

**WESTINGHOUSE FINAL REPORT: DESIGN AND FABRICATION
OF A PROTOTYPE SYSTEM FOR PHOTOVOLTAIC RESIDENCES
IN THE SOUTHWEST**

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**P.F. Pittman
R.T. Dressler**

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ABSTRACT

A single-family residence including a solar photovoltaic (PV) power system was designed for the Southwest. The residence utilizes passive solar and energy-conservation techniques to minimize the annual electrical load. A Prototype of the electrical system was constructed at the Southwest Residential Experiment Station in Las Cruces, New Mexico, and maintained for one year. The array is integrally mounted using a new panel installation concept and produces 5.7-kilowatts peak at standard test conditions (100 milliwatts per square centimeter, 28-degrees Celsius, with an air mass of 1.5.) The system is interactive with the utility and uses a voltage-fed, self-commutated power conditioner. The system operates automatically, turning on and off as the sun rises and sets.

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OVERVIEW

In 1975, the U. S. Energy Research and Development Administration (ERDA) funded several conceptual design studies to investigate both the technology and economics of solar photovoltaic (PV) electric power systems. Included in these studies, in which Westinghouse was one of three participants, were systems ranging from those small enough to power a single-family residence to large, central station power plants in the hundreds of megawatts. One of the conclusions of these studies, completed in 1977, was that residential solar photovoltaic (PV) power systems could be built from a technology standpoint and that they showed promise economically in future years if solar cell module prices could be reduced significantly.

Based on these preliminary results, additional studies were performed by ERDA's successor, the U. S. Department of Energy (DOE). The follow-up studies delved into regional variations in residential systems and went into much greater detail than those performed earlier.

In 1978, the Solar Photovoltaic Energy Research, Development, and Demonstration Act (Public Law 95-590) was passed on the basis of the positive results of these and other studies. It outlined a ten-year program to reduce PV system costs to levels competitive with traditional energy sources. One of the four major application sectors defined by the act as requiring an implementation plan was the residential sector. The prepared plan defined the need for a DOE Solar Photovoltaic Residential Project, which resulted in the creation of the Southwest Residential Experiment Station, where Prototype systems were constructed and operated to obtain system operating experience. The work described in this report was part of this DOE project and was done by the Westinghouse Advanced Energy Systems Division at Pittsburgh, PA, under New Mexico State University Subcontract Number 1-4-23550X2 directed by Dr. John F. Schaefer, program manager.

The Southwest Residential Experiment Station, operated by the New Mexico Solar Energy Institute, is located in Las Cruces, New Mexico. Included there are eight contractor-constructed Prototypes of roughly the same size, each one differing from the others in some respect.

Included also at the Southwest Residential Experiment Station is an extensive data gathering and logging system that collects data regarding the performance of all of the Prototypes and monitors energy usage in several nearby lived-in residences. The monitored house data are used to control on-site load simulators in the Prototypes.

Although this program included the design of both a full-size residence and a Prototype, only the Prototype was constructed. The project was organized with Westinghouse as the prime contractor and the architectural firm of Burt Hill Kosar Rittelmann Associates (BHKR) as a team member. The responsibility for the design and construction of the Prototype structure was assumed by BHKR. Construction was accomplished by BHKR through an agreement with the Burns Peters Group, an architectural firm, and the Luther Construction Company, a construction firm, both located in Albuquerque. Westinghouse designed the PV system, assisted with integration into the structure, furnished the system components, and was responsible for system performance.

The experience obtained from the construction of the Prototype was invaluable and is widely applicable to the design and construction of other solar PV systems of comparable size. The operating experience obtained from the year of operation was also invaluable because it showed in a very practical way which parts of the system would be most troublesome. In many cases, problems identified and solved during the operating period would never have been identified if an operating prototype had not been constructed. The results and conclusions obtained from the operating experience are also widely applicable to other systems of comparable size.

The principal purpose of the current work was to make possible the next step after the conclusion of five years of studies--to build actual operating

hardware. This purpose was fully accomplished and the results of this work are of significant value in regard to the design and construction of future solar PV power systems.

1.0 RESIDENCE DESIGN

1.1 INTRODUCTION

The Westinghouse Residential Photovoltaic Prototype Power System Project was divided into two parts. Initially, a full-size residence was designed with approximately 204.5 m² (2,200 ft²) of living space. The design included the use of energy-conservation techniques, and, where applicable, passive solar design features to minimize the annual energy requirements of the residence were also used. Included as an integral part of the design was a solar photovoltaic (PV) electric power system. The PV system was composed of a solar array, which serves as the watertight skin of the south-facing roof, and a power conditioner interfacing with the utility and on-site loads. The area of the solar array was chosen to be large enough for the system to produce at least 50 percent of the annual energy requirement of the residence.

1.2 ARCHITECTURAL DESIGN

In order to successfully design a PV residence, it is important to understand that the PV power system is in reality only a subsystem of the overall building system. A number of key elements must be optimized in each application to yield a successful design:

1. Energy-conserving building design
2. Building mechanical system design
3. PV power system design
4. Efficient load design
5. Location
6. Utility energy costs and rate structures

To successfully achieve the most cost-effective PV power system for building applications, proper consideration must be given to the integration of all of these key elements. In the residence design for the Southwest, these key items

were considered. In addition, the understanding of the introduction of a new product or process into the residential market place was considered. The result, as illustrated in Figure 1.1, is a residence that is somewhat grandiose in appearance and cost, intended to appeal to those individuals interested in higher priced homes. The primary reason for this approach is based on the premise that the early residential market will be in either the remote or high-priced homes. For this reason it was felt the design should address the early application. Although the 204.5 m² (2,200-ft²) home is large and open, many energy-conserving features have been incorporated. Several features such as berming and shading are illustrated in the elevations shown in Figures 1.2 and 1.3.

Because the Southwest is prone to large diurnal swings in temperature, this area is conducive to the use of passive technologies. By utilizing direct gain spaces during the winter months, heating requirements can be reduced. This, coupled with an appropriate amount of mass, lends itself to a significant reduction of the overall heating load. In addition to the heating benefit of

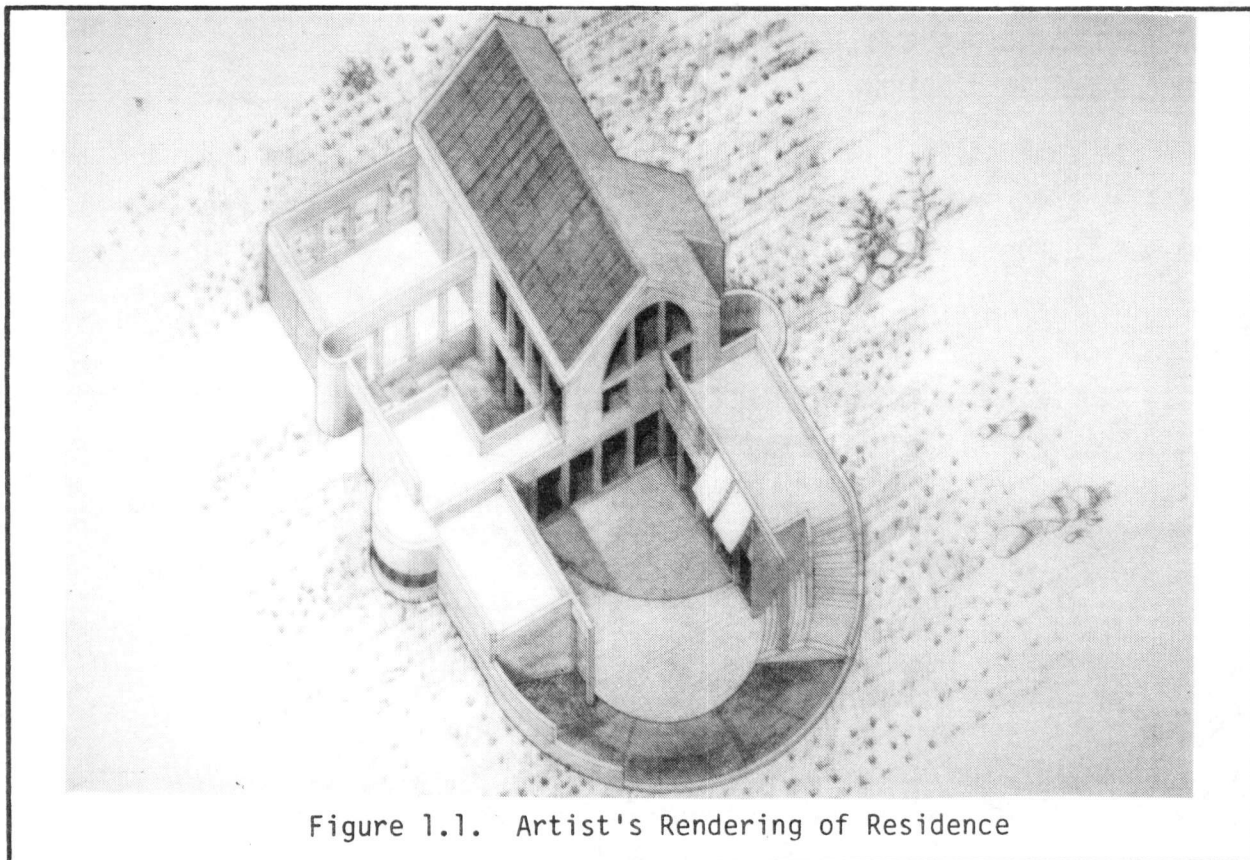
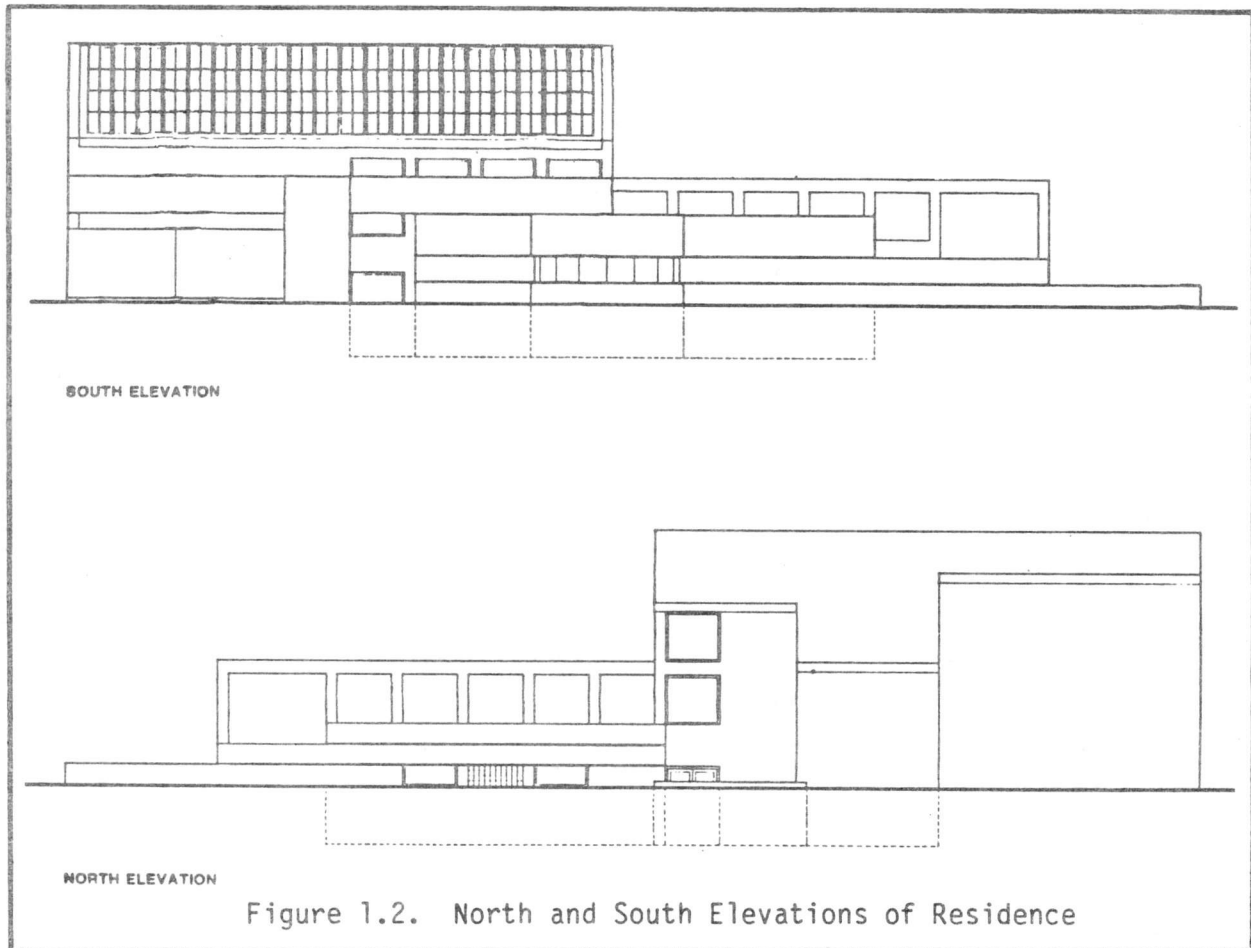


Figure 1.1. Artist's Rendering of Residence



direct gain spaces, daylight benefits can be realized, reducing the artificial lighting requirements for the residence. Because a potential for space overheating exists during the spring, fall, and summer months, it is anticipated that a number of shading devices will be used to shade all of the south- and east-facing glazing. By providing shading devices and by utilizing operable windows, it will be possible to maintain comfortable temperature within the residence without utilizing mechanical cooling systems for large parts of the year.

