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Integrated Residential Photovoltaic Array Development

QUARTERLY REPORT NO. 1
PREPARED UNDER JPL CONTRACT 955893
REPORT DATE: APRIL 10, 1981

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Research
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REPORT DATE: APRIL 10, 1981
PREPARED BY: G.C. ROYAL, III

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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ABSTRACT

This first quarterly report on a contract to develop an optimal integrated residential photovoltaic array describes sixteen conceptual designs produced by eight teams. Each design concept was evaluated by an industry advisory panel using a comprehensive set of technical, economic and institutional criteria. Key electrical and mechanical concerns that affect further array sub-system development are also discussed.

Three integrated array design concepts were selected by the advisory panel for further optimization and development. From these concepts a single one will be selected for detailed analysis and prototype fabrication. The three concepts selected are the following:

1) An array of frameless panels/modules sealed in a "T" shaped zipperlocking neoprene gasket grid pressure fitted into an extruded aluminum channel grid fastened across the rafters.

2) An array of frameless modules pressure fitted in a series of zipperlocking EPDM rubber extrusions adhesively bonded to the roof. Series string voltage is developed using a set of integral tongue connectors and positioning blocks.

3) An array of frameless modules sealed by a silicone adhesive in a prefabricated grid of rigid tape and sheet metal attached to the roof.

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SECTION 1

SUMMARY

This report discusses the first of three tasks to define an integrated residential photovoltaic array. An optimum array configuration will satisfy the needs of the earliest and largest market and provide electricity for the least life cycle cost. This study emphasizes a systems approach to design optimization that considers detailed electrical, mechanical, economic and institutional factors. Further emphasis is the minimization of cost drivers for these factors at several levels of annual production.

The study began with the competitive selection of 8 teams to produce a set of design concepts. A workshop was conducted to review the current technology base for residential photovoltaic systems. Workshop materials referenced the following module/array topics: circuit design and performance; wiring; mounting; installation, reliability and maintenance; codes and standards; roof construction; and life cycle cost. These materials were drawn from previous system definition and array requirements and 12 prototype designs for which detailed array and system analyses have been performed.

The teams developed a total of 16 design concepts over a nine-week period. Each concept was evaluated by an industry advisory panel convened by the AIA/RC on the basis of the following criteria categories: market penetration; fabrication requirements; design and specification requirements; installation requirements; operation requirements; and maintenance requirements. Three design concepts selected for further development by the advisory panel follow:

1) an array of frameless modules sealed in a zipperlocking neoprene gasket grid in a grid of aluminum channels fastened across the rafters;
2) an array of frameless modules sealed in a zipperlocking EPDM extrusion adhesively bonded to the roof; and,
3) an array of frameless modules sealed by a silicone adhesive in a prefabricated grid of rigid tape and sheet metal attached to the roof.

This report summarizes the assumptions, rationale and methodology used in the selection of the design concepts. Further concerns to be addressed in subsequent study activities are also discussed.

SECTION 2

INTRODUCTION

The objective of this study is to develop optimal roof mounted arrays for residences that provide energy for the least life cycle cost. Development of an optimal array will follow an integrated systems approach that considers detailed electrical, mechanical and environmental requirements, as well as such regional variations as codes, construction practices and local costs. The resulting array design will be fabricated in a prototype partial roof/array model to identify additional roof array interface concerns in production, manufacturing, installation or maintenance. Program activity is organized into the three tasks listed below.

Task 1 - Alternative Design Concept Development

Task 2 - Preferred Design Concept Optimization

Task 3 - Prototype Roof/Array Section Fabrication

In Task 1 three (3) generic integrated photovoltaic array design concepts are selected from a number of alternative concepts for residential applications. This effort began with a solicitation to over 200 architects, engineers, homebuilders and designers that asked for a statement of their capability to develop design concepts to satisfy technical, economic and institutional concerns. An industry advisory panel was convened by the AIA/RC to select the most capable teams to develop a set of design alternatives.

A workshop held at the AIA/RC for the design teams was used to establish a uniform starting point for the nine week concept design period. The workshop was organized into three sessions. First an overview of program activities and research results was presented. Next, project activities and concept documentation requirements were reviewed. Then a series of technical presentations were given for the following topics: system design; module design; wiring and connector design; safety standards; and residential roof construction.

At the end of the concept design period, a presentation was given by each of the eight design teams to the advisory panel. The following characteristics were reviewed in the presentation for each of the 16 concepts developed: appropriateness for earliest and largest market penetration; fabrication requirements; designed array output, modularity and specification; array circuit design, wiring and module connection; panel/module attachment; installation requirements; operation and maintenance requirements; and, costs. Three concepts were selected by the advisory panel for further development, prior to selection of a preferred design for Task 2.

Design teams, workshop participants, and advisory panel members are identified in Figure (2-1).

Based on the results of Task 1, one design concept will be selected for further analysis and development under Task 2. Detailed production design development and engineering trade-off studies will be performed to further optimize the design for minimum life-cycle cost for the installed array. Based on this detailed information, refined life-cycle cost estimates will be generated for annual module production levels of 10000, 50000, and 500000 m^2. A set of drawings and specifications will be prepared to permit fabrication, installation and operation of the array design by a third party. In addition, a full-scale prototype section/array roof will be defined and a fabrication cost estimate prepared.

The Task 3 activity will include the fabrication on a full-scale representative prototype section of the selected residential photovoltaic array complete with electrical and mechanical interconnectors and array/roof interface hardware. While this prototype section need not be electrically operational, it will serve as a useful model to identify additional fabrication, installation, maintenance and other concerns.

A block diagram of program activities is shown in Figure (2-2). As of this reporting date, all effort has been completed under Task 1 with the exception of further development of the three selected concepts. This report describes the results of the activities completed.

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PROJECT ACTIVITY DIAGRAM

INTEGRATED RESIDENTIAL

PHOTOVOLTAIC ARRAY DEVELOPMENT

Figure 2-2

TASK 1

- Convene Advisory Committee to review issues, approve draft of RFP
- Develop and distribute RFP
- Develop LCC data requirements
- Select 8 Firms; Advisory Committee supplies technical assistance
- Advisory Committee selects three best concepts

Task 1 Documented

TASK 2

- Advisory Committee review 3 designs and selects optional design
- Subcontracting firm develop optional design in detail
- Arch. P.V. contractor, manufacturer and LCC consultant provide technical assistance
- Advisory Committee review and approves construction and specification documents

Advisory Committee Representative

AIA/RC

Heery Energy Consultants

Energy Design Associates

NAHB Research Foundation

Solarex, Inc.

TASK 3

- Model Fabricator provides full-scale prototypical model based on a representative section based on construction documents

Entire Project Documented for JPL

SECTION 3

TECHNICAL DISCUSSION

This discussion summarizes key elements of the criteria, methodology and rationale for selection of three design concepts from those considered. The first section is a discussion of the assumptions and evaluation criteria used in concept selection. The next section is a description of each design considered. Subsequently, evaluation methodology is described and major concerns for each concept are identified. Then, the rationale and justification for selection of three concepts is presented.

The classification of mounting types in this study is based on a performance approach. This approach distinguishes between mounting types based on the method used to satisfy two roof functions: weather protection and structural stability. This classification does not consider height differences between array surface and roof, or material replacement.

Integral-mounted arrays provide both permanent and temporary weather protection. Replacement support for lateral roof loads is required. Modular array-edge support is required.

Direct-mounted arrays provide only permanent weather protection. Replacement support for lateral roof loads is not required. Modular array-edge support may not be required.

Standoff/Rack-mounted arrays do not provide weather protection. Replacement support for lateral roof loads is not required. Modular array-edge support is required.

3.1 EVALUATION CRITERIA

The spectrum of technical, economic and institutional issues that affect the fabrication, installation and operation of a residential photovoltaic array have been grouped into six categories of evaluation criteria. Evaluation objectives are the minimization of cost drivers associated with each category. A partial listing of criteria follows the list of categories below.

- Market Penetration
- Fabrication
- Design and Specification
- Installation
- Operation
- Maintenance

MARKET PENETRATION

The focus of this category is minimization of cost drivers for earliest and largest market penetration. The characteristics of the maturing market as well as the mature market are expected to establish a basis for the interrelationship of fabrication, installation, residential construction, operations and maintenance.

- The concept must satisfy the largest middle-income mass market.
- The concept must serve a variety of housing sizes, types, and roof shapes.
- The concept must allow flexibility of selection by both large and small volume builders.
- The concept must allow flexibility in installation timing.
- The concept must fit within the typical product delivery and service chain of the homebuilding industry.

Fabrication

The focus of this category is an optimization of personnel, material and equipment requirements from component delivery through shipment of the assembly. That optimization should consider both number and type of personnel, material and equipment throughout the assembly sequence.

- The concept must optimize the mixture of factory and field labor for array assembly.

- The concept must minimize the requirements for component inventory.
- The concept must minimize the cost for shipping and handling yet retain acceptable durability.

Design and Specification

The focus of this category is minimization of project-specific design engineering. Elements considered include the ability to use equivalent products, as well as the standardization of code approval, labor coordination, and engineering documentation.

- The concept must use the design engineering capability normally employed by the builder or contractor.
- The concept must minimize field inspection and approval requirements of local building and zoning codes, the National Electrical Code (NEC), fire codes and insurance warrants.
- The concept must allow use of equivalent materials and products in standard construction practice.
- The concept must allow flexibility in labor and schedule coordination that meets standard practice conditions.
- The concept's documentation must follow standard practice for reliability, performance and cost estimates.

Installation

The focus of this category is minimization of installation time and cost. Key concerns include array durability during site delivery and storage, sequence of installation, required tools, equipment, labor and supervision. An additional concern is minimization of field requirements for field qualification and acceptance of the installed array.

- The concept must have little impact on the normal structural and environmental exposure of the building.
- The concept must be compatible with standard construction practices, tools and equipment.
- The concept must minimize field approval of electrical connections, field cabling and grounding.
- The concept must minimize safety risk during installation.
- The concept must optimize handling and installation durability.

- The concept must optimize mechanical attachment and electrical connection requirements.

Operation

The focus of this category is the optimization of reliable output performance to match the requirements for system interface consistent with standard safety conditions.

- The concept array must generate electricity within an acceptable output range for size and temperature conditions.
- The concept array output must satisfy balance of system interface requirements such as input voltage.
- The concept must minimize grounding concerns and requirements.
- The concept must address appropriate power and dimensional modularity concerns.
- The concept must satisfy lifetime reliability and durability conditions at an acceptable cost.

Maintenance

The focus of this category is the optimization of field maintenance, repair and replacement consistent with least initial costs.

- The concept must minimize the requirements for identification, removal and replacement of failed parts consistent with reliability and durability conditions.
- The concept must not interfere with normal building maintenance and repair.
- The concept must minimize added life safety and building risks.

3.2 DESCRIPTION OF CONCEPTS CONSIDERED

Design concepts were developed by eight design teams for each of four mounting strategies. In certain cases, the concepts were appropriate for more than one mounting type. The following discussion summarizes key elements of concepts developed for each of the mounting strategies. A tabular summary of system descriptions is listed in Table (1). Condensed drawings of each concept follow and appear as Figures 3-21 through 3-33.

Integral Mounting Concepts

Sample 1. Eighteen (18) unframed panels/modules are pressure fitted in a "T" shaped neoprene gasket grid and sealed by a ziplocking strip. The gasket grid is pressure fitted into an aluminum channel extrusion grid fastened across the rafters. Array voltage is developed along the roof height using a series string of two (2) panels/modules. Array current is developed along the roof length using nine (9) panel/module pairs attached to busbars at the top and bottom of the array. Array termination is near the gutter along the roof rake.

Sample 2. Ten (10) panel frames each made from two extruded aluminum carriage pieces joined by lateral angles are bolted along the rafters. Each of the nine (9) modules pressure fitted in a panel overlaps the lower one and is held in place by a lap bar. The modules are wired in series by commercially available 'quick connectors' with return branch conductors attached to the rafters. Array voltage is developed along the roof height from two (2) adjacent panels wired in series through a junction box for each panel pair. Array current is developed along the roof length from the five (5) panel-pair junction boxes wired in parallel within the attic near the ridge using redundant armored bus cable conductors.

Sample 3. Eighty (80) frameless modules are sealed using a silicone adhesive to a prefabricated grid of rigid tape and metal channels bolted across rafters. Array voltage is developed along the roof length using a series string of 20 modules. Array current is developed along the roof height using 4 parallel-wired module rows.

Integral Mounting Concepts (Cont'd)

Sample 4. Forty (40) gasketed modules are sealed in a set of prewired mounting channels nailed along the length of the rafters. Array voltage is developed along the length of the roof using a series string of 20 modules. Array current is developed along the height of the roof using two (2) parallel-wired module rows.

Sample 5. Twenty-four (24) unframed modules are pressure fitted between a series of extruded aluminum batten strips and plywood support strips mounted along the rafters. Waterproof seal is provided by butyl glazing tape at the top and sides of the modules. Array voltage is developed along the roof length using three (3) modules wired in series. Array current is developed along the roof height from eight (8) branch circuits installed in three (3) rows. The bottom row contains two (2) branch circuits while each of the two upper rows contain three (3) branch circuits. Array termination occurs in the power conditioning eqiupment room beneath the array.

Direct Mounting Concepts

Sample 6. Fifty-six (56) unframed modules are pressure fitted in a grid of thermoplastic "T" and "I" shaped glazing gaskets fastened to the roof. The "I" shaped sections have been coextruded with embedded busbars for parallel module wiring. Each module rests on a ribbed plastic backing sheet. Array voltage is developed along the roof length from a seven (7) module series string wired through junction boxes located in the attic. Array current is developed along the roof height from eight (8) modules wired in parallel through the integral busbars within the thermoplastic grid. Array termination occurs through the ridge vent in the attic.

Sample 7. Eighty (80) frameless modules are sealed by a silicone adhesive in a prefabricated grid of rigid tape and sheet metal attached to the roof. Array voltage is developed along the roof length using a series string of twenty (20) modules. Array current is developed along the roof height using four (4) parallel-wired rows.

Direct Mounting Concepts (Cont'd)

Sample 8. Forty (40) gasketed modules are sealed in a set of prewired mounting channels mechanically fastened to the roof. Array voltage is developed along the length of the roof using a series string of 20 modules. Array current is developed along the height of the roof using two (2) parallel-wired module rows.

Standoff Mounting Concepts

Sample 9. Forty (40) unframed modules are pressure fitted in a series of zipperlocking EPDM rubber extrusions adhesively bonded to the roof. Array voltage is developed along the roof height using six (6) series-wired modules interconnected by integral tongue connectors and positioning blocks. Array current is developed along the roof length using five (5) branch circuits. Array termination occurs near the gutter.

Sample 10. Eighteen (18) framed and sealed panel/modules are fastened to 30 unequal leg "T" shaped brackets bolted to the rafters. The longest leg of each bracket is overlapped by an existing shingle. Array voltage is developed along the roof height using a series string of two (2) panels/modules. Array current is developed along the roof length using nine (9) panel/module pairs attached to busbars at the top and bottom of the array. Array termination is near the gutter along the roof rake.

Sample 11. Twelve (12) aluminum framed panels with laterally supporting "T" struts are clamped to a standing seam insulated metal roof deck mounted on the rafters. Each of the ten (10) gasketed modules pressure fitted in a panel frame are wired in series by commercially available "quick-connectors" beneath the modules. The return branch conductor is placed along the standing seam within the conduit formed by the panel frame and a continuous finish cap. Branch wiring is routed beneath the ridge flashing into the attic space below. Array voltage is developed along the roof height from two (2) panels wired in series through a junction box for each panel pair. Array current is developed along the roof length

Standoff Mounting Concepts (Cont'd)

Sample 11. (Cont'd) from the six (6) panel-pair junction boxes parallel-wired within the attic near the ridge using redundant armored bus cable conductors.

Sample 12. Forty-two (42) unframed modules are pressure fitted in a series of zipperlocking EPDM rubber extrusions adhesively bonded to the roof of a manufactured house. Array voltage is developed along the roof height using six (6) series-wired modules interconnected by integral tongue connectors and positioning blocks. Array current is developed along the roof length using seven (7) branch circuits. Array termination occurs near the gutter.

Sample 13. Twenty-four (24) framed panels/modules are pressure fitted in five (5) "T" shaped tracks along the length of the roof. Each track is lag-bolted to the rafters through a neoprene gasket strip. Array voltage is developed along the roof length using a series string of six (6) pin connected panels/modules. An integral wiring harness within each track terminates at a junction box on the high voltage side of the series string. Array current is developed along the roof height from four (4) track junction boxes connected by flexible conduit. Array termination near the gutter is made at a seal fitted roof penetration.

Sample 14. Eighty (80) gasketed modules are pressure fitted between a series of PVC hold down caps and extruded aluminum channels fastened to the roof. Array voltage is developed along the roof height from eight (8) series-wired modules mounted as two adjacent colunms, each of four modules. Array current is developed along the roof length from ten (10) series strings that each terminate in standard junction boxes beneath the roof.

Sample 15. Eighty (80) gasketed modules are mounted over a series of continuous metal pans and pressure fitted in steel battens fastened to the roof. Array voltage is developed along the roof height from eight (8) series wired modules mounted as two adjacent columns, each of four modules. Array current is developed along the roof length from ten (10) series strings that each terminate in standard junction boxes beneath the roof.

Rack Mounted Concepts

Sample 16. Eighty (80) gasketed modules are pressure fitted in a series of PVC hold down caps and extruded aluminum channels bolted to a slotted steel rack. Array voltage is developed along the rack height from eight (8) series wired modules mounted as two adjacent columns, each of four modules. Array current is developed along the rack length from ten (10) series strings that each terminate in standard junction boxes.

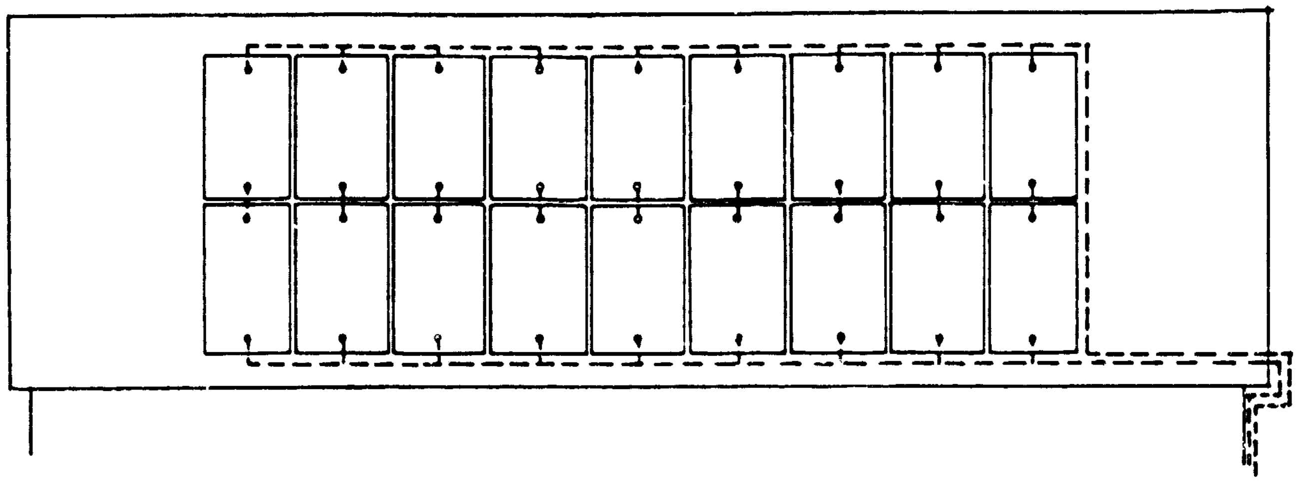
TABLE 1

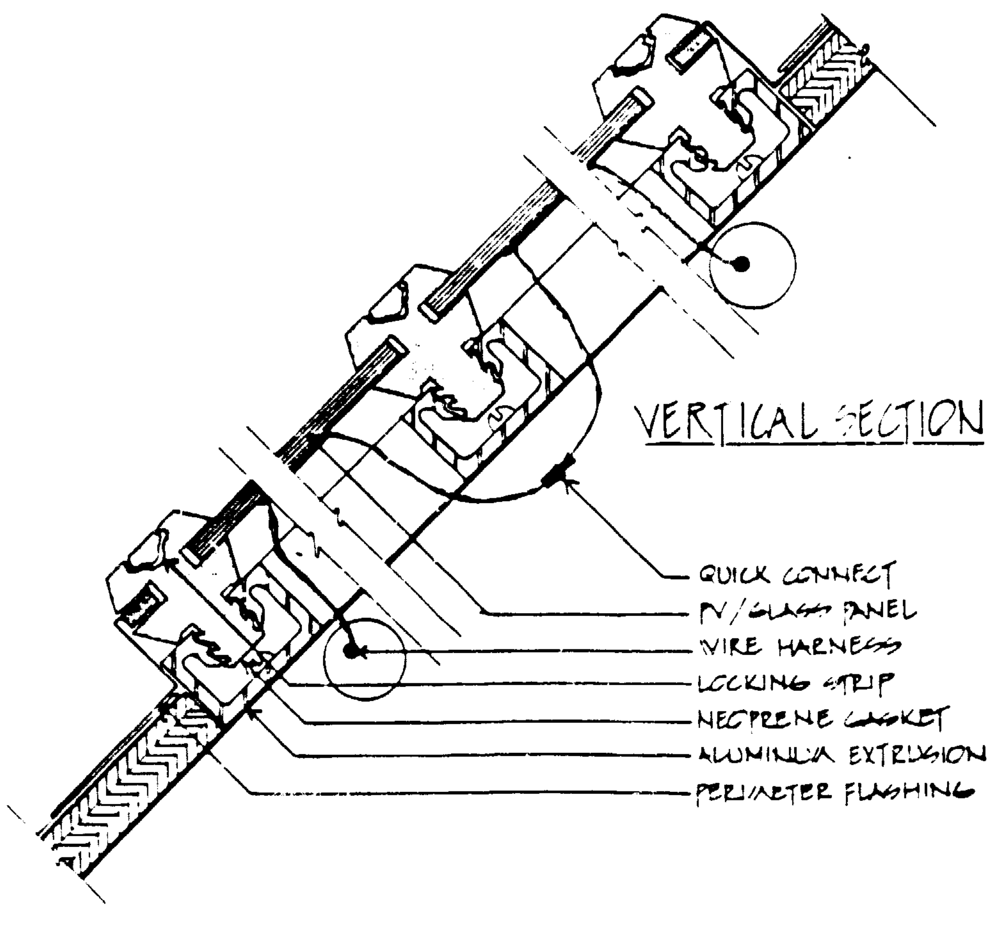
TABULAR SUMMARY OF INTEGRATED RESIDENTIAL PV ARRAY DESIGN CONCEPTS

MOUNTING TYPE	DESCRIPTION	SAMPLE N = 16	OUTPUT Wp	AREA M^2	TOTAL \$/Wp	HARDWARE \$/Wp	WIRING \$/Wp	CREDITS \$/Wp
Integral	Eighteen (18) unframed panels/modules are pressure fitted in a "T" shaped neoprene gasket grid and sealed by a ziplocking strip. The gasket grid is pressure fitted into an aluminum channel extrusion grid that is screwed directly to the rafters.	1	4455	41.43	1.31	0.50	0.03	0.13
	Ten (10) framed panels each made from two extruded aluminum carriage pieces joined by lateral angles are bolted to the rafters. Each of the nine (9) modules pressure fitted in a panel overlaps the lower one and is held in place by a lap bar.	2	9760	76.2	1.41	0.70	0.13	0.30
	Eighty (80) frameless modules are sealed using a silicone adhesive to a prefabricated grid of rigid tape and sheet metal bolted to the rafters.	3	9990	78.1	1.07	0.23	0.04	0.11
	Forty (40) gasketed modules are sealed in a set of prewired mounting channels nailed along the length of the rafters.	4	9990	78.1	1.11	0.27	0.04	0.11
	Twenty-four (24) unframed modules are pressure fitted between a series of extruded aluminum batten strips and plywood support strips mounted directly to the rafters. Waterproof seal is provided by butyl glazing tape at the top and sides of the modules.	5	4200	50.5	1.19	0.40	0.06	0.17
Direct	Fifty-six (56) unframed modules are pressure fitted in a grid of thermoplastic "T" and "I" shaped glazing gaskets that are screwed to the roof sheathing. The "I" shaped sections have been coextruded with embedded busbars for module parallel wiring. Each module rests on a ribbed plastic backing sheet.	6	9250	83.3	1.10	0.20	0.05	0.06
	Eighty (80) frameless modules are sealed by a silicone adhesive in a prefabricated grid of rigid tape and sheet metal attached to the roof.	7	9990	78.1	1.13	0.23	0.04	0.05
	Forty (40) gasketed modules are sealed in a set of prewired mounting channels mechanically fastened to the roof.	8	9990	78.1	1.18	0.27	0.04	0.05

