the established functions which include the basic production area, the final assembly area, and the warehouse area. The basic production line, which produces the encapsulated cell subassembly, is identical for all three concepts.

Table 3-6. Direct Material Inventory for Concept No. 1

Item Description	Quantity Required per Module	Estimated Cost per Module (1980 $'s)
Solar Cells	72	--
Tempered Glass Coverplate (5 mm thick)	0.805 m^2	$11.82
EVA/Craneglass	1.610 m^2	5.20
Primer	80 ml	0.85
Solder-Plated Copper Foil (75 μm thick)	0.090 m^2	0.34
Solder-Plated Copper Foil (500 μm thick)	0.010 m^2	0.20
Solder	6 g	1.86
Aluminum Foil (50 μm thick)	0.805 m^2	0.38
ByPass Diode Chip	3	2.10
Sunstorm Board	1.014 m^2	1.39
Substrate Foam	0.207 m^2	0.65
Substrate Skin (Flexseal)	0.261 m^2	1.80
Contact Cement	200 ml	0.51
Adhesive Bonding Strip	0.124 m^2	0.19
Amp FCC Positive Termination	1	3.40
Amp FCC Negative Termination	1	2.40
Total		$33.29

Table 3-7. Direct Material Inventory for Concept No. 2

Item Description	Quantity Required per Module	Estimated Cost per Module (1980$'s)
Solar Cells	72	--
Tempered Glass Coverplate (5 mm thick)	0.769 m^2	$11.29
EVA/Craneglass	1.537 m^2	4.96
Primer	77 ml	0.81
Solder-Plated Copper Foil (75 μm thick)	0.090 m^2	0.34
Solder-Plated Copper Foil (500 μm thick)	0.010 m^2	0.20
Solder	6 g	1.86
Aluminum Foil (50 μm thick)	0.769 m^2	0.36
Bypass Diode Chip	3	2.10
Plastic Tray Housing	1	14.00
Butyl Sealant	29 g	0.22
Solarlok Panel Mounted Connector	2	0.90
Total		$37.04

Table 3-8. Direct Material Inventory for Concept No. 3

Item Description	Quantity Required per Module	Estimated Cost per Module (1980$'s)
Solar Cells	72	--
Tempered Glass Coverplate (5 mm thick)	0.805 m^2	$11.82
EVA/ Craneglass	1.610 m^2	5.20
Primer	80 ml	0.85
Solder-Plated Copper Foil (75 μm thick)	0.090 m^2	0.34
Solder-Plated Copper Foil (500 μm thick)	0.010 m^2	0.20
Solder	6 g	1.86
Aluminum Foil/ Tedlar Laminate	0.805 m^2	3.42
Bypass Diode Chip	3	2.10
EPDM Gasket	29 g	0.22
Aluminum Framing Extrusion (long)	2	4.30
Aluminum Framing Extrusion (short)	2	2.50
Corner Key Bracket	4	0.60
Solarlok Female Connector	2	0.90
Total		$34.31

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.

Table 3-9. Summary of Production Parameters

	Concept No.		
	1	2	3
Basic Production Area			
Process Yield (%)	99	99	99
Equipment Cost (1980$)	846,000	846,000	846,000
Manpower (No of Employees)	7.0	7.0	7.0
Floor Space (ft^2)	2,664	2,664	2,664
Utilities			
Electricity (kW)	29.6	29.6	29.6
Air (cfm)	6.0	6.0	6.0
Water (gpm)	13.1	13.1	13.1
Final Assembly Area			
Process Yield (%)	99	100	100
Equipment Cost (1980$)	127,000	88,000	111,000
Manpower (No of Employees)	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$)	30,000	30,000	30,000
Manpower (No of Employees)	3.0	3.0	2.5
Floor Space (ft^2)	1,620	1,272	1,272
Totals			
Equipment Cost (1980$)	1,003,000	964,000	987,000
Manpower (No. of Employees)	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

The total production requirements for each of the module design concepts, as summarized at the bottom of Table 3-9, include a total work force which ranges from 12.3 persons for 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.

These cost-related production parameters were used along with the direct material cost for each module to determine the overall module production cost in accordance with the methodology outlined in Table 3-10. The direct labor cost was calculated based on 7,128 hours per year of plant operation at an average hourly rate of $7.00. A factor of 1.25 was applied to the estimated process direct labor requirement to account for inefficiencies and other non-productive activities such as coffee breaks.

Table 3-10. Production Cost Methodology

Production Costs Are Calculated As The Sum Of:

1. Direct Labor

$$= \frac{\text{(No. Of Employees) (7128) (1.25) (7.00)}}{\text{(Annual Production Rate)}}$$

2. 170 Percent Labor Overhead
3. Direct Material
4. 3 Percent Material Overhead
5. Process Equipment Charge

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

6. Floor Space Rental

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

7. Utility Services

(a) Electricity $= \dfrac{\text{(Power - kW) (7128) (0.04)}}{\text{(Annual Production Rate)}}$

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

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

The direct labor costs, which were calculated as outlined in Item 1 of Table 3-10, 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 3-10. Similarly, the factory floor space was rented at an annual rate of \$5.50 per square foot and prorated on a per-module basis.

The expenses associated with process related utility services were accounted for as shown in Item 7 of Table 3-10. The most significant of these is the charge for electricity which is prorated over the annual production rate at \$0.04 per kWh.

Table 3-11 applies this methodology in calculating the module production cost for each design concept. 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, 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. Table 3-12 presents these prices as a function of solar cell cost using the same production cost methodology.

Table 3-11. 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

Table 3-12. Module FOB Factory Price Sensitivity to Solar Cell Cost

Solar Cell Unit Cost (1980$'s)	Estimated Factory FOB Price (1980$/ Module)		
	Concept No. 1	Concept No. 2	Concept No. 3
0	88.36	86.02	83.27
1	179.16	175.91	173.15
2	269.98	263.54	260.82
3	360.78	355.70	352.94
4	451.59	445.59	442.83
5	542.39	535.48	532.72

3.3 ARRAY INSTALLATION DETAILS

3.3.1 CONCEPT NO. 1 - DIRECT-MOUNTED, OVERLAPPING SHINGLE

The installation of the direct-mounted, overlapping shingle module is illustrated in Figures 3-19 through 3-24. Eleven rows, or courses, of shingle modules are installed as shown in Figure 3-19. Seven 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. The detail at the ridge employs a row of dummy modules which do not contain solar cells, but are otherwise constructed to be identical to the active modules. The roof is completed along the south side of the ridge line by the application of conventional asphalt shingles. The glass covered top row of dummy modules provides a positive protection for the flat-conductor cable (FCC) bus runs which terminate the array circuit at the ridge. The AMP, Inc., undercarpet FCC system is employed throughout the array as the conductor matrix to make the parallel and series connections which are required to produce the single branch circuit of seven parallel by eleven series-connected modules. Intermediate horizontal FCC runs are placed at every course to perform this cross-strapping by crimp connection with the FCC terminations for each module.

3.3.2 CONCEPT NO. 2 - INTEGRALLY-MOUNTED WITH PLASTIC TRAY

Figures 3-25 through 3-28 illustrate the installation approach to be used with the integrally-mounted configuration with the plastic tray substrate. As in the previous concept, the array consists of eleven rows of seven modules each arranged as shown in Figure 3-25. 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 as shown in Figure 3-26. The U-shaped aluminum extrusions run normal to these purlins and form the watertight seal with the east-west edges of the modules as shown in Figures 3-27 and 3-28. Any water leakage

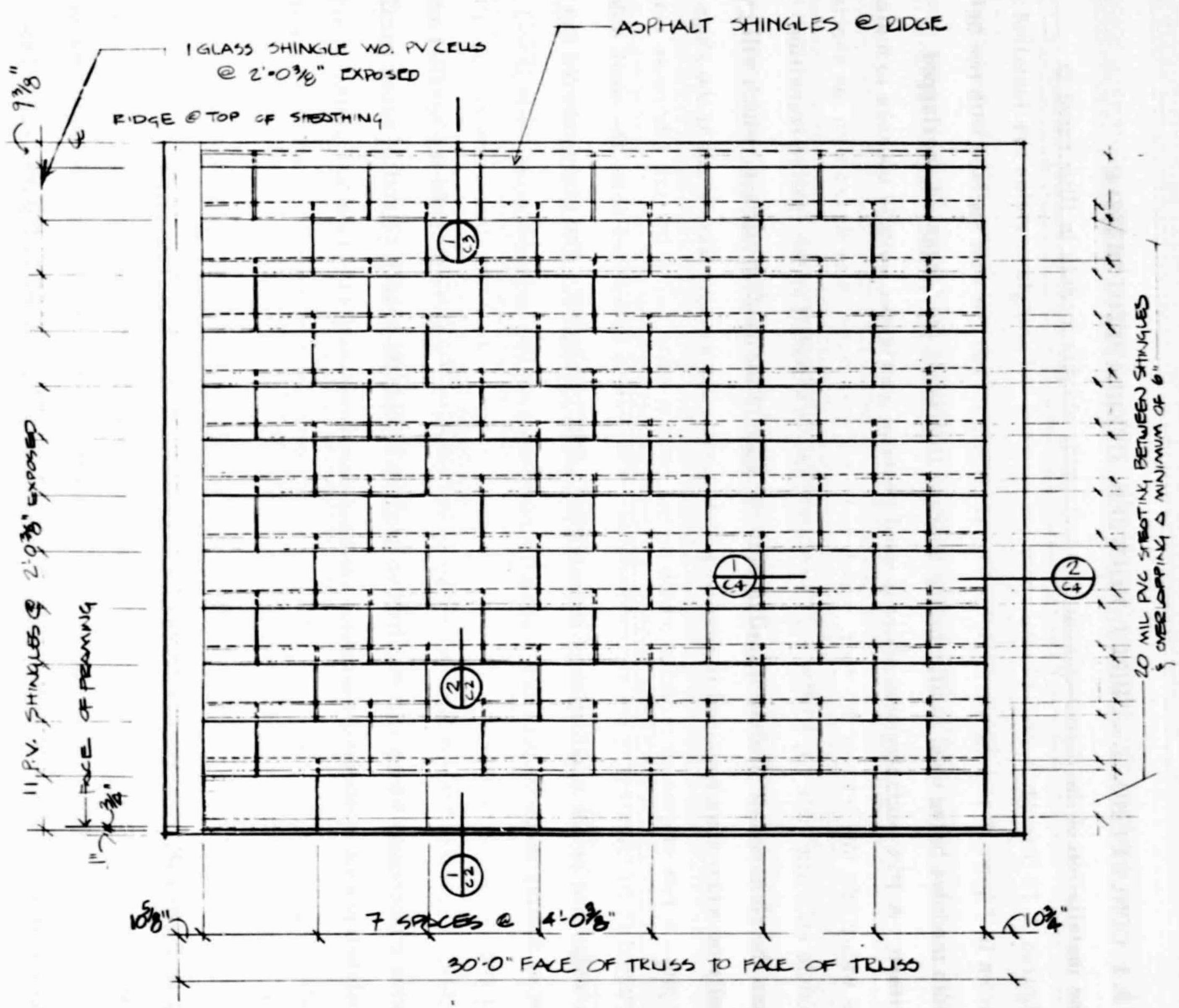

Figure 3-19. Installation Details for Concept No. 1
(Overall Roof Layout)

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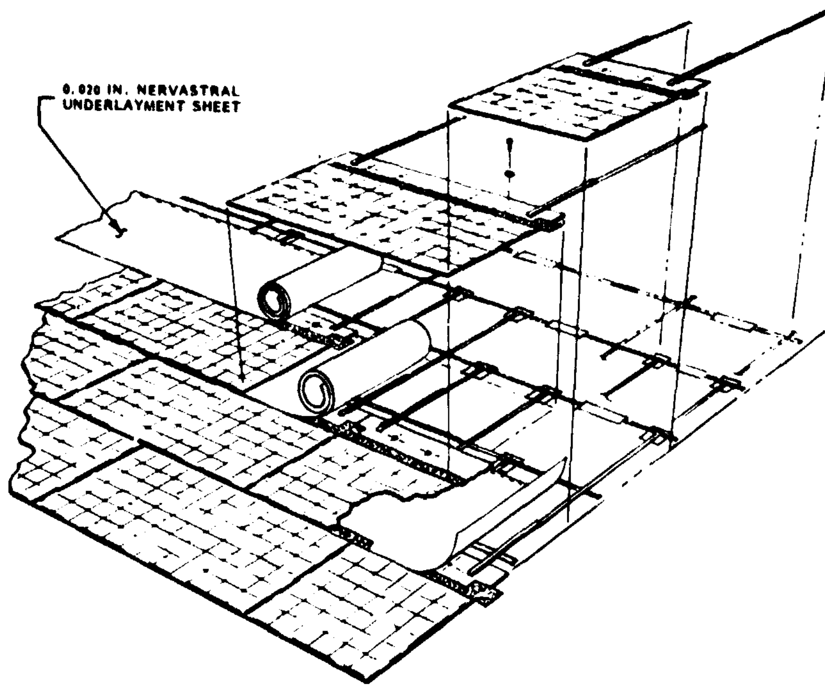