Because cooling can be a significant part of the load for a residence in the Southwest during the summer months, passive cooling techniques have been utilized. It is intended that evaporative cooling from the courtyard pool in front of the large areas of glazing will assist in cooling of the residence. In addition, with the large area of operable glazing available, significant

amounts of air flushing are possible during those periods where cool nighttime ambient temperatures exist. In combination with the significant mass existing in this structure and the low humidity typical of the Las Cruces area, it is anticipated that only a minimum of mechanical cooling will be necessary to handle the extreme conditions of high temperature and high occupancy--in other words, when latent loads are high as a result of a large number of occupants or during extended periods of extremely high temperatures.

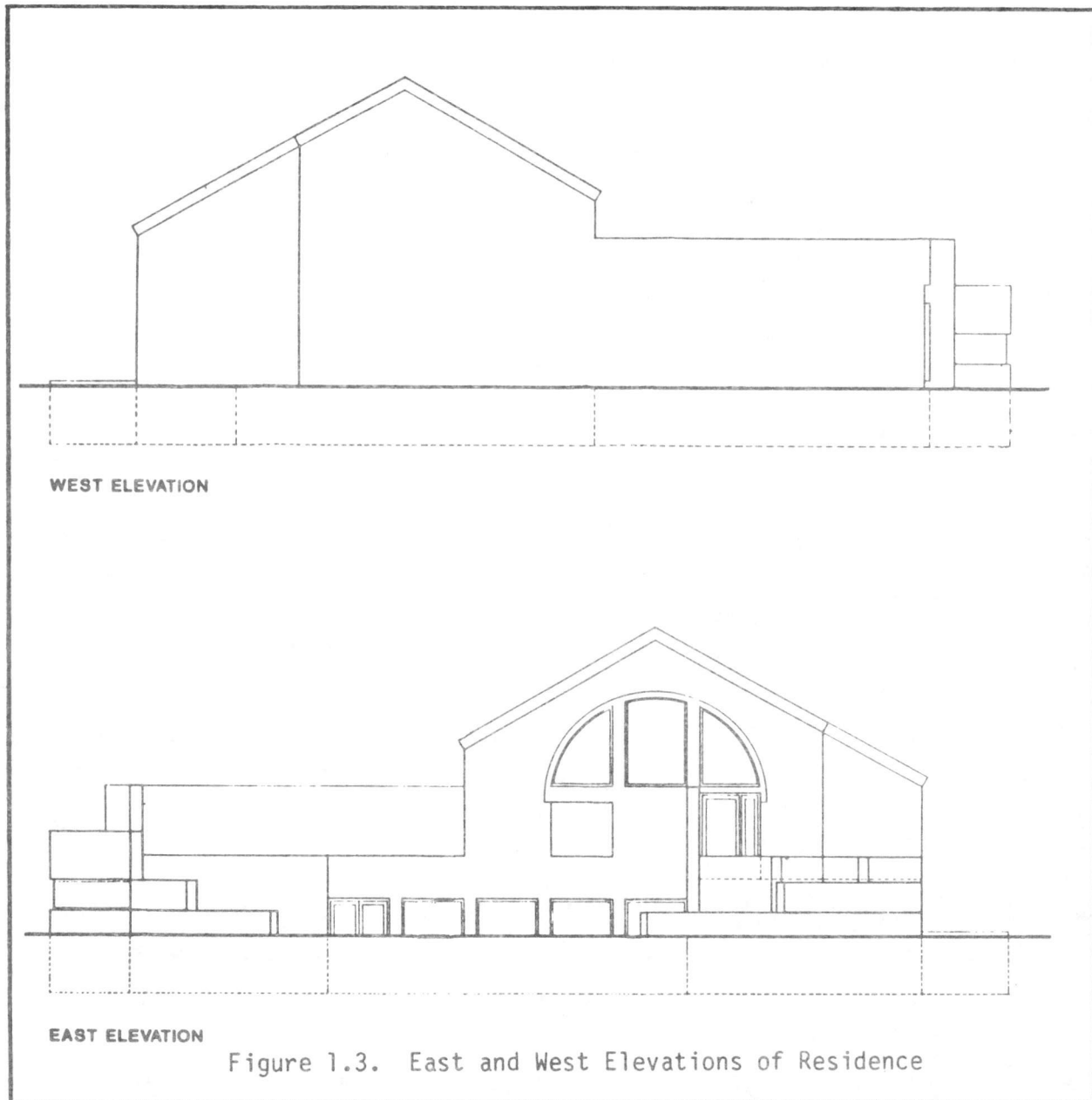


Figure 1.3. East and West Elevations of Residence

However, the heating and cooling loads used for the energy balance and the resulting calculations of percentage of energy supplied by the PV system (section 1.3.2) did not include the results of ventilation load reduction, and hence they are conservative.

In order to reduce heat gain and heat loss through the walls of this structure, the building is extensively insulated. The wall sections accommodate six inches of batt fiberglass with an R-value of 19. The roof section, which consists of cathedral ceilings, is insulated with four inches of Styrofoam tongue-and-groove insulation with an R-value of 22. This unconventional roof insulation system is necessary to provide an adequate air space for continuous venting behind the PV array. Cooling of the array is achieved through the use of a continuous ridge and soffit venting system coupled with this air space. It is important to note that a portion of the array is installed over a non-conditioned attic space that exists over the garage.

The design of the full-sized residence began with the PV array as an integral part of the concept. Careful placement of the bathrooms and kitchen, as seen in Figures 1.4 and 1.5, was necessary to avoid disturbing the array surface