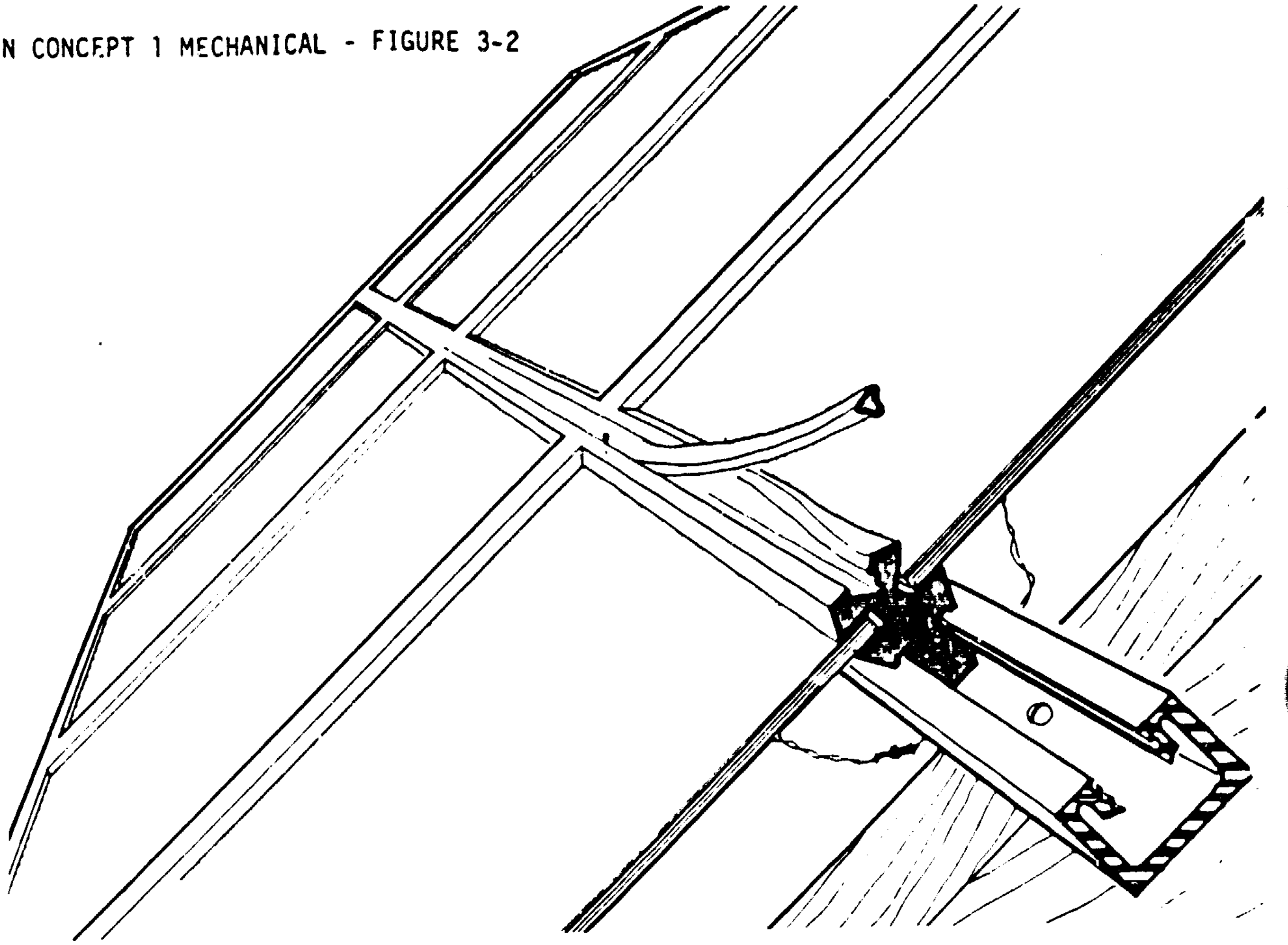
TABLE 1 (CONT'D)

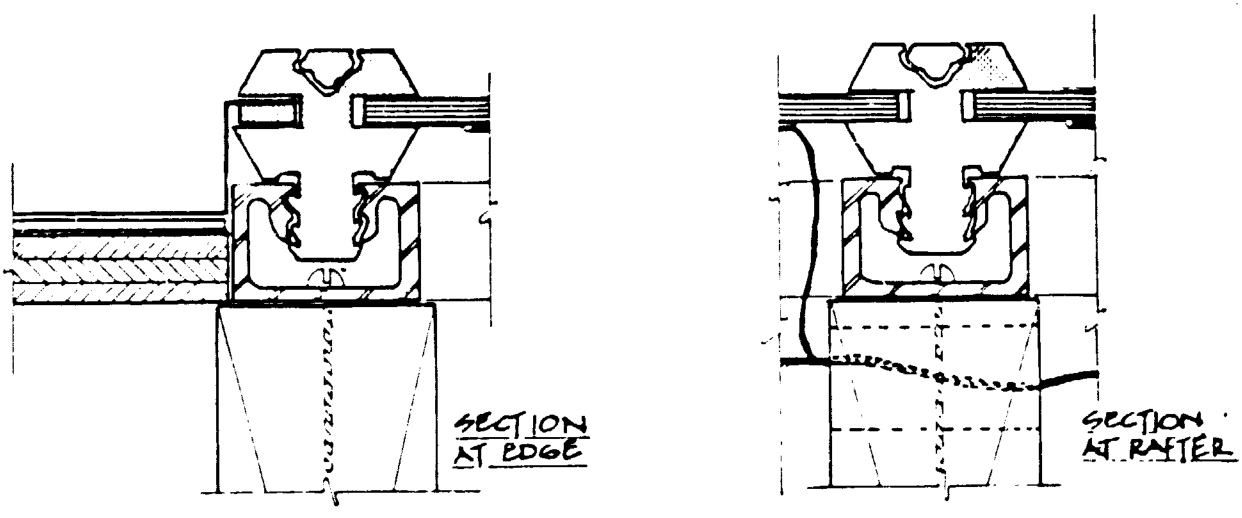
MOUNTING TYPE	DESCRIPTION	SAMPLE N = 16	OUTPUT Wp	AREA M^2	TOTAL $/Wp	HARDWARE $/Wp	WIRING $/Wp	CREDITS $/Wp
Standoff	Forty (40) unframed modules are pressure fitted in a series of zipperlocking EPDM rubber extrusions adhesively bonded to the roof surface.	9	5158	59.5	1.22	0.30	0.01	0
	Eighteen (18) framed and sealed panel/modules are fastened to 30 unequal leg "T" shaped brackets bolted to the rafters. The longest leg of each bracket is overlapped by an existing shingle.	10	4275	45.81	1.52	0.59	0.02	0
	Twelve (12) aluminum framed panels with laterally supporting "T" struts are clamped to a standing seam insulated metal roof deck mounted on the rafters. Each of the ten (10) gasketed modules pressure fitted in a panel frame are wired in series by commercially available "quick connectors" beneath the modules.	11	7800	76.7	2.55	1.77	0.19	0.31
	Forty-two (42) unframed modules are pressure fitted in a series of zipperlocking EPDM rubber extrusions that are adhesively bonded to the roof surface.	12	5860	67.6	1.15	0.24	0.01	0
	Twenty four (24) framed panels/modules are pressure fitted in five (5) "T" shaped tracks along the length of the roof. Each track is lag bolted to the rafters through a neoprene gasket strip.	13	4400	36.8	1.74	0.73	0.04	0
	Eighty (80) gasketed modules are pressure fitted between a series of PVC hold down caps and extruded aluminum channels fastened to the roof.	14	6648	59.7	1.63	0.25	0.23	0
	Eighty (80) gasketed modules are mounted over a series of continuous metal pans and pressure fitted in steel battens fastened to the roof.	15	8360	74.7	1.71	0.47	0.18	0.06
Rack	Eighty (80) gasketed modules are pressure fitted in a series of PVC hold down caps and extruded aluminum channels bolted to a slotted steel rack.	16	6952	65.7	1.92	0.56	0.22	0



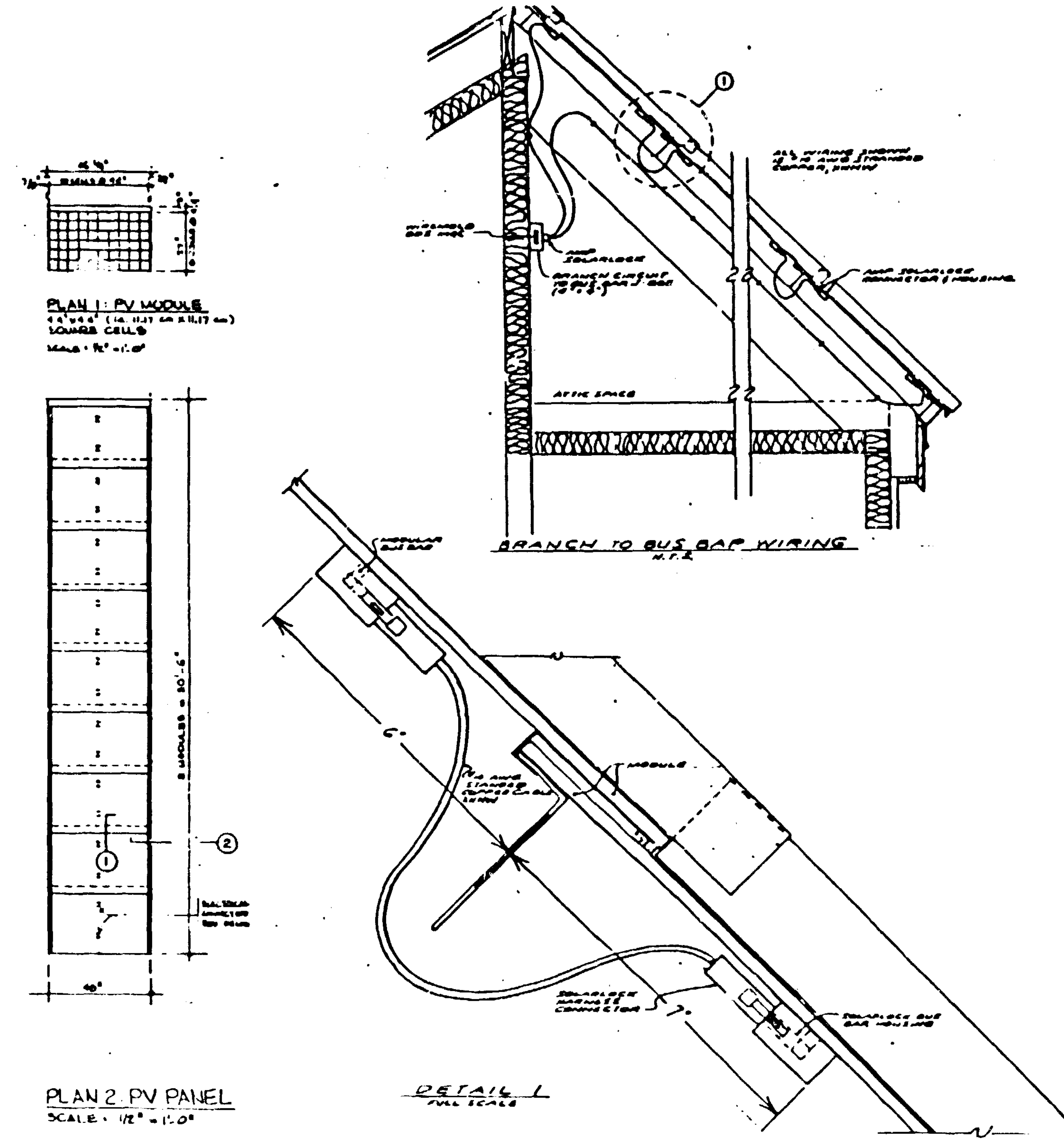

VERTICAL SECTION
QUICK CONNECT
PV/GLASS PANEL
WIRE HARNESS
LOCKING STRIP
NEOPRENE GASKET
ALUMINUM EXTRUSION
PERIMETER FLASHING

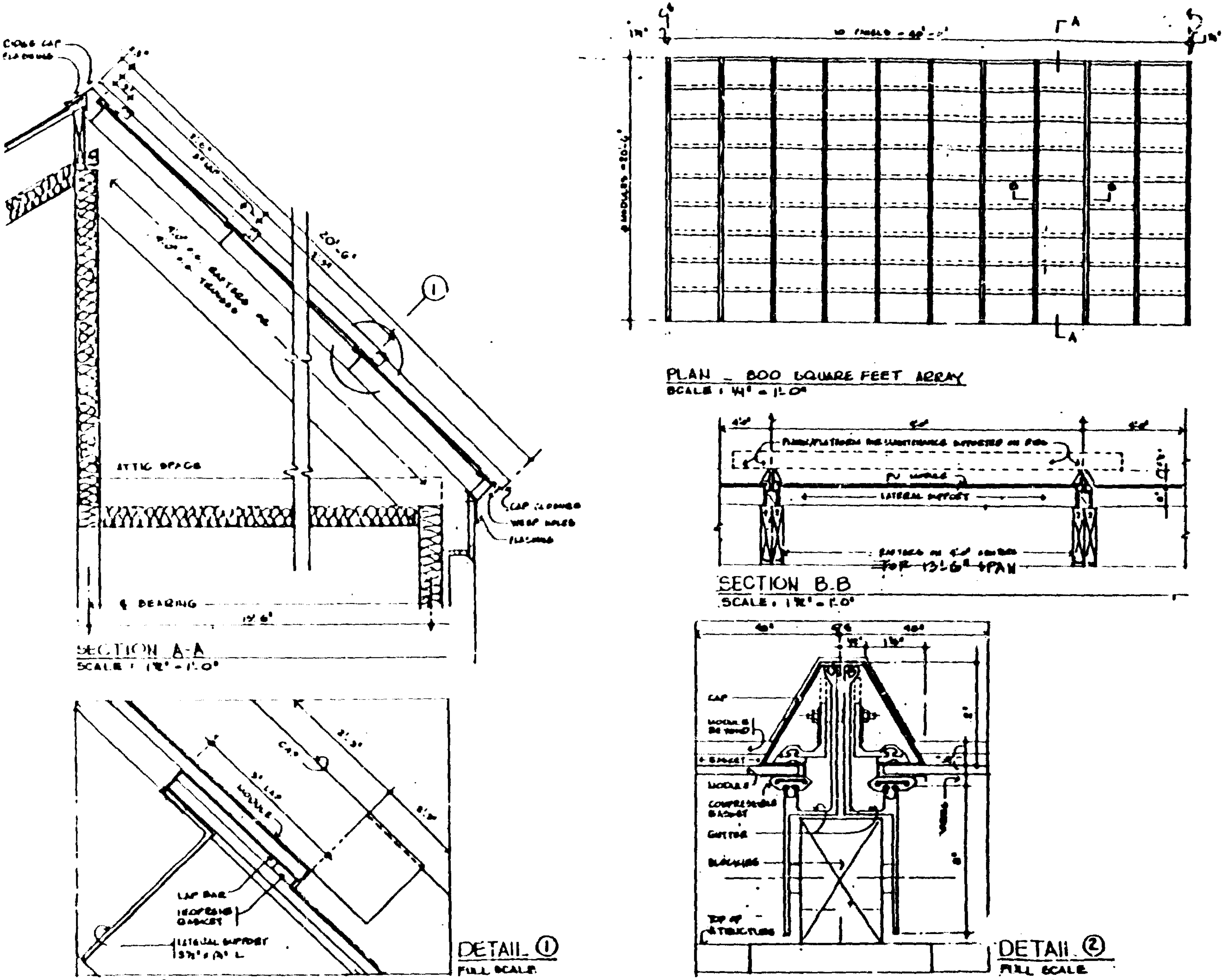
DESIGN CONCEPT 1 MECHANICAL - FIGURE 3-2





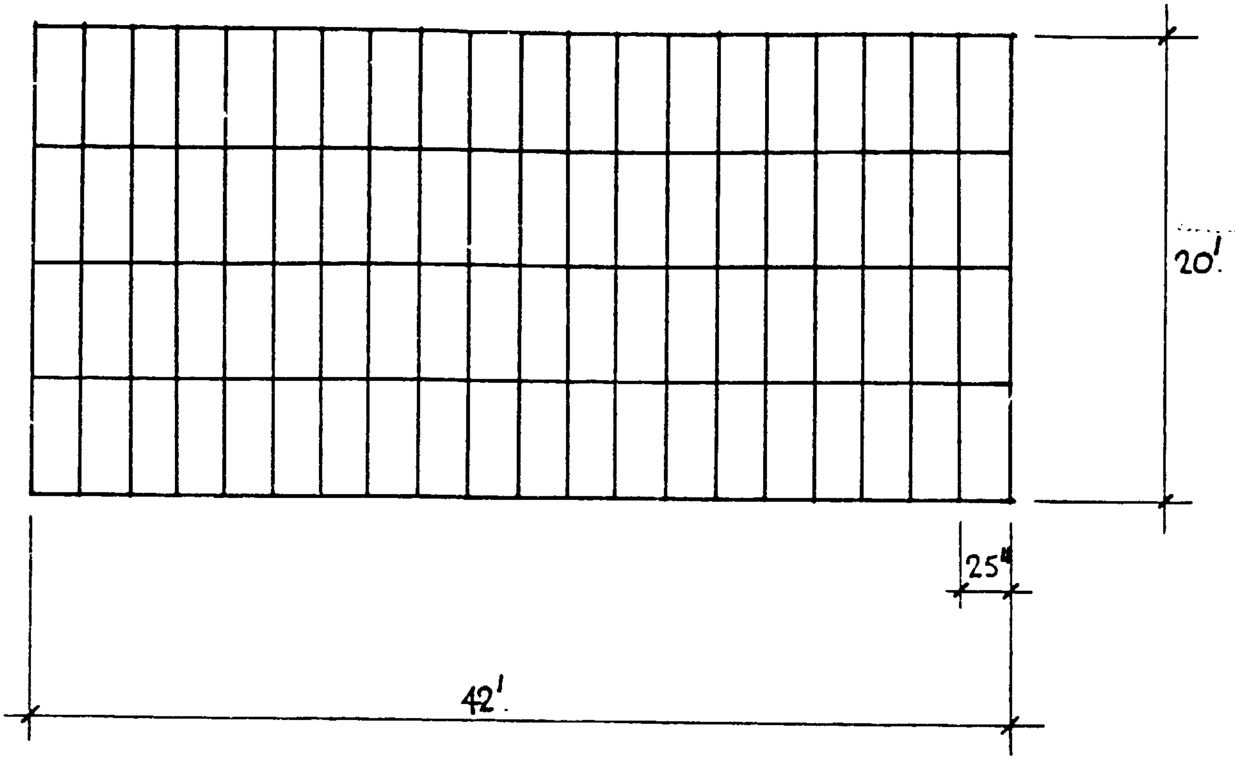
HORIZONTAL SECTION

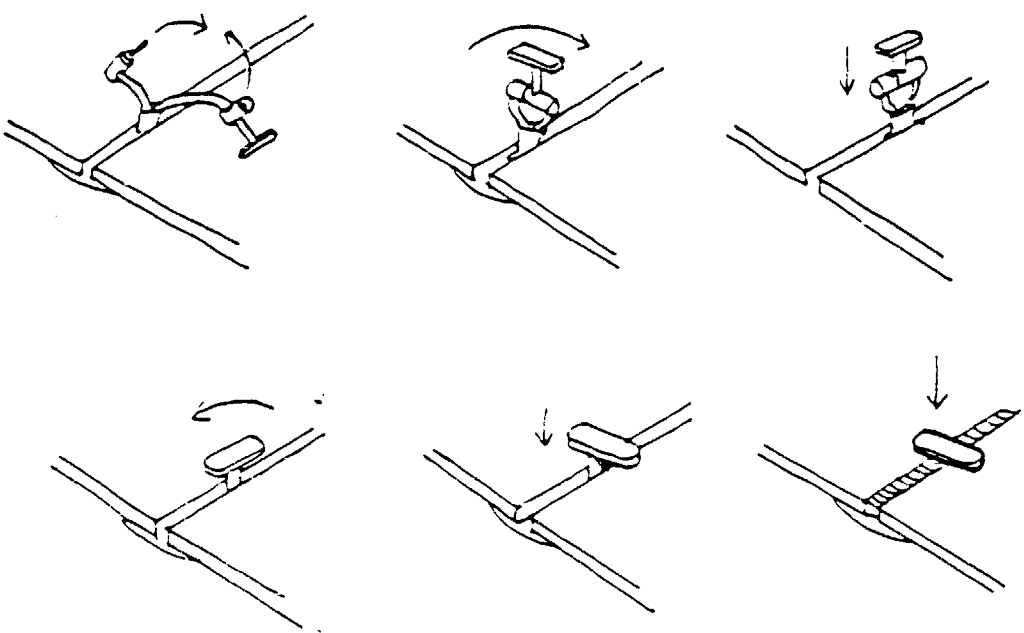

PLAN 1: PV MODULE
SQUARE CELLS
PLAN 2 PV PANEL
SCALE: 1/2" = 1'-0"
ATTIC SPACE
BRANCH TO BUS BAR WIRING
N.T.S.
MODULE
DETAIL 1
FULL SCALE

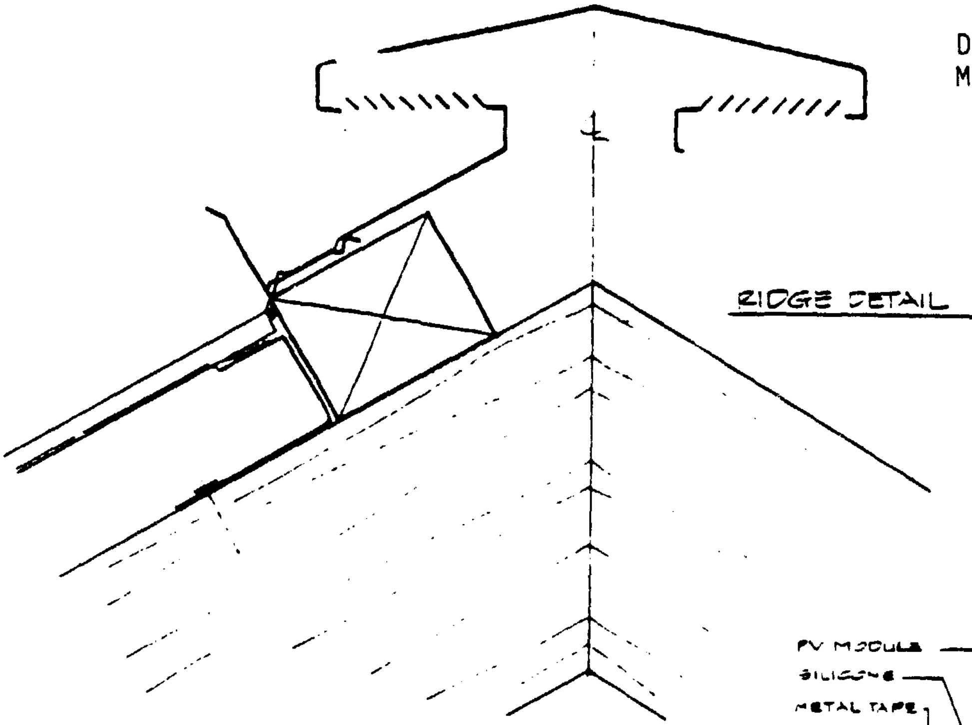


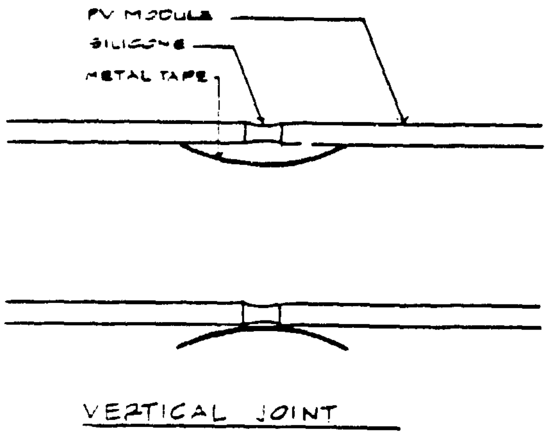
DESIGN CONCEPT 2 MECHANICAL - FIGURE 3-4