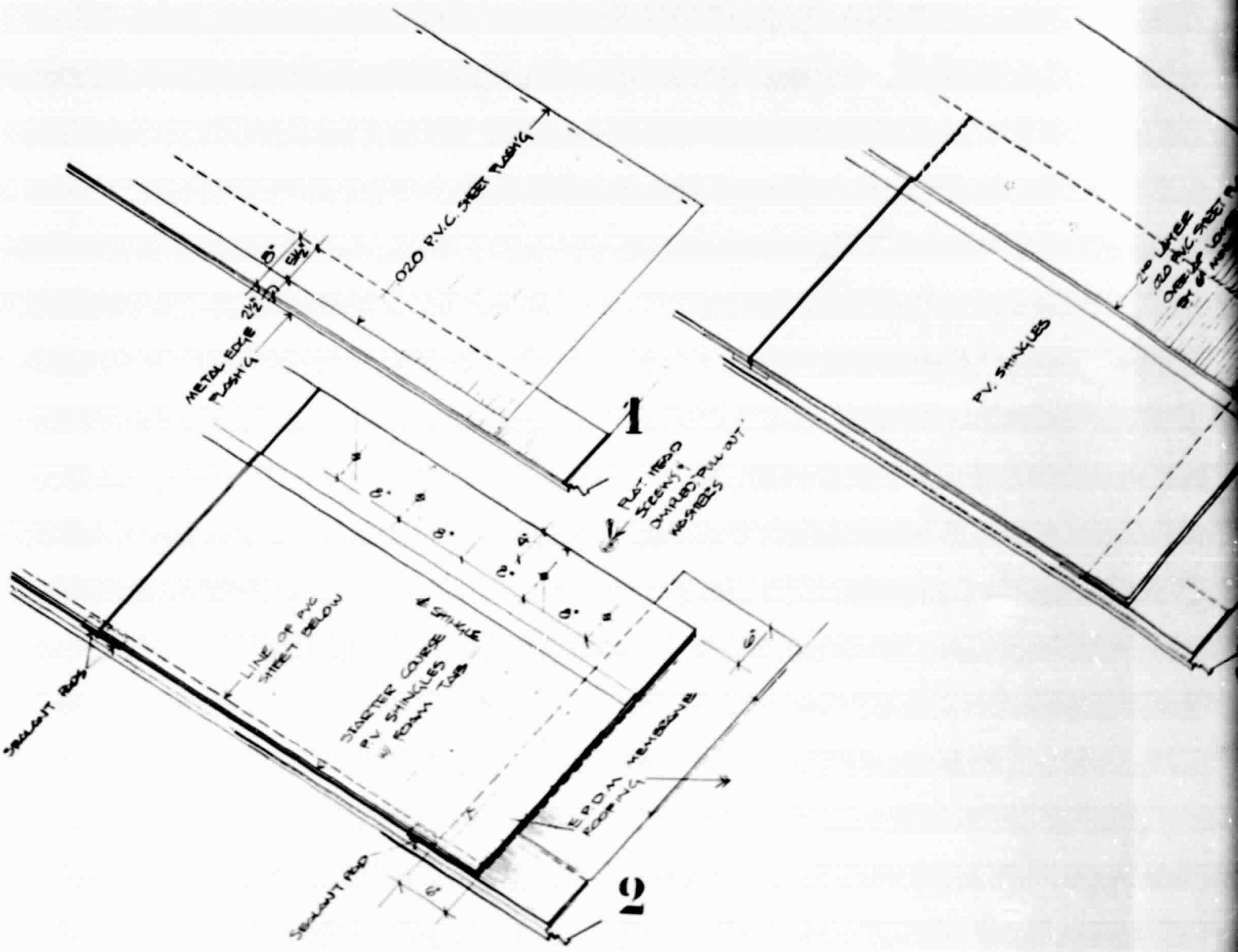
Figure 3-20. Installation Details for Concept No. 1
(Pictorial View of Overlapped Arrangement)

through the clamping strip will run down the extrusion channel and drip off the eave as shown in Figure 3-28. 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.

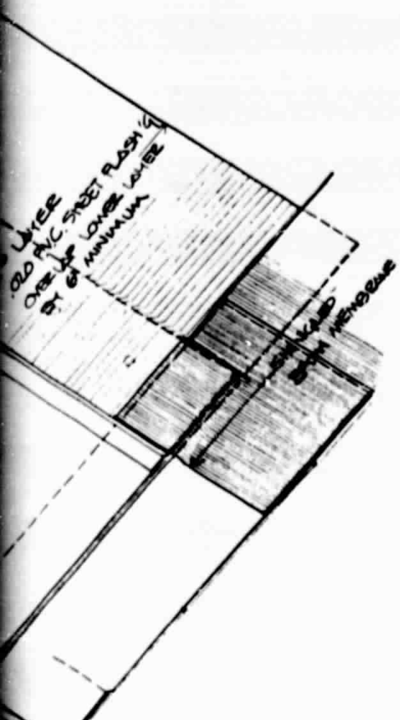
The AMP Solarlok interconnection system is employed for the series wiring of the eleven modules in each branch circuit. The integral mounting scheme used for this installation will place all these electrical connections and harnesses in the attic space for easy access.

3.3.3 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 Figures 3-29 through 3-34. The array of 77 modules 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 as shown in Figure 3-32. A system of 2x2 purlins are nailed to the longerons to form a lattice structure for the mounting of the module frames by clamping as shown in Figure 3-30.



FOLDOUT FRAME 1



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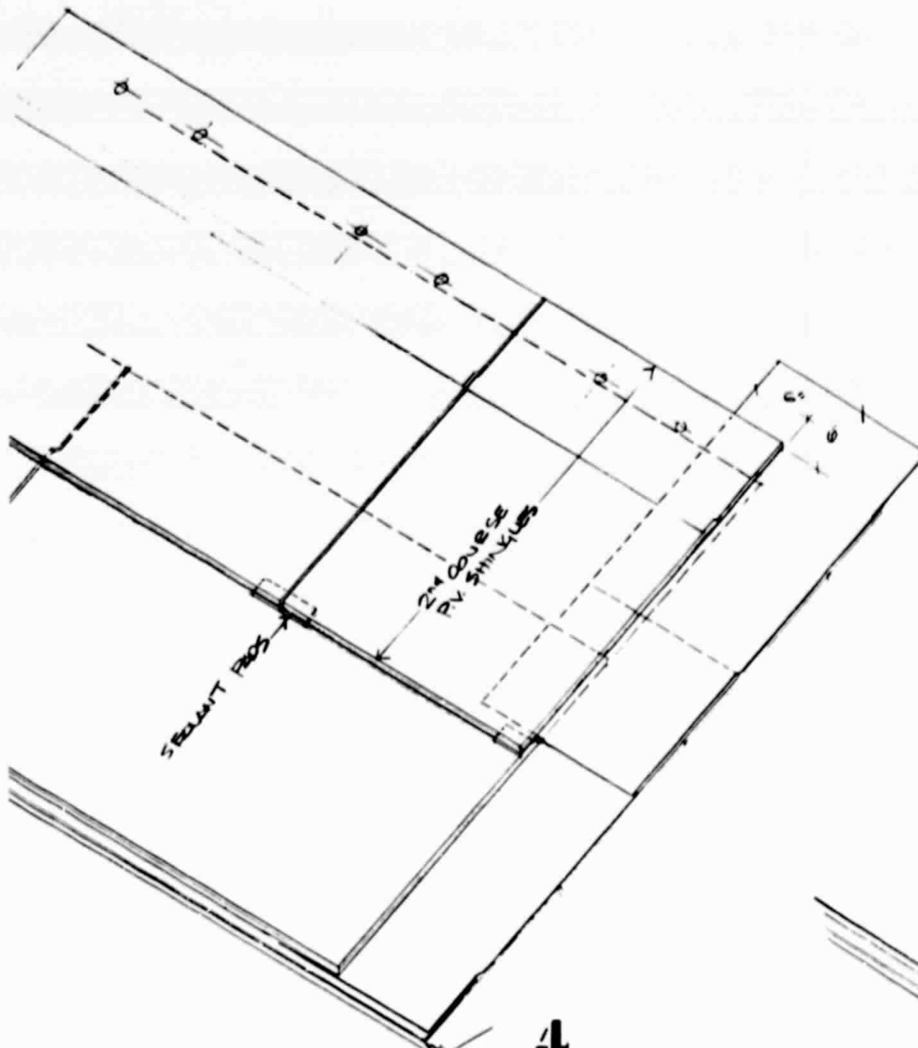

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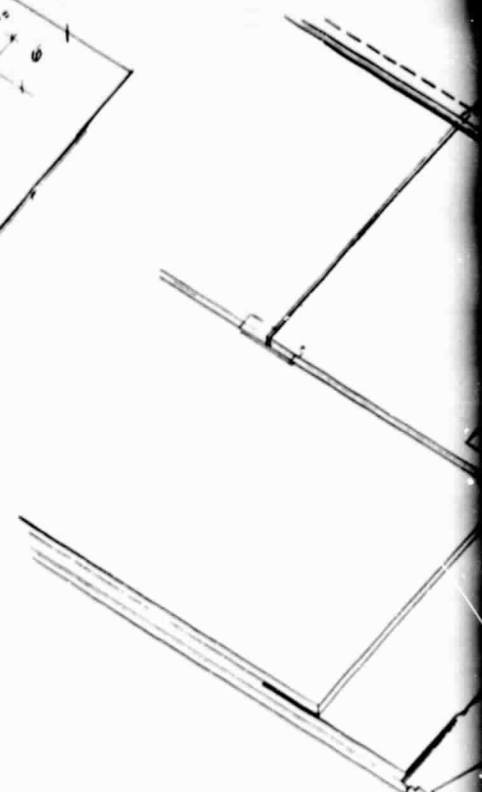
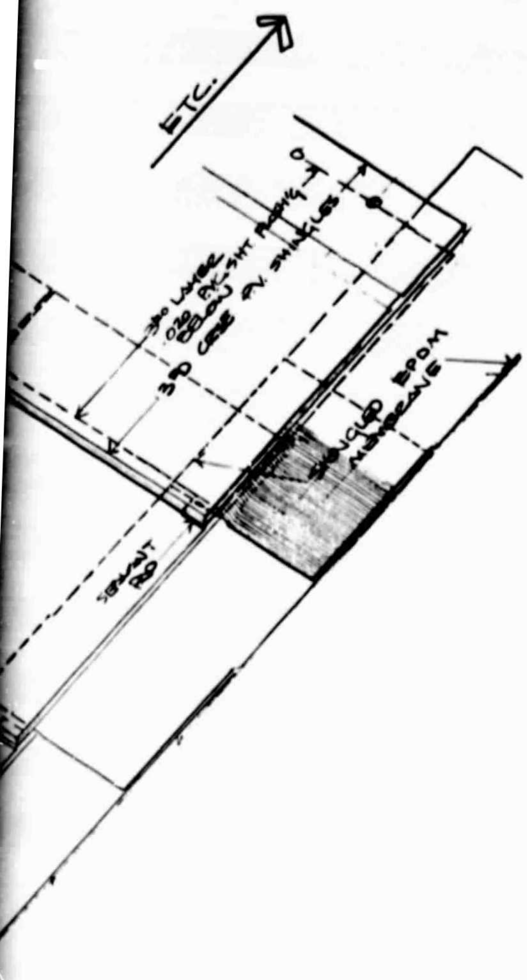


FOLDOUT FRAME 2



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FOLDOUT FRAME 3

Figure 3-21. Installation Details for Concept No. 1 (Eave and Rake Details)