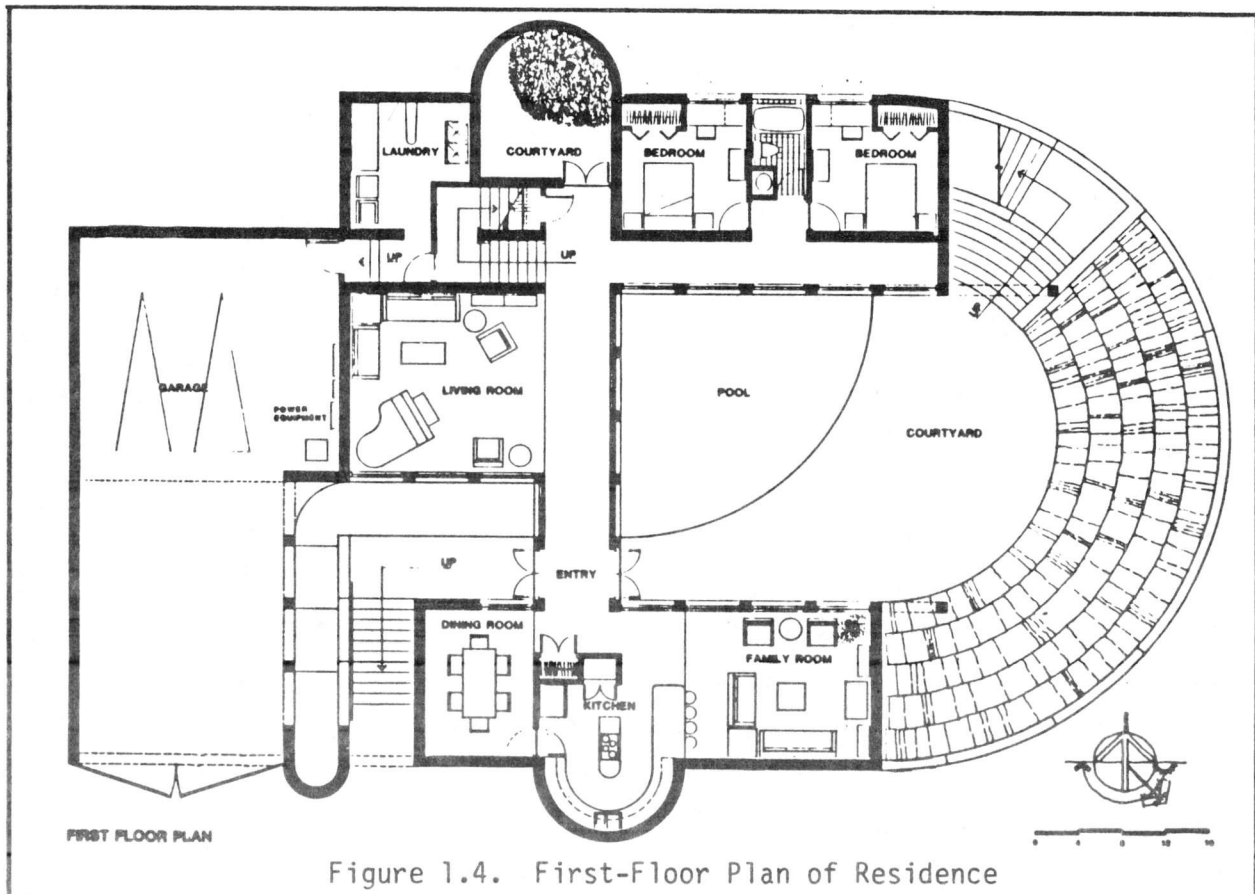


Figure 1.4. First-Floor Plan of Residence

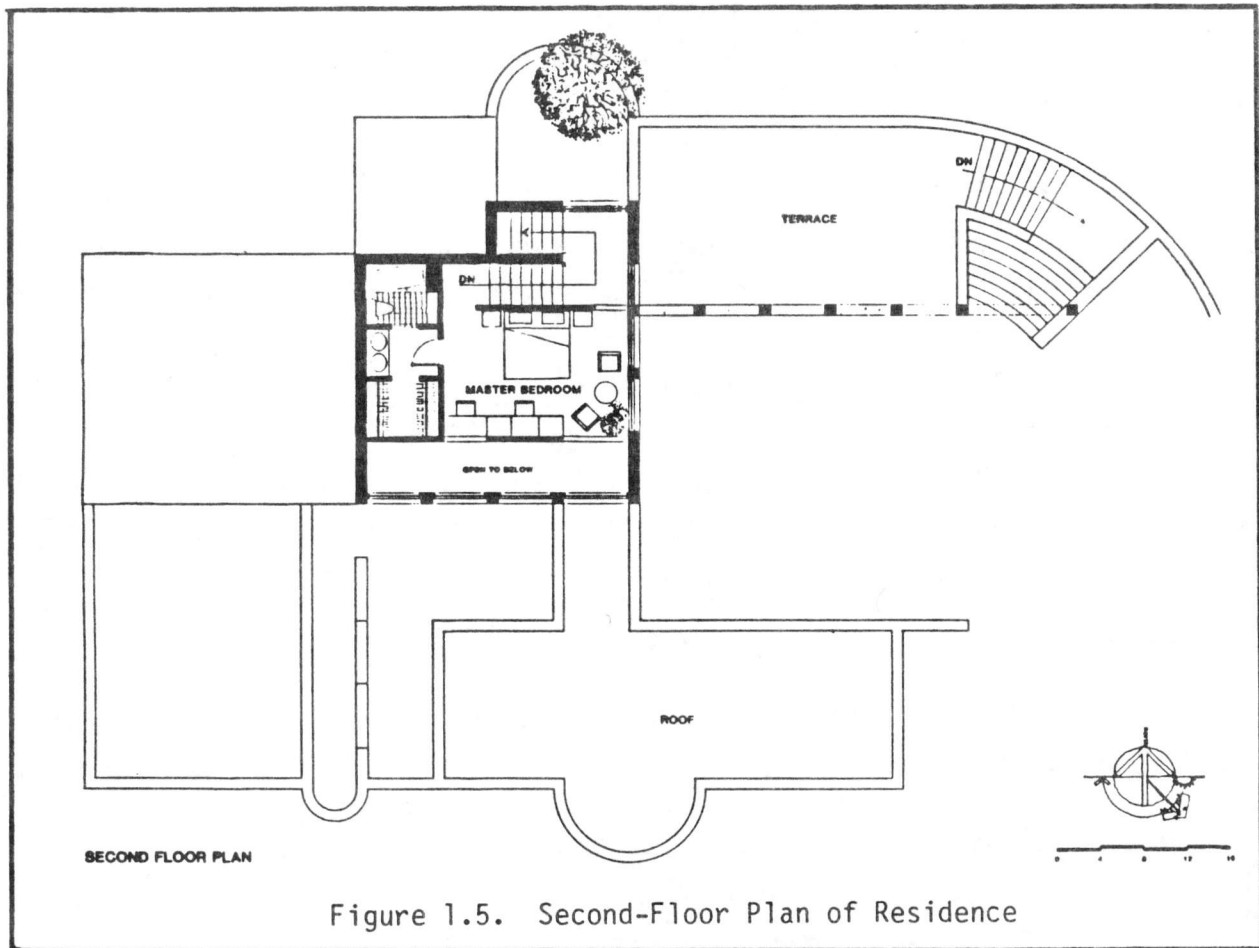


Figure 1.5. Second-Floor Plan of Residence

with plumbing vents, which must protrude through the roof. All of these penetrations can be accommodated through the north-facing slope or the portions of the residence surrounding the courtyard. The size and shape of the array were also considered to ensure the proper aspect ratio and aesthetic qualities associated with the PV array.

Internal to the residence, four distinct areas have been established. These areas are (1) the southern wing, which includes the primary family living area consisting of the dining room, kitchen, and family room; (2) the northern wing, which consists of two bedrooms and a bathroom; (3) the central core area which consists of the entry hall, living room, and second-story master bedroom and bath; and (4) a central courtyard area. By grouping these areas in this manner, it is possible to isolate spaces and activities for privacy and for zonal control of the HVAC system.

As the entire residence is set down into the site and the predominant visual path is to the courtyard/pool area, the direct visual link to the outdoors is to a finished, aesthetically pleasant landscape with the desert-like terrain of the Las Cruces area providing a panoramic backdrop to the home.

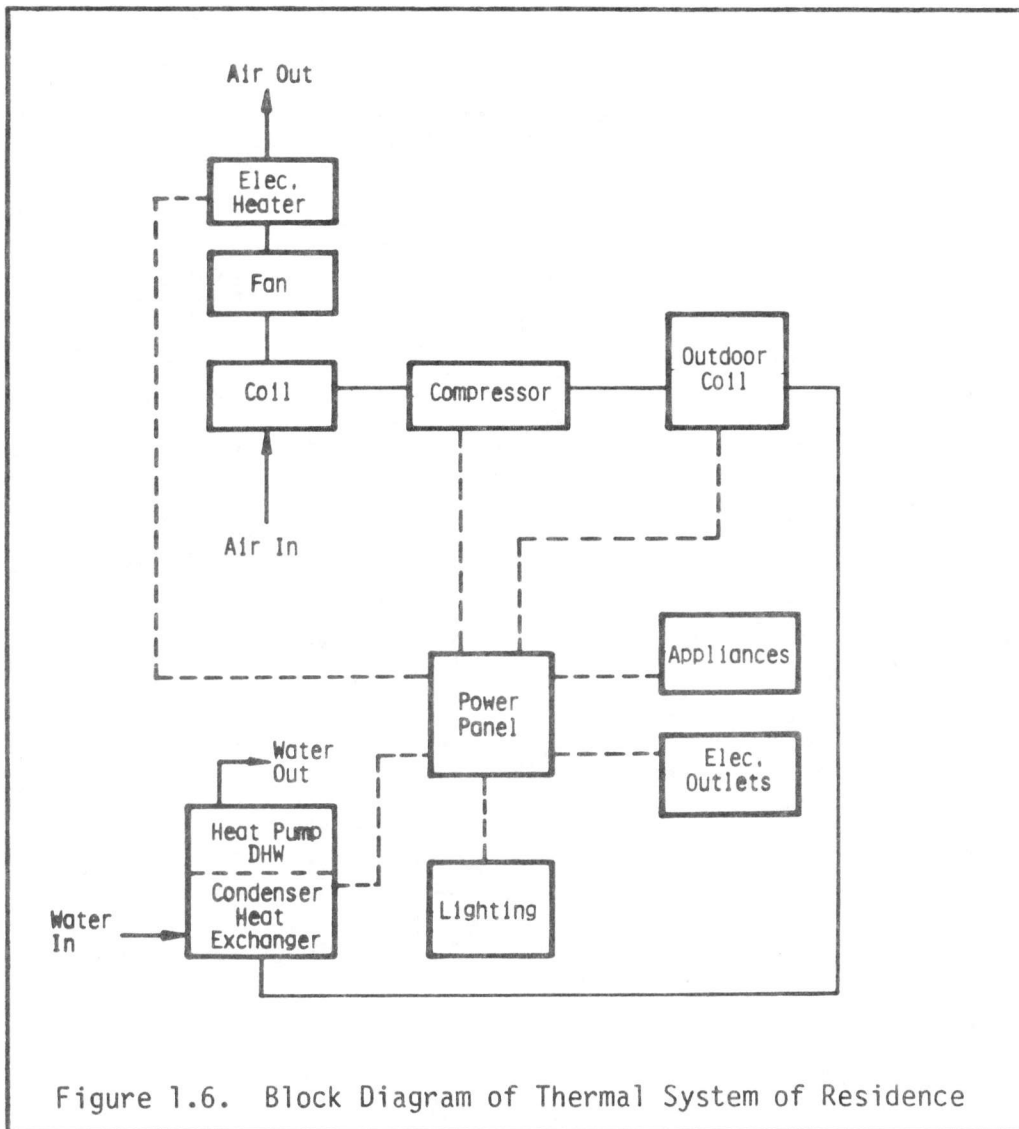
Table 1.1 describes the heating and cooling thermal energy delivered by the heat pump system as obtained from a TRNSYS analysis of the structure using weather data.

TABLE 1.1 HEATING AND COOLING LOADS OF RESIDENCE						
Month	Thermal Energy Supplied and Rejected					
	QR2		QAC		QVENT	
	kWh	MBTU	kWh	MBTU	kWh	MBTU
January	3,468	11,844	-0-	-0-	-376	-1,284
February	1,420	4,850	-0-	-0-	-740	-2,527
March	834	2,848	50	171	-2,392	-8,169
April	78	267	370	1,264	-2,248	-7,677
May	8	28	2,200	7,513	-2,326	7,944
June	-0-	-0-	4,446	15,183	-1,553	5,304
July	-0-	-0-	4,756	16,242	-1,602	5,471
August	-0-	-0-	3,648	12,458	-2,129	7,271
September	192	656	2,238	7,643	-1,890	6,455
October	228	779	697	2,380	-3,161	-10,795
November	1,147	3,917	-0-	-0-	-1,135	-3,876
December	<u>3,357</u>	<u>11,464</u>	<u>-0-</u>	<u>-0-</u>	<u>-150</u>	<u>-513</u>
Total	10,732	36,653	18,405	62,854	-19,702	-67,286

QR2 = Thermal energy supplied to the house for heating
 QAC = Thermal energy supplied to the house for cooling
 QVENT = Equivalent displacement of thermal energy due to the use of ambient air for ventilation purposes

A block diagram of the thermal systems that provide space heating and domestic hot water is shown in Figure 1.6. A conventional air-to-air heat pump satisfies the bulk of the heating load. The heated air is circulated throughout the house by a fan. During the brief periods when the heating load cannot be satisfied by the heat pump, a resistance heater is energized.

The domestic hot water is heated by a small dedicated heat pump, incorporated into the hot water system, and by reject heat from the air conditioner compressor. The hot water tank incorporates sufficient storage insulated well enough that the entire load can be served by the heat pump alone.



1.3 HOUSE ENERGY AUDIT

Included in the contract requirements is a constraint calling for the PV power system to provide at least 50 percent of the annual residential energy load. In addition to meeting this requirement for the large house designed in this project, a smaller 162.6 m² (1,750 ft²) residence conceptually designed for a previous study is also included, plus the output gains resulting from several anticipated improvements in cell and inverter performance using the same size array.

1.3.1 RESIDENTIAL LOADS

The loads are divided into five categories: (1) nominal 115-V electric, (2) nominal 230-V electric, (3) space heating, (4) space cooling, and (5) domestic hot water. The nominal electric load comprises those lights and appliances that normally operate at 115-V ac. Included are all residential lighting loads, all kitchen appliances, excluding the range and oven, and all other small appliances and loads supplied from the 115-V ac line. This load varies over the year primarily insofar as the number of daylight hours varies. The nominal electrical loads assumed are shown by month in Table 1.2.

The next category, the 230-V electrical load, includes the major appliances in the residence drawing sufficient power to require connection to the 230-V ac line. These generally include heating loads such as the oven, range, and electric clothes dryer. These loads are assumed to vary throughout the year and are larger near the December holidays. The 230-V loads assumed are shown by month in Table 1.2 also.

The third and fourth categories, the heating and cooling loads, are assumed to be supplied by a heat pump with resistive backup. The heating load was obtained from an hourly model providing simulation of the residential heating system requirements based upon the structure thermal design and use of an advanced heat pump. Hourly weather data obtained from TMY weather tapes for the El Paso area were used to perform annual simulations of the performance of the residence resulting in the annual electrical energy balance.

TABLE 1.2
RESIDENTIAL ELECTRICAL LOAD DURING THE YEAR

Time Period		115 Volt CASE 1		115/230 Volt CASE 2	
Month	Days	kWh/Day	kWh/Period	kWh/Day	kWh/Period
January	31	16	496	22	682
February	28	16	448	22	616
March	31	15	465	21	651
April	30	14	420	20	600
May	31	13	403	19	589
June	30	12	360	18	540
July	15	12	180	18	270
July	16(1)	6	96	12	192
August	31	12	372	18	558
September	30	13	390	19	570
October	31	14	434	20	620
November	30	15	450	21	630
December	14	16	224	22	308
December	17(2)	17	289	23	391
Year TOTAL	365	--	5,027	--	7,217

(1) Two-week vacation assumed with reduced consumption
(2) Heavier consumption assumed near holiday season

Another load category, the domestic hot water, is assumed to be satisfied by a dedicated heat pump and by reject heat from the air-conditioner compressor. The annual COP of the hot water heat pump is assumed to be approximately 2.0.

Shown in Table 1.3 are the loads for the standard residence designed for Las Cruces and a smaller residence designed for the Southwest region from an earlier study.* This residence has an area of 162.6 m² (1,750 ft²) of living space. The total annual load of 21,246 kWh for the Las Cruces

*"Regional Conceptual Design and Analysis Studies for Residential Photovoltaic Systems", March 1980 prepared for Sandia Laboratories under DOE Contract 07-6924 by Westinghouse Research and Development Center.

design is reduced to 14,740 kWh if the Southwest house design with an area of 162.6 m² (1,750 ft²) is used.