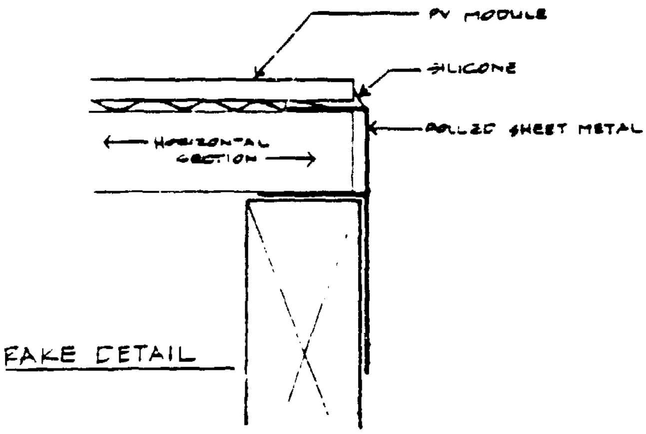
DESIGN CONCEPT 3 ELECTRICAL - FIGURE 3-5

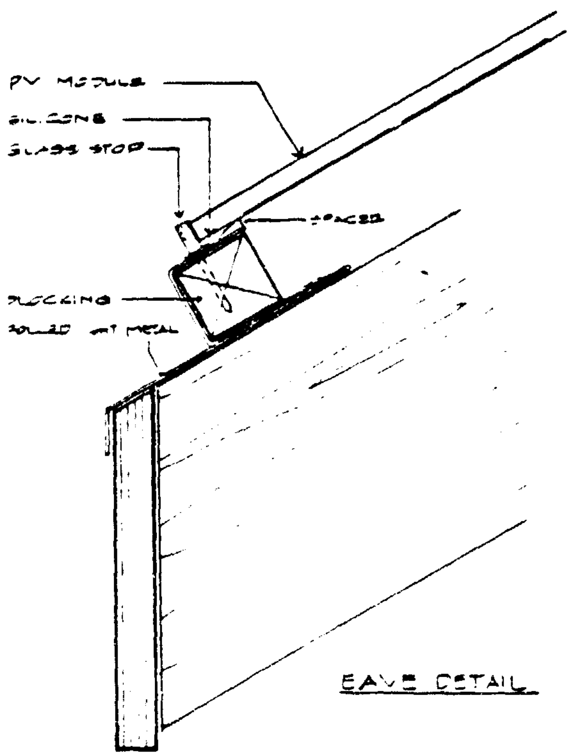


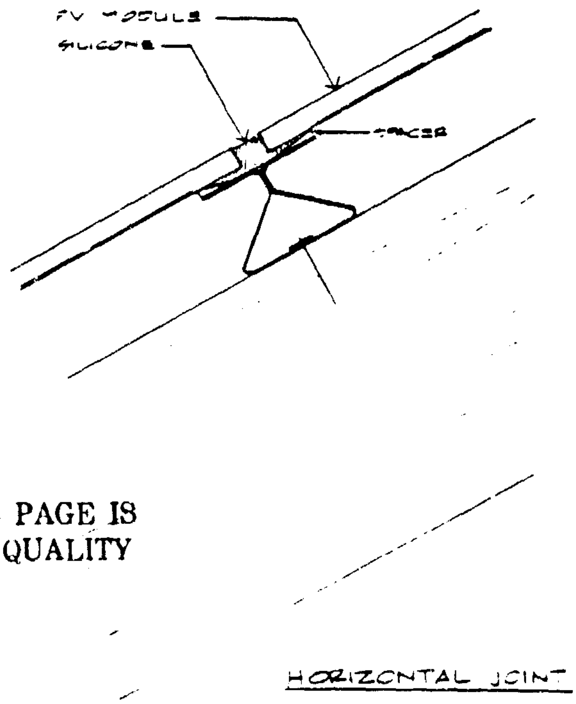


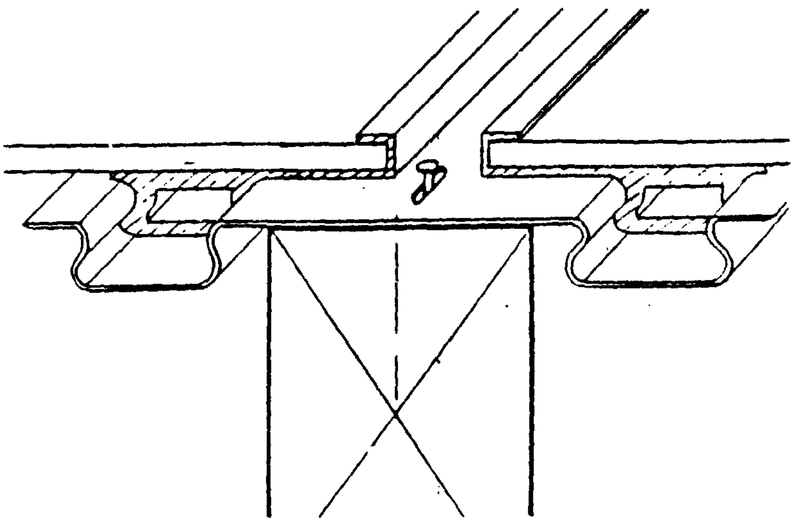

RIDGE DETAIL


PV MODULE
SILICONE
METAL TAPE
VERTICAL JOINT


PV MODULE
SILICONE
ROLLED SHEET METAL
HORIZONTAL SECTION
RAKE DETAIL


PV MODULE
SILICONE
GLASS STOP
SPACER
BLOCKING
EAVE DETAIL


PV MODULE
SILICONE
SPACER
HORIZONTAL JOINT



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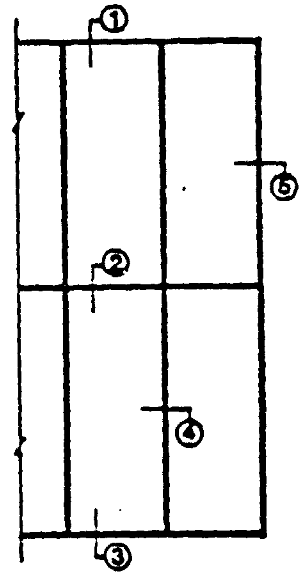
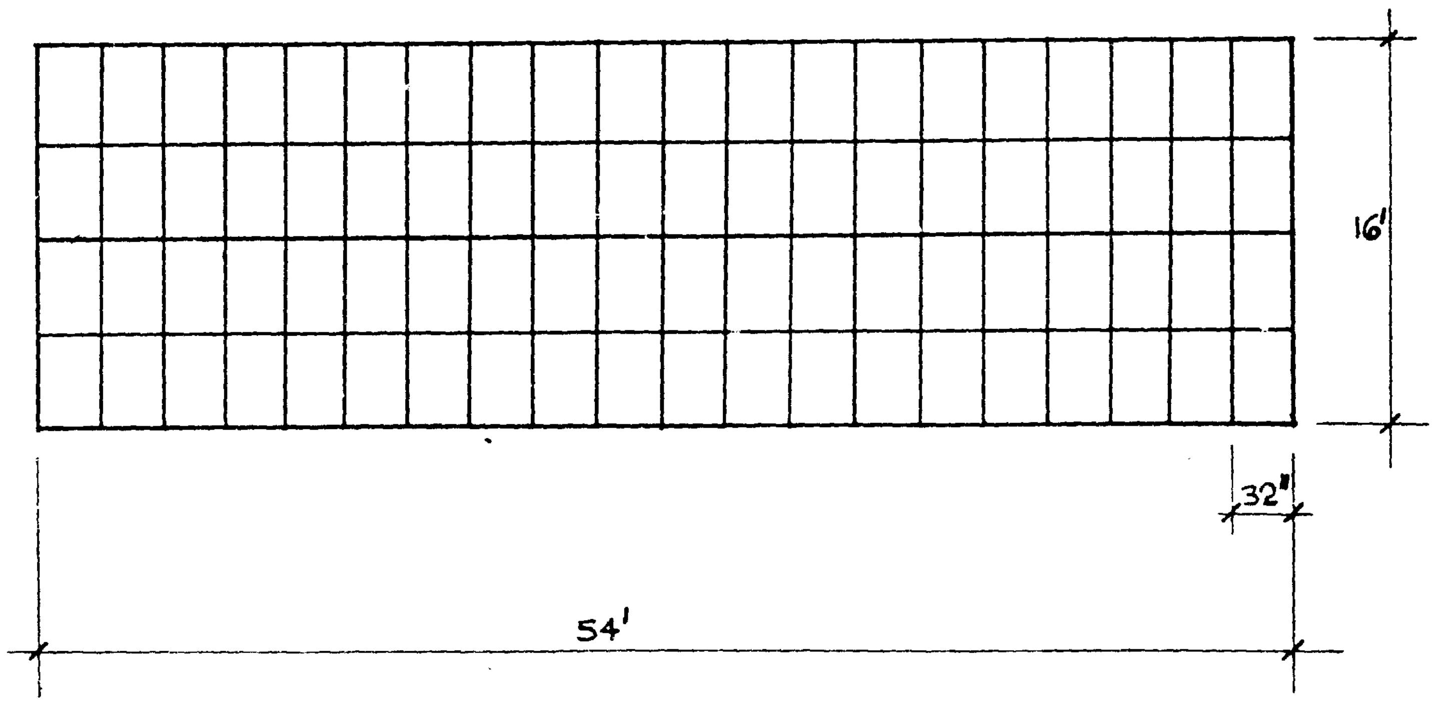
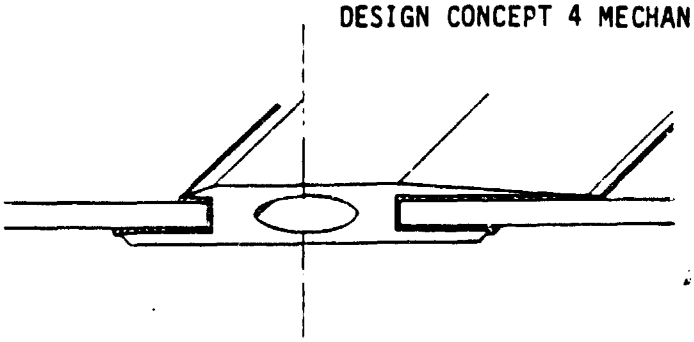




DESIGN CONCEPT 4 MECHANICAL - FIGURE 3-8



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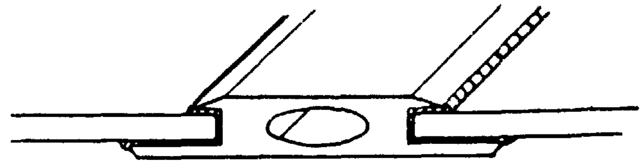

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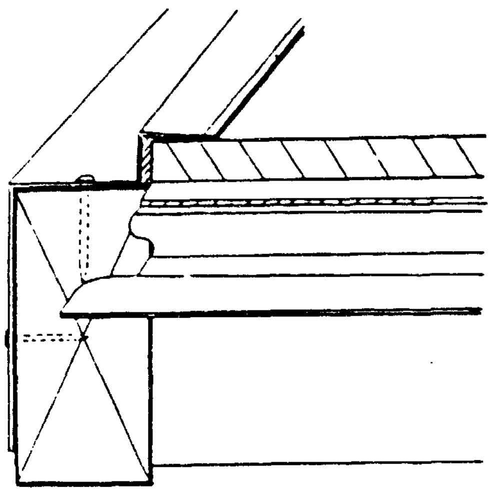

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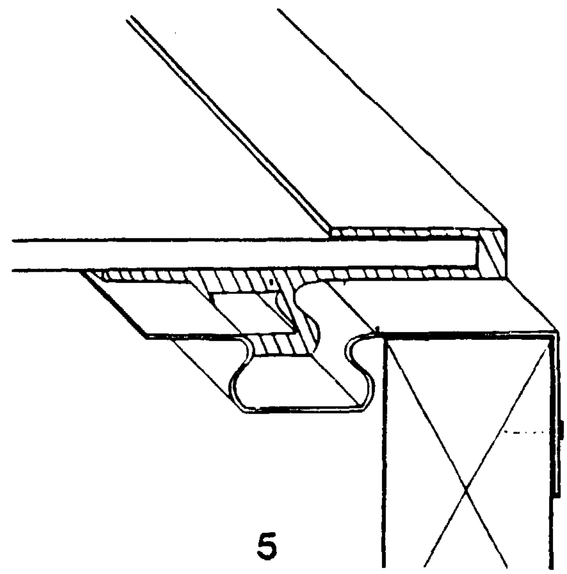

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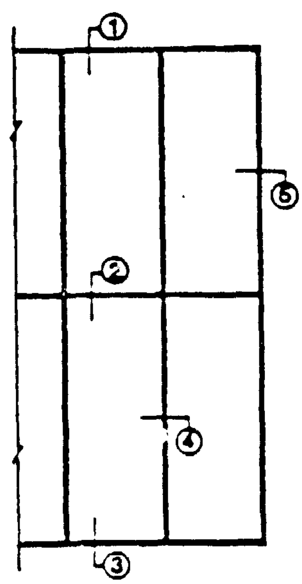
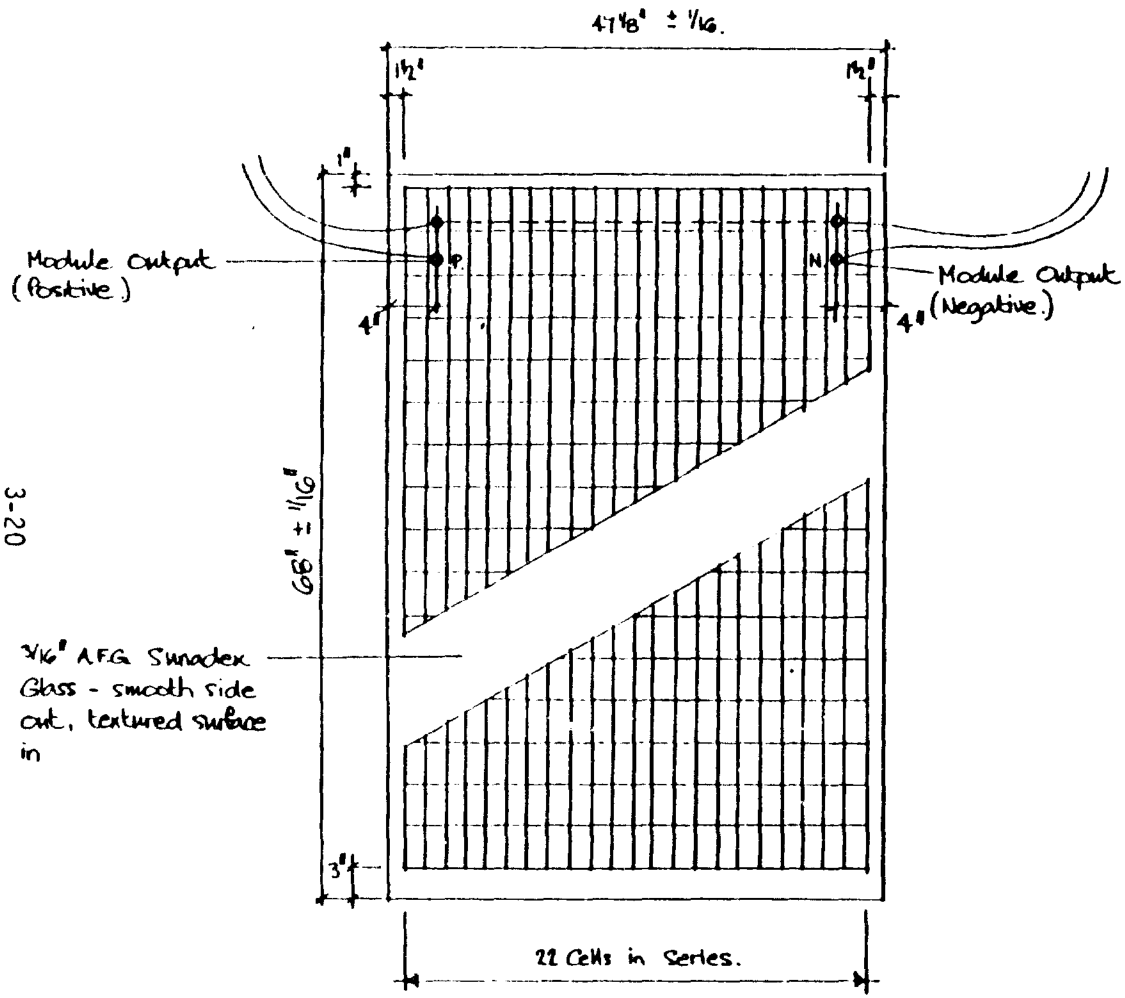
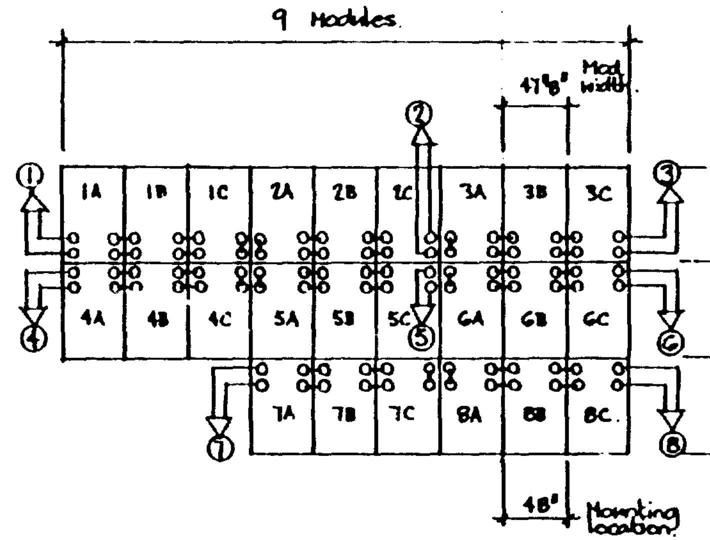




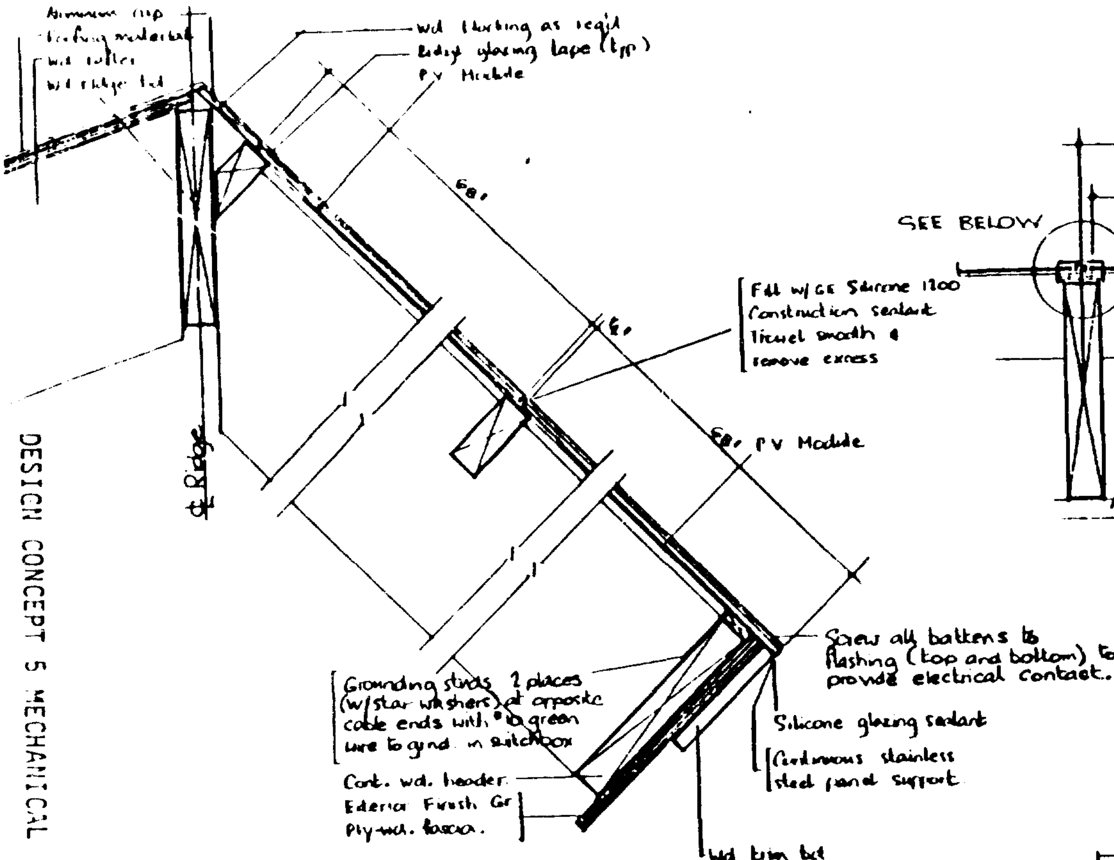
TYPICAL P.V. MODULE.



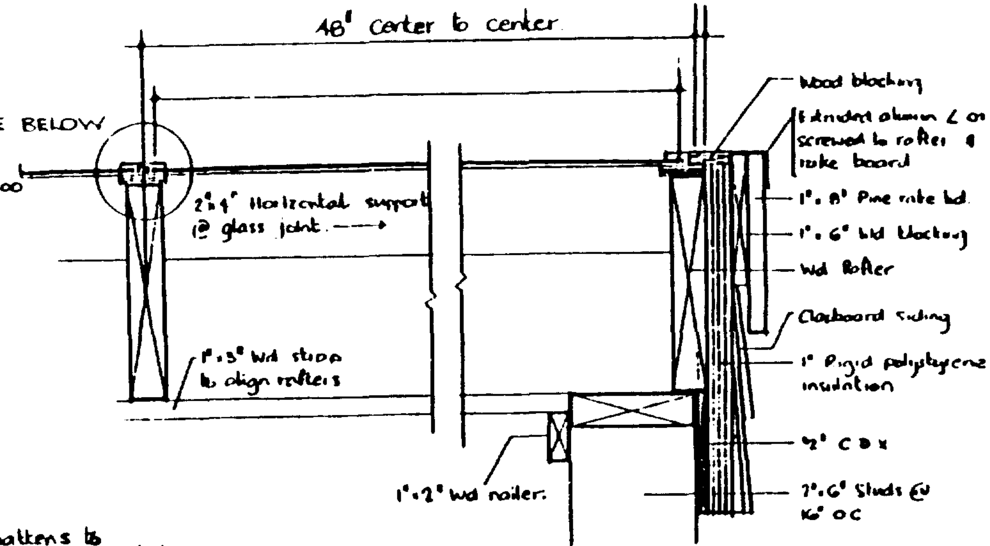
ARRAY WIRING DIAGRAM & CONFIGURATION.