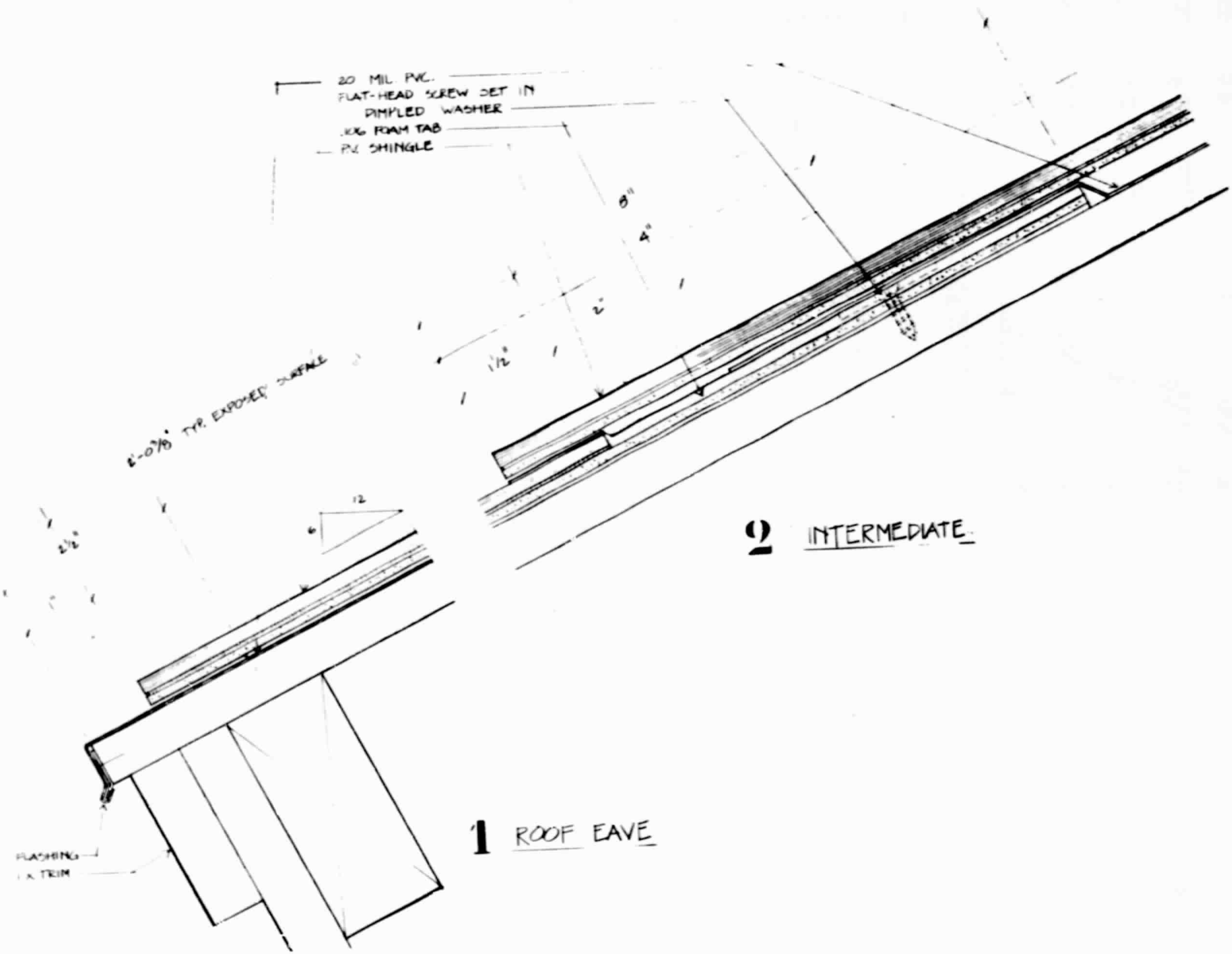


Figure 3-22. Installation Details for Concept No. 1
(Section at Eave)

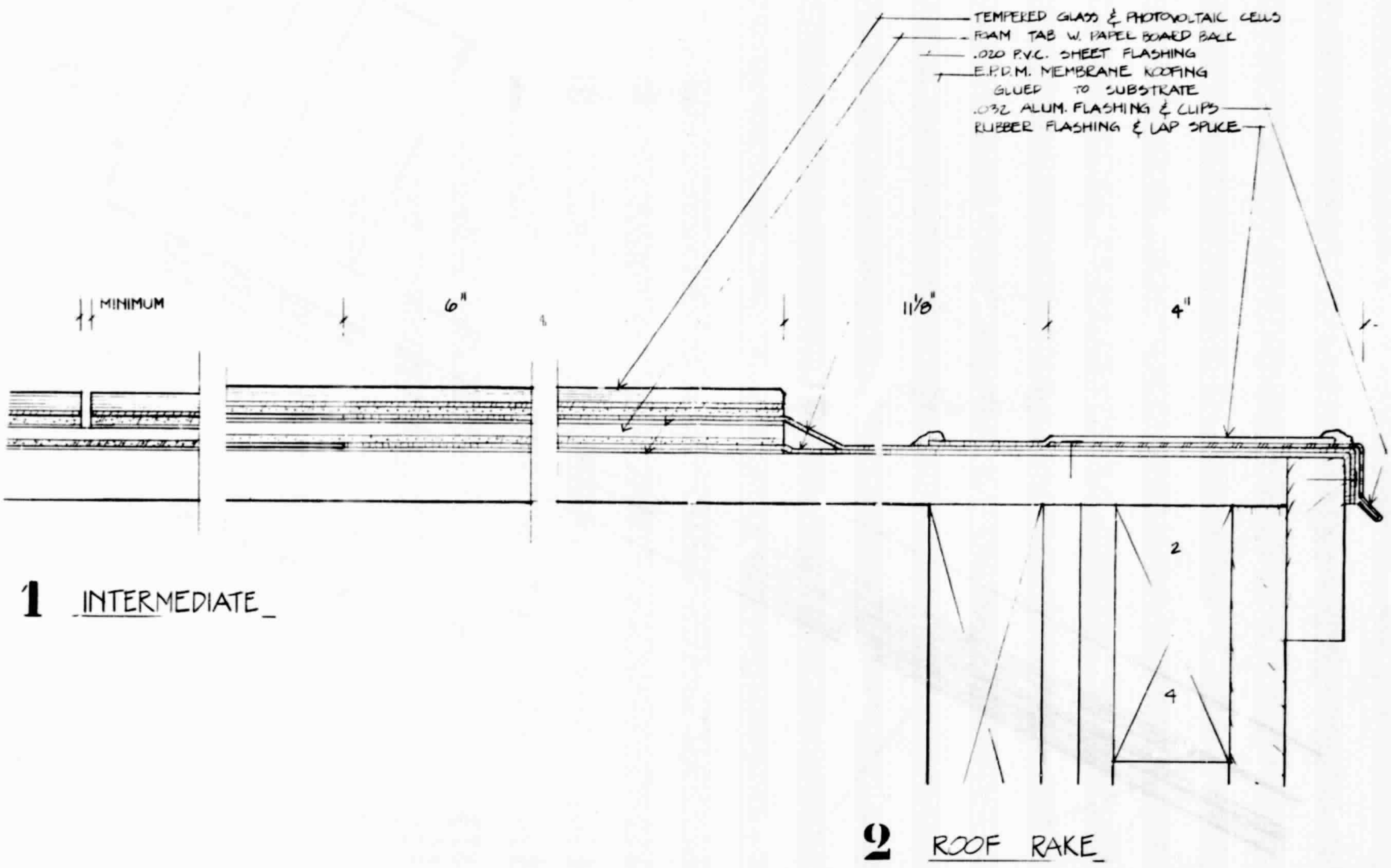


Figure 3-23. Installation Details for Concept No. 1
(Section at Rake)

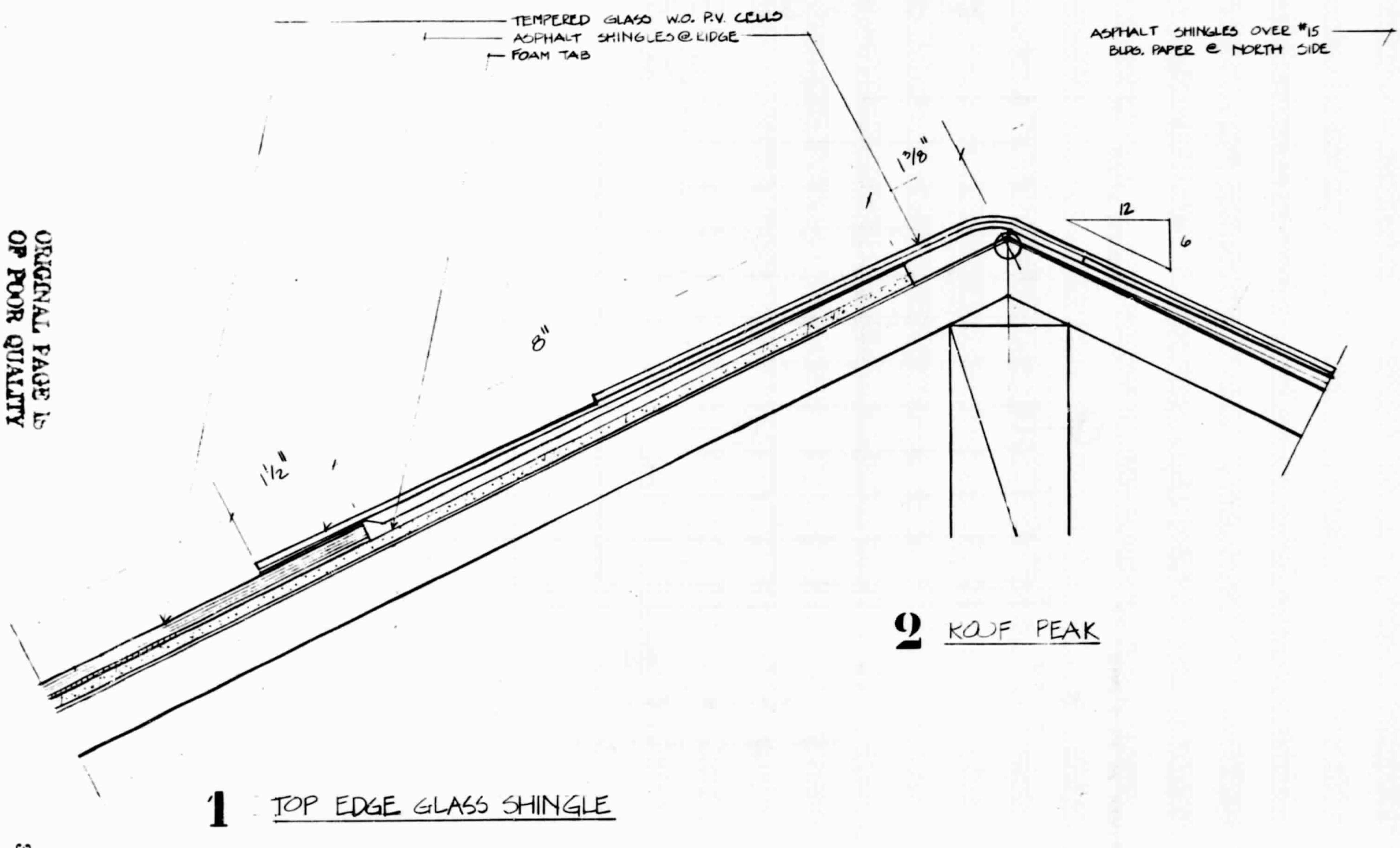
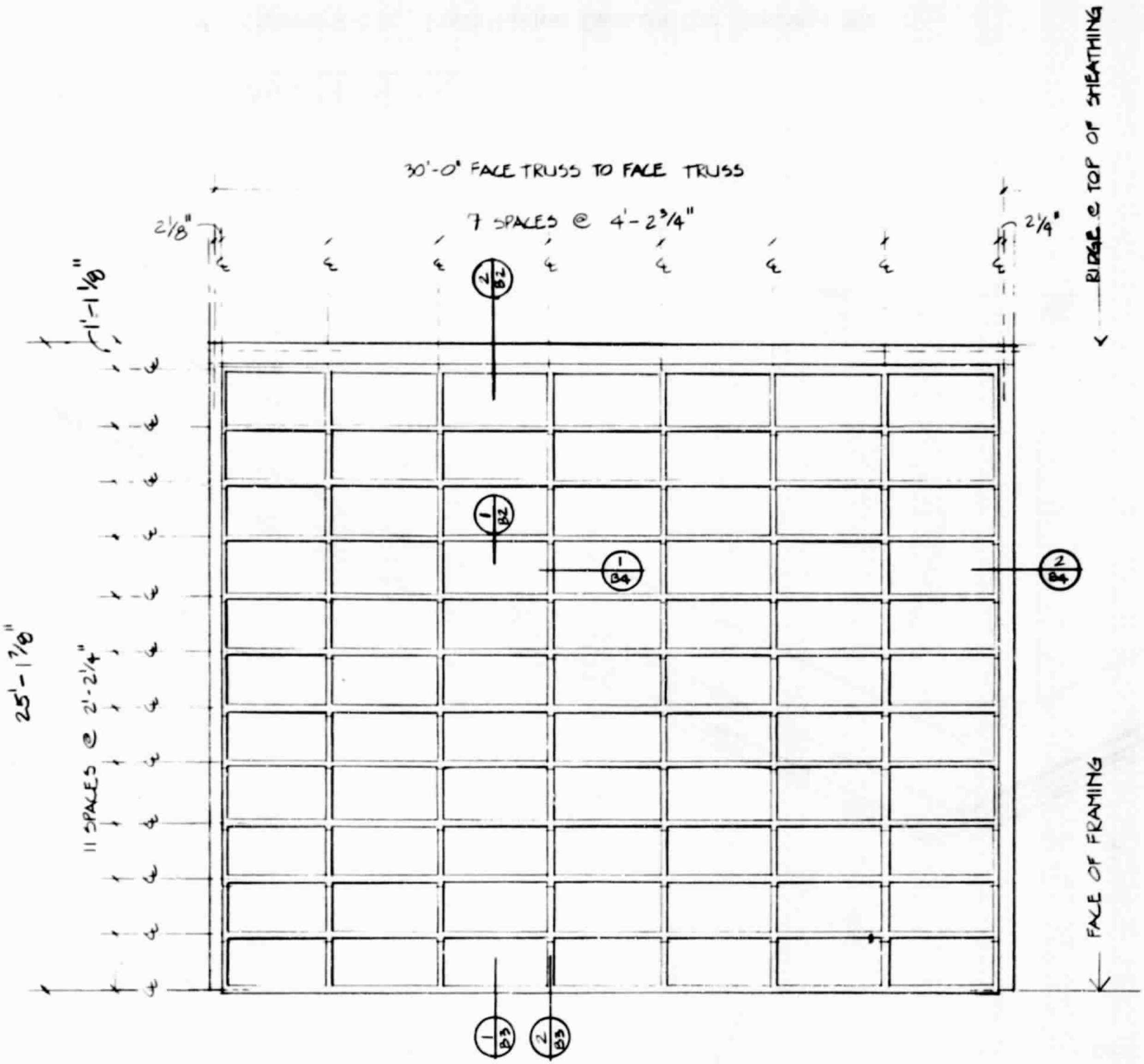