	<u>Las Cruces Design</u>	<u>1,750-Sq-Ft Design</u>
NOMINAL LOAD	7,217 kWh	7,217 kWh
HEAT PUMP LOAD:		
HEATING	3,392	1,330
COOLING	8,639	4,195
HOT WATER LOAD	<u>1,998</u>	<u>1,998</u>
TOTAL	21,246 kWh	14,740 kWh

1.3.2 PV SYSTEM OUTPUT

The annual PV system output was obtained from simulations of system operation using hourly weather data obtained from TMY weather tapes for the El Paso area. System output depends upon the type of performance assumed for each subsystem used. Different system output levels were obtained by varying the assumptions made regarding the array and power conditioning subsystems. These are shown in Table 1.4, where the resulting annual system output is shown correlated with the subsystem assumptions made. Also shown is the percentage of energy supplied by each system assumed.

The three subsystem performance parameters varied are Power Conditioning Unit (PCU) efficiency, cell packing factor, and nominal cell efficiency (at standard test conditions). Four combinations of these parameters are shown ranging from values applicable to presently available hardware, as used in the construction of the Prototype, to values applicable to the improved subsystems anticipated in the next several years. Corresponding annual system outputs vary from a low of 10,785 kWh using available hardware, to a high of 17,775 kWh using the most improved subsystems anticipated. In each case, the array area remained fixed

with the system output increase coming from improved cell efficiency and packing factor and improved power conditioner performance. The system simulation program used to obtain annual system output was the CSCL 3 program developed by Westinghouse on earlier DOE programs.

1.3.3 ENERGY PERFORMANCE EVALUATION

The requirement that the PV system provide at least 50 percent of the annual residential load is demonstrated in Table 1.4. The 50-percent requirement is met with the present technology array installed on a 58-m² area for the Las Cruces design. The system, when utilizing a PCU with higher efficiency and modules with higher cell packing factors, both of which will be available in a few years, and higher nominal cell efficiencies, can produce 17,775 kWh, or 84 percent of the residential load. For the more modest Southwest residence, the system will produce 73 percent of the energy required, and the anticipated upgrade will provide 120 percent.

TABLE 1.4 ESTIMATED SYSTEM OUTPUT (Annual Energy in Kilowatt-Hours)				
	System as Designed and Constructed	System with Higher Efficiency Inverter	System with Higher Efficiency Inverter and Higher Packing Factor	System with Higher Efficiency Inverter, Higher Packing Factor and Higher Cell Efficiency
● Power Conditioner Efficiency	86%	94%	94%	94%
● Cell Packing Factor	72	72	95	95
● Nominal Cell Efficiency	14	14	14	16
ANNUAL SYSTEM OUTPUT	10,785	11,790	15,550	17,775
ANNUAL REQUIREMENT SUPPLIED BY PV SYSTEM:				
Las Cruces Design	51%	56%	73%	84%
SW Design-162.6 m ² (1,750 ft ²)	73%	80%	105%	120%

The percentages of the residential load given here are algebraic results obtained by dividing annual PV production by annual residence load ($\times 100$). One should not construe from this that all of the PV-produced energy is used in the residence. The actual amount used is a function of the instantaneous relationship of power produced to power consumed, integrated over the year.

2.0 PROTOTYPE SYSTEM DESCRIPTION

2.1 STRUCTURAL DESIGN

In order to evaluate a residential PV system without installing it in a full-sized, lived-in residence, it was necessary to design a structure that closely resembled the installation of a full-sized residence. The design developed for the Prototype system emulates as closely as possible the full-sized residence. Particular attention was given to the mounting system and cooling of the 20 PV panels making up the array.

The roof section of the Prototype includes the same mounting details and interior conditions and utilizes the same building components as one would expect for the full-sized residence. Figure 2.1 shows the south elevation of the Prototype PV system structure. The north elevation as seen in Figure 2.2 shows a nearly identical elevation to that of the elevation seen for the full-sized residence in Figure 1.2. An important factor in the design of the Prototype structure relates to the fact that the PV array would be over both a non-conditioned space, the garage, and a conditioned space, the master bedroom, in the proposed full-sized design. This condition was duplicated in the Prototype structure. The various internal conditions can be seen in Figure 2.3, the interior space identical to the garage, and Figure 2.4, the interior conditioned space. As can be seen in these sections through the Prototype, these spaces are identical to those designed for the full-sized residence, except for the dimensional variation required to facilitate the integration of the odd-sized, 70.5-cm (27.75-in) width panels. This unusual dimension was a direct result of the lack of appropriate-sized modules on the PV market. To accommodate the nominal 30.5-cm by 121.9-cm (1-ft by 4-ft) ARCO industrial modules, it was necessary to generate additional extrusions to allow for the fabrication of panels. This will be described in the sections that follow.

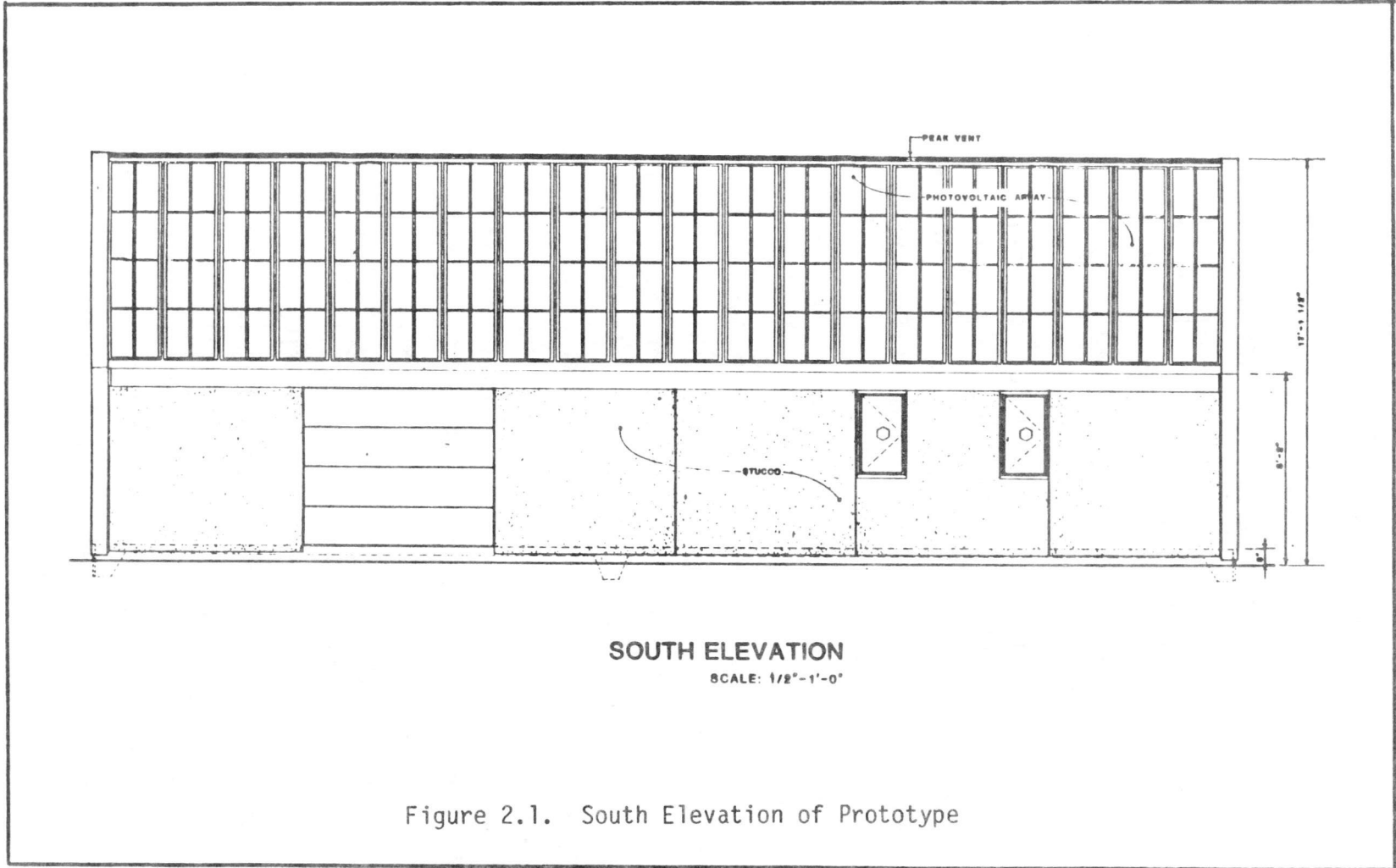


Figure 2.1. South Elevation of Prototype

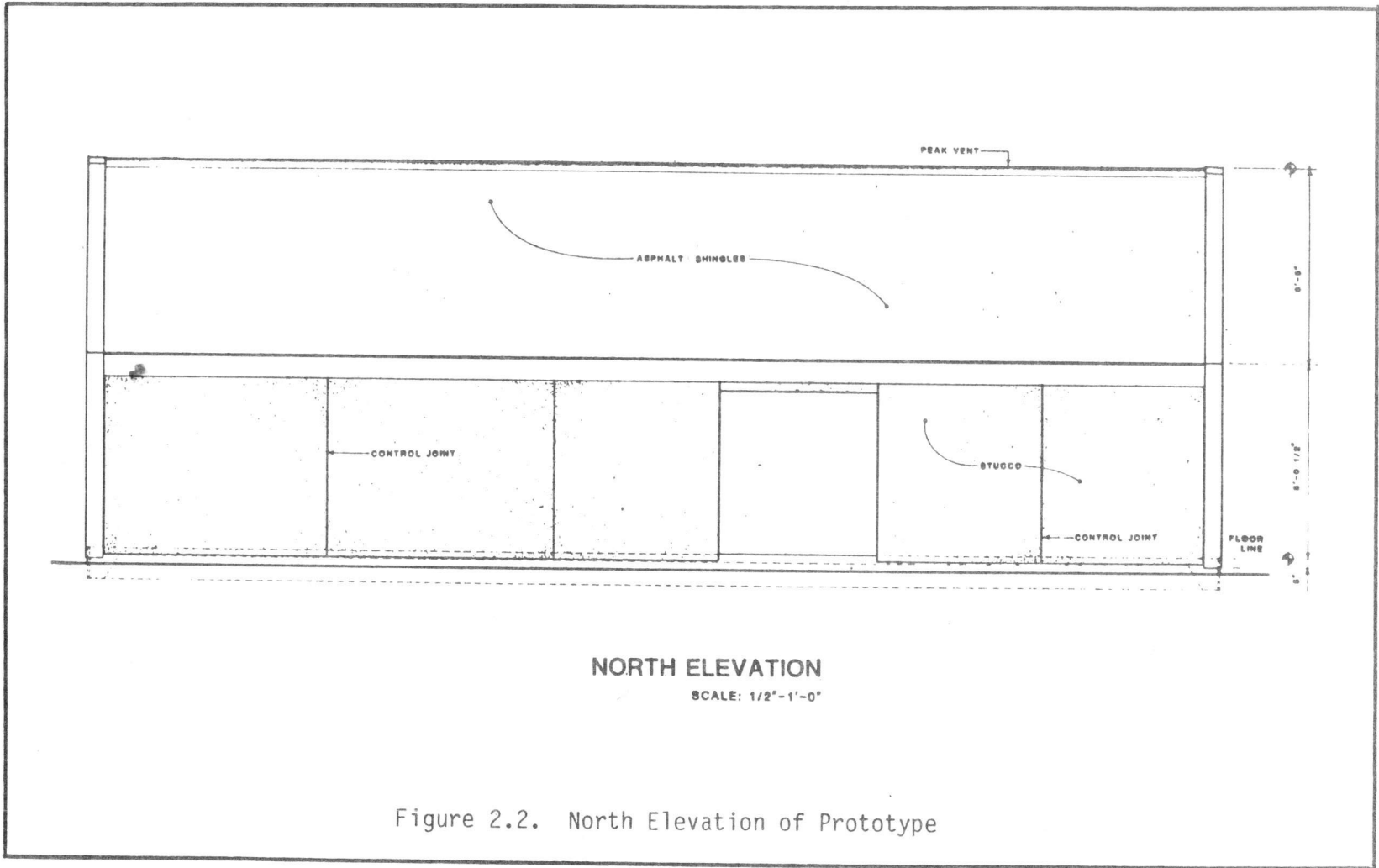
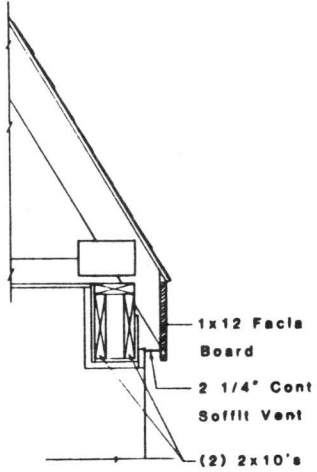
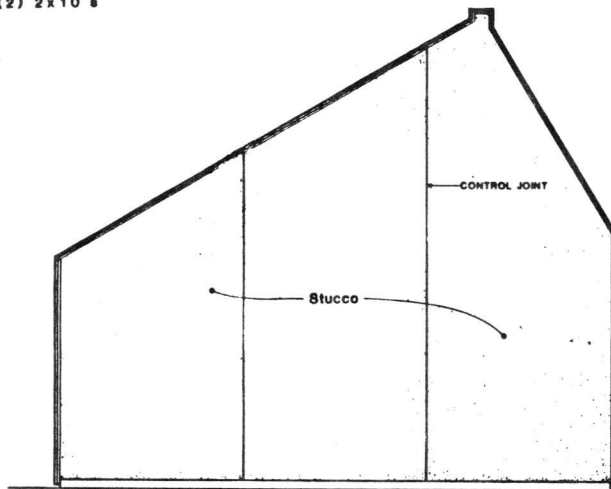