NOTES :
1. 24 Modules
2. Nominal 28°C Operation of Array 205.2 Volts at 20.5 Amps = 4.2 KW.
3. 175 WATT/MODULE x 24 M. = 4200 W.
4. Shunt Diodes built into Module.
5. All strings wired to D.C. Interface box.
6. All battens and adjacent flashings screwed together and wired to ground.

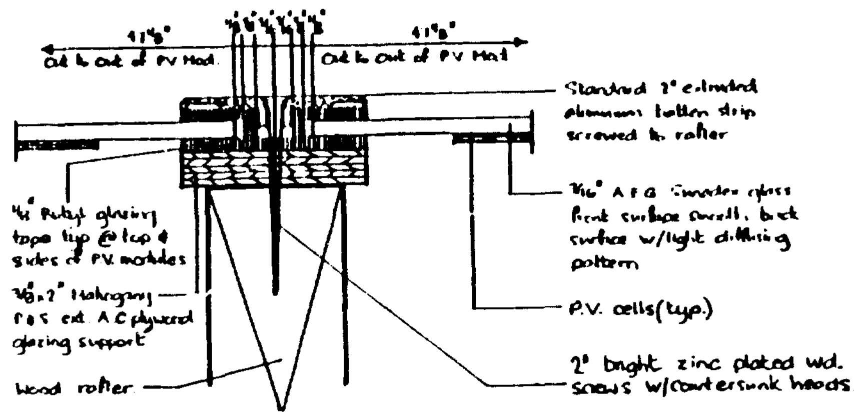
P.V. Module Sizing and Array Configuation.



SECTION THROUGH ROOF BAY

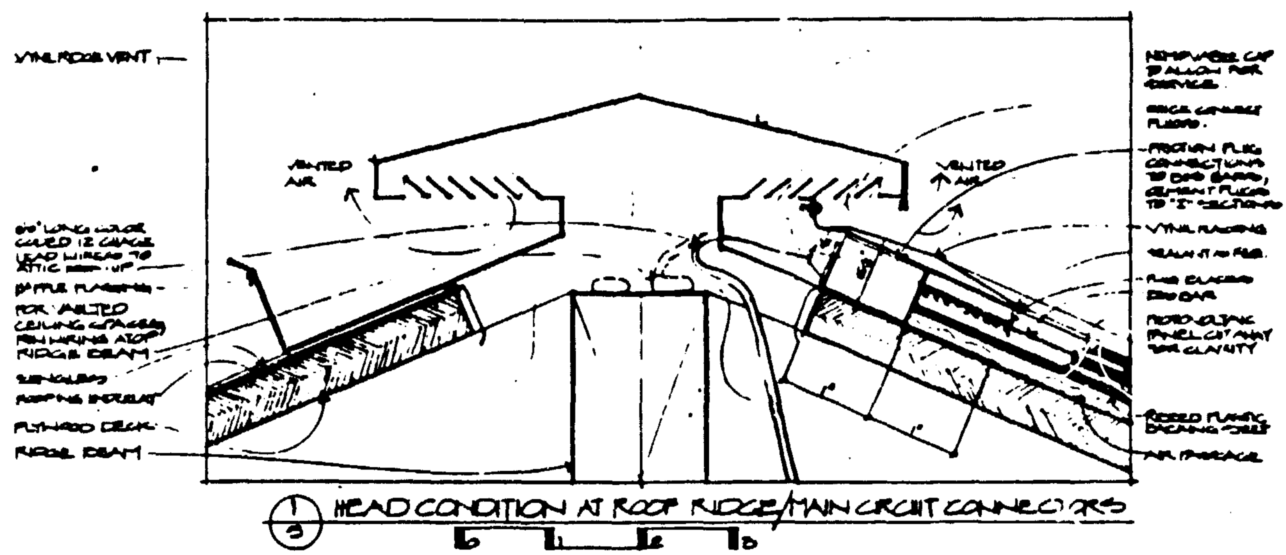


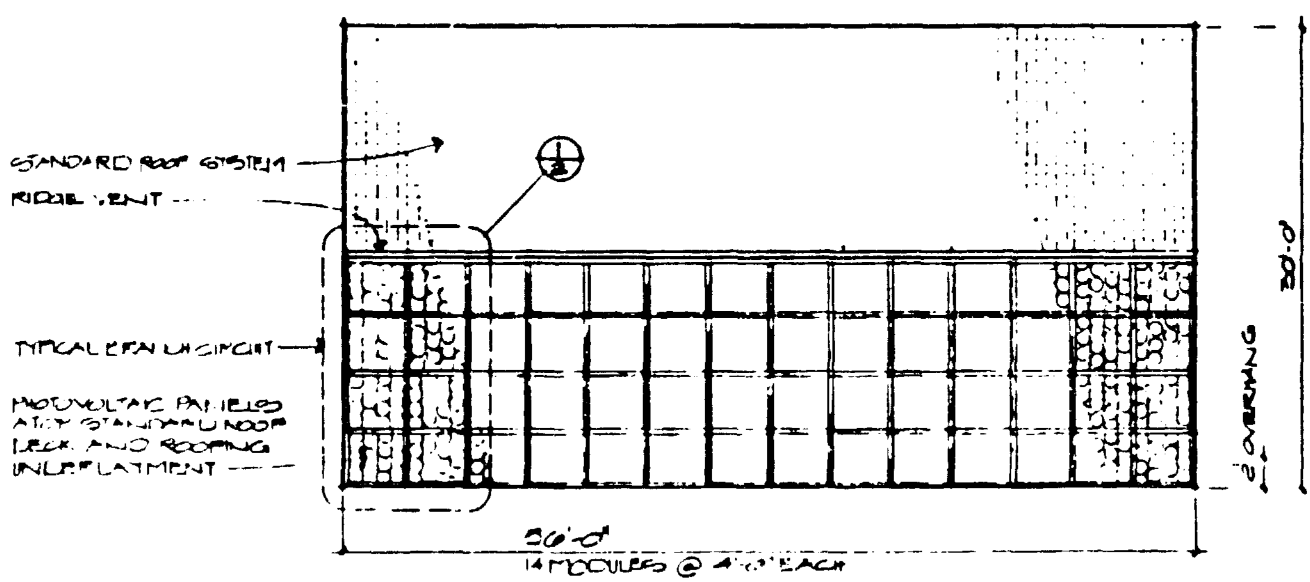
END WALL SECTION.



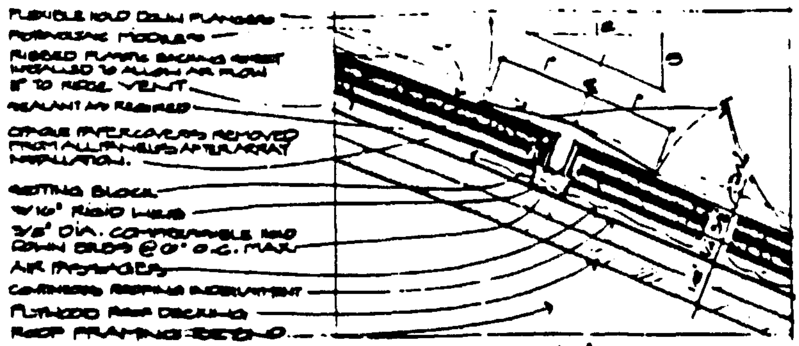
TYPICAL BATTEN DETAIL.

DESIGN CONCEPT 5 MECHANICAL - FIGURE 3-10

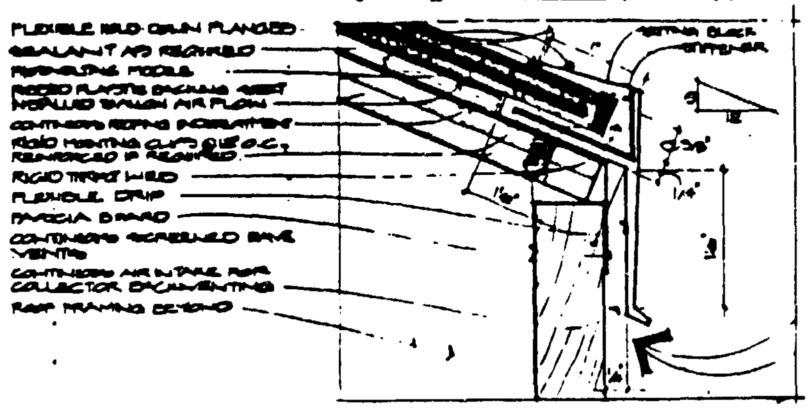

VENTED AIR
VENTED AIR
VINYL FLASHING
AIR PASSAGE
RIDGE BEAM
PLYWOOD DECK
SHINGLES
HEAD CONDITION AT ROOF RIDGE/MAIN CIRCUIT CONNECTORS


STANDARD ROOF SYSTEM
RIDGE VENT
TYPICAL BRANCH CIRCUIT
PHOTOVOLTAIC PANELS ATOP STANDARD ROOF DECK AND ROOFING UNDERLAYMENT
30'-0"
14 MODULES @ 4'-0" EACH
2' OVERHANG
0 2 4 8

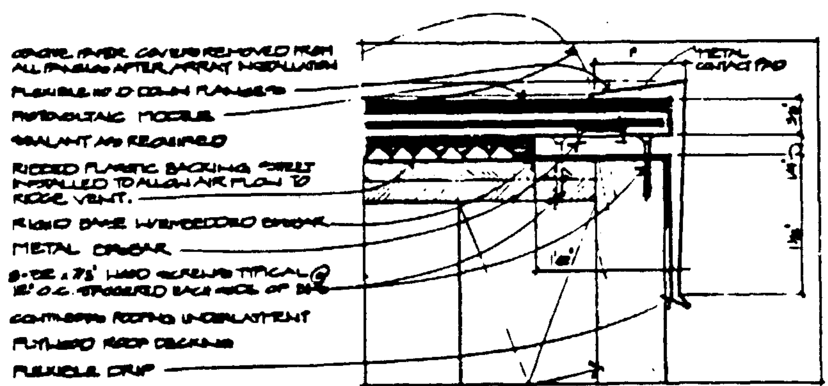
ROOF PLAN



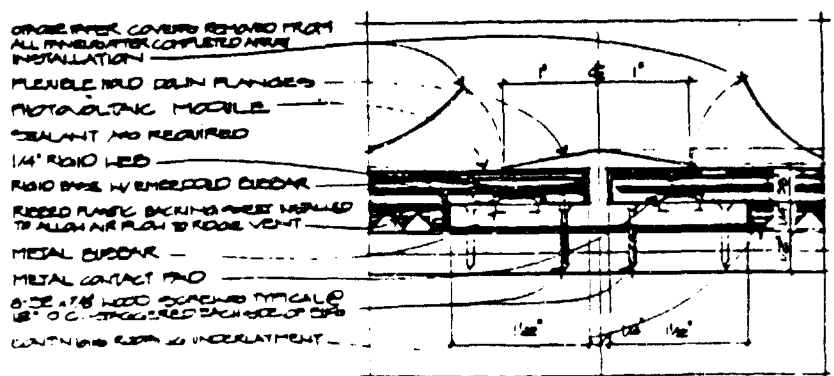
HORIZONTAL 'T' GLAZING GASKET



FASCIA EDGE GASKET



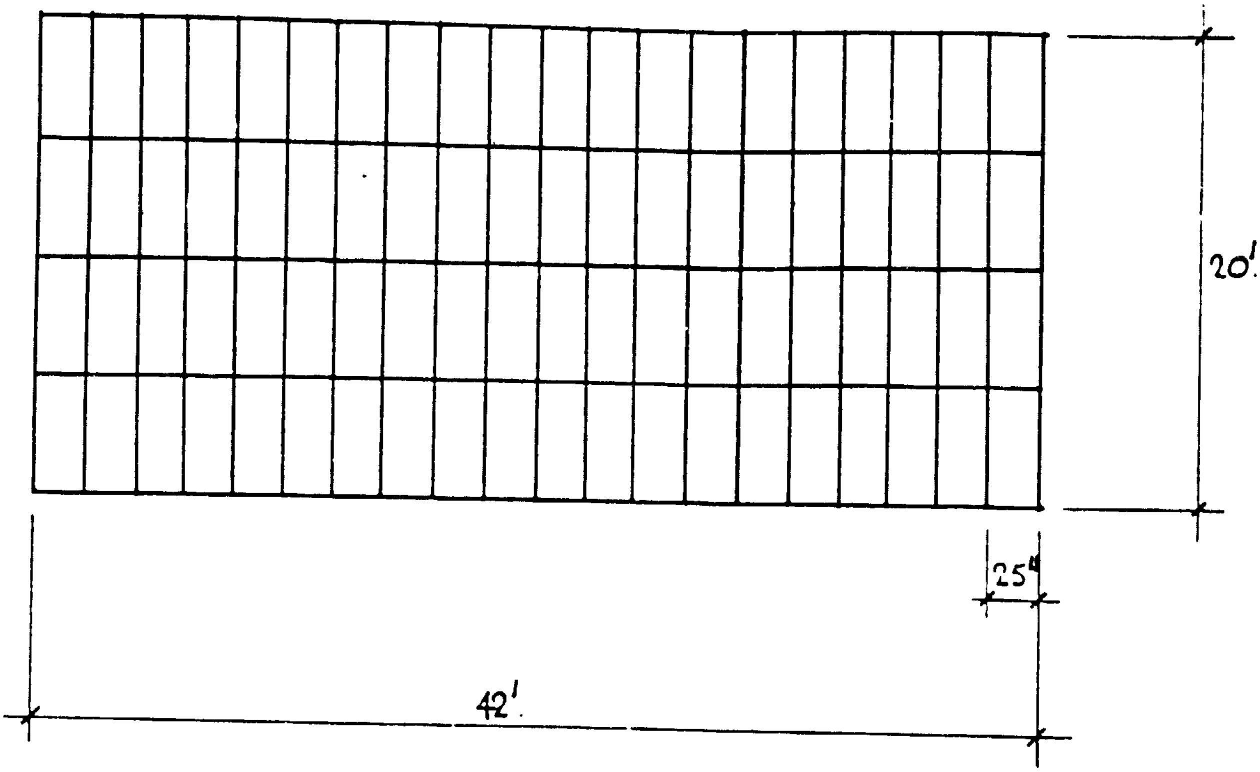
RAKE EDGE GLAZING GASKET

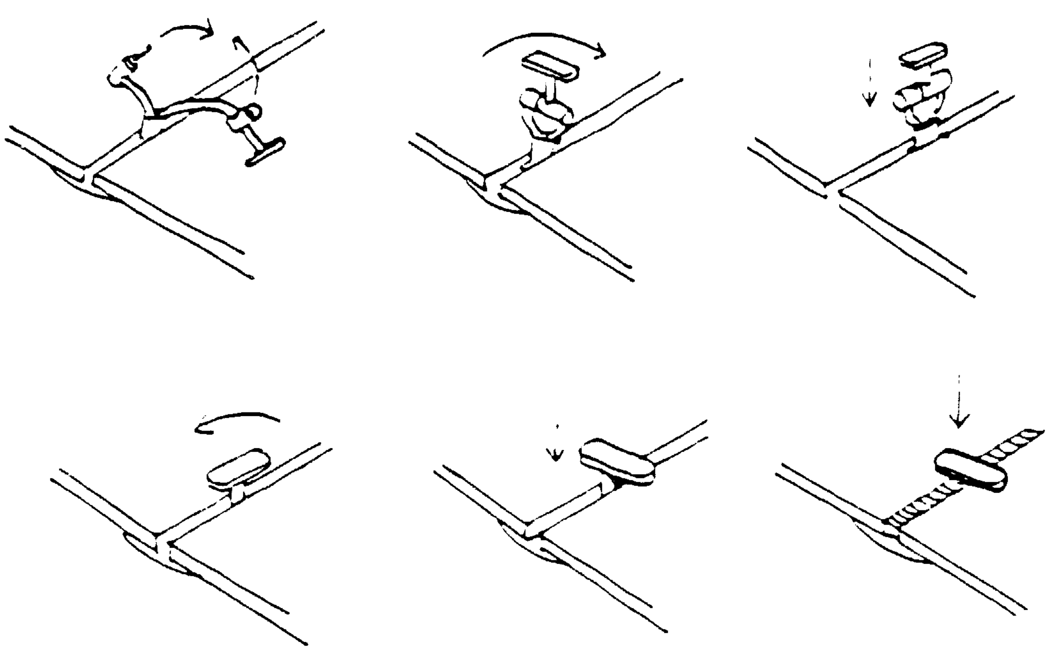


VERTICAL 'T' GLAZING GASKET

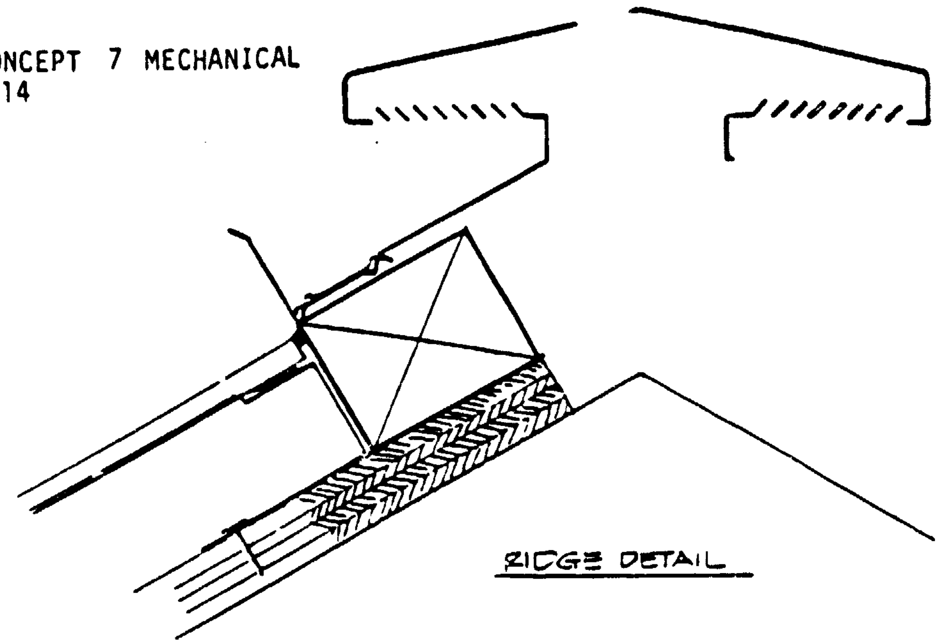
DESIGN CONCEPT 6 MECHANICAL - FIGURE 3-12