Figure 3-24. Installation Details for Concept No. 1
(Section at Ridge)



PANEL LAYOUT FOR 6/12 SLOPE

Figure 3-25. Installation Details for Concept No. 2 (Overall Layout)

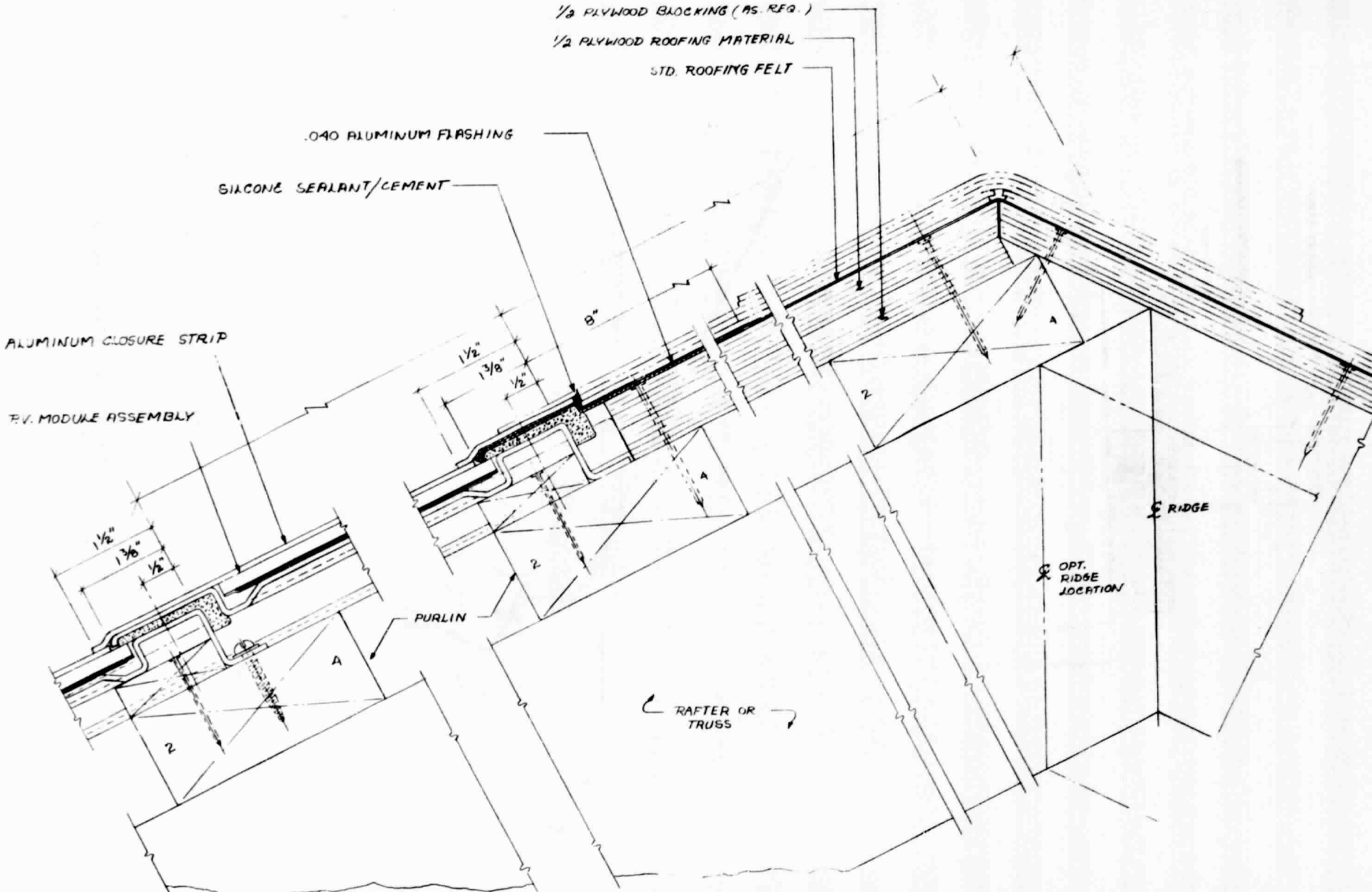


Figure 3-26. Installation Details for Concept No. 2
(Section at Ridge)

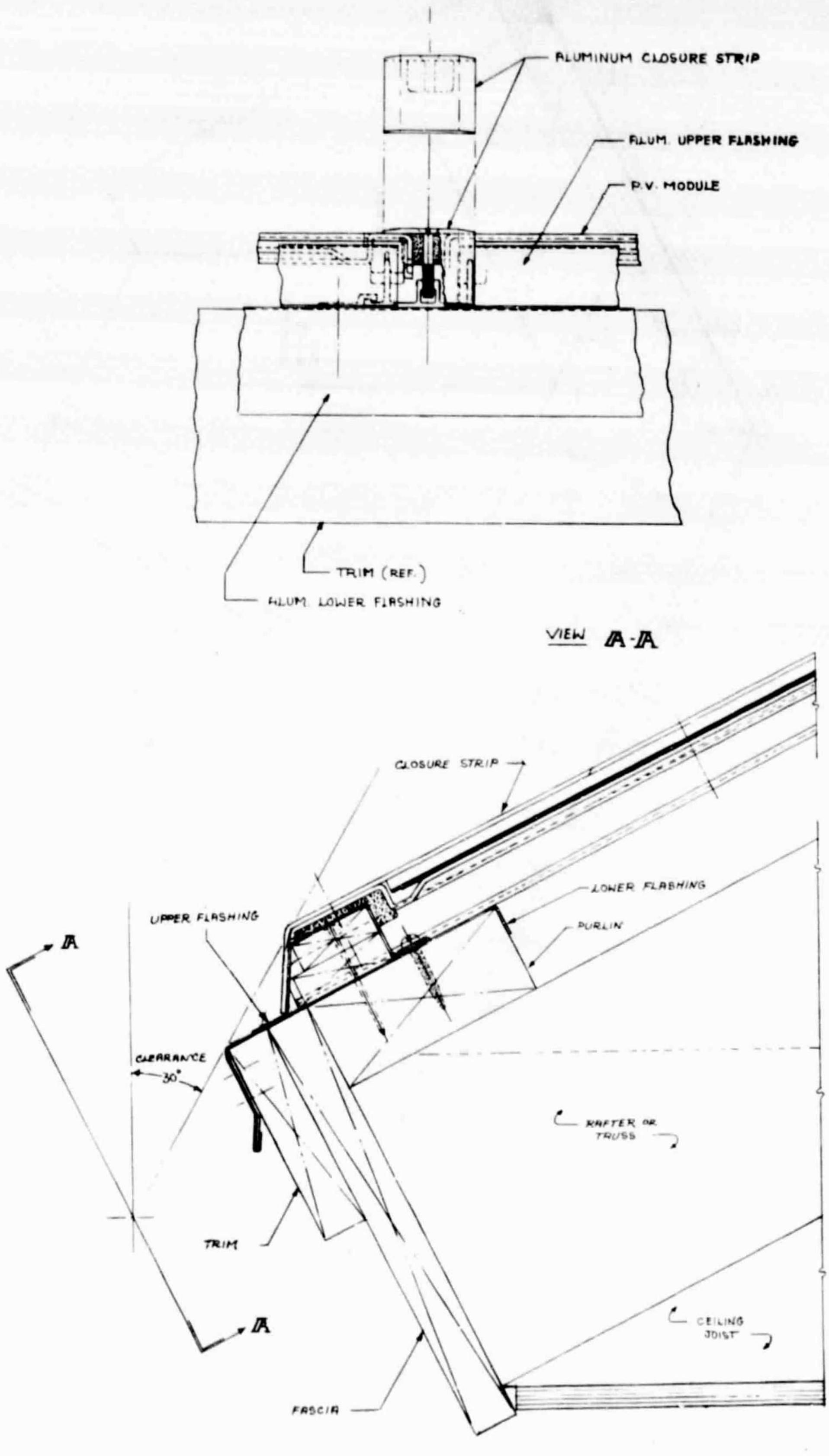


Figure 3-27. Installation Details for Concept No. 2
(Section at Eave)

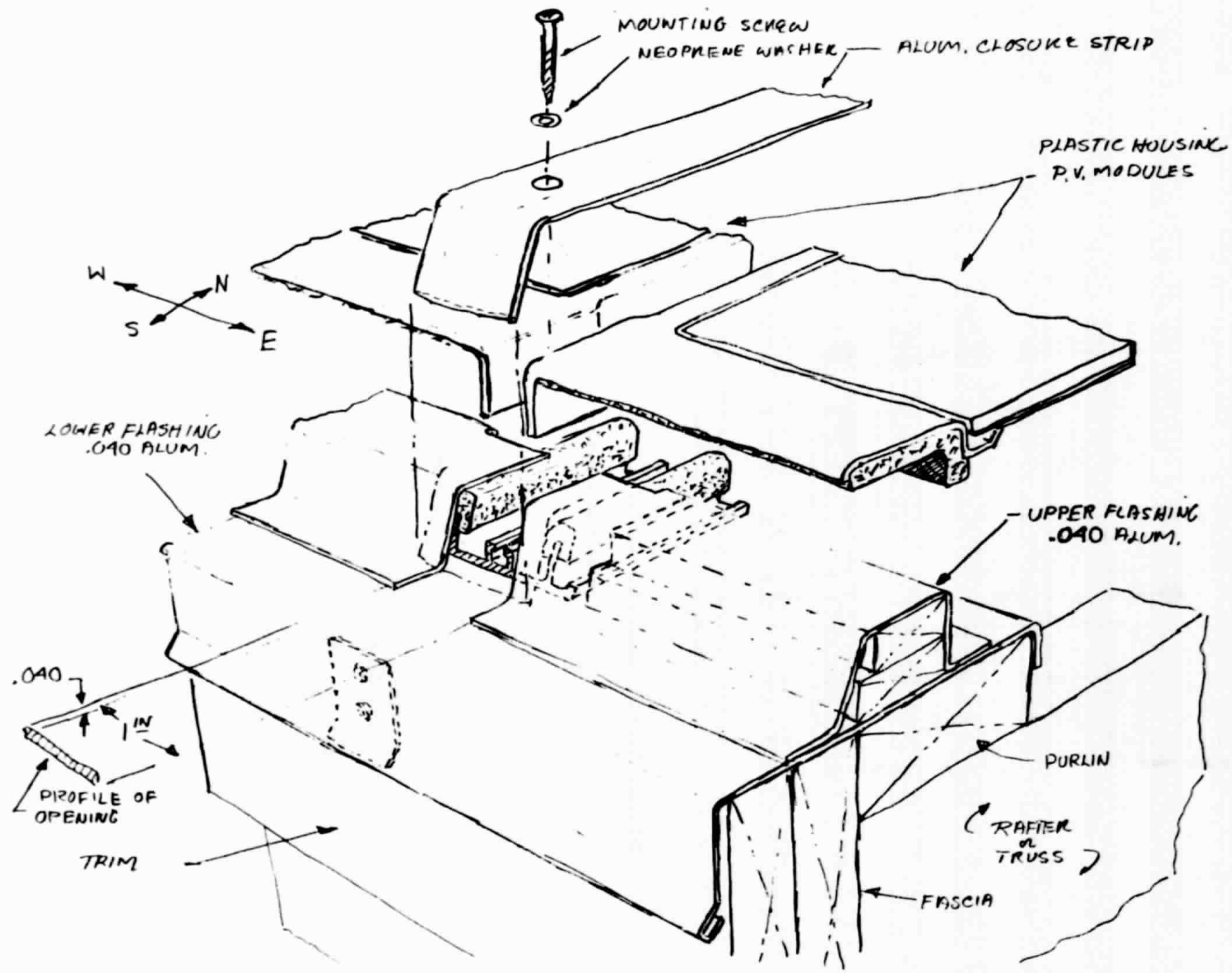


Figure 3-28. Installation Details for Concept No. 2
(Pictorial View at Eave)