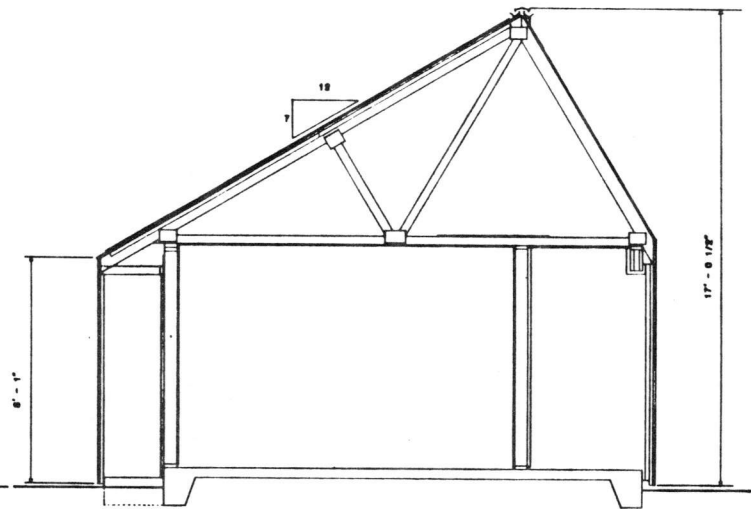
Figure 2.2. North Elevation of Prototype



**NORTH WALL
DETAIL**
SCALE: 1 1/2" 1'-0"



WEST ELEVATION (EAST ELEVATION SIMILIAR)
SCALE: 1/2" 1'-0"



SECTION B-B'
SCALE: 1/2" 1'-0"

Figure 2.3. West Elevation of Prototype Through Unconditioned Space

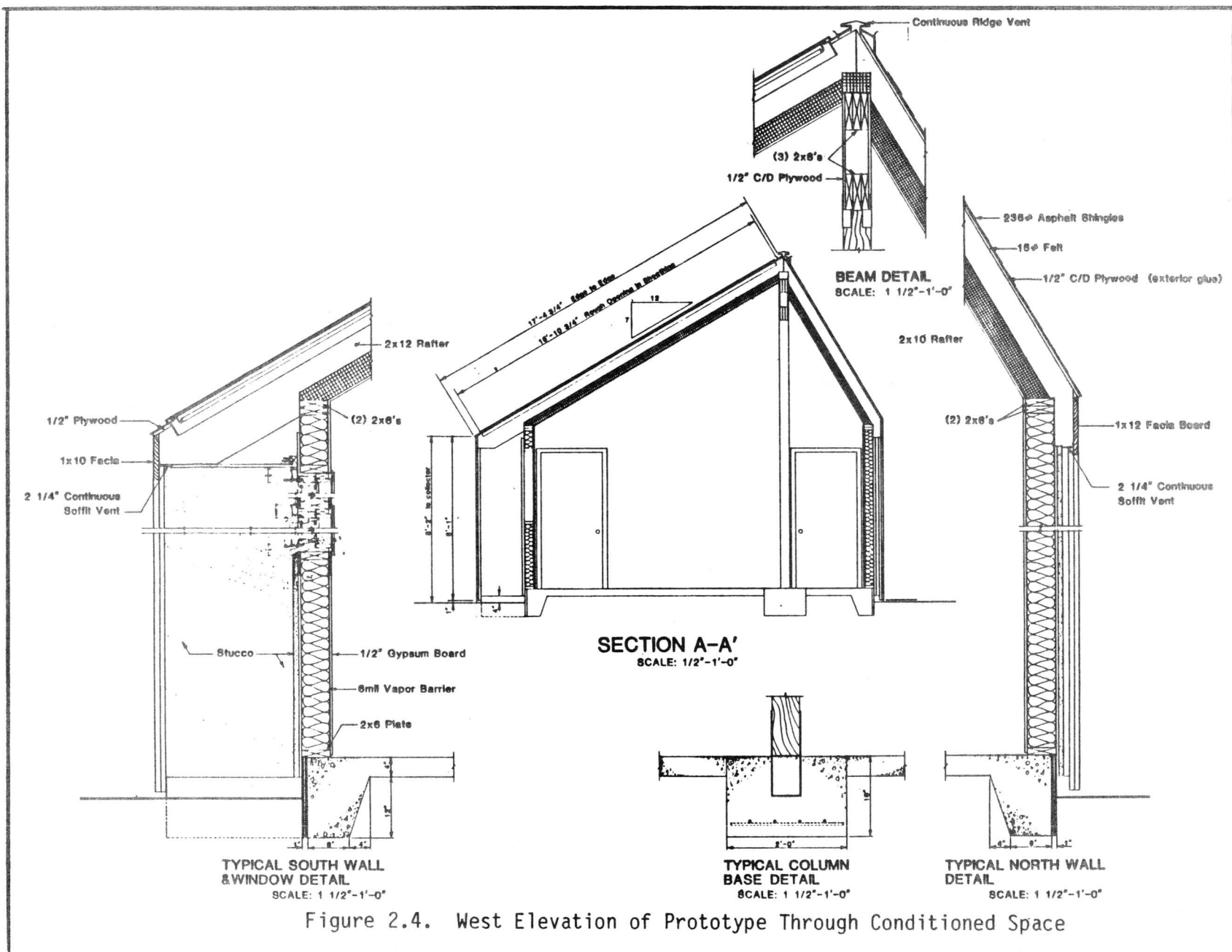


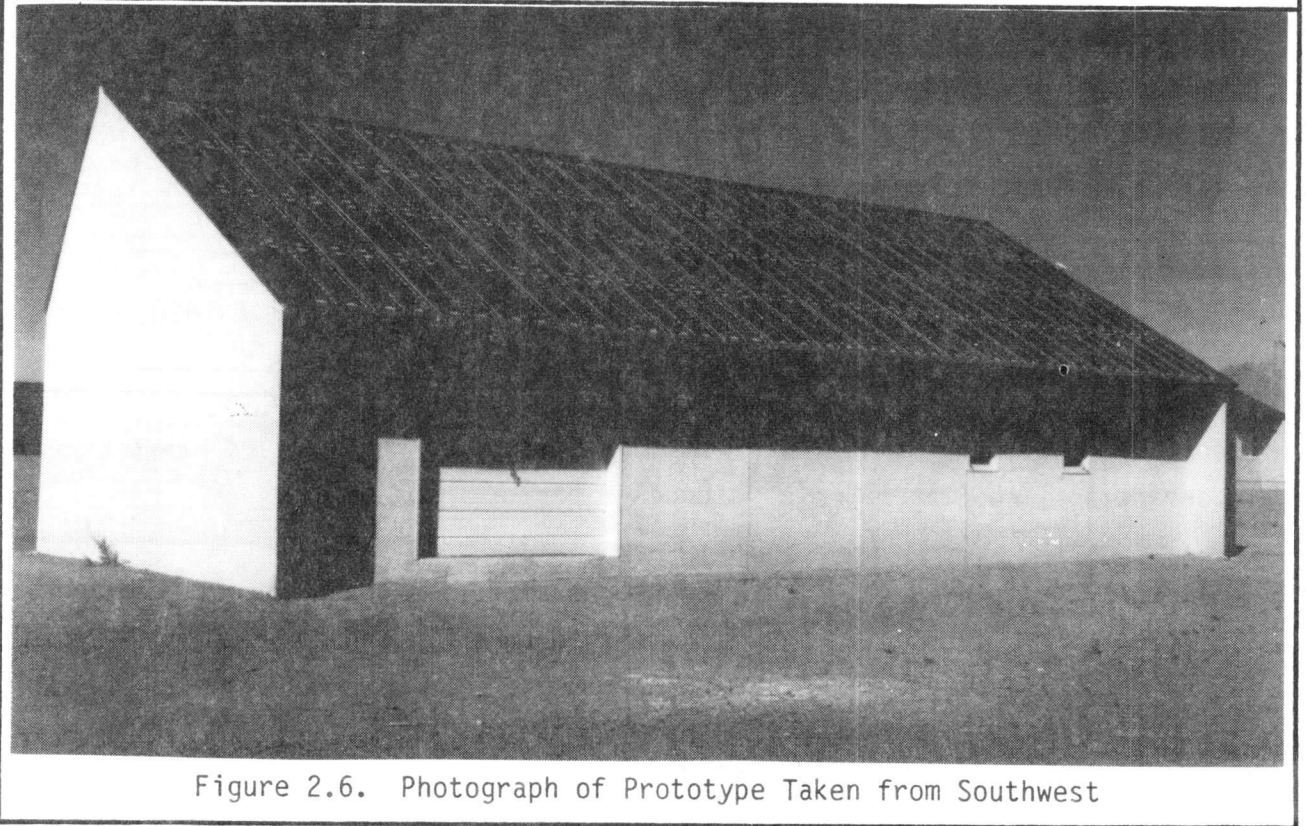
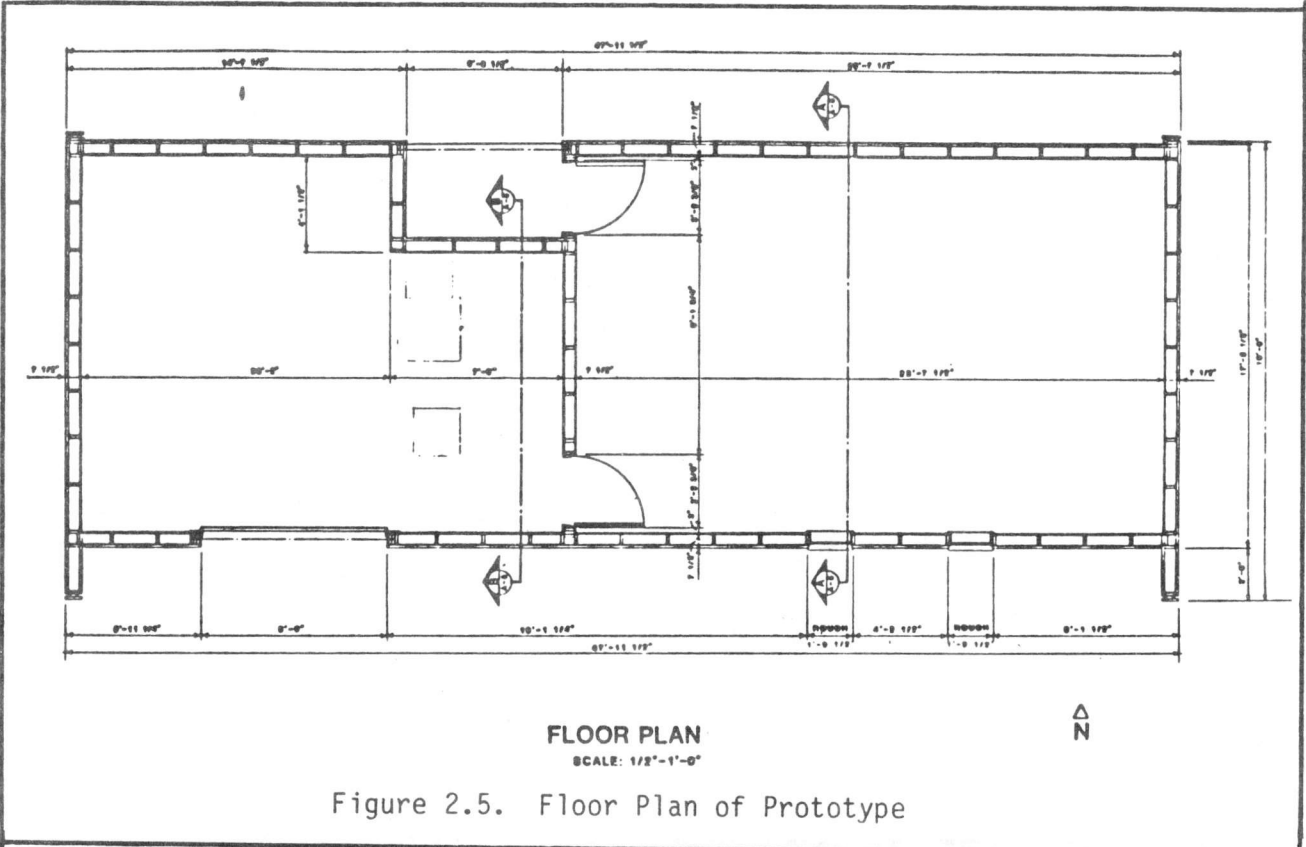
Figure 2.4. West Elevation of Prototype Through Conditioned Space