DESIGN CONCEPT 7 ELECTRICAL - FIGURE 3-13

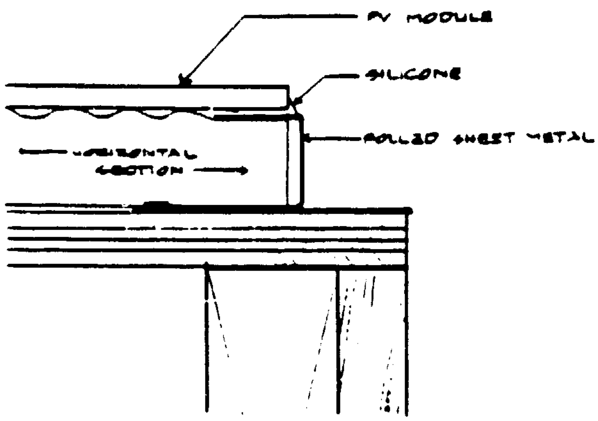




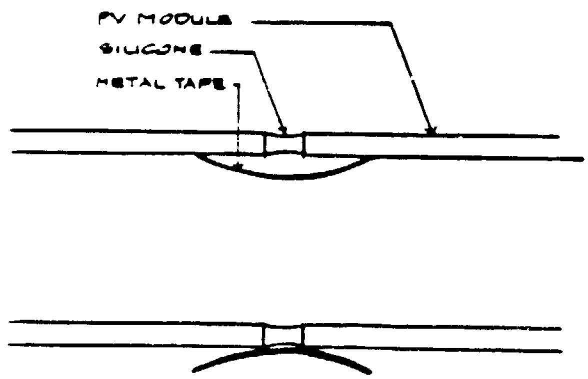
DESIGN CONCEPT 7 MECHANICAL
FIGURE 3-14



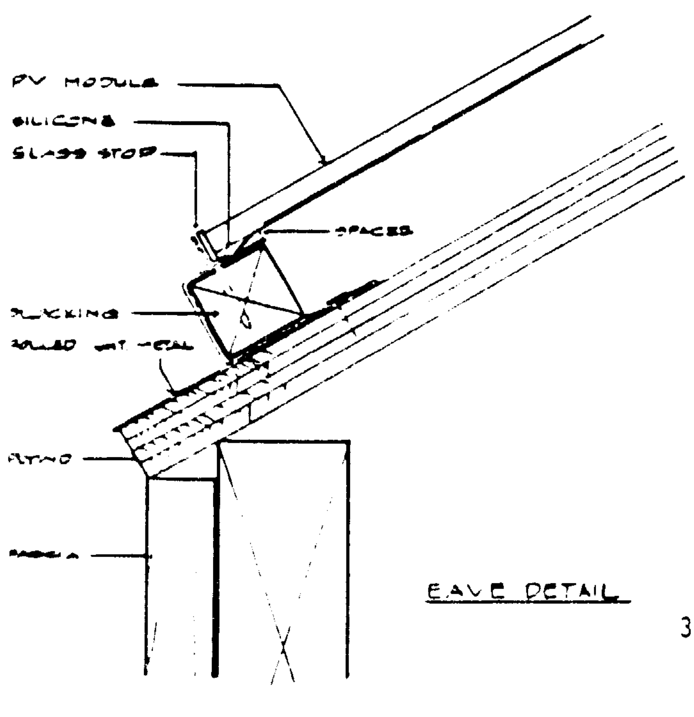
RIDGE DETAIL



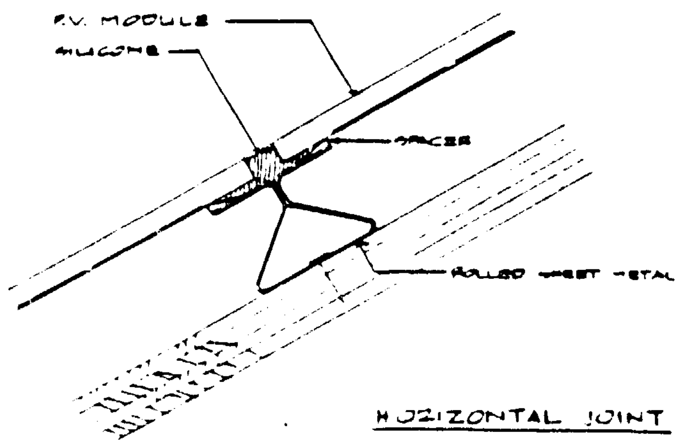
RAKE DETAIL



VERTICAL JOINT

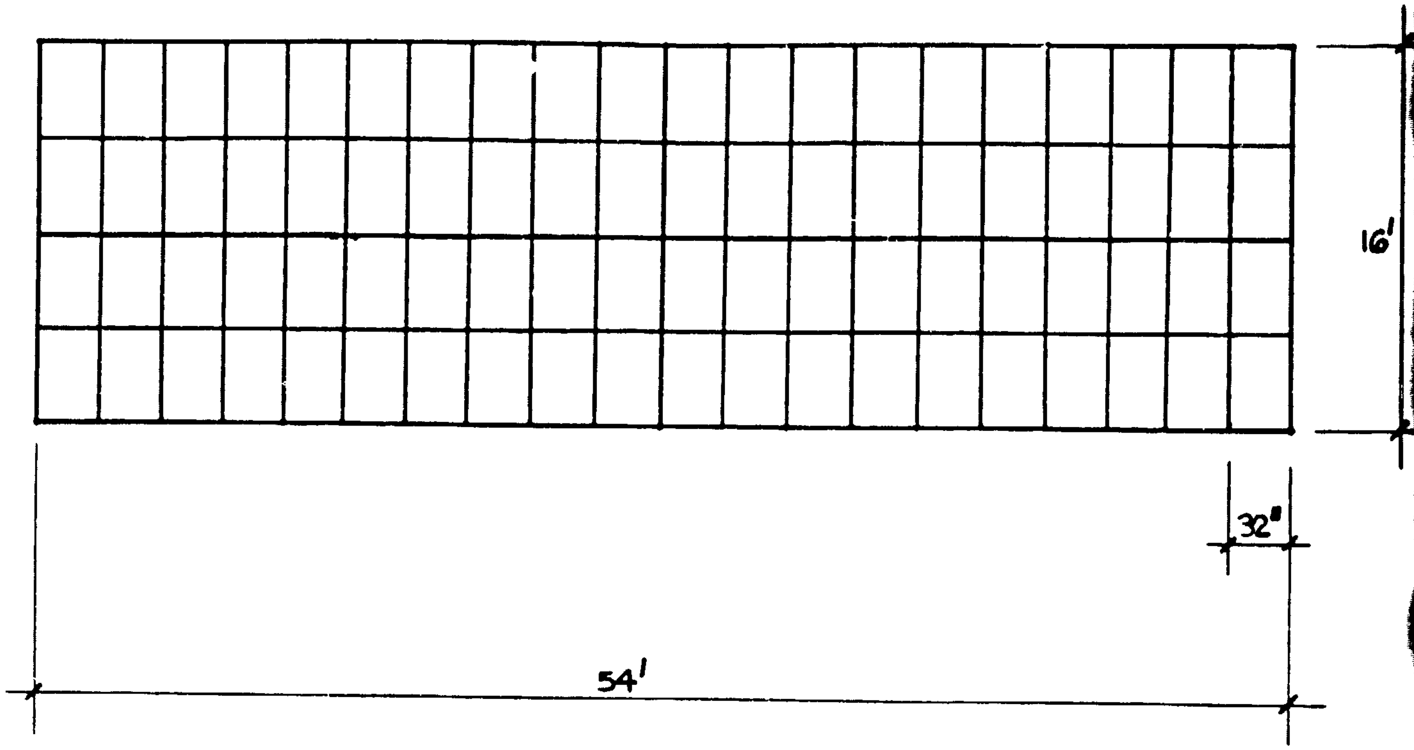


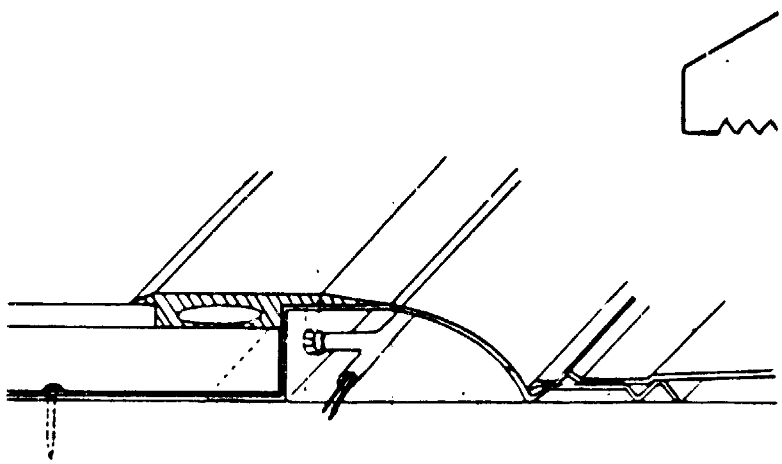
EAVE DETAIL



HORIZONTAL JOINT

DESIGN CONCEPT 8 ELECTRICAL - FIGURE 3-15





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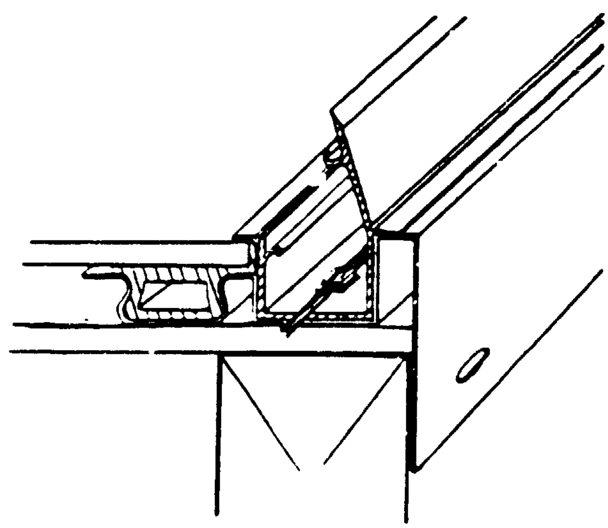

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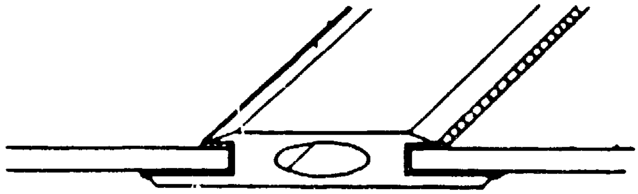

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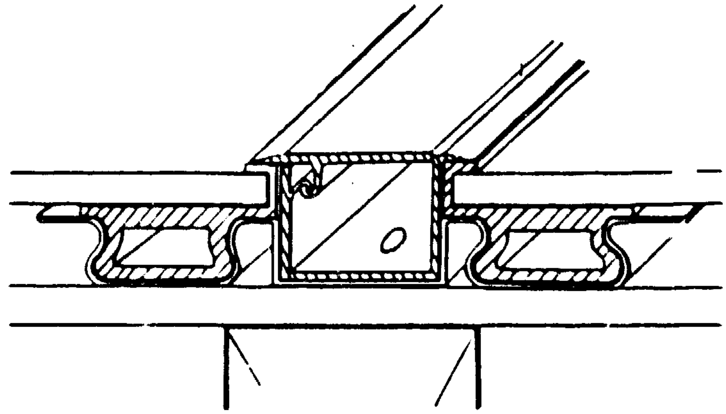

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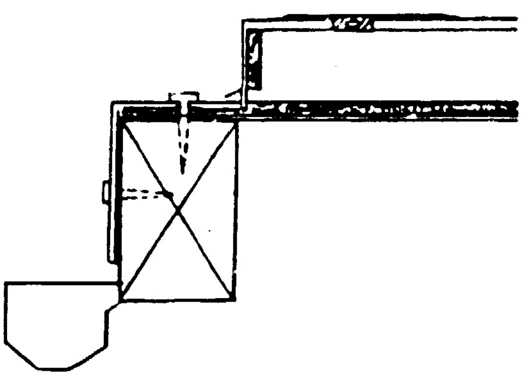

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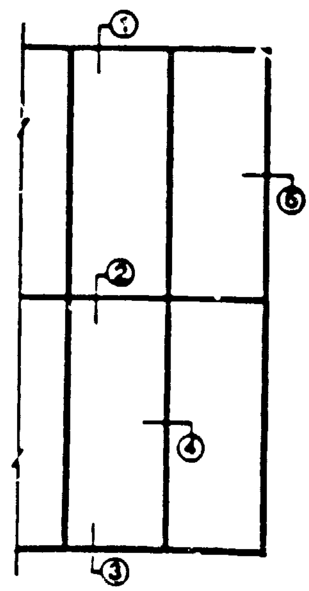
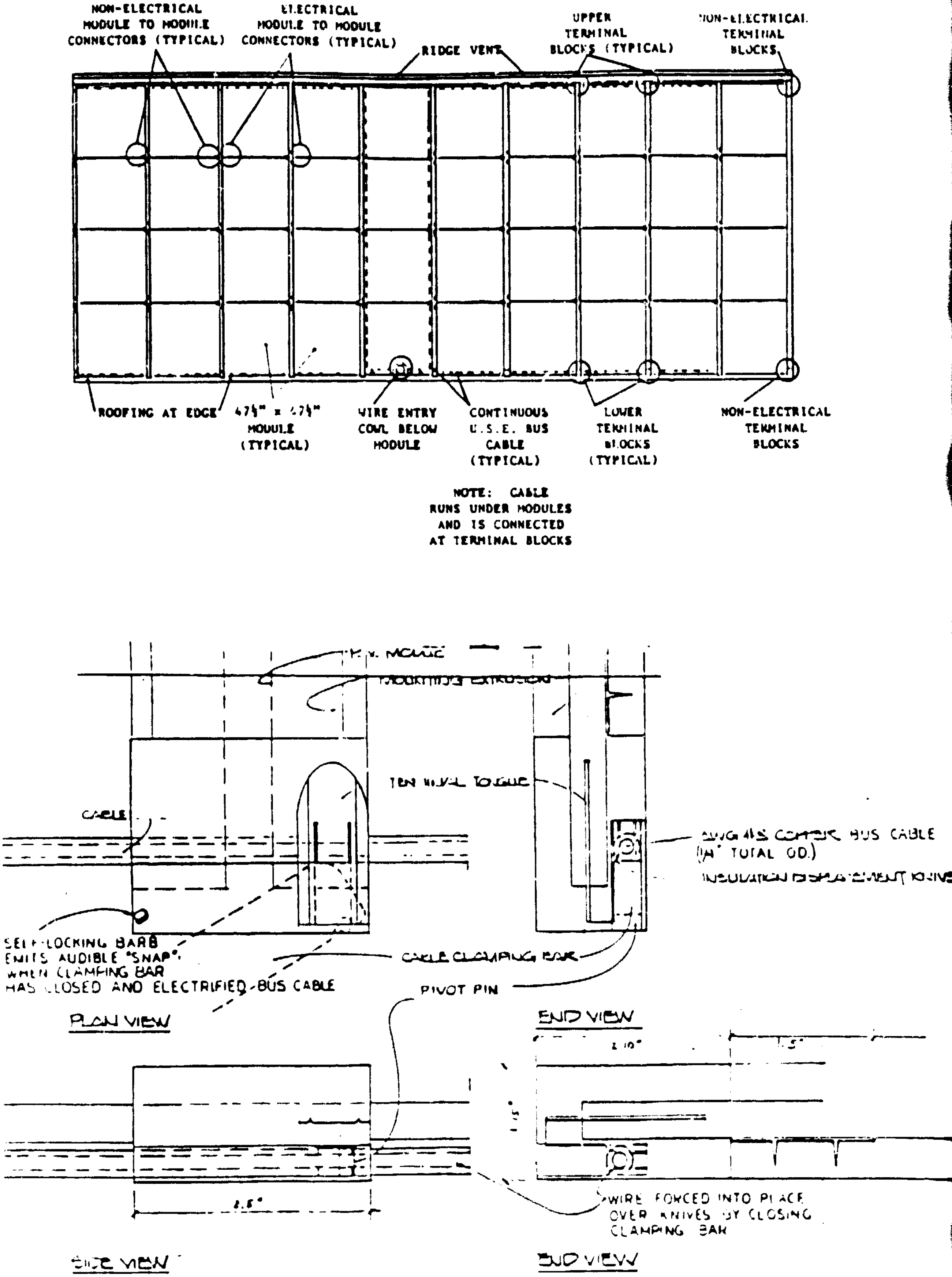
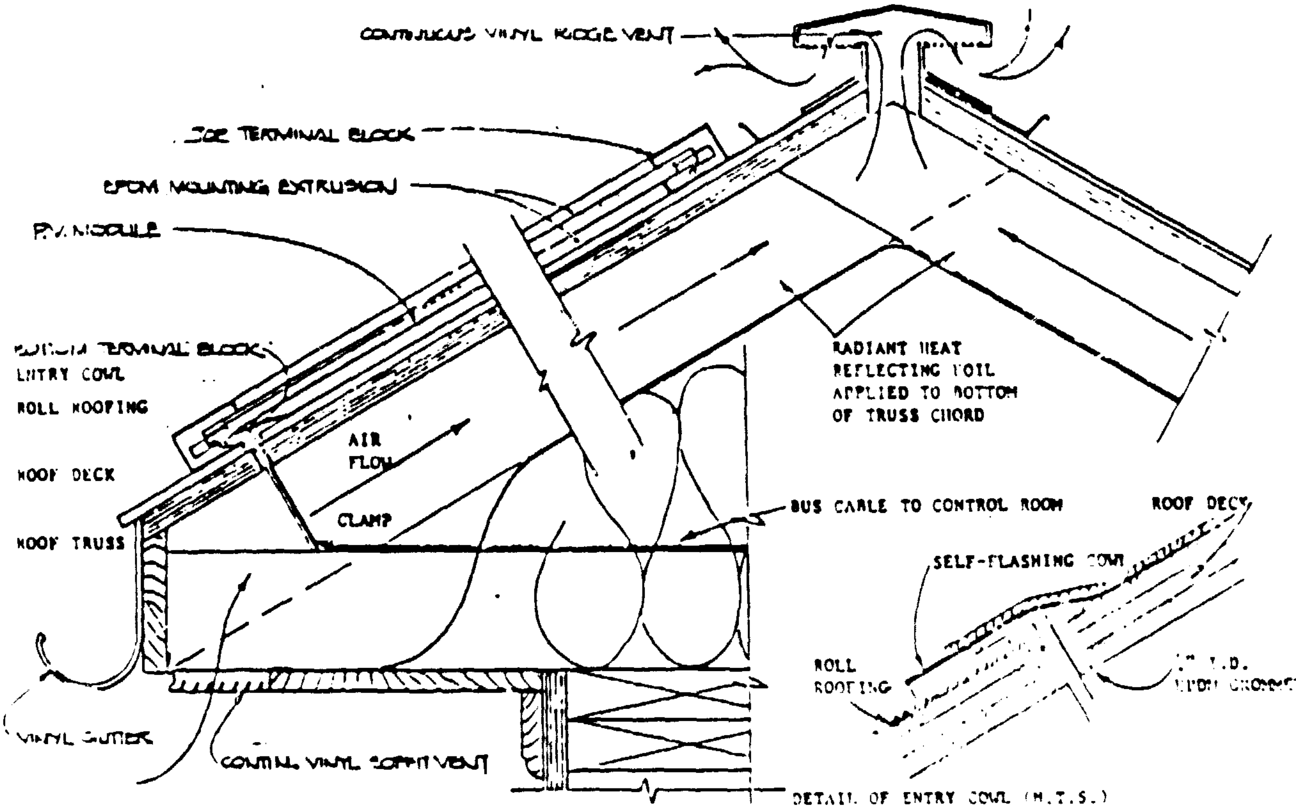


DESIGN CONCEPT 9 ELECTRICAL - FIGURE 3-17





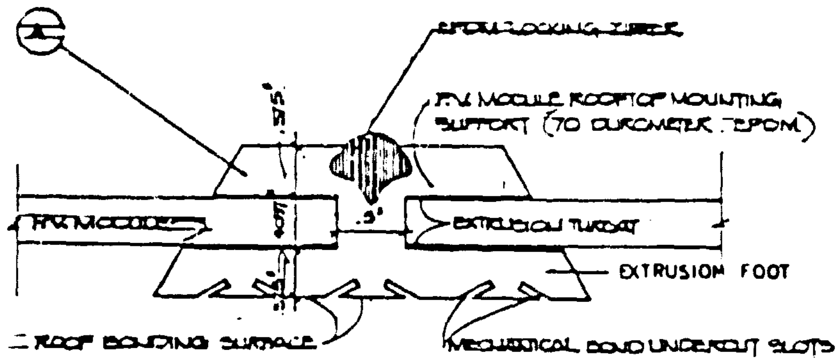


FIG A-1 - CENTER EXTRUSION

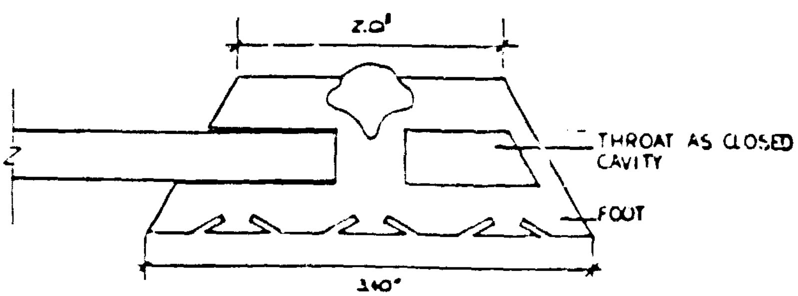
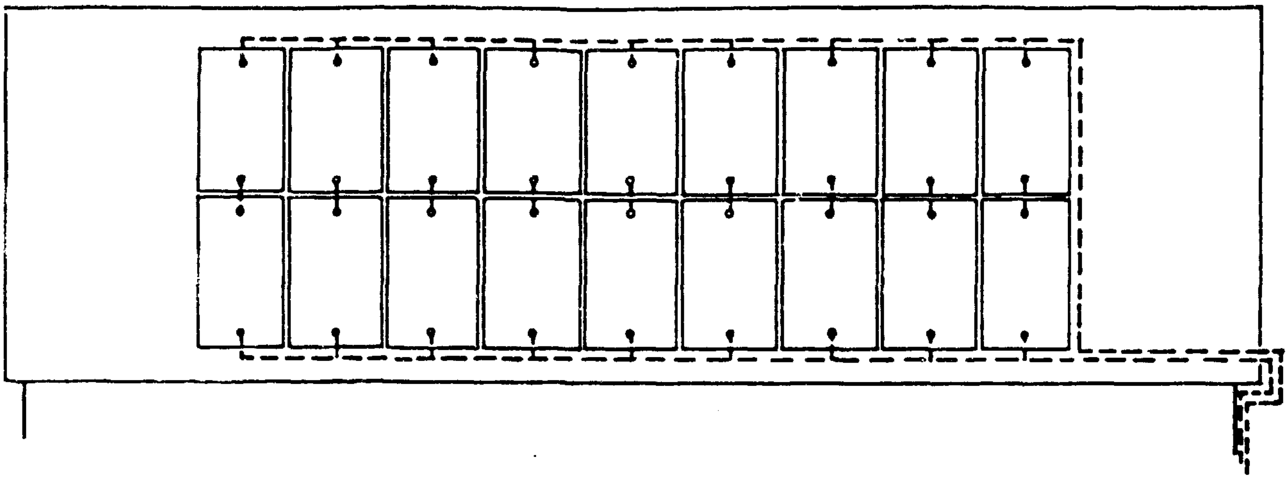
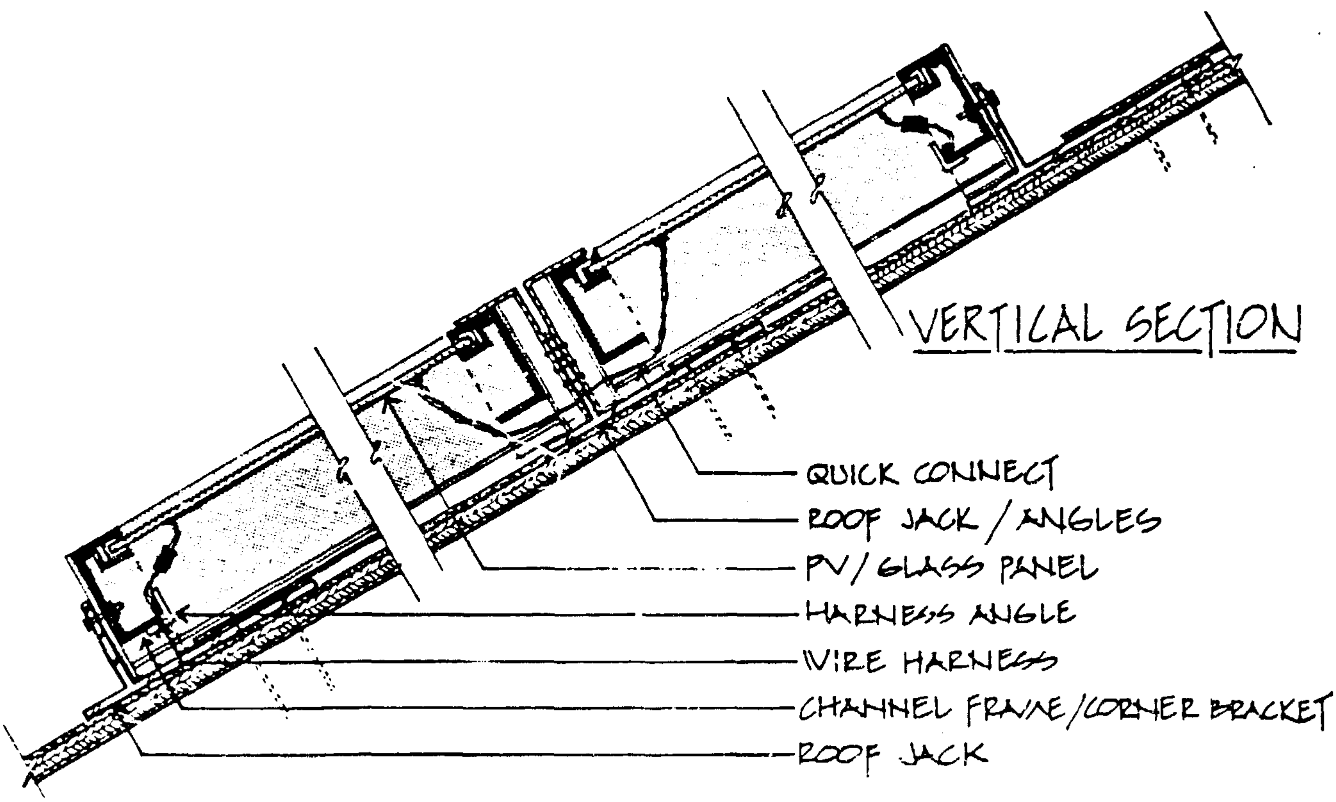
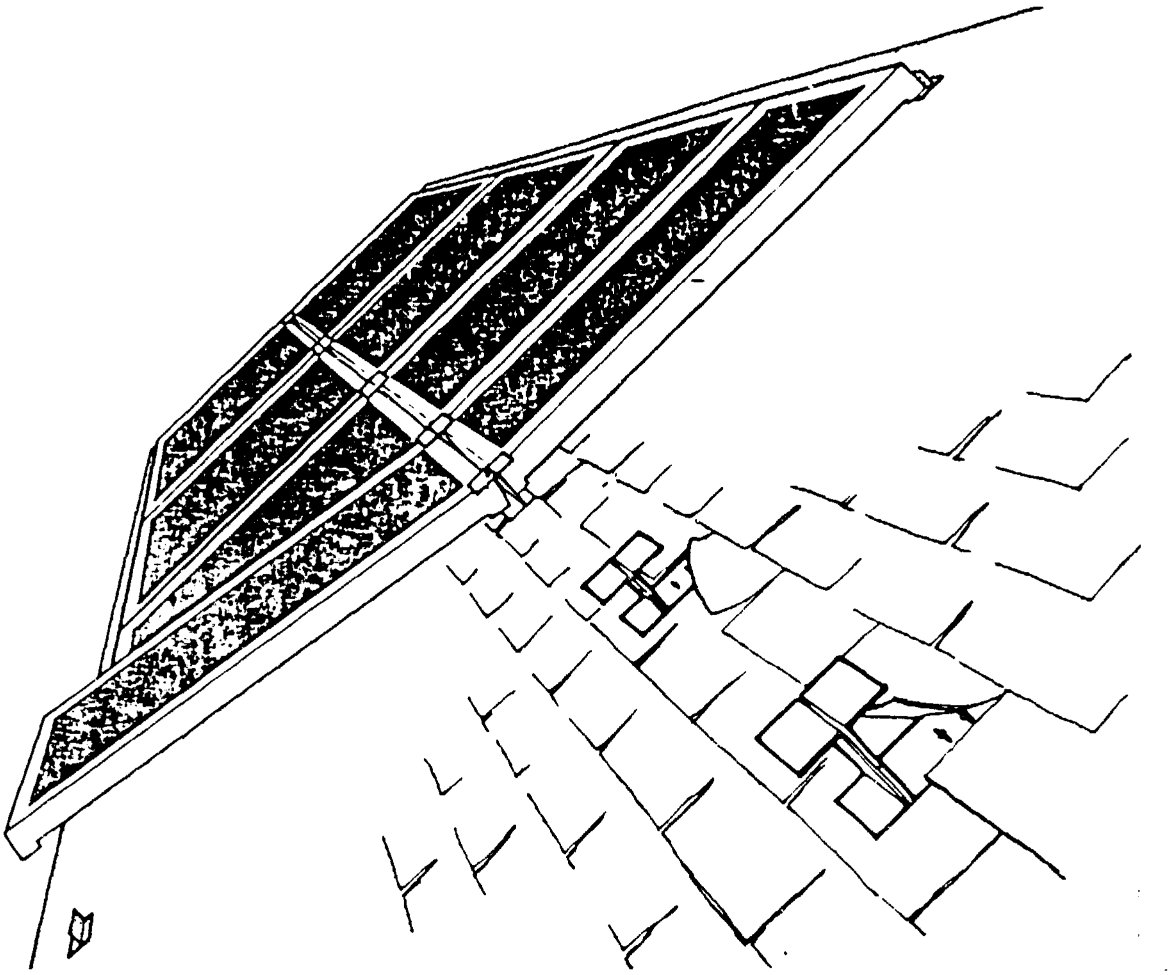
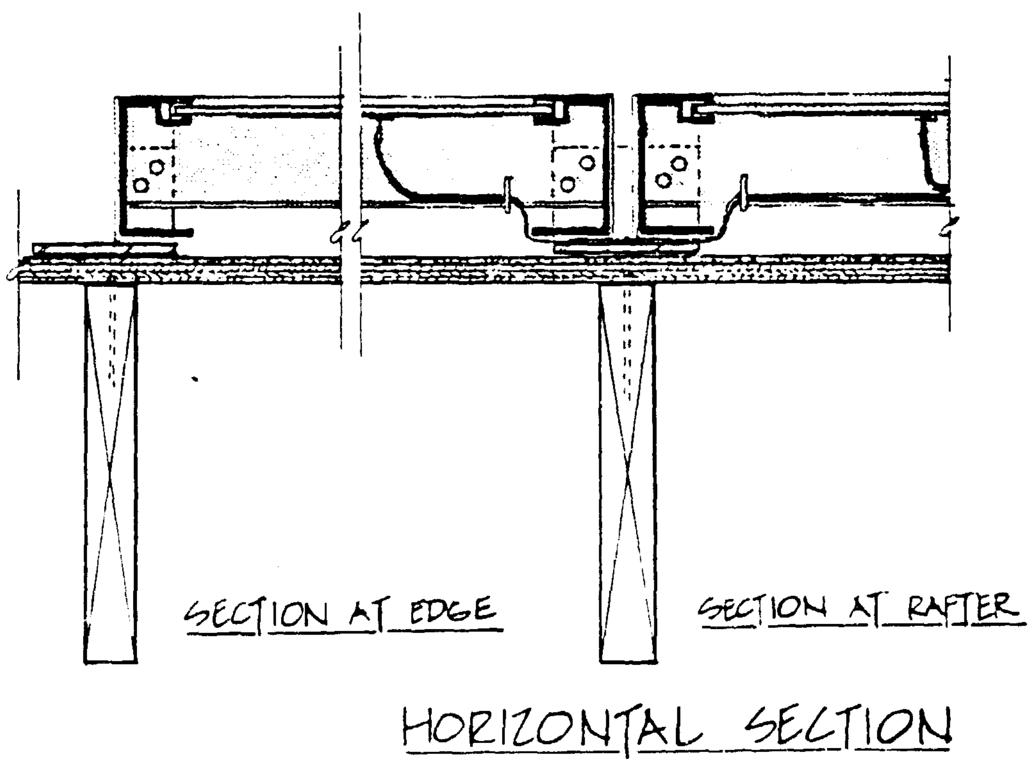