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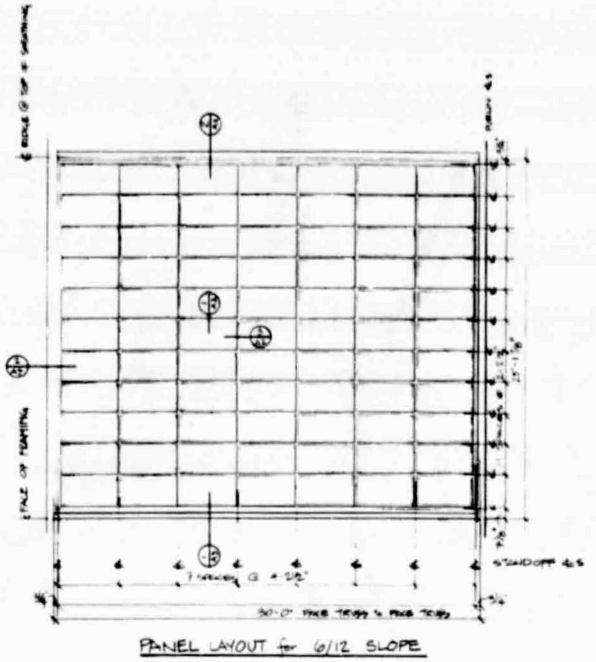

Figure 3-29. Installation Details for Concept No. 3
(Overall Layout)

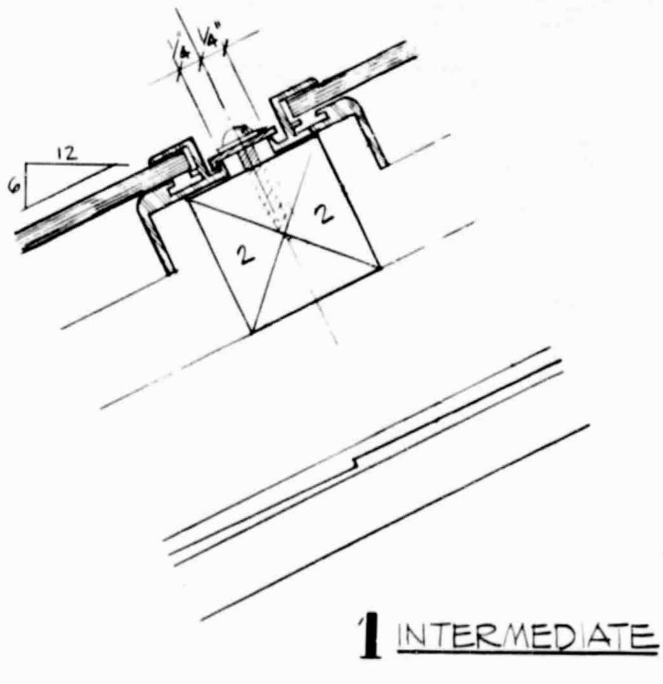

Figure 3-30. Installation Details for Concept No. 3
(Section Looking West)

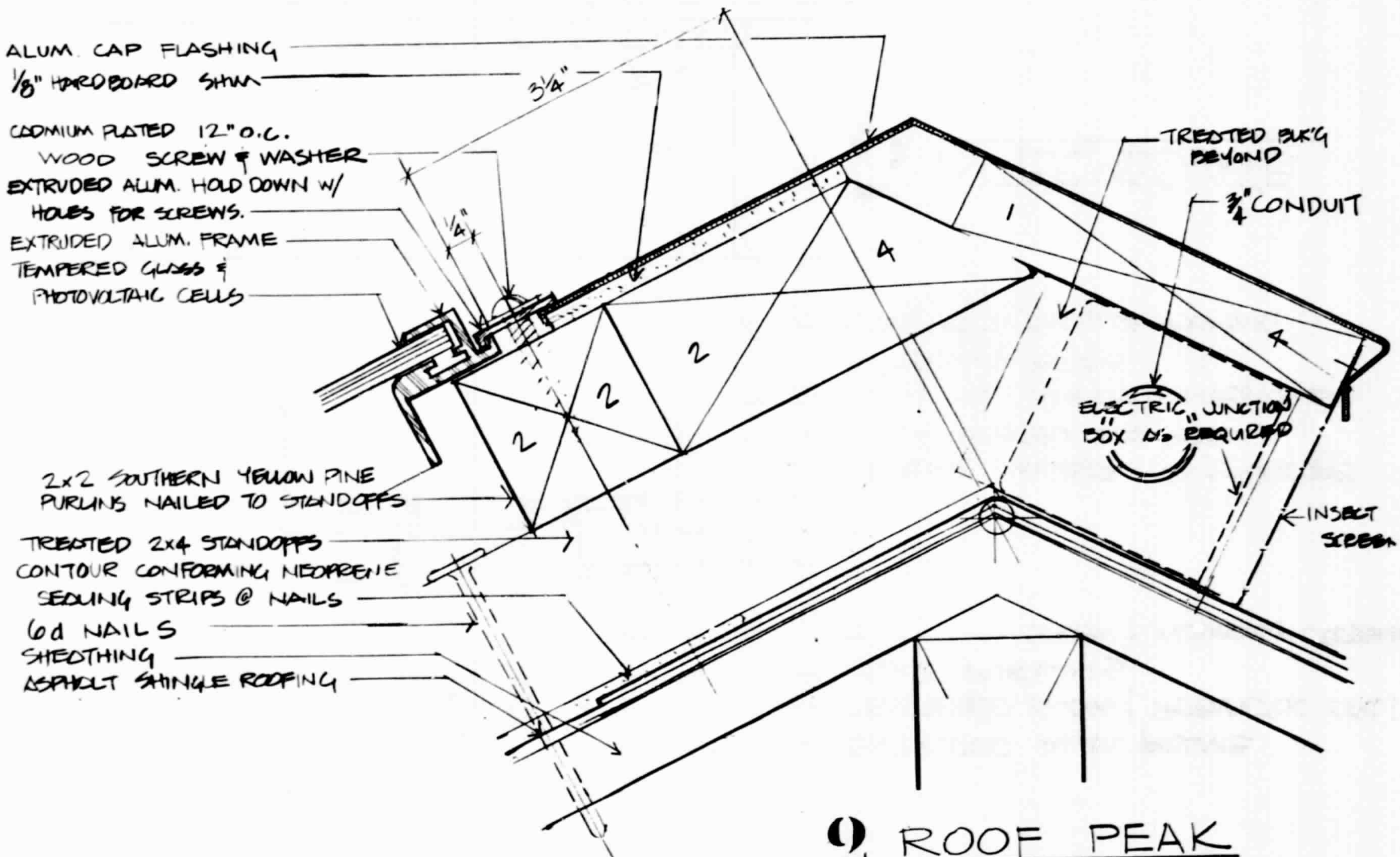

Figure 3-31. Installation Details for Concept No. 3
(Section at Ridge)

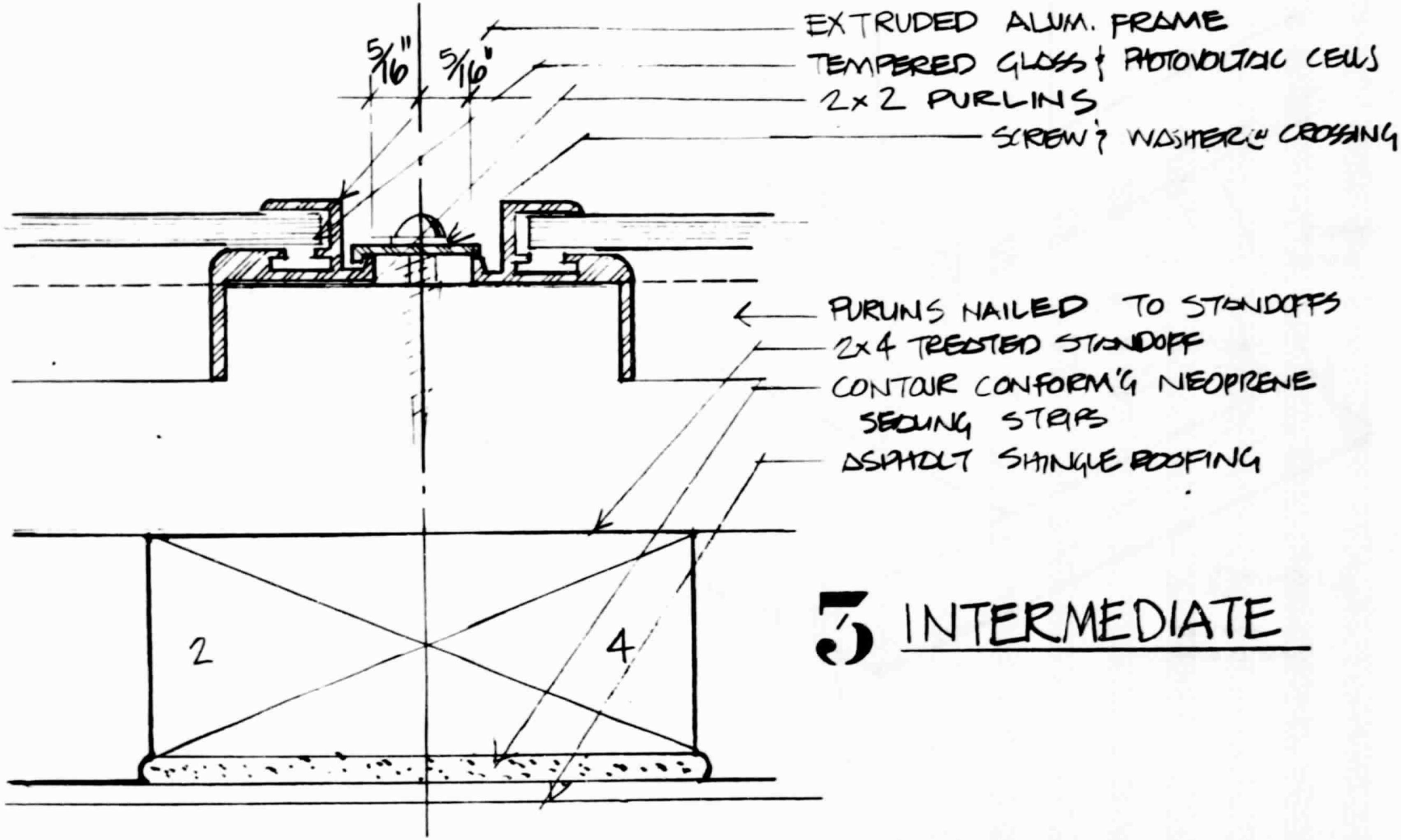

Figure 3-32. Installation Details for Concept No. 3
(Section Looking North)

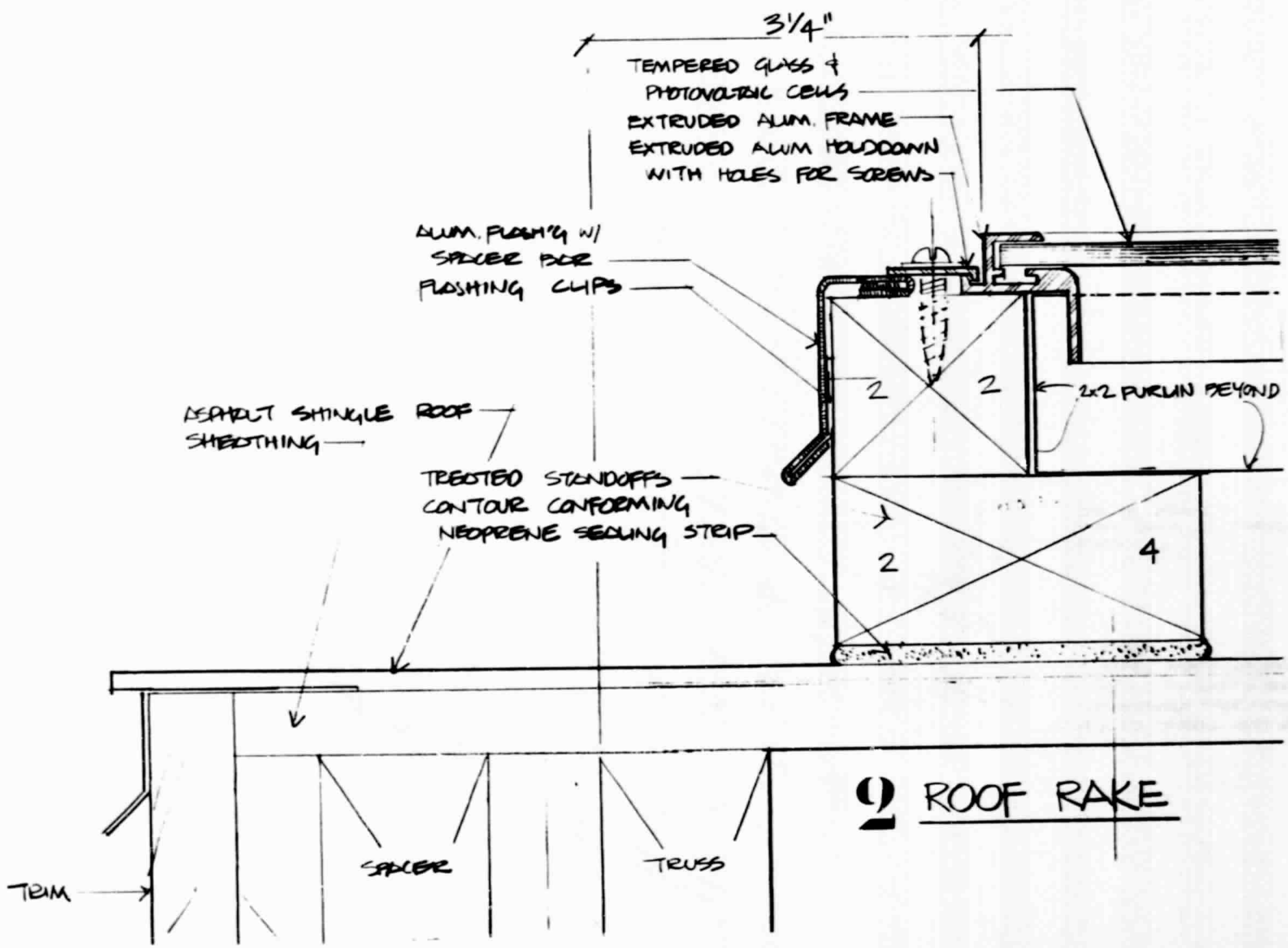

Figure 3-33. Installation Details for Concept No. 3
(Section at Rake)