Identical insulation and venting techniques have been used as previously described in the full-sized residence description. A detailed section of the Prototype can be seen in Figure 2.4, which more precisely describes the materials used in this system. A floor plan of the Prototype structure is shown in Figure 2.5.

The roof that accommodates the integrally mounted PV array consists of 5.08 cm x 30.48 cm (2 in x 12 in) roof rafters and PV panels over the conditioned space, and wood trusses and PV panels over the non-conditioned space. The panels are only slightly heavier than the sheathing, roofing felt, and shingles they replace. Typically, the roofing rafters for such a structure would consist of 5.08 cm x 10.16 cm (2 in. x 4 in.) trusses or 5.08 cm x 15.24 cm (2 in. x 6 in.) rafters. Based on these facts, detailed roof loading calculations were deemed unnecessary. Preliminary calculations on previous work indicated that a considerable margin of safety did exist, precluding the need for extensive structural calculations for this project.

Photographs of the completed Prototype structure are shown in Figures 2.6 and 2.7. Figure 2.6 was taken from the southwest and shows the array and west side of the Prototype. The garage door is visible on the west side of the south wall. Figure 2.7 is a view taken from the northeast showing details of the north side of the Prototype. The main entrance is a single door located in the center of the north side.

The lack of need for workmen with special skills for constructing the Prototype structure or installing the PV panels cannot be overemphasized. The construction of this Prototype took place over a three-week period, utilizing carpenters, electricians, and laborers normally found at residential and commercial job sites. Throughout the entire construction process, three to four people were employed. This number does not differ from a conventional residential building project, nor does the experience level change. The panel installation process is described in section 2.2.1.4.



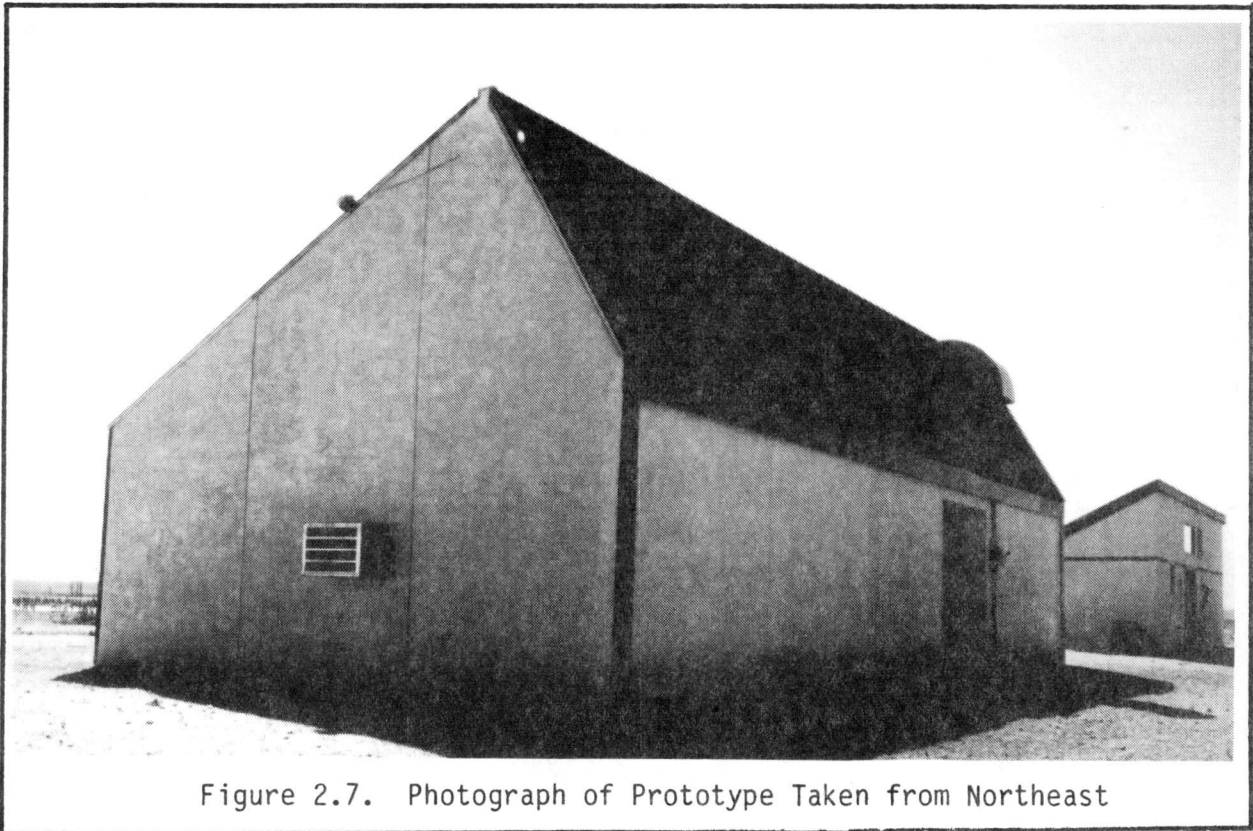


Figure 2.7. Photograph of Prototype Taken from Northeast

2.2 MECHANICAL

2.2.1 SOLAR ARRAY

The solar array consists of 160 solar cell modules arranged in a rectangular matrix 40 wide and 4 high. The array is integrally mounted, serving simultaneously as the watertight skin of the roof as well as an electrical generator. To accomplish this, 20 special aluminum panel frames housing groups of eight modules each are nested between the rafters. Because watertight seals are made both between the modules and panel frames as well as between the panels and rafters, the array serves as a watertight membrane, eliminating the need for conventional roofing material.

The array design was based on a panel system developed for a flat-plate, air-heating thermal collector by Solar Energy Engineering and the General Solar Systems Division of General Extrusion, Inc. The main panel and array framing system consists of two major components:

- Panel Frame
- Roof Rafter Riser

The panel frames consist of two lengths of aluminum extrusions fabricated into rectangular frames using mitred and welded corners. This framing system uses a technique common to the glazing industry, known as joggle glazing, and allows for the installation and removal of glass panes, in this case PV module laminates, in an extremely easy fashion. Continuous picture frame gaskets are used to ensure the watertight integrity of the PV modules and the roofing system. The roof rafter riser is the key element in the panel-to-structure interface. A continuous extruded aluminum rafter riser is placed over each roof rafter to accommodate the caulking sealant between the building and the panel, ensuring a watertight seal.

The weight of the solar panels installed in the roof is only slightly greater than that of the sheathing and other roofing material they replace. Therefore, because the weight difference is very small, a detailed roof loading calculation was considered unnecessary and was not performed.

2.2.1.1 Solar Cell Module

The solar cell modules used are catalog items manufactured by ARCO Solar, Inc., designated Type ASI 16-2300. Complete modules include both a laminate, incorporating the solar cells and glass superstrate, and an aluminum mounting frame attached to the laminate to seal the edges and provide a convenient means to mount the module. Since for this array the modules are mounted in special aluminum panel frames, the standard Type ASI 16-2300 module edge mounting frame was not needed. Therefore, frameless laminates were purchased from ARCO.

A drawing showing the physical size of the Type ASI 16-2300 laminate is shown in Figure 2.8. The materials used to form the laminate are shown in Figure 2.9.

Shown in Figures 2.10 and 2.11 are front and back photographs of a standard Type ASI 16-2300 module with an aluminum edge frame. These photographs show details of the 4-in. round solar cells in the front view, and the redundant post electrical connection terminals located within a circular plastic junction box in the back view. The modules purchased for use in the Prototype array possess the same features as the Type ASI 16-2300 standard modules.