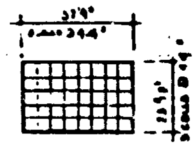
FIG-A-1a - ARRAY END EXTRUSION




VERTICAL SECTION
QUICK CONNECT
ROOF JACK / ANGLES
PV / GLASS PANEL
HARNESS ANGLE
WIRE HARNESS
CHANNEL FRAME / CORNER BRACKET
ROOF JACK

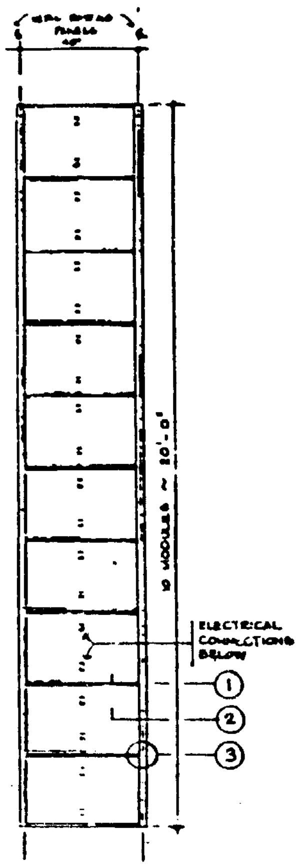



SECTION AT EDGE
SECTION AT RAFTER
HORIZONTAL SECTION



PLAN 1: PV MODULE

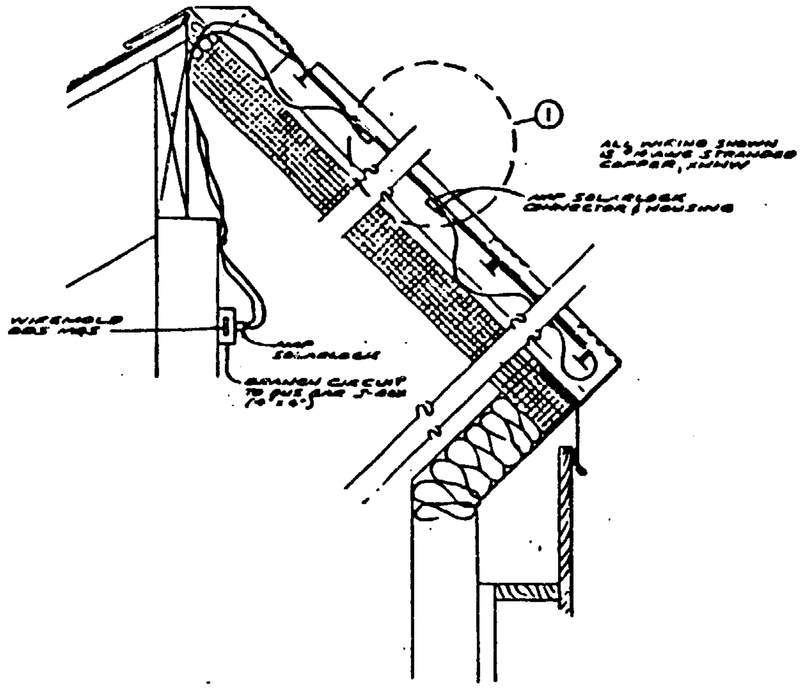
SCALE: 1/2" = 1'-0"



PLAN 2 - PV PANEL

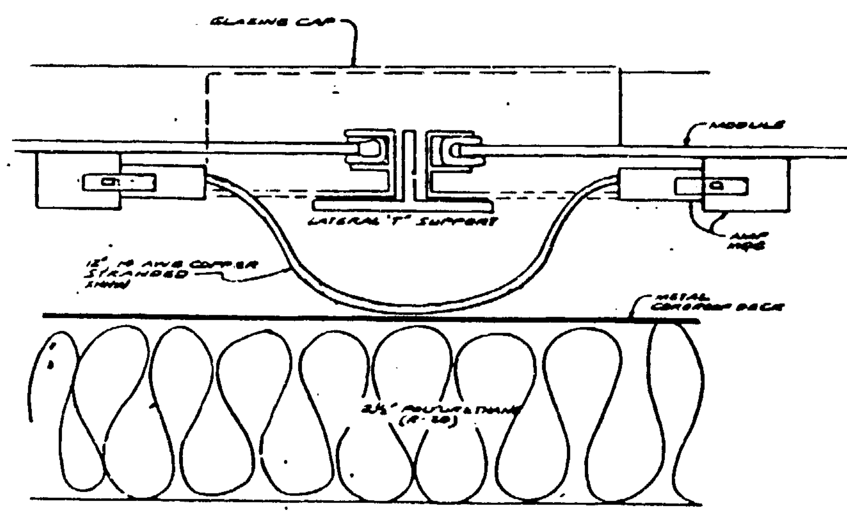
INSTALLED ONTO RIBS OF INSULATED METAL ROOF

SCALE: 1/2" = 1'-0"



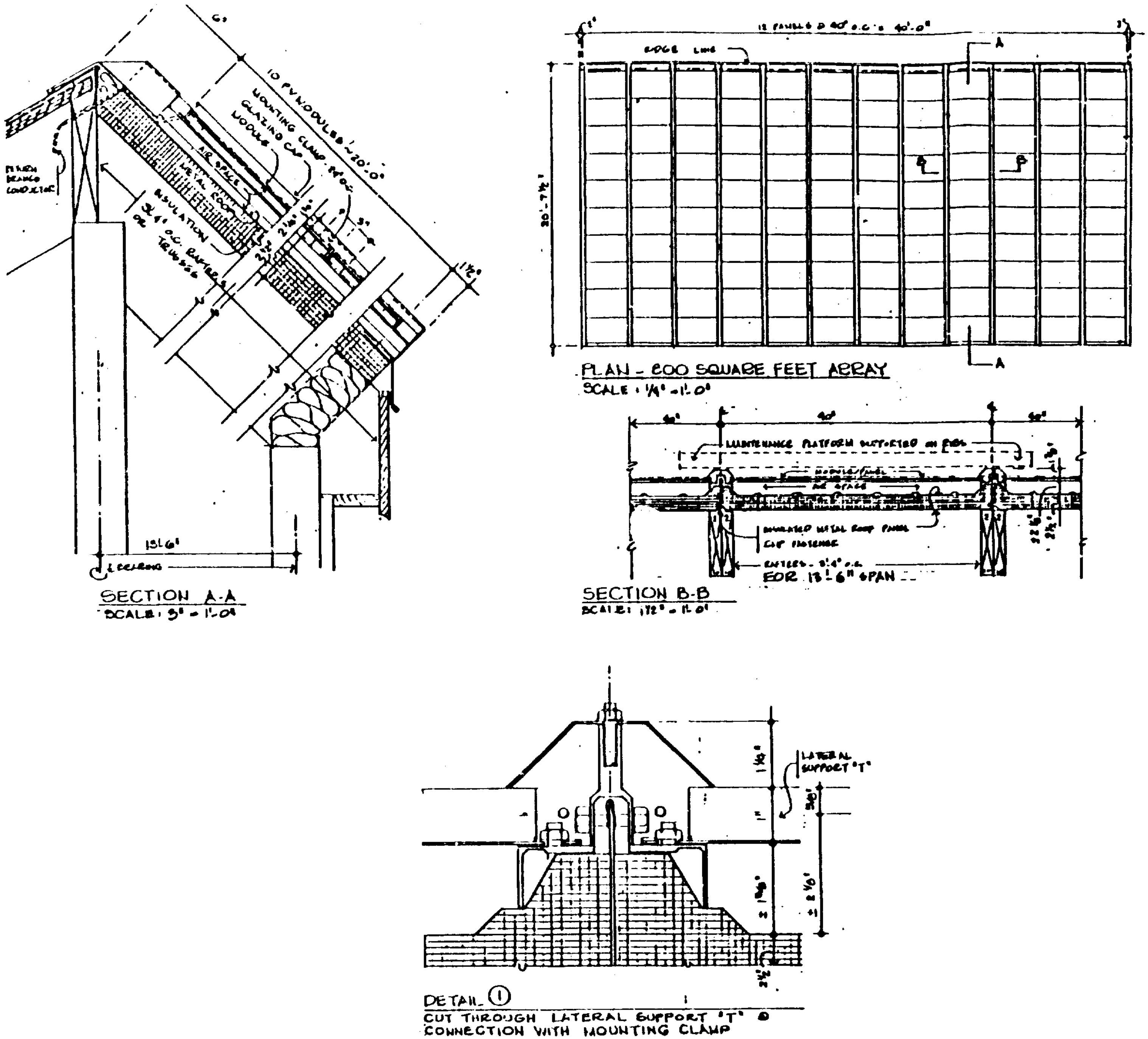
BRANCH TO BUS BAR WIRING

N.T.S.