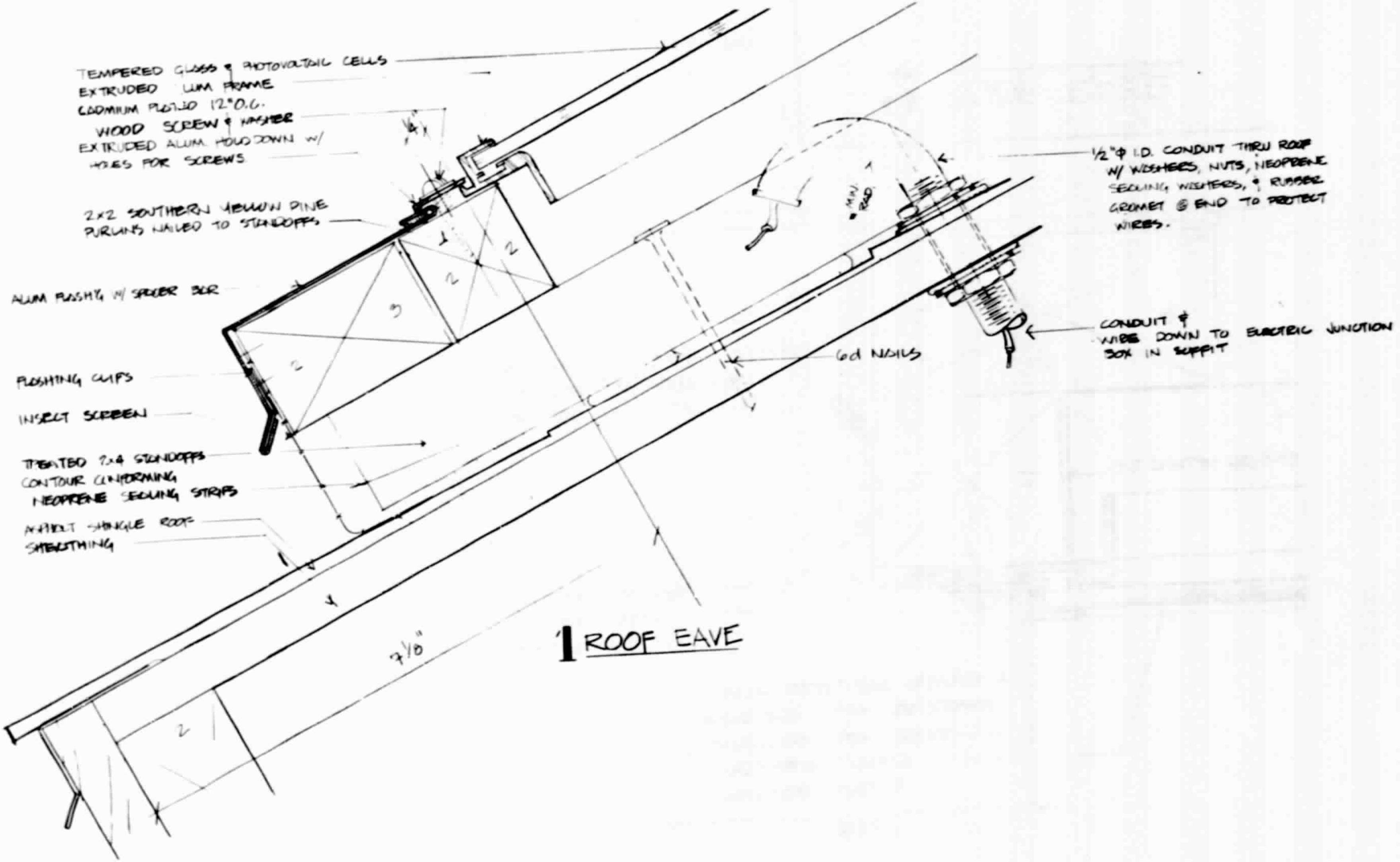

Figure 3-34. Installation Details for Concept No. 3
(Section at Eave)

The ridge detail is completed by flashing over onto the north-facing roof surface as shown in Figure 3-31. This built-up area provides an ideal mounting location for the junction boxes required to terminate the positive bus for each of the seven 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 INSTALLATION COST ANALYSIS

3.4.1 INTRODUCTION AND ASSUMPTIONS

The installation cost for each of the three module design concepts was estimated based on the array details presented in Section 3.3. An experienced residential general contractor in the Boston, MA area was employed to work with Massdesign Architects and Planners in the formulation of this cost estimate based on the following assumptions and constraints.

1. The array size is the same for each case and consists of 77 modules which represent 55.44 m^2 of solar cell area on each residence. Thus, the specified annual module production rate represents the installation of 900 arrays of the size considered in this evaluation.

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. The cost of the special scaffolding required for module installation is amortized over many jobs at a rental charge of $30 to $50 per day, depending on the complexity of the set-up.

3.4.2 CONCEPT NO. 1 - DIRECT-MOUNTED, OVERLAPPING SHINGLE

The installation cost estimate for the direct-mounted, overlapping shingle approach described in Section 3.3.1 is presented in Table 3-13. With this mounting approach the cost estimate includes the installation of the plywood roof sheathing which requires a half-day of activity by the two-man carpenter crew. The shingle modules must be installed immediately since no watertight roofing material is used over the sheathing. The same carpenter crew spends an additional half-day erecting the special scaffolding, which might consist of four 2x10 beams running up and down the roof about 8 inches from the surface. Roofing brackets are mounted on the top surface of these beams on 2 foot centers. Two horizontal runs of planks are placed at the bottom to provide a continuous east-west working platform raised up off the roof. As the work progresses upward, the planks are leapfrogged up, with other planks placed up one bay to act as steps. The next day a 3-man crew, consisting of an electrician, an electrician's helper, and a glazier arrive to install the modules. While the glazier is laying the lower flashing and the first layer of PVC, the electricians layout the flat-conductor cable (FCC) for the array negative termination.

The first row of shingles is laid down by the glazier, and as he goes, the electrician and helper follow and make up FCC connections and lay down the FCC horizontal cable at the same time. Then at the end of a row, the glazier lays down the next PVC layer, and the process continues from the same end as before. Alternatively, the PVC could be cut into 6 foot long sheets, and laid as you go along, with joints occurring in the middle of a shingle. At each end of each row, the glazier would lay down the interleaving EPDM flashing.

At the top, the positive bus would be laid and connections made to it, and the system connected to the service entry terminal box. The glazier would then install the last dummy row and finish the top flashing.

It is estimated that the actual installation could be done in two days. The carpenter crew would then spend another half-day removing the special scaffolding.

Table 3-13. Installation Cost Estimate for Concept No. 1

	Quantity	Item	Unit Price	Price (1980$'s)	
Material	100 SF	EPDM Sheet	$1/SF	$ 100	
	900 SF	PVC Flashing	20¢/SF	180	
	2 Rolls	Aluminum Flashing	$11/roll	22	
	15 Sheets	5/8 in. Plyscord Sheathing	$18/sheet	432	
		Electrical Materials		50	
	280 LF	FCC #12 AWG	50¢/LF	140	
	190 LF	FCC #10 AWG	60¢/LF	114	
	7	Dummy Shingles	$30/each	210	
	3 Days	Scaffold Rental	$50/day	150	
		Total Material		$1,398	
Labor	1.5 Days	Carpenter and Helper @ $201.60/day		302	
	2 Days	Glazier, Electrician and Electrician Helper @ $430.40/day		861	
		Total Labor		$1,163	
		Subtotal Labor and Materials			$2,561
		20% Mark-Up for Overhead and Profit			512
		Total			$3,073

3.4.3 CONCEPT NO. 2 - INTEGRALLY-MOUNTED WITH PLASTIC TRAY

The installation cost of the integrally-mounted module with the plastic tray substrate, as described in Section 3.3.2, was estimated with the results as given in Table 3-14. This mounting approach requires that the array installation be done in sequence during the construction so that the building can be closed against the weather before interior work is started. At the time the modules are installed to complete the roof there may be no electrical service to the house, so it is assumed that the array interconnection will be performed at a later time with the electrical crew working in the attic.

Table 3-14. Installation Cost Estimate for Coucept No. 2

	Quantity	Item	Unit Price	Price (1980$'s)
Material	3 Sheets	1/2 in. Plyscord	$13/sheet	$ 39
	472 BF	Clear Fir	55¢/BF	260
	30 LF	Finish 1 x 1	33¢/LF	10
	2 Sheets	5/8 in. Plyscord	$18/sheet	36
	2 Rolls	Aluminum Flashing	$11/roll	22
	120 LF	#14 Wire	3.5¢/LF	4
	31 LF	#4 Wire	20¢/LF	6
	8	Outlet Boxes	$5/each	40
	60 LF	Conduit	20¢/LF	12
	200 LF	Aluminum Extrusion	70¢/LF	140
	70	Solarlok Harness	$2.50/each	175
		Scaffold Rental		30
		Total Material		$ 774
Labor	1-1/2 Days	Carpenter and Helper @$201.60/day (including benefits - typical)		302
	1 Day	Electrician and Helper @$296/day		296
	2 Days	2 Glaziers and Helper @$380.80/day		762
		Total Labor		$1,360
		Subtotal Labor and Materials		$2,134
		20% Mark-Up for Overhead and Profit		427
		Total		$2,561

Carpenter crew spends one and a half days (3 man-days) to erect the ladder jacks and planks, install the purlins, and mount all flashing which must be in place before the modules can be installed.

A 3-man crew, consisting of two glaziers and a helper, arrives the next day to install the modules from the bottom up, in columns, making no electrical connections. Sealing strips and caulking are installed as necessary to make the roof watertight. The metal tracks, which secure the modules to the roof structure, are attached to complete the installation. At the end of the second day, this crew dismantles the staging and returns it to the shop.

At some future time, the two-man electrical crew spends one day in the attic, before it is insulated, walking on loose sheets of plywood left up there by the carpenters. All electrical connections are made and tested.

3.4.4 CONCEPT NO. 3 - STAND-OFF MOUNTED WITH ALUMINUM FRAME

The installation cost estimate for the stand-off mounting approach described in Section 3.3.3 is presented in Table 3-15. This estimate includes the cost of the plywood roof deck which is applied during the normal building construction phase. Roll roofing is then applied in the area to be ultimately covered by the photovoltaic modules and conventional asphalt shingles are used to complete the roof surface around the perimeter. This roll roofing, which functions as the watertight membrane, should not be left exposed to the direct ultraviolet radiation for more than six months prior to the module installation.

The installation of the solar array begins with one day of activity by a two-man crew (carpenter and helper) to mount all the stand-offs and transverse purlins, and to set-up the ladder jacks and wood planks at the eaves. For the next two days a two-man crew (electrician and electrician's helper) install the modules, including the electrical harnesses between modules, and mount the conduits and junction boxes at the ridge and eaves. On the fourth and final day the carpenter crew returns, installs the flashing at all four sides of the roof, removes the scaffolding, cleans-up and delivers the scaffolding to the shop or to the next job site.

The cost estimate presented in Table 3-15 provides for no electrical grounding of the module frames or other conductive elements of the installation. If such grounding is required it is estimated that the cost of the installation would be increased by approximately $300.