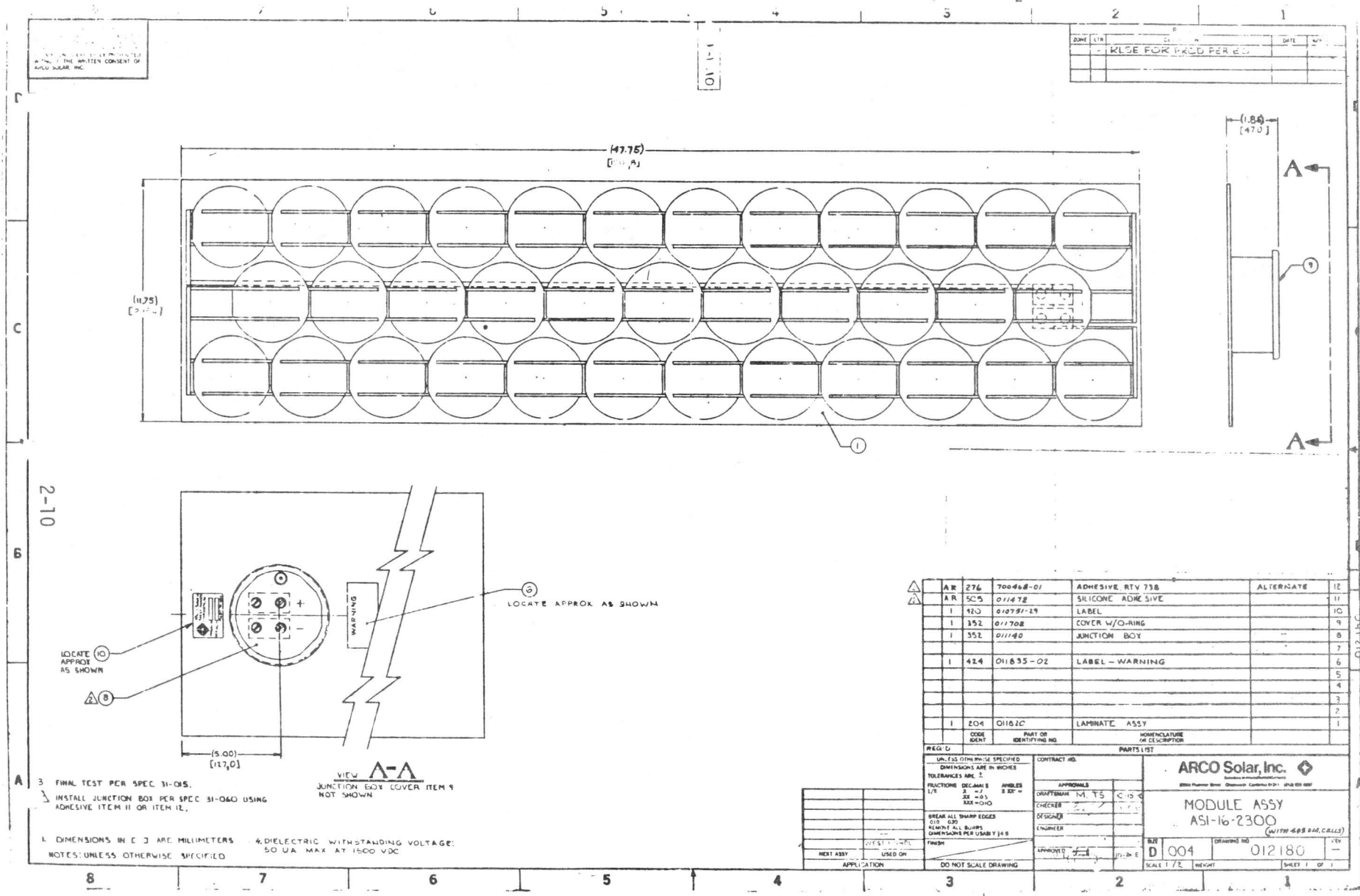
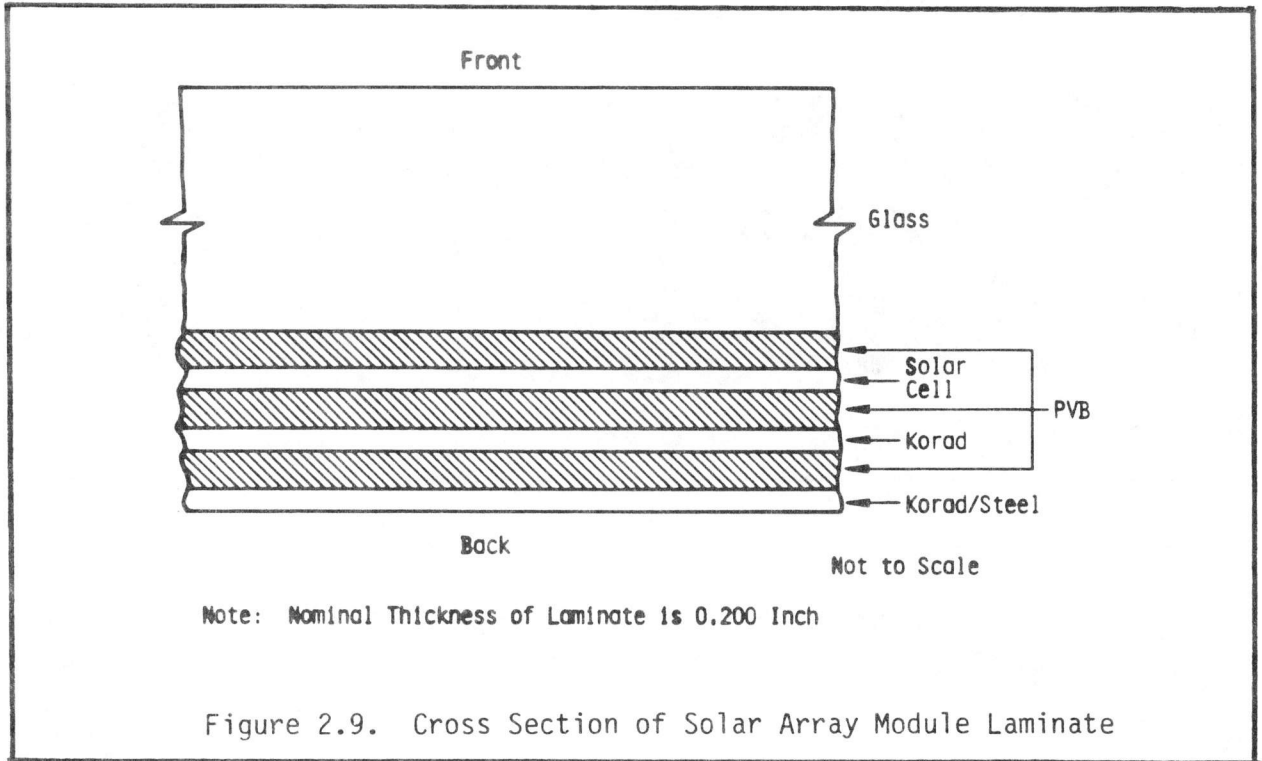


Figure 2.8. Module Assembly Drawing



2.2.1.2 Solar Cell Module Doublets

The first step in the panel fabrication process consisted of mounting module laminate pairs in aluminum frames fabricated from aluminum extrusions. The use of module doublets is undesirable because of added weight and cost, but it became necessary for two reasons. First, a single solar cell module of the necessary width was not available, making it necessary to place two side by side. Secondly, conventional joggle glazing requires at least 0.5 inch of unobstructed glass edge surface to ensure proper mounting. Because the cell-to-glass edge spacing of the laminate used was only 0.571 cm (0.225 in), the laminate could not be joggle glazed directly. The aluminum doublet frame placed around the outside of each doublet provided the necessary unobstructed area needed to utilize conventional joggle glazing gasketing techniques in aluminum instead of glass. Figure 2.12 illustrates the doublet structure with details of the piece parts used and the steps followed during assembly.

The solar cell module laminates were shipped by the vendor in sealed plastic bags without laminate edge sealing. During the process of doublet fabrication,

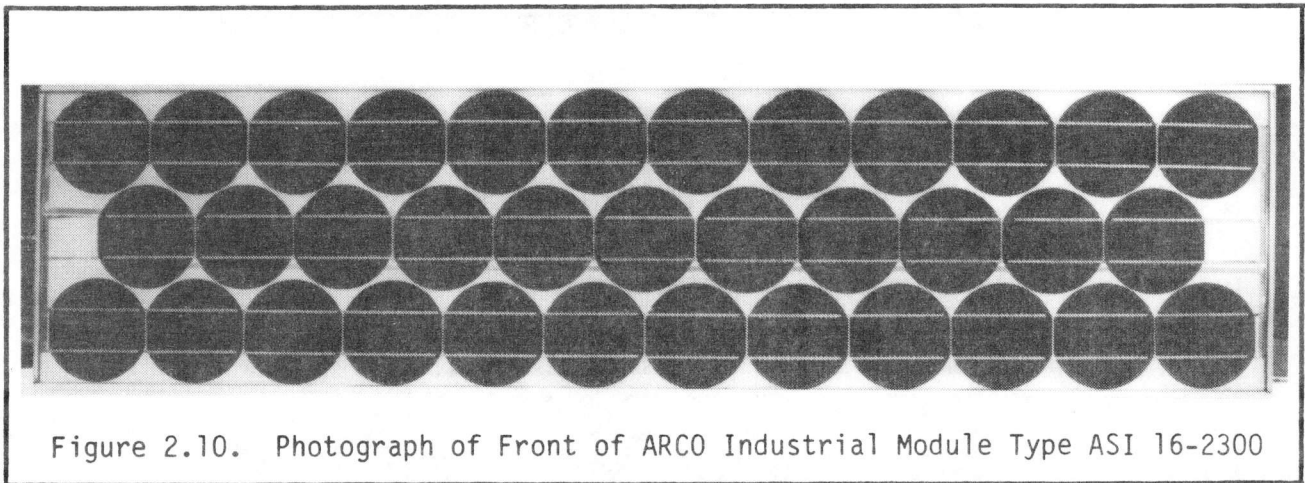


Figure 2.10. Photograph of Front of ARCO Industrial Module Type ASI 16-2300

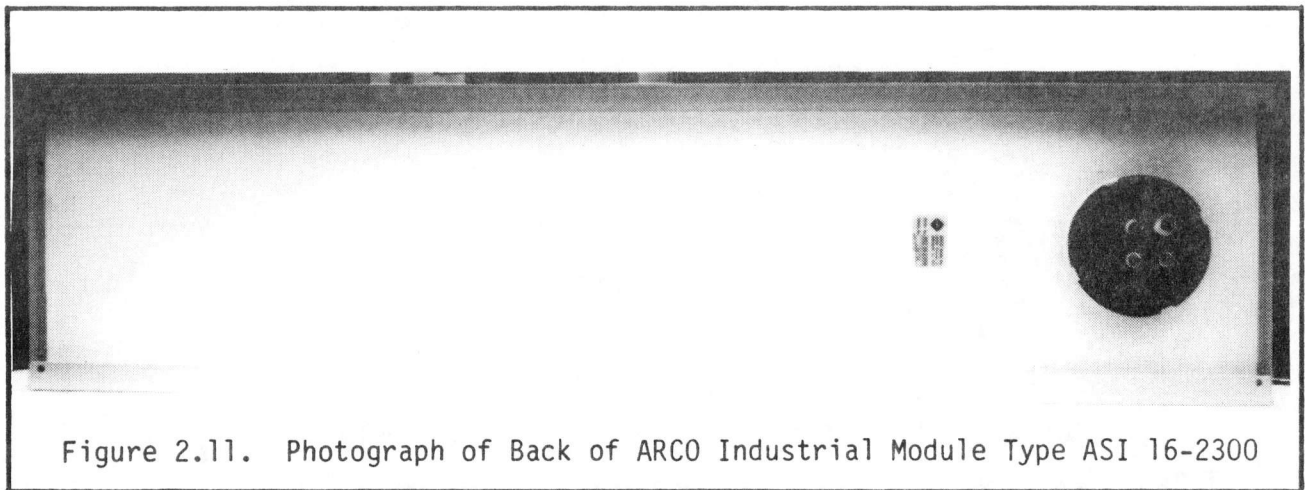
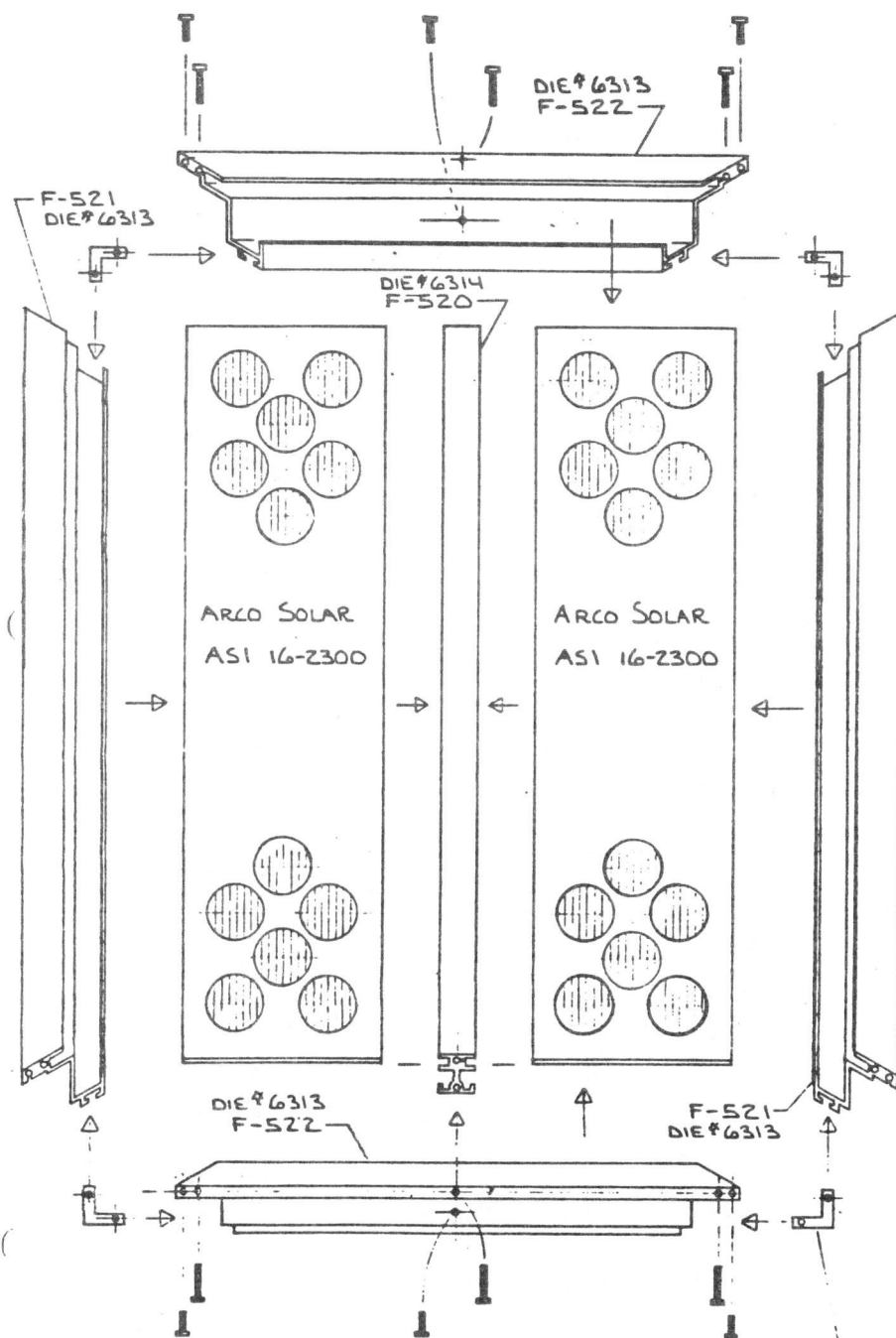