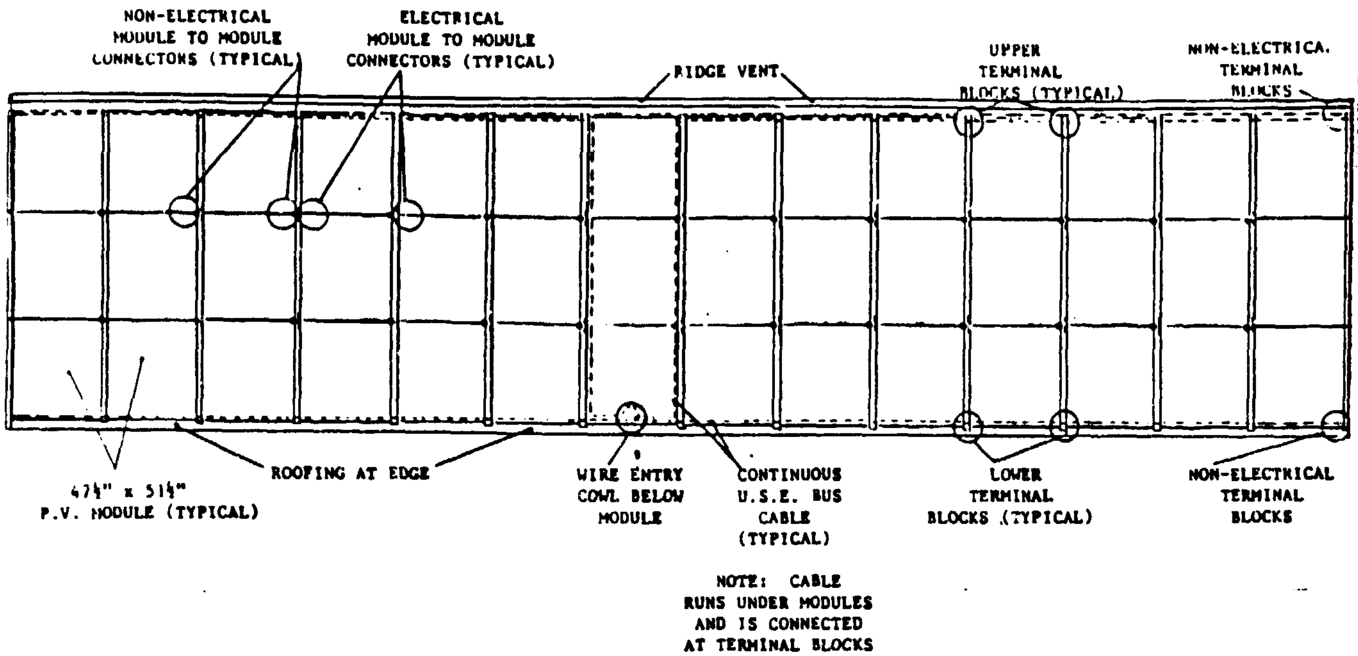
DETAIL 1

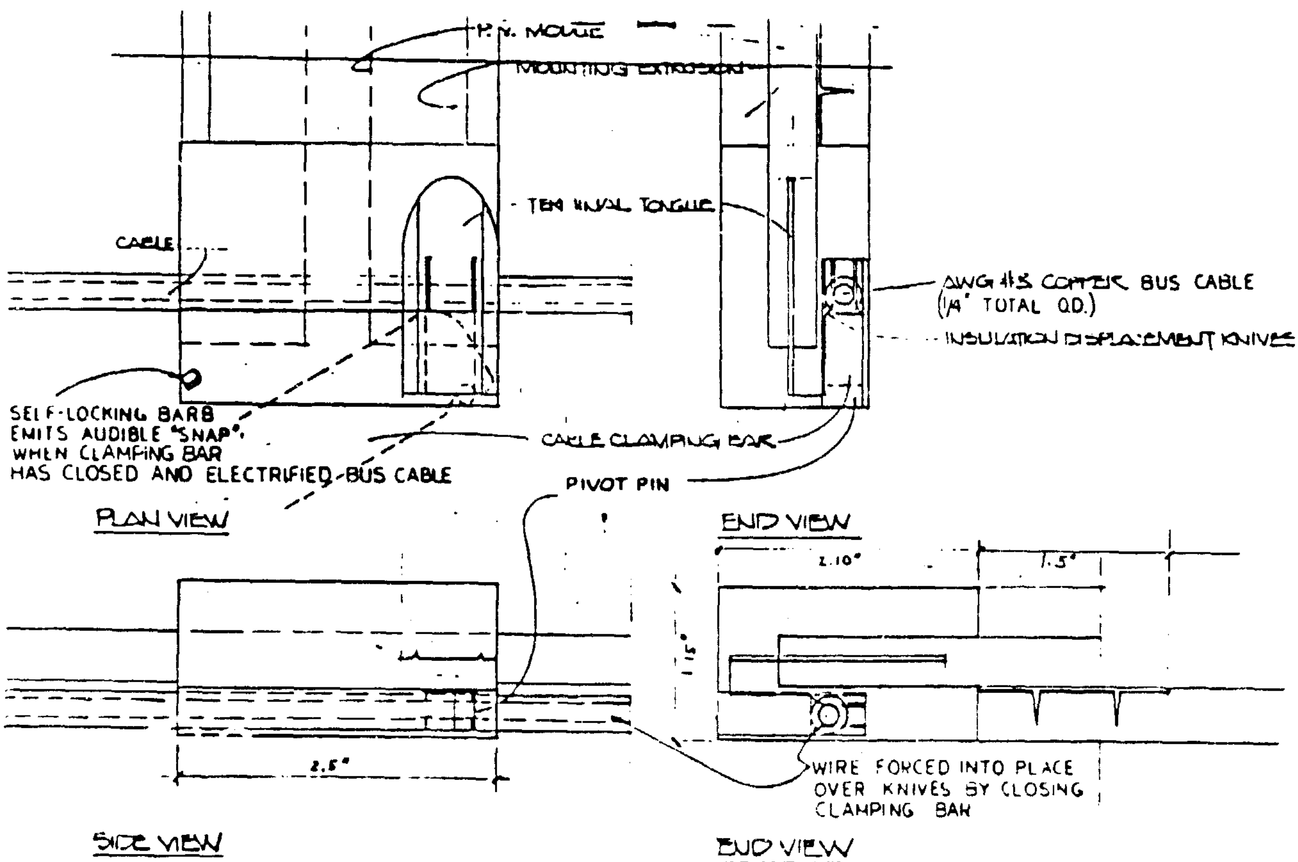
FULL SCALE

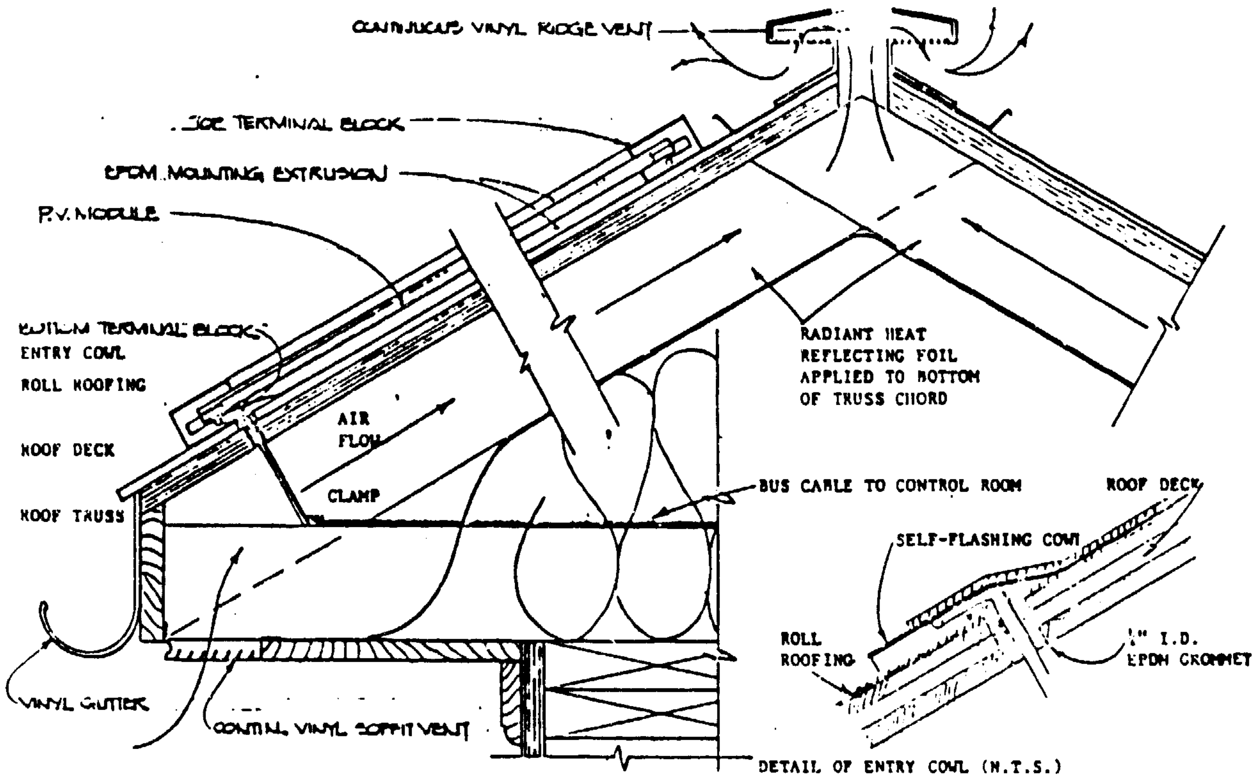


DESIGN CONCEPT 11 MECHANICAL - FIGURE 3-22

DESIGN CONCEPT 12 ELECTRICAL - FIGURE 3-23







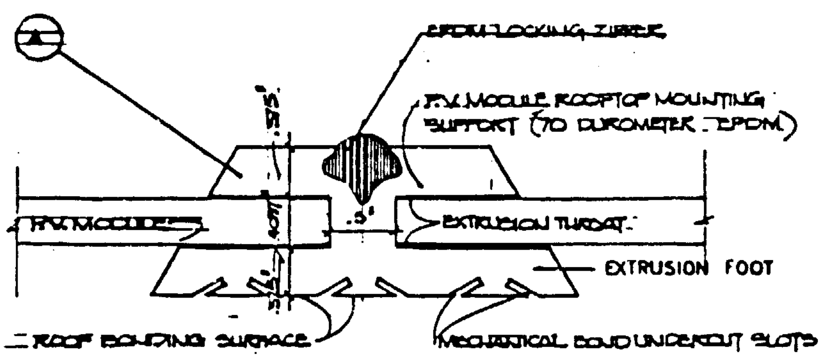


FIG A-1 - CENTER EXTRUSION

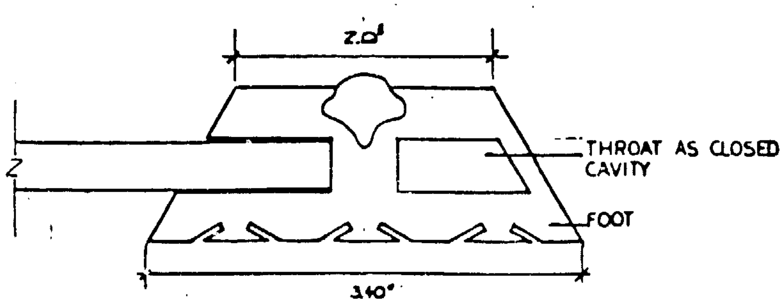


FIG-A-1a - ARRAY END EXTRUSION

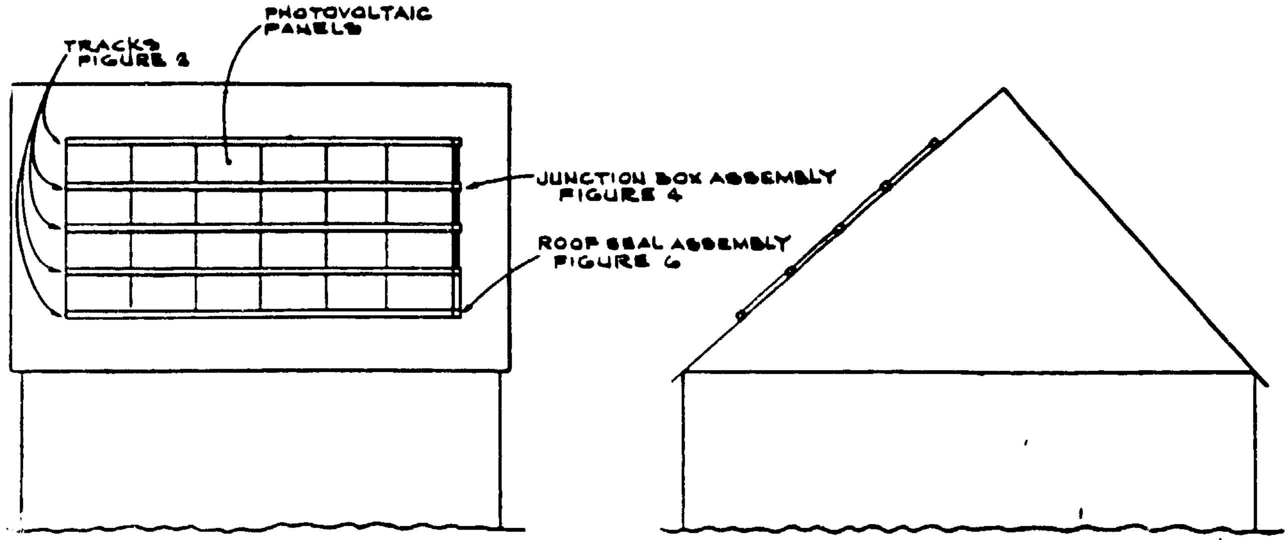
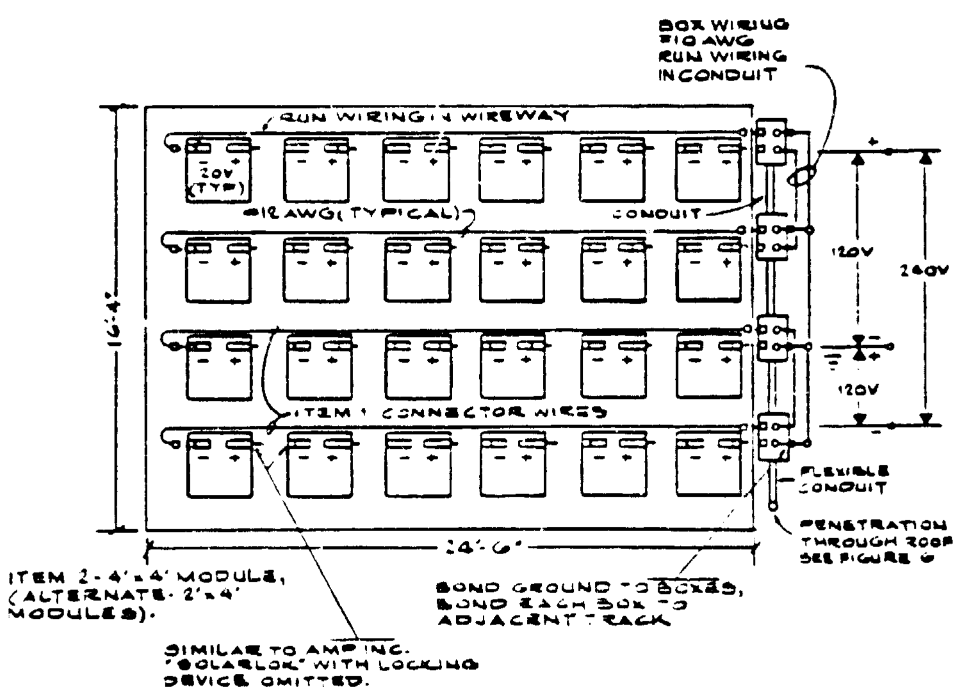


FIGURE 1
ARRAY ASSEMBLY



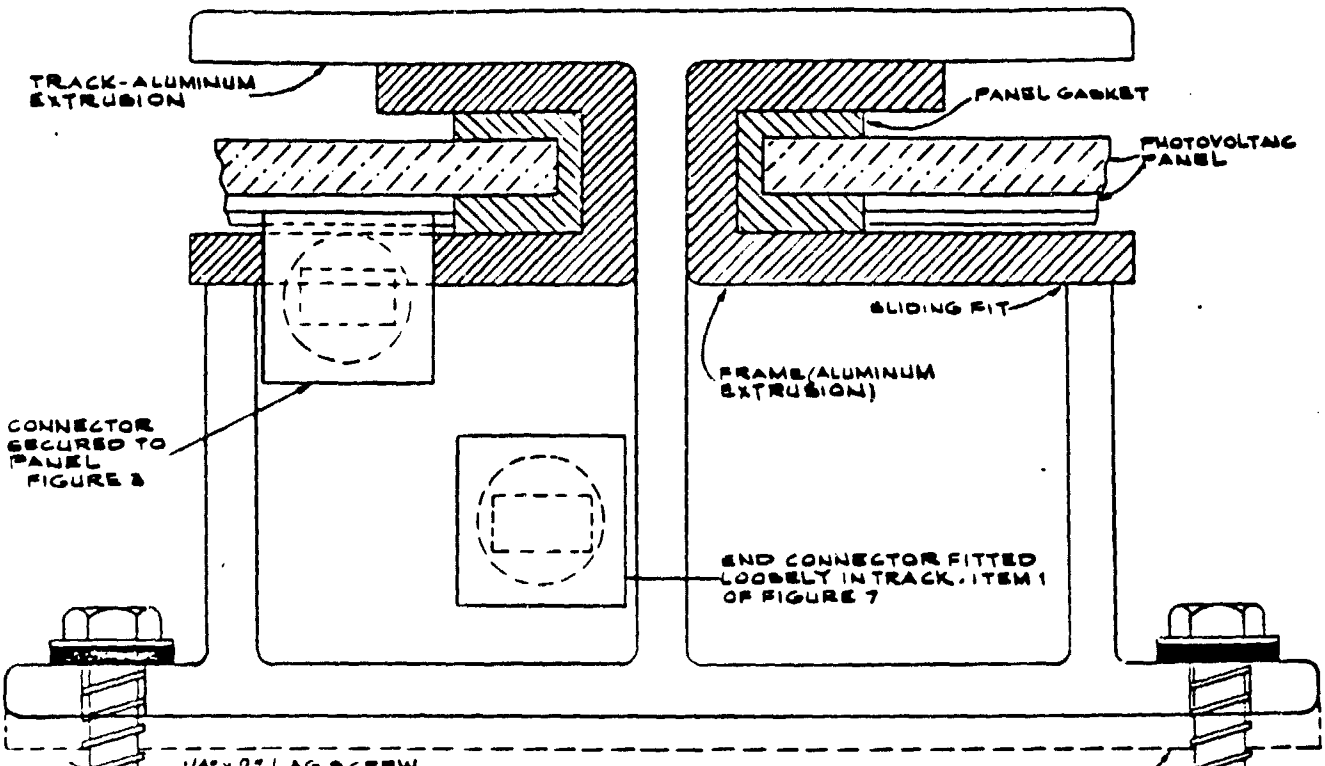


FIGURE 2

TRACK CROSS SECTION

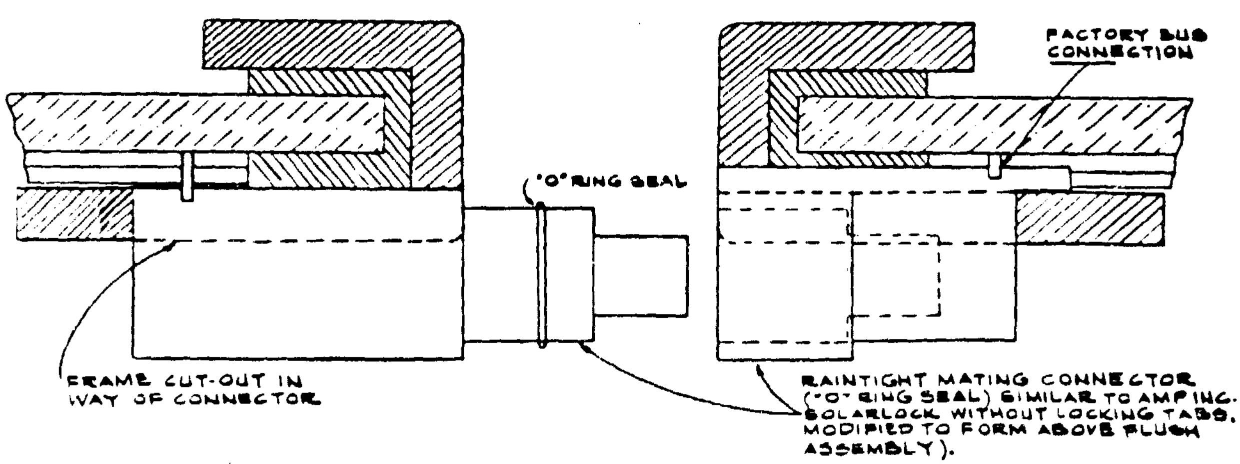
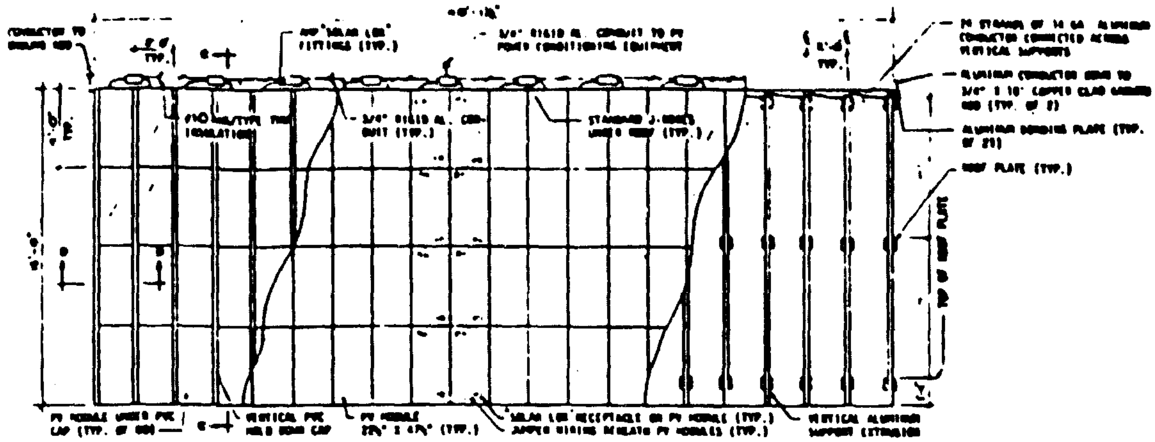
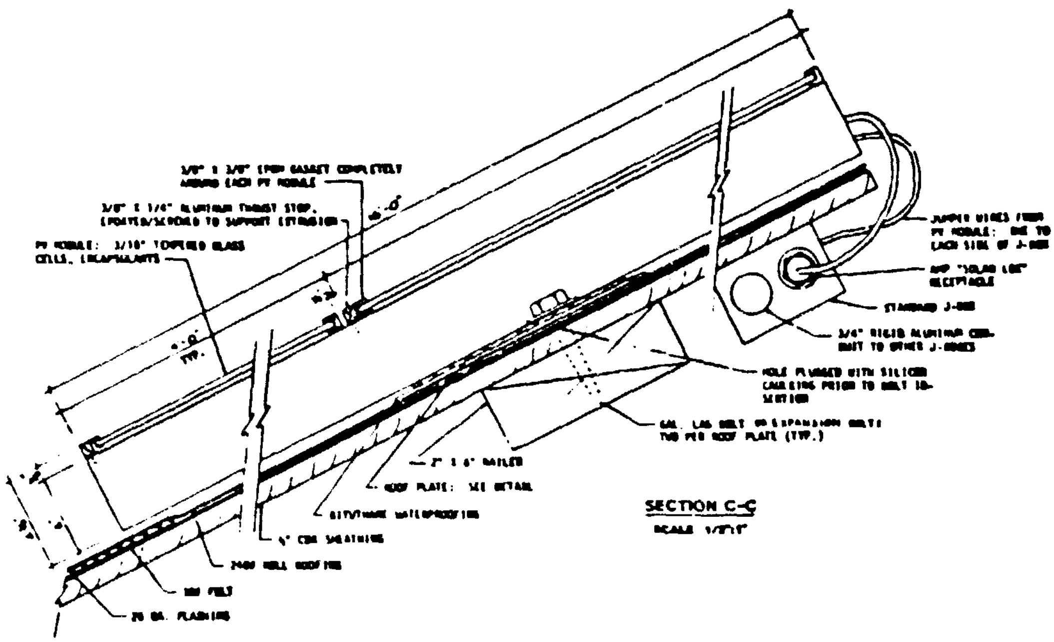