Table 3-15. Installation Cost Estimate for Concept No. 3

	Quantity	Item	Unit Price	Price (1980 $'s)
Material	138 BF	2 x 4 Treated Pine	58¢/BF	$ 80
	120 BF	2 x 2 Ripped Clear Fir	$1.08/BF	130
	1 Sheet	Hardboard	$6/sheet	6
	84	Neoprene Pads	$1/pad	84
	2 Rolls	Aluminum Flashing	$11/roll	22
	15 Rolls	Roll Roofing	$14/roll	210
	24 Sheets	5/8 in. Plyscord Sheathing	$18/sheet	432
	1 Square	Shingles	$22/square	22
	120 LF	#14 Wire	3.5¢/LF	4
	31 LF	#4 Wire	20¢/LF	6
	8	Outlet Boxes	$5/each	40
	60 LF	Conduit	20¢/LF	12
	70	Solarlok Harness	$2.50/each	175
		Ladder Jacks & Staging Rental		30
		Total Material		$ 1,253
Labor	3.5 Days	Carpenter and Helper @ $201.60/day		706
	2 Days	Electrician and Helper @ $296/day		592
		Total Labor		$ 1,298
		Subtotal Labor and Materials		$2,551
		20% Mark-Up for Overhead and Profit		510
		Total		$3,061

3.5 COST SUMMARY AND CONCLUSIONS

The total installed price of the residential array can be calculated as the sum of the FOB factory module price; the cost of shipping, handling, marketing, and distribution; and the installation cost of the module. Table 3-16 summarizes these values for each of the three

Table 3-16. Cost Summary (1980 $'s per Module)

Cost Category	Concept No. 1	Concept No. 2	Concept No. 3
Module FOB Factory Price	88.36	86.02	83.27
Shipping, Handling, Marketing and Distribution Cost	---	---	---
Installation Cost	39.91	33.26	39.75
Total	128.27	119.28	123.02

module concepts considered. The module FOB factory price was obtained from Table 3-11, while the installation cost was prorated on a per-module basis by dividing the total array installation cost from Tables 3-13, 3-14 and 3-15, by 77, for Concept No. 1, 2, and 3, respectively. The cost of shipping, handling, marketing and distribution has not been considered in this analysis, since little is known about the distribution channels to be used for a product of this type where the installation is handled by local contractors specializing in roof-mounted residential photovoltaic systems. If the distribution and marketing of these products is through local electrical supply firms, this cost factor may be a significant fraction of the total module FOB factory price. The total installed module price, which neglects this shipping, handling, marketing and distribution cost factor, is presented in Table 3-17 as a function of the assumed unit cost of the solar cells. 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 3-17. Total Installed Cost Sensitivity to Solar Cell Cost

Solar Cell Unit Cost (1980 $'s/Cell)	Installed Array Cost (1980 $'s/Module)		
	Concept No. 1	Concept No. 2	Concept No. 3
0	128.27	119.28	123.02
1	219.07	209.17	212.90
2	309.89	296.80	300.57
3	400.69	388.96	392.69
4	491.50	478.85	482.58
5	582.30	568.74	572.47

3.6 RECOMMENDED DESIGN APPROACH

3.6.1 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. Compatible with integral mounting. 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.

3.6.2 DESCRIPTION OF RECOMMENDED DESIGN

A module/array concept which incorporates the features described above has been formulated as the recommended design approach to be further developed during the detailed design and analysis phase of the contract. As shown in Figures 3-35 through 3-38, this concept builds upon the same basic encapsulated cell subassembly to produce a module design with an elastomeric gasket as a frame around all four sides. This "P" -shaped EPDM gasket is bonded with the leg of the "P" attached to the underside of encapsulated cell subassembly so that the bulb of the "P" shape forms a frame around the entire perimeter. The rear surface of the encapsulated cell subassembly is covered with the aluminum foil/tedlar laminate to provide the required insulation resistance between the solar cell circuit and the external environment. The by-pass diode chips are mounted within the laminate alongside the solar cell circuit at one edge. In the installation, this inactive module area along one of the 1.22 m (4 ft) edges is overlapped by the bottom edge of the module which is directly above, as shown in Figure 3-36. A pressure-sensitive adhesive, which is applied to the rear surface of the "P" gasket, functions as the sealant between these overlapped module edges. The closure of the watertight joints along the vertical separations between modules, which is a key feature of this design approach, is accomplished as shown in Figure 3-37 using the roll-formed steel section shown in Figure 3-38. This specially designed section is configured to provide the jogged-step necessary to conform to the difference in height associated with the overlapped seam between modules. These channel sections are