Figure 2.11. Photograph of Back of ARCO Industrial Module Type ASI 16-2300

the channels in the aluminum extrusions that were to be fitted over the laminate edges were filled with Pliogrip[®] 6411, a moisture cure adhesive, manufactured by Goodyear. The Pliogrip[®] served to hold the laminates firmly to the frames, provide watertight seals, and seal the edges of all laminate materials, preventing moisture penetration into the solar cell region while permitting differential thermal expansion movement between the laminates and aluminum frames. A photograph of an assembled doublet is shown in Figure 2.13.

2.2.1.3 Solar Cell Panels

Panels of sufficient length to hold four doublets end-to-end were fabricated using welded aluminum extrusions. Details of the piece parts used are shown in Figure 2.14. The corners of the aluminum frame were mitred and welded. Rear cross-members between doublets were welded into place.



NOTE: CORNER KEY CONSISTS OF 1 ANGLE AND 2 SET SCREWS (TYCO LARGE ANGLE)

Figure 2.12. Assembly Drawing of Module Doublet

Each panel housed four doublets held in place by front and back picture-frame-shaped EPDM gaskets made by Tremco (Types TR-212E and 1127E). The drawing in Figure 2.15 shows cross sections of both the doublet and panel frames and illustrates the gasket mounting technique used. The rear gasket is held permanently in the panel frame by a projection forced into a cavity formed in the panel extrusion. After the doublet has been "joggled" into place, the front gasket is forced into position between the doublet and the front of the panel extrusion. The front gasket can be removed to make possible the removal and replacement of a single doublet from the front of the array.

Overall panel dimensions are shown in Figure 2.16. All panels are identical except for those located at the east and west ends of the array that have wide side flanges of the type shown. The approximate weight of a panel is 61 kg (135 lb).

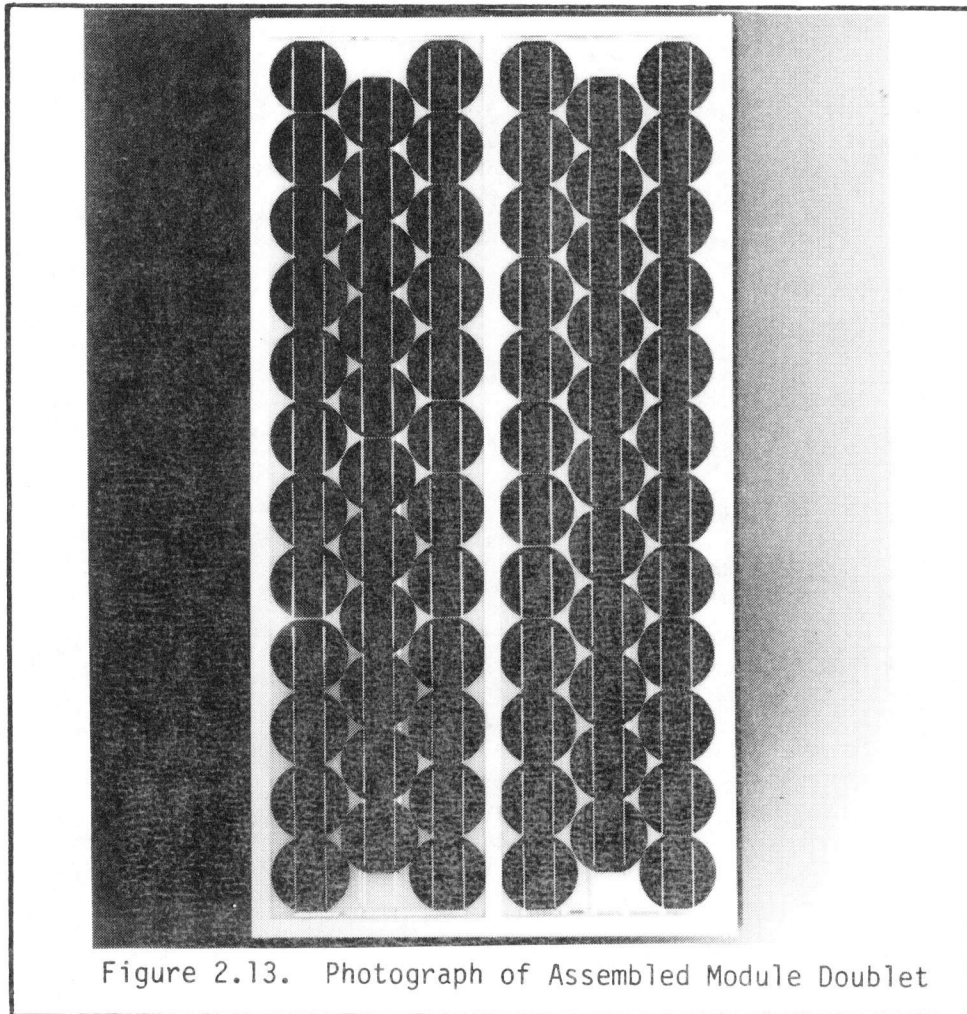


Figure 2.13. Photograph of Assembled Module Doublet

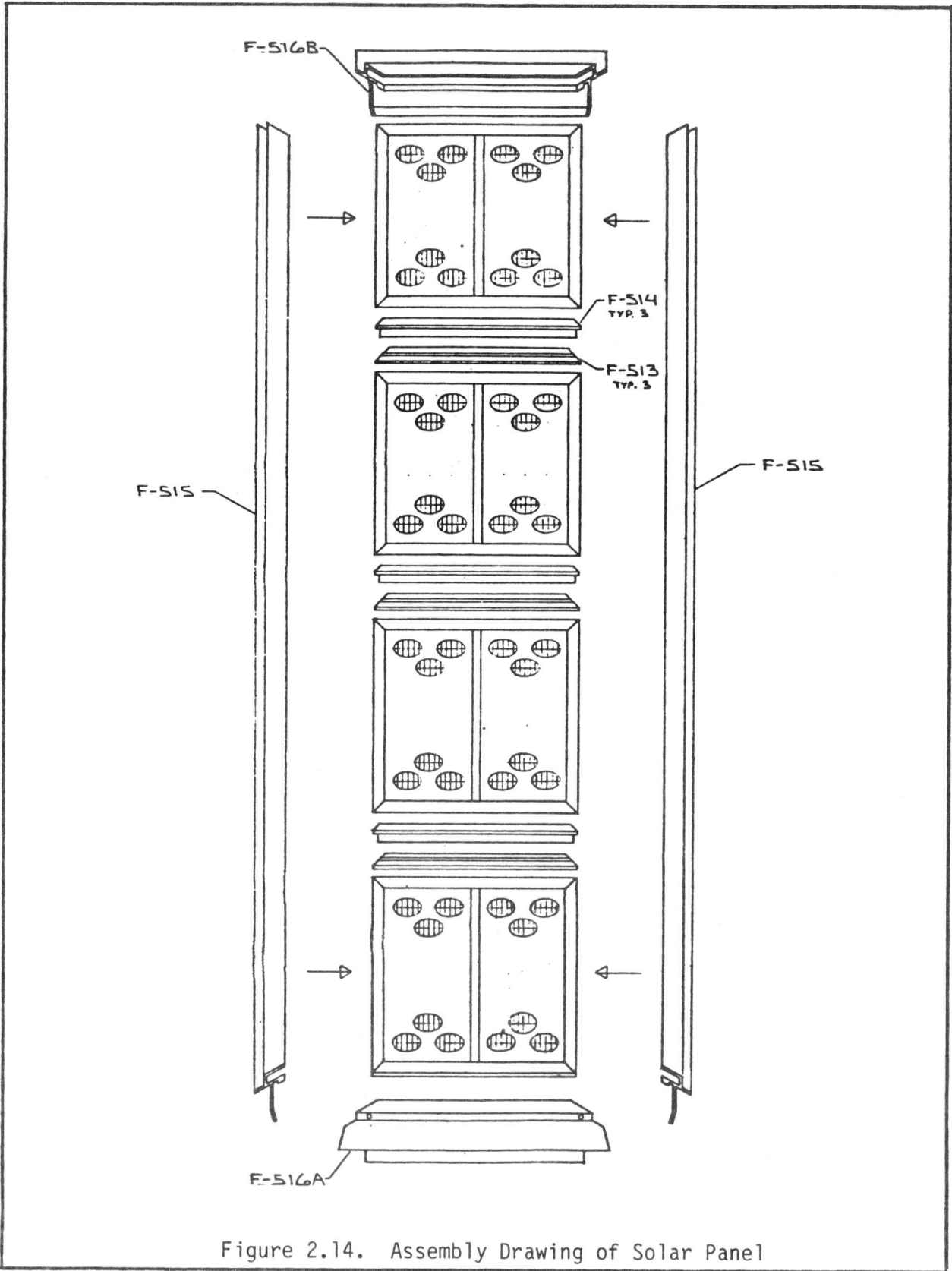


Figure 2.14. Assembly Drawing of Solar Panel

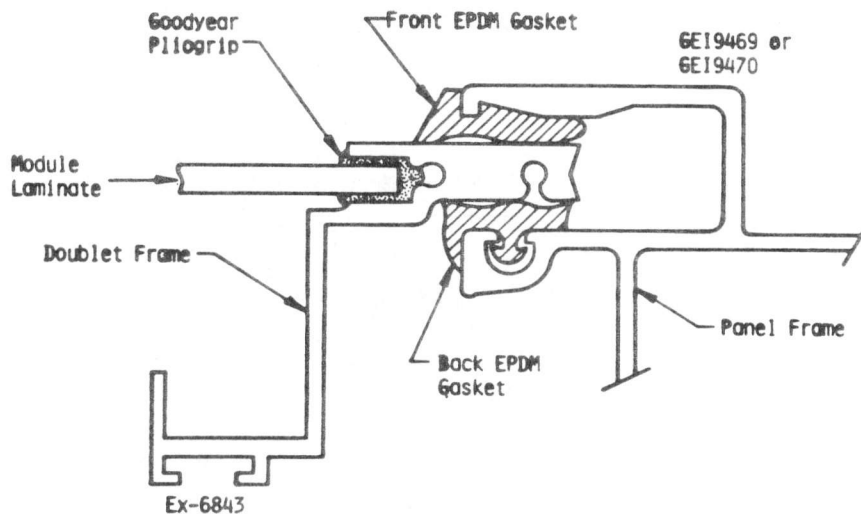


Figure 2.15. Cross Section of Panel Showing Doublet Gasketing Details