FIGURE 3

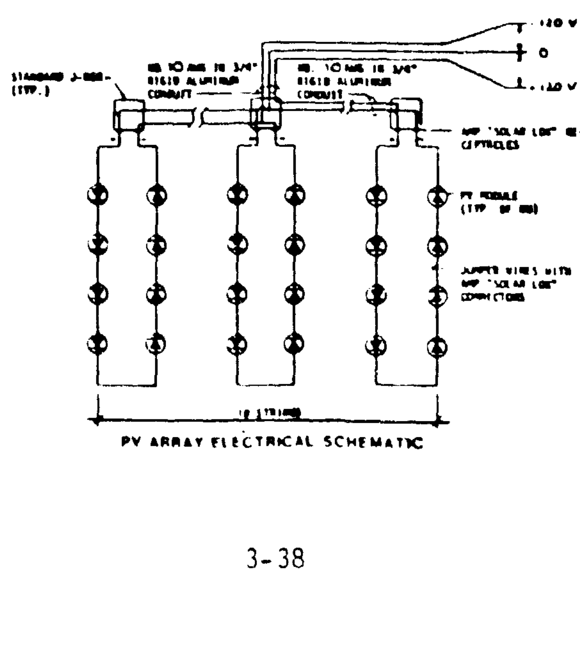
FRAME CONNECTOR ASSEMBLY



PV ARRAY ROOF PLAN

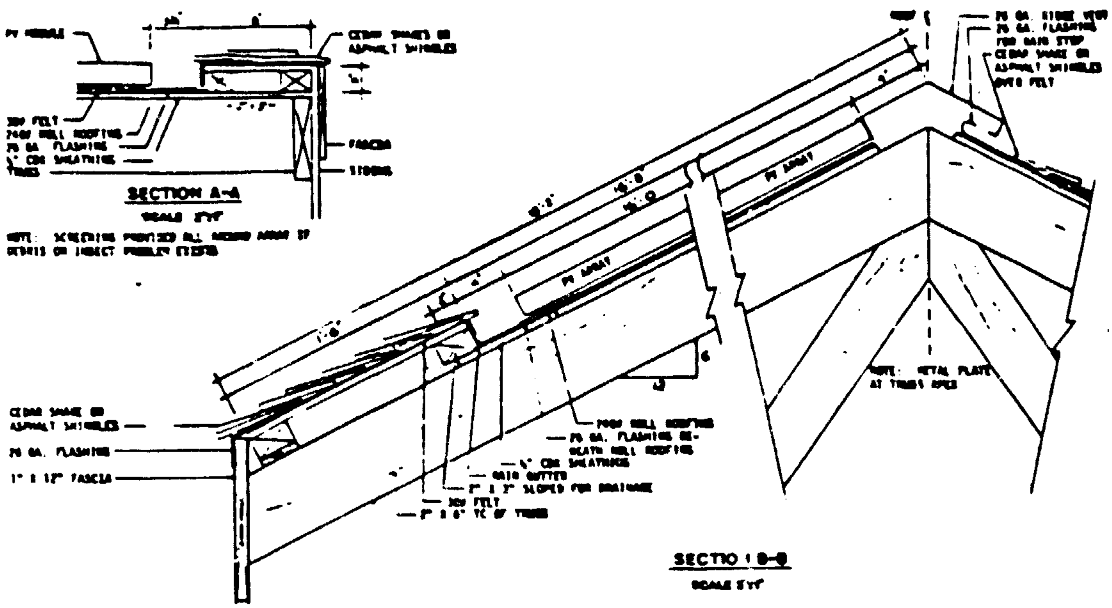


SECTION C-C



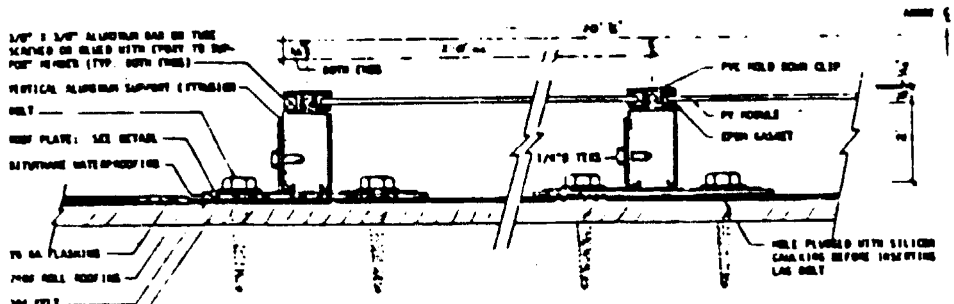
PV ARRAY ELECTRICAL SCHEMATIC

DESIGN CONCEPT 14 MECHANICAL - FIGURE 3-28

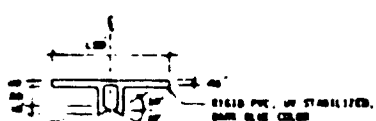


SECTION A-A

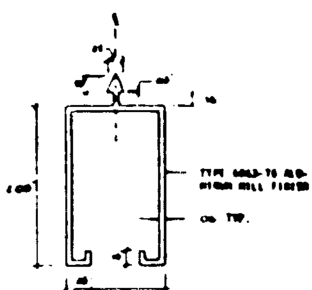
SECTION B-B



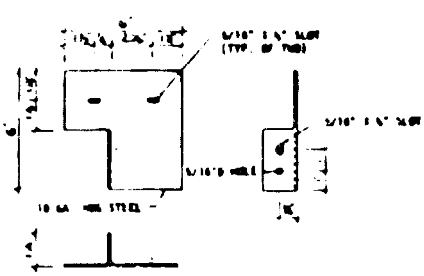
SECTION D-D



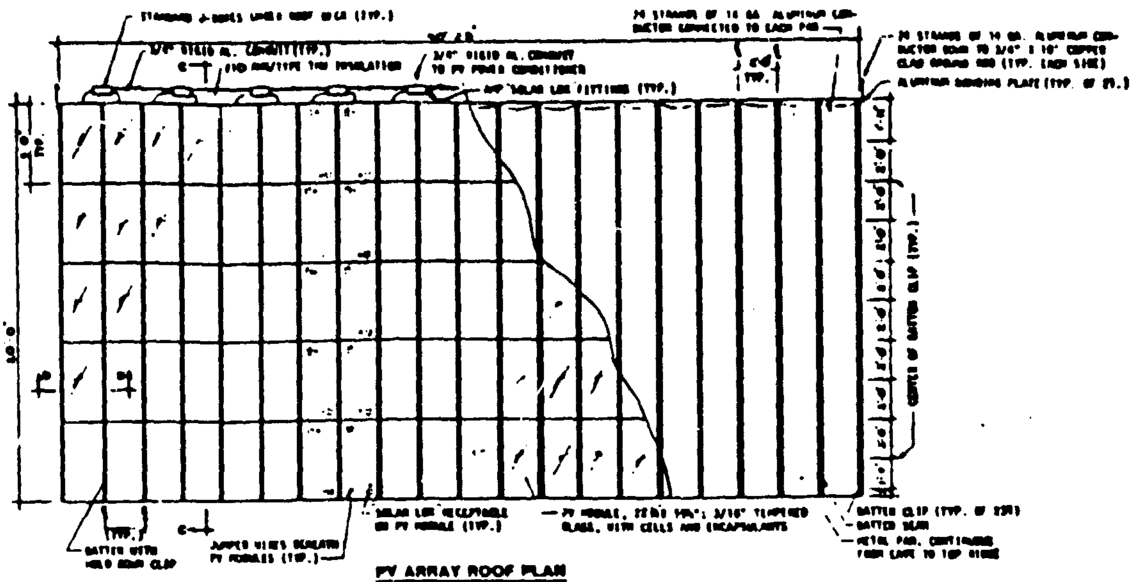
PVC HOLD DOWN CLIP
(RIGID, UV STABILIZED)
FULL SCALE



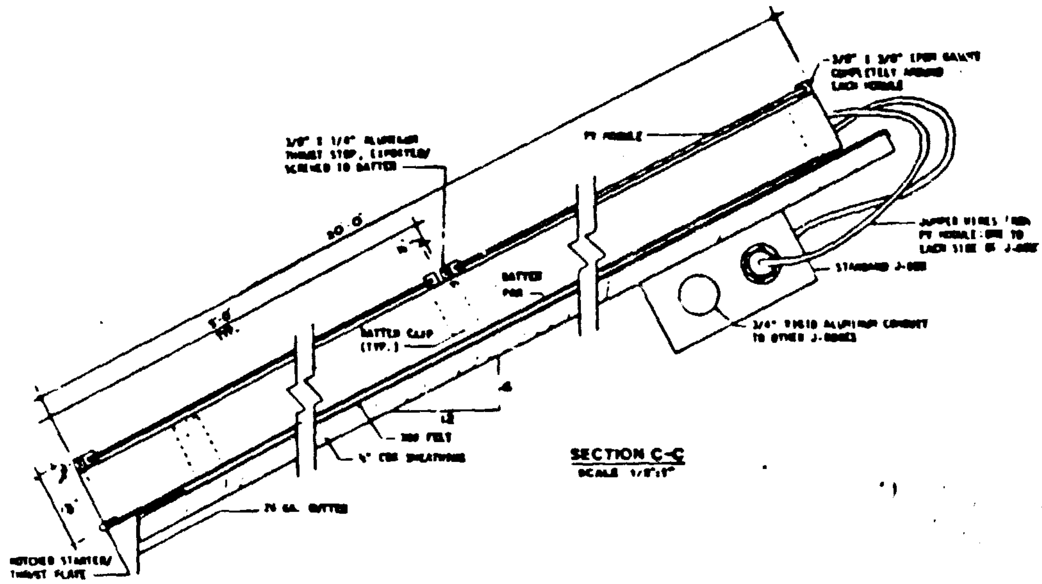
VERTICAL ALUMINUM SUPPORT EXTRUSION
FULL SCALE



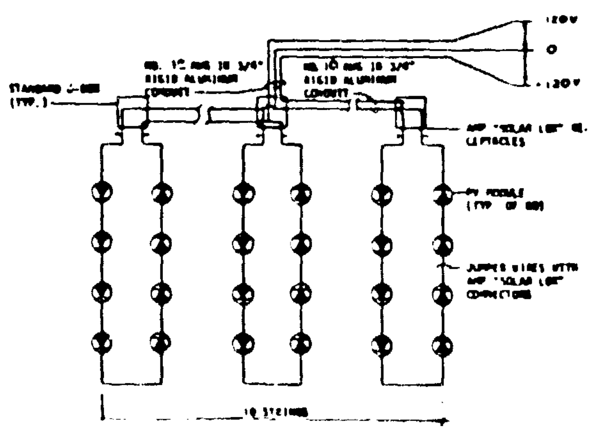
ROOF ATTACHMENT PLATE



PV ARRAY ROOF PLAN

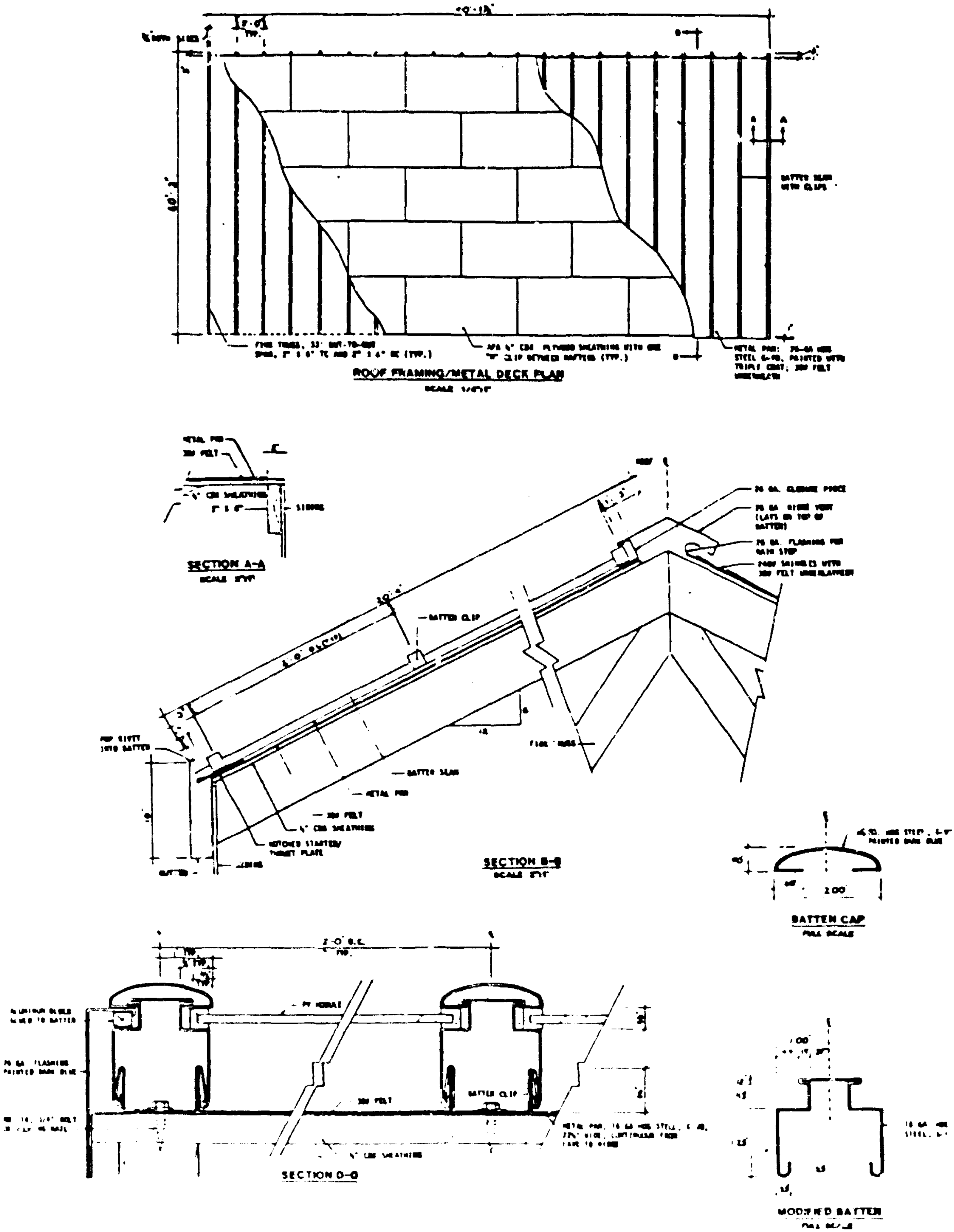


SECTION C-C

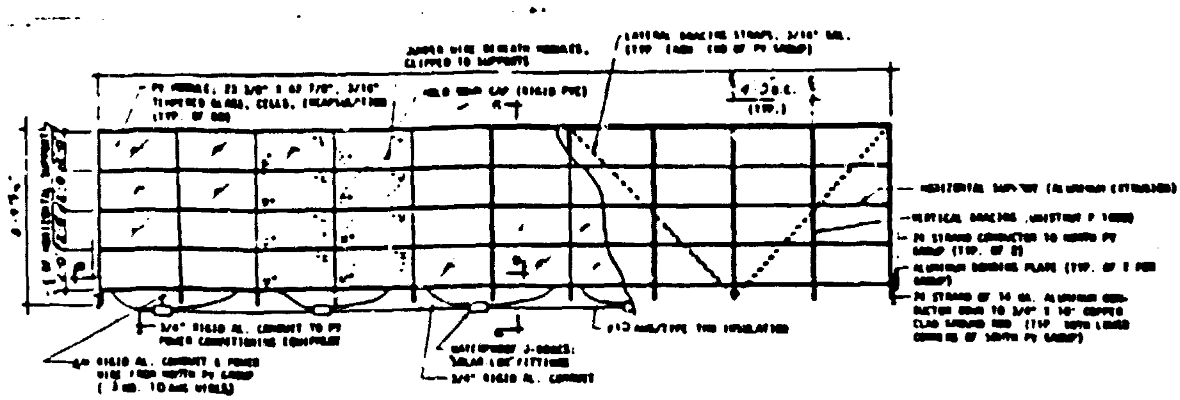


PV ARRAY ELECTRICAL SCHEMATIC

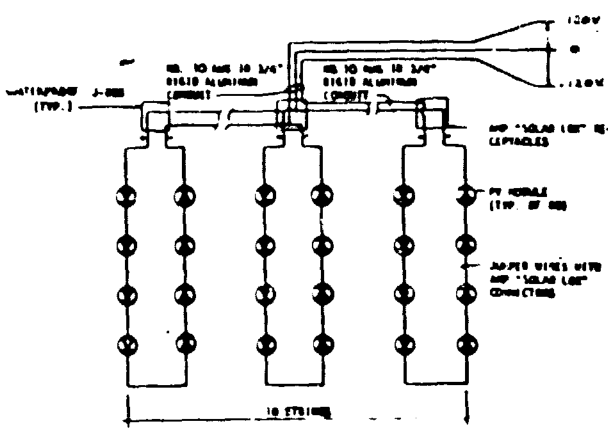
NO SCALE


ROOF FRAMING/METAL DECK PLAN
SECTION A-A
SECTION B-B
BATTEN CLIP
BATTEN CAP
2'-0" O.C.
SECTION D-D
MODIFIED BATTEN

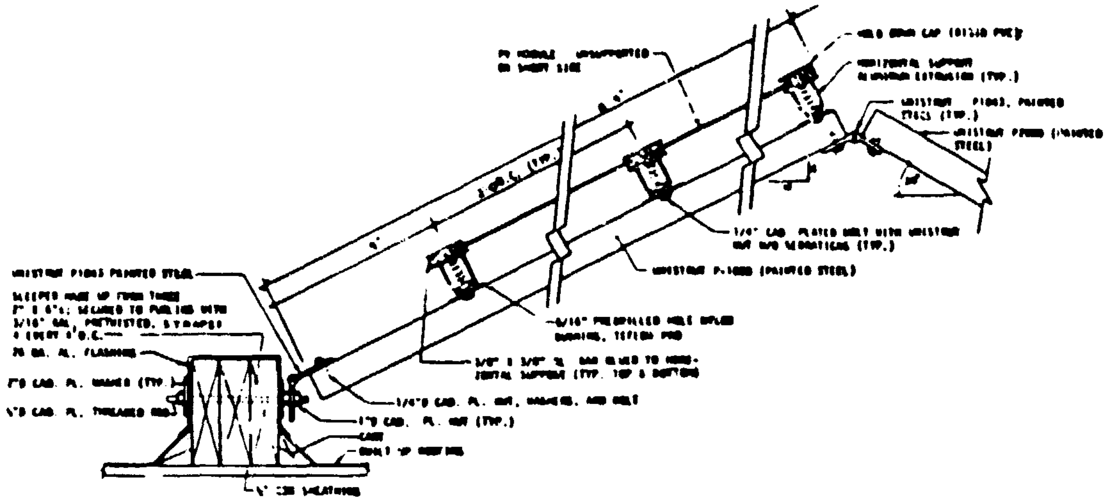
DESIGN CONCEPT 16 ELECTRICAL - FIGURE 3-31



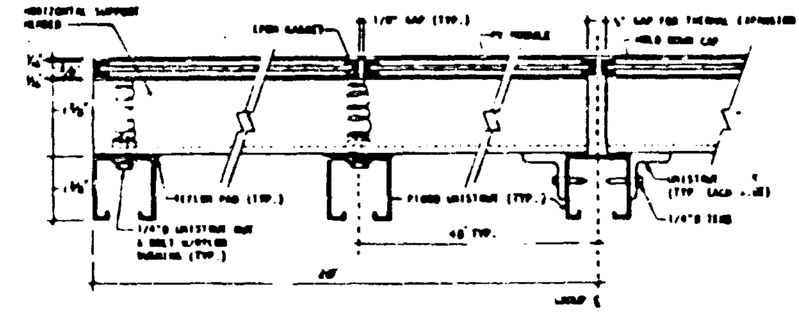
SOUTH GROUP PV ARRAY ROOF PLAN
(NORTH GROUP IDENTICAL)



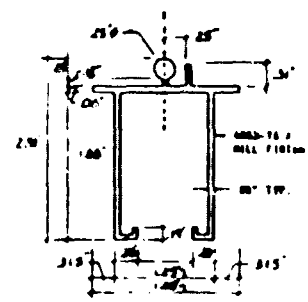
PV ARRAY ELECTRICAL SCHEMATIC
NO SCALE



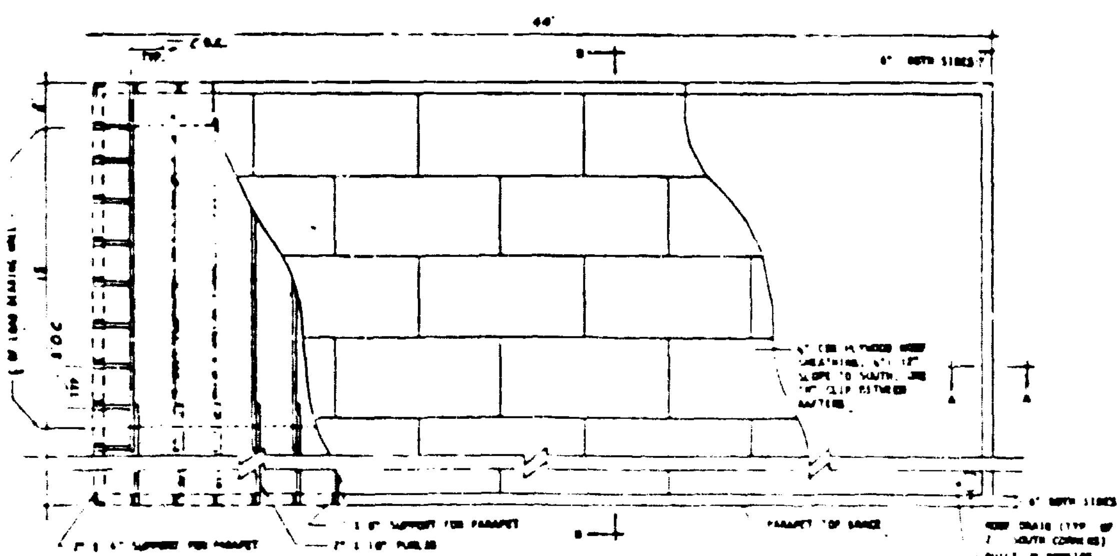
SECTION C-C



SECTION D-D



HORIZONTAL SUPPORT MEMBER



ROOF FRAMING PLAN

3.3 CONCEPT EVALUATION

Key evaluation objectives include: a) identification of major concerns that affect concepts using the criteria discussed in Section 3.1; and, b) identification of each concept's significance in the optimization of three generic concepts for least life cycle cost. Two stages of evaluations were conducted following each team's concept presentation. Major concerns for proof of concept were assessed by the advisory panel using the market penetration, fabrication, design and specification, installation, operation and maintenance criteria. Then statistical methods were employed to rank the significance of each concept for cost optimization.

Factors that affect development and evaluation of all design concepts are first discussed. Next factors that affect optimum use by mounting type are summarized, followed by an identification of major concerns for each concept. Factors that have broad applicability to design concept development have been grouped into several major categories. A discussion of key assumptions and evaluation observations in each category follows their listing below.

- circuit configuration and wiring
- alignment and attachment
- reliability and operation
- codes and standards qualification
- roof construction practices
- life cycle cost estimation

Circuit Configuration and Wiring

An important assumption used was that array voltage is developed to satisfy the voltage window of present day inverters to produce 240 Vac single phase output for residential loads. Key considerations include: minimization of busbar length; minimization of grounding needs; optimization of electrical potential location and proximity; minimization of field electrical connections and cabling; and optimization of circuit design to improve performance reliability.

If module grounding needs can be minimized, major cost benefits from reductions in the number of field connections can be realized using module voltages higher than 30 Vdc at -20^{o}C to reach present day inverter input voltage requirements. Generic circuit configurations either develop array voltage along the roof height with current along the roof length, or voltage along the roof length and current along its height. In the first configuration constant electrical potential along the eave can be maintained, as a safety precaution, while for the second wiring costs associated with busbar length can be minimized.

Alignment and Attachment

Major alignment concerns include minimization of individual module positioning, reduction of cumulative positioning error and reduction of rough-framing to finished-trim tolerance error. Panel/module attachment at the roof/array interface must be durable and constructionally stable. The interface must prevent water penetration, thermal expansion, and other environmental hazards from causing damage to either the array or the residence. Important criteria to evaluate the effectiveness of attachment was whether the array surface serves as a watertight membrane. Live loads, dead loads, snow and wind loads have been considered on a regional basis to ensure that damage to the array or residence will not result.

Reliability and Operation

A major assumption was that module replacement would occur once every four years, for a total of five replaced modules over the twenty-year service life of the array. Among the types of degradation expected: soiling was assumed to be minimized by natural washing processes, assisted by some homeowner upkeep; yellowing and insulation breakdown was assumed to be minimized by optimized module design. A fixed cell failure rate from cell cracking was assumed to have a nominal value of one per ten thousand per year. Fatigue and corrosion resulting in module wearout was expected to occur after 25 years.

Codes and Standards Qualification

While efforts are underway to incorporate photovoltaic systems in building codes, specific provisions for photovoltaic arrays are not yet included. Currently, arrays incorporated into or built onto roofs may be evaluated under existing codes using requirements for such diverse elements, depending on array mounting type, as roof coverings, roof structures, skylights, and veneers. It was assumed that successful integration of the array/roof interface will guide solutions to the inconsistencies of code inspection and approval.

Roof Construction Practices

Not only did evaluation of each concept consider ease of array installation preferably requiring minimal tools and expertise, it also considered minimal departure from standard building construction practices. A key issue of standard practice is dimensional modularity of rafter or trussed roof framing as well as that of sheathing and roofing materials. Minimal impact on framing will permit continued use of standard engineering design of chords and web members provided by truss fabricators in response to critical factors such as dead loads, concentrated loads, snow loads and truss spacing. Minimal impact on framing will permit continued use of 3/8 in Group I plywood without staggered joints or end blocking material using metal "H" clips to provide the required edge support at the midspan of each truss space. Minimal impact on roofing material will permit use of the standard 240 lb. (per 100 ft^2) asphalt shingle with a typical life expentancy of up to 25 years that employs self-sealing tabs to provide extra protection against wind.

Life Cycle Cost Estimation

The cost used throughout the program is the life cycle cost (LCC). Included in the LCC are the costs of installation and maintenance as well as the manufacturing cost of the hardware under assumed annual module production volumes of 50000 m^2, 100000 m^2 and 500000 m^2. The impact of array hardware choices can be expressed meaningfully only by using LCC methods to reflect application-oriented and hardware design oriented constraints. An early evaluation was conducted to identify the life cycle cost sensitivity of trade-offs between initial costs and replacement costs for an assumed replacement scenario. A result of this study was to focus on minimization of initial array cost for all of the design concepts considered.

Integral Mounting Concepts

Major concerns in use of integral mounted arrays include weather tightness, alignment and attachment to rough framed rafters and electrical connection beneath the roof.

Concept 1 uses a proven and available technology that compares favorably with other integral concepts. Small array size appears to limit potential relative cost reductions for such components as flashing and gasketing. Branch circuit wiring costs appear reduced at the expense of increased internal panel/module wiring costs. Modules may require non-standard environmental protection at job site prior to installation.

Concept 2 combines the technical benefits of prefabricated assembly with an aesthetically pleasing appearance. Non-standard roof framing and ability of panel frames to resist racking appear to be the major installation concerns. A high batten profile that may result in partial cell shadowing appears to be the major operation concern.

Concept 3 applies a glazing technology developed successfully for the commercial building industry to residential construction. A key concern is the grid's ability to resist pre-installation damage and subsequent lift forces after installation. Another concern is the amount of time needed for sealant curing.

Concept 4 allows flexibility of either integral, direct or standoff with minimal electrical wiring cost. One major concern is material continuity at the intersection of horizontal and vertical mullions. A further concern is the assurance of a watertight membrane under field conditions.

Concept 5 uses a proven and available technology appropriate for early market penetration in custom homes. Embrittlement of the butyl tape on wood members may require flashing for long term reliability. Module size may require further concern for handling, shipping, snow and wind loading at the glass thickness specified.

Direct Mounting Concepts

Major concerns in use of direct mounted arrays include weatherability of roof connections, cell operating temperature penalties, and field cabling requirements.

Concept 6 provides a good exploration of the potential benefits of coextruded thermoplastics and embedded metal. Key concerns include mechanical attachment, module alignment, moisture protection, and installation inspection. Electrical connection concerns include module movement, access to connectors and module polarity reversal.

Concept 7 applies a glazing technology developed successfully for the commercial building industry to residential construction. A key concern is the grid's ability to resist pre-installation damage and subsequent lift forces after installation. Another concern is the amount of time needed for sealant curing.

Concept 8 allows flexibility of either integral, direct or standoff mounting with minimal electrical wiring cost. One major concern is mechanical continuity at the intersection of horizontal and vertical mullions. Further concerns include assurance of a watertight membrane.

Standoff Mounting Concepts

Major concerns in use of standoff mounted arrays include protection of roof penetrations, minimization of additional material and prevention of debris and vermin collection beneath the array.

Concept 9 relies upon a module interconnector incorporated with alignment blocks. Mechanical concerns include the need for EPDM gaskets together with alignment blocks, capability of adhesive to hold array and close tolerances for fastening. Further concerns include the need for detailing to minimize collection of debris and vermin. Electrical concerns include handling requirements for small interconnects.

Concept 10 uses a proven and available technology that compares favorably with other integral concepts. Small array size appears to limit potential relative cost reductions for such components as flashing and gasketing. Branch circuit wiring costs appear reduced at the expense of increased internal panel/module wiring costs. Modules may require environmental protection at job site prior to installation.

Concept 11 applies a concept developed for commercial applications to residential applications that holds promise to minimize NOCT, and improve array efficiency. Mechanically, key concerns include: the need for further study to minimize collection of debris and vermin; the need to further consider thermal expansions; and the need to minimize special roof framing. Electrical concerns include significant grounding requirements and partial cell shading potential.

Concept 12 relies upon a unique module interconnect incorporated with alignment blocks attached to glazing gaskets. Concerns include attachment of the alignment blocks to the EPDM gaskets, the capability of the specified adhesive to withstand loading conditions and close tolerances and handling requirements for small interconnects. Further concerns include the need for detailing to minimize collection of debris and vermin.

Concept 13 focuses on the reduction of module installation alignment and attachment requirements. Effectiveness of module interconnection is sensitive to series string location that requires further study to improve interconnect standardization. Operation concerns include the need for improvement of ice and water drainage arrested by the horizontal rails. Removal of an entire row of modules for one module replacement appears acceptable only with high reliability assumptions.

Concept 14 provides a good representation of present technology capability and cost using readily available components. Key concerns include prevention of water leakage and the minimization of field assembled parts.

Concept 15 provides a good representation of present technology capability and cost using readily available components. Key concerns include the minimization of field assembled parts, and the dependence on present module construction and performance.

Rack Mounting Concepts

Major concerns in use of rack mounted arrays include additional load and subsequent structural requirements as well as applications limited by total cost and aesthetic considerations.

Concept 16 provides a good representation of present technology capability and cost using readily available components. Key concerns include minimization of structural dead load and resistance to wind uplift.

3.4 CONCEPT SELECTION

Three concepts were selected from sixteen candidates to represent several distinguishing characteristics. These characteristics include proof-of-concept status, innovative design focus, and mounting type.

Concepts were classified into three proof-of-concept stages. Several concepts that use off-the-shelf components appear currently ready for field use. Concepts that modify methods, components or materials from other construction sectors or industries may require structural and/or durability tests prior to field use. Concepts that are based upon new methods, components or materials may require further prototype development and testing prior to field use. It was assumed that concept test qualification would require one year. This would yield concept field applications in two years. Prototype concept development was limited to two years as one of the program groundrules. Concept field applications are expected two years after prototype development.

Concepts were classified into three areas of innovative design focus: module design; wiring; and installation. Innovative module design features include the use of large area (i.e. larger than $1m^2$) modules with square or rectangular cells for improved packing density and methods that allow the safe use of modules with open circuit voltages higher than 30 Vdc at -20°C. Innovative wiring features include the elimination of wiring harnesses, the use of pre-wired mounting hardware, and the safe minimization of wire size and insulation. Innovative installation factors include minimization of individual module/panel alignment, replacement of mechanical fastening with mastics, use of pre-cut glazing gaskets, minimization of construction trade constraints, and minimization of module rows to reduce the complexity of panel frames.

Concepts using the same mounting type were compared to evaluate the effects of design trade-offs peculiar to that mounting. While reductions in hardware/gasket costs contributed the most to lower total-net-installed costs, the effect of changes in wiring cost, roof support costs, and material replacement credits was not uniform. Examples of large material replacement credits did not result in lower costs per peak watt for integral systems. Additionally, nominal reductions in wiring cost did not yield significantly lower integral mounting costs. In either direct or standoff mounting, savings from roof credits and wiring costs did not significantly reduce total costs below levels achieved through savings in hardware/gasket installation.

The three design concepts selected are identified as concept numbers 1, 7, and 9.

Design Concept 1 represents that group of concepts fabricated with "off-the-shelf" components using a minimum of assembly steps. This concept relies on the transfer of skills between the commercial glazing industry and the homebuilding industry; the use of non-standard construction practices and tolerances appear minimized. Further design optimization may be required for array operation and maintenance, dependent upon module reliability assumptions. Loading, watertightness and attic temperature assumptions may require verification.

Design Concept 7 represents that group of concepts using modified techniques, components and materials. It minimizes individual module alignment and replaces mechanical fastening. While the rigidity and durability of the grid during installation is of concern, there appears to be sufficient rigidity during operation. In view of the concept's technology basis from the commercial building market, rigidity, module uplift and deflection may require empirical verification. Further design optimization may be required for array installation, dependent upon loading and mounting assumptions.

Design Concept 9 represents that group of concepts fabricated with new components. Handling connectors of this size is of concern though it appears that through optimization, standard construction practices and tolerances can be maintained. Further design optimization in prototype development may be required, dependent upon module size and reliability assumptions. Loading, watertightness, and component damage may require empirical verification in prototype tests.

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

Three integrated array design concepts were selected by the advisory panel for further optimization and development using a comprehensive set of technical, economic and institutional criteria. The concepts selected are the following:

1) An array of frameless panel/modules sealed in a "T" shaped zipperlocking neoprene gasket grid pressure fitted into an extruded aluminum channel grid fastened across the rafters using off-the-shelf components.

2) An array of frameless modules sealed by a silicone adhesive in a prefabricated grid of rigid tape and sheet metal attached to the roof that minimizes individual module alignment.

3) An array of frameless modules pressure fitted in a series of zipperlocking EPDM rubber extrusions adhesively bonded to the roof. Series string voltage is developed using a set of integral tongue connectors and positioning blocks that eliminates wiring harnesses.

Further design optimization will be undertaken for these concepts to develop design trade-off data relative to module size, module reliability, structural loading, watertightness and component damage.