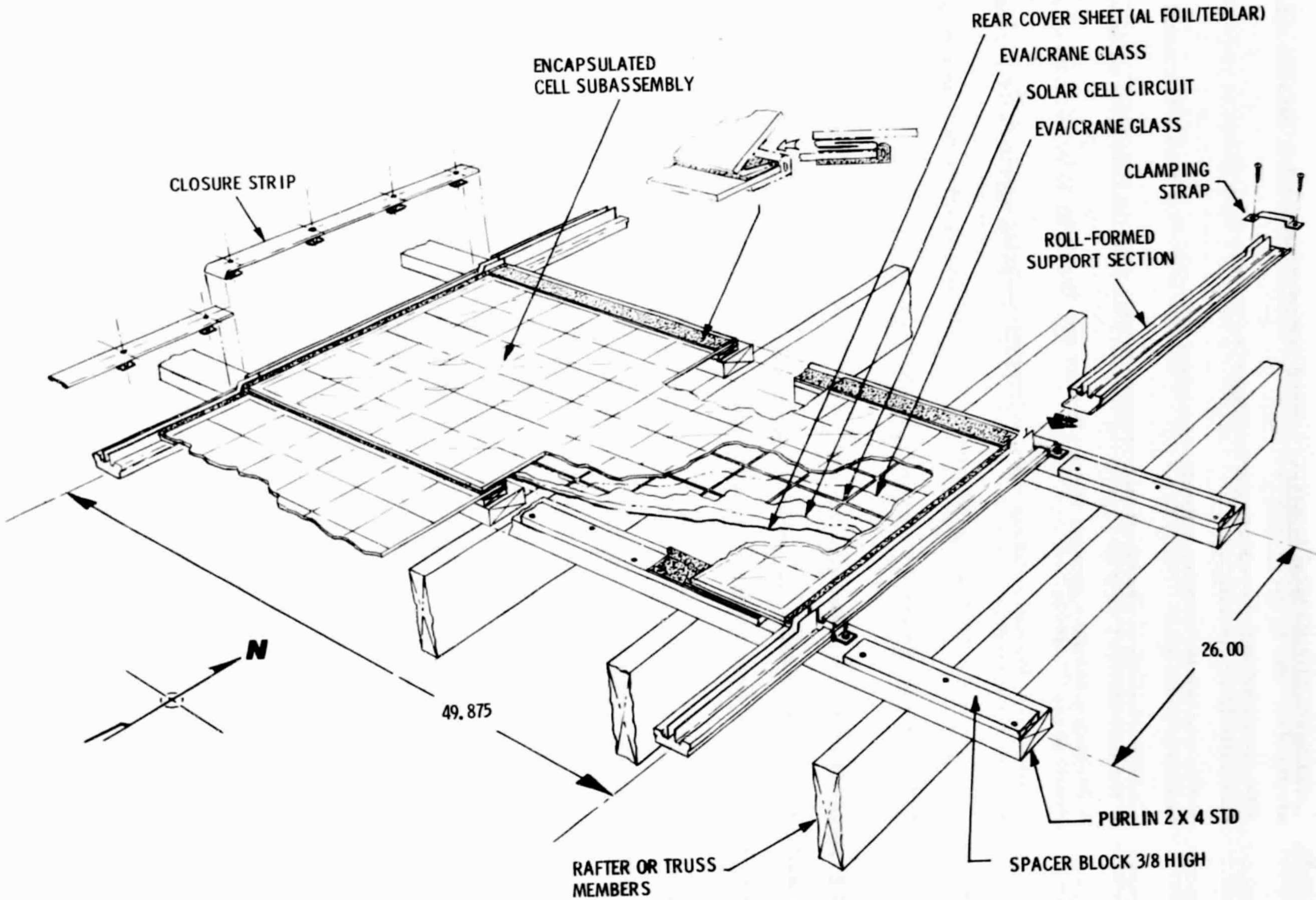

Figure 3-35. Recommended Design Concept

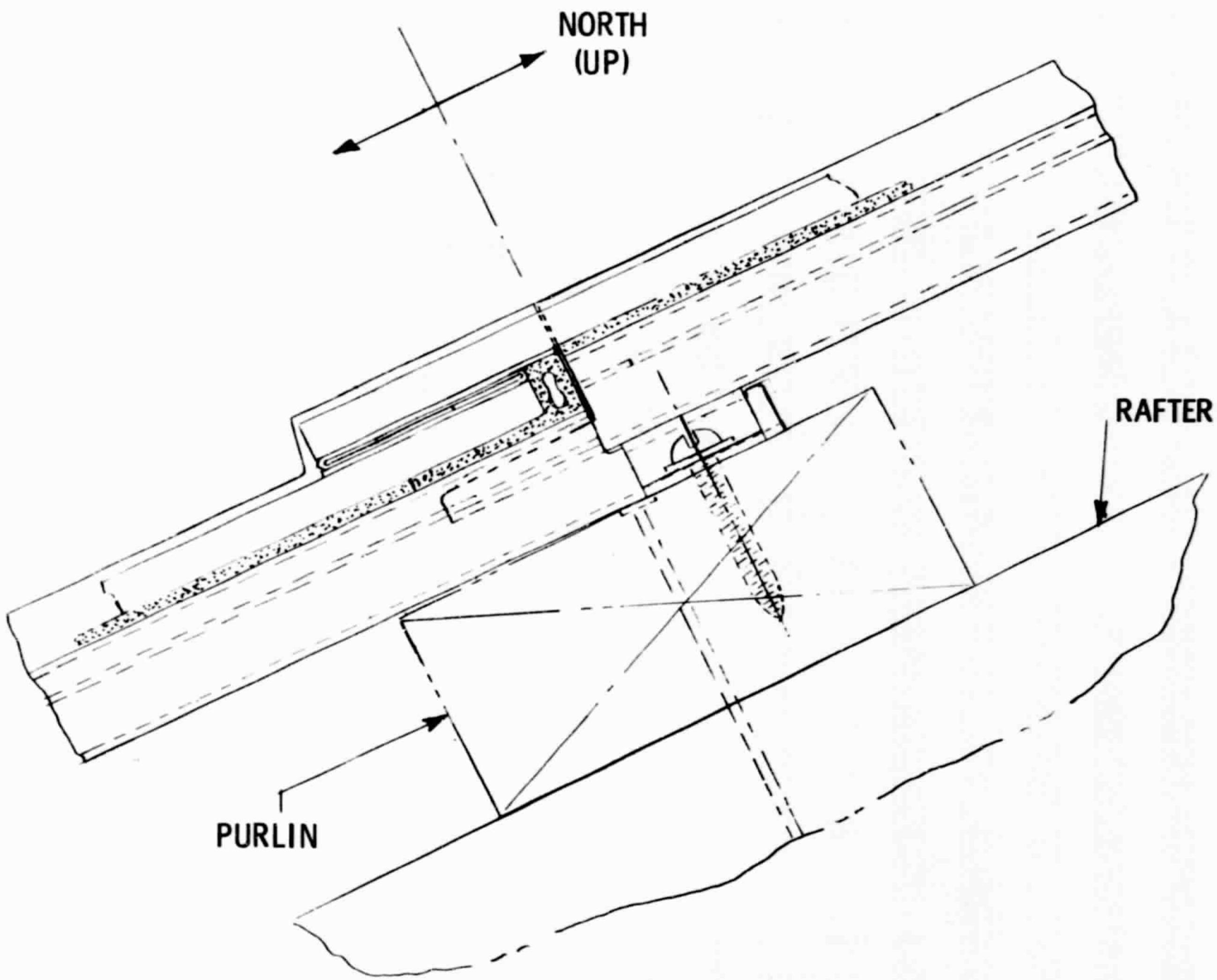

Figure 3-36. Typical Overlapped Section Along the North-South Edges

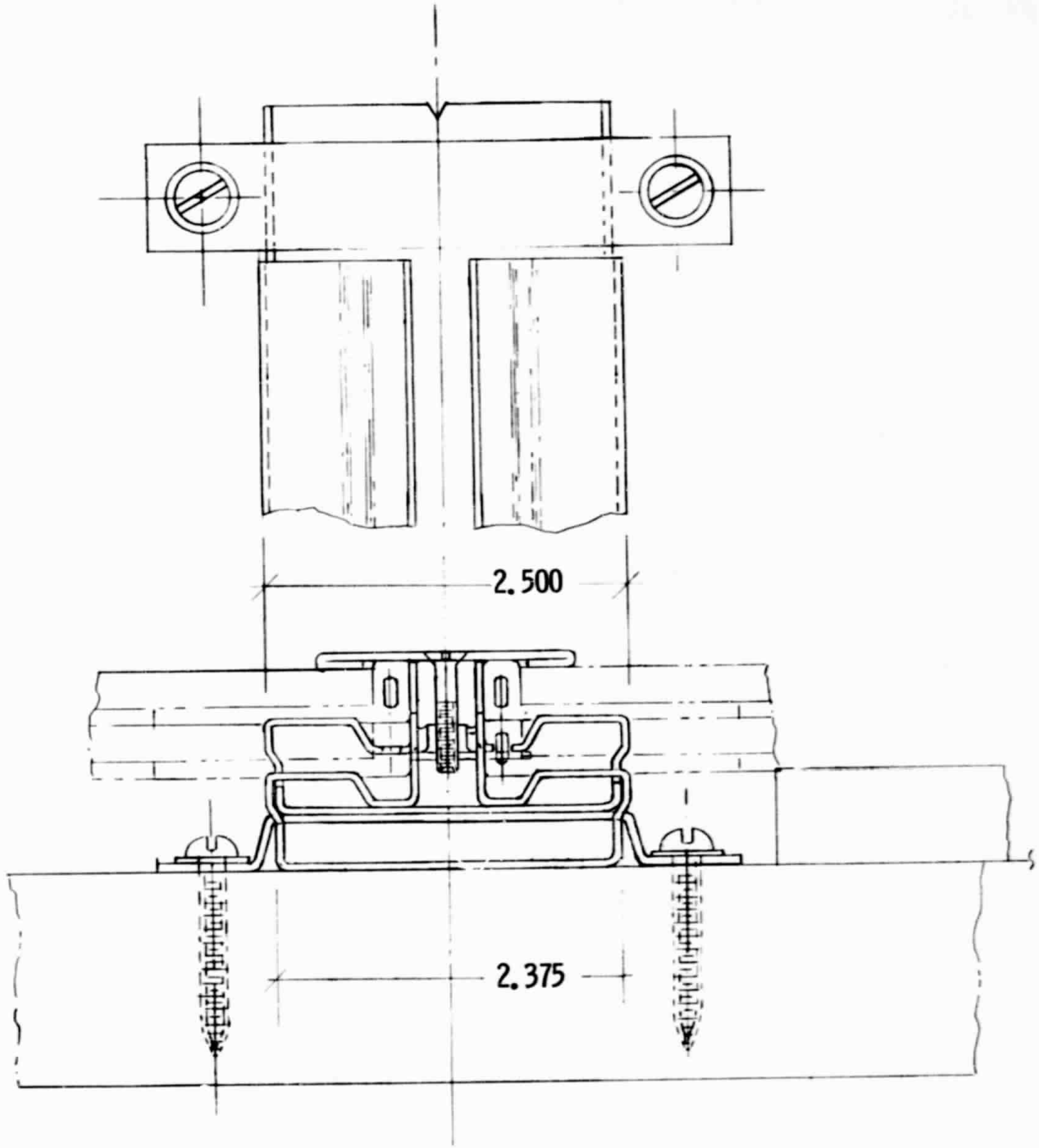

Figure 3-37. Closure Joint Along the East-West Edges

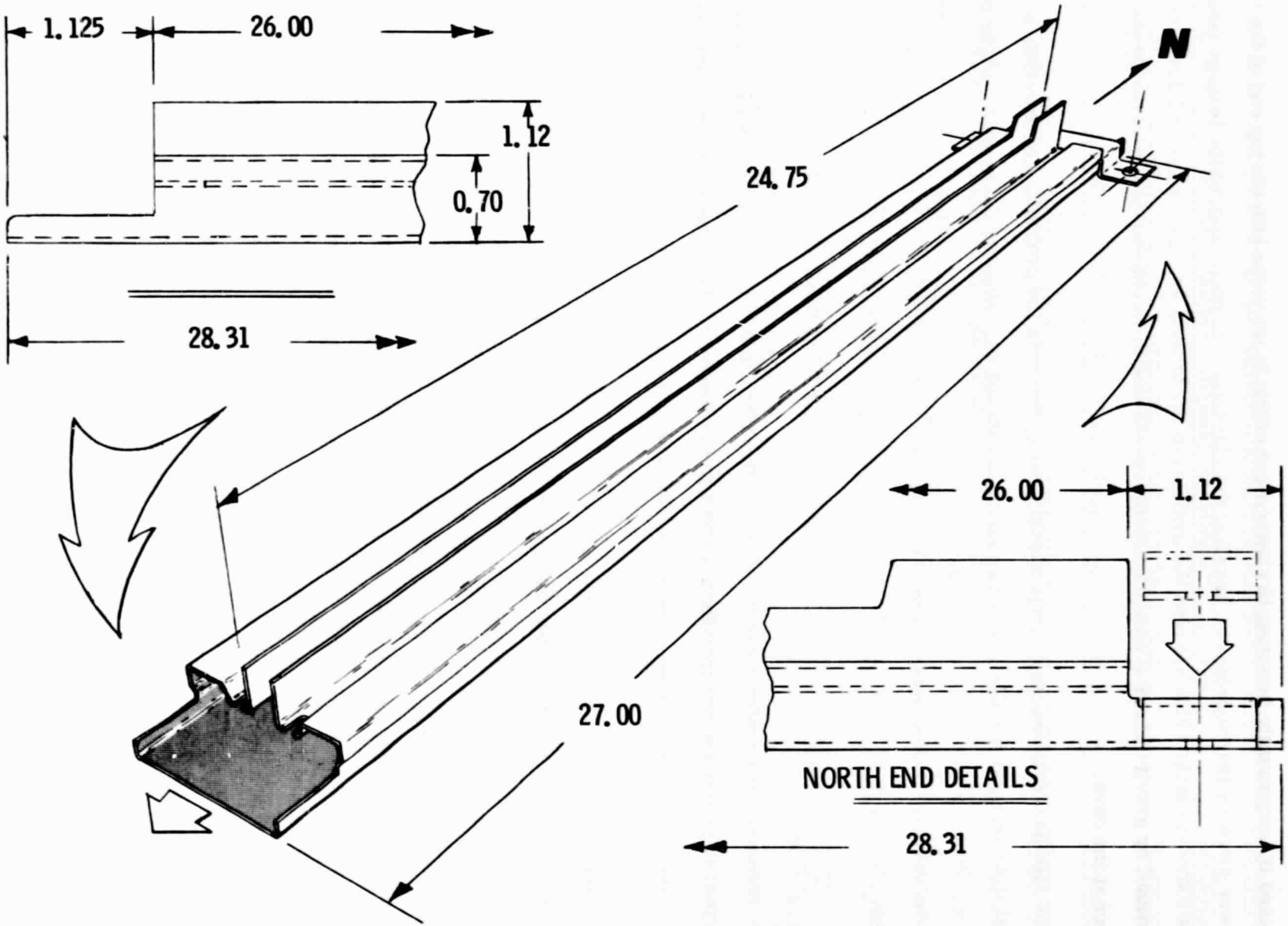

Figure 3-38. Roll-Formed Support and Closure Section

joined by sequentially inserting the bottom end of the upper piece into the top end of the lower piece as the modules are installed in columns up the roof. Any water leakage through the clamping strip which secures the modules to the formed sections is carried down the channel by gravity where it cascades from one channel to another before dripping off the roof at the eave.

This module/array design concept should greatly increase the probability of providing a leak-free integral installation by employing the forces of gravity as the primary means of water shedding both in the overlapped edges, which form the seal going down the roof, and in the vertical closure joints, where leakage is to a channel which drains off the roof at the eave.

3.6.3 COST IMPLICATIONS

The recommended design concept, which is described in Section 3.6.2, was analyzed with respect to production and installation costs and compared to the three previously selected concepts which were evaluated as part of the Task 1 activity.

The production equipment and utility services required for the final assembly operations on the recommended module design are summarized in Table 3-18. The value of the direct material content of the recommended module, as given in Table 3-19, was combined with the estimated direct assembly labor and floor space requirements, as summarized in Table 3-20, to yield the total estimated FOB factory price given in the last column of Table 3-21. When compared to the production costs of the other design concepts, it is apparent that this recommended design represents a significant reduction in the total factory FOB price of the module. When this reduced production cost is coupled with the low installation cost associated with the integrally-mounted array, the low-cost potential of this recommended design is fully realized as shown in the last column of Table 3-22.

Table 3-18. Production Equipment and Utility Requirements for the Recommended Module Design Concept

Item	Estimated Cost (1980 $'s)	Utility Services
Module Invert	3K	0.8 kW
Gasket Dispenser (includes adhesive application)	20K	
Assembly Bench	5K	
Overhead Vacuum Transfer	5K	0.2 kW
Roller Conveyor	2K	
Terminal Bench (tilt table)	1K	0.1 kW
Test Station	50K	0.5 kW
Box Station	1K	
Interim Conveyor	1K	
Misc. Handling Devices	2K	
	90K	1.6 kW

Table 3-19. Direct Material Inventory for the Recommended Module Design Concept

Item Description	Quantity Required per Module	Estimated Cost per Module (1980 $'s)
Solar Cells	72	--
Tempered Glass Coverplate	0.812 m^2	11.92
EVA/Craneglass	1.624 m^2	5.25
Primer	81 ml	0.86
Solder-Plate Copper Foil (75 μm thick)	0.090 m^2	0.34
Solder-Plate Copper Foil (500 μm thick)	0.010 m^2	0.20
Solder	6 g	1.86
Aluminum Foil/Tedlar Laminate	0.812 m^2	3.45
Bypass Diode Chip	3	2.10
Gasket Bonding Adhesive	29 g	0.22
Molded Framing Gasket	3.8 m	3.20
Solarlok Panel Mounted Connector	2	0.90
Total		30.30

Table 3-20. Comparison of Module Production Parameters

	Concept No.			
	1	2	3	Recommended
<u>Basic Production Area</u>				
Process Yield (%)	99	99	99	99
Equipment Cost (1980 $'s)	846,000	846,000	846,000	846,000
Manpower (No. of Employees)	7.0	7.0	7.0	7.0
Floor Space (ft^2)	2,664	2,664	2,664	2,664
Utilities				
Electricity (kW)	29.6	29.6	29.6	29.6
Air (cfm)	6.0	6.0	6.0	6.0
Water (gpm)	13.1	13.1	13.1	13.1
<u>Final Assembly Area</u>				
Process Yield (%)	99	100	100	100
Equipment Cost (1980 $'s)	127,000	88,000	111,000	90,000
Manpower (No. of Employees)	4.5	2.3	3.0	2.[illegible]
Floor Space (ft^2)	1,656	1,152	1,070	936
Utilities				
Electricity (kW)	1.9	1.6	2.5	1.6
Air (cfm)	6.0	--	--	--
<u>Production Warehouse Area</u>				
Equipment Cost (1980 $'s)	30,000	30,000	30,000	30,000
Manpower (No. of Employees)	3.0	3.0	2.5	2.0
Floor Space (ft^2)	1,620	1,272	1,272	1,200
<u>Totals</u>				
Equipment Cost (1980 $'s)	1,003,000	964,000	987,000	966,000
Manpower (No. of Employees)	14.5	12.3	12.5	11.0
Floor Space (ft^2)	5,940	5,088	5,006	4,800
Utilities				
Electricity (kW)	31.5	31.2	32.1	31.2
Air (cfm)	12.0	6.0	6.0	6.0
Water (gpm)	13.1	13.1	13.1	13.1

Table 3-21. Module Production Cost Summary (1980$'s Per Module)

Category	Concept No.			
	1	2	3	Recommended
Direct Labor	13.02	11.05	11.23	9.88
Labor Overhead (170%)	22.13	18.79	19.09	16.80
Cost Of Capital Equipment	2.89	2.78	2.84	2.78
Cost of Utility Services	0.13	0.13	0.13	0.13
Rent For Floor Space	0.47	0.40	0.40	0.38
Direct Material	33.97	37.41	34.36	30.61
Material Overhead (3%)	1.02	1.12	1.04	0.92
Subtotal	73.63	71.68	69.39	61.50
Profit And Warranty Service (20%)	14.73	14.34	13.88	12.30
Total Factory FOB Price	88.36	86.02	83.27	73.80

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

Cost Category	Concept No.			
	1	2	3	Recommended
Module FOB Factory Price	88.36	86.02	83.27	73.80
Shipping, Handling, Marketing and Distribution Cost	--	--	--	--
Installation Cost	39.91	33.26	39.75	33.26
Total	128.27	119.28	123.02	107.06

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

The evaluation of the three selected module/array concepts has led to the recommendation of a fourth design approach which incorporates the best features of these initial design selections to yield an "optimized" integrated residential array which promises to have a substantially lower installed price then any concept previously investigated.

This recommended design concept employes a unique approach to integral mounting which has the potential for long-life, leak-free performance. The sealing approach makes maximum use of the sloping roof surface and the force of gravity to provide an array design which does not rely on gasketed or caulked joints as the primary method of waterproofing.

The low-cost potential of this concept is realized through the use of a simple elastomeric seal as the frame around the module perimeter. This seal is subsequently mated with sections of a specially designed roll-formed steel channel to mechanically attach the modules to the roof structure and to make the watertight joint between modules in the slant height direction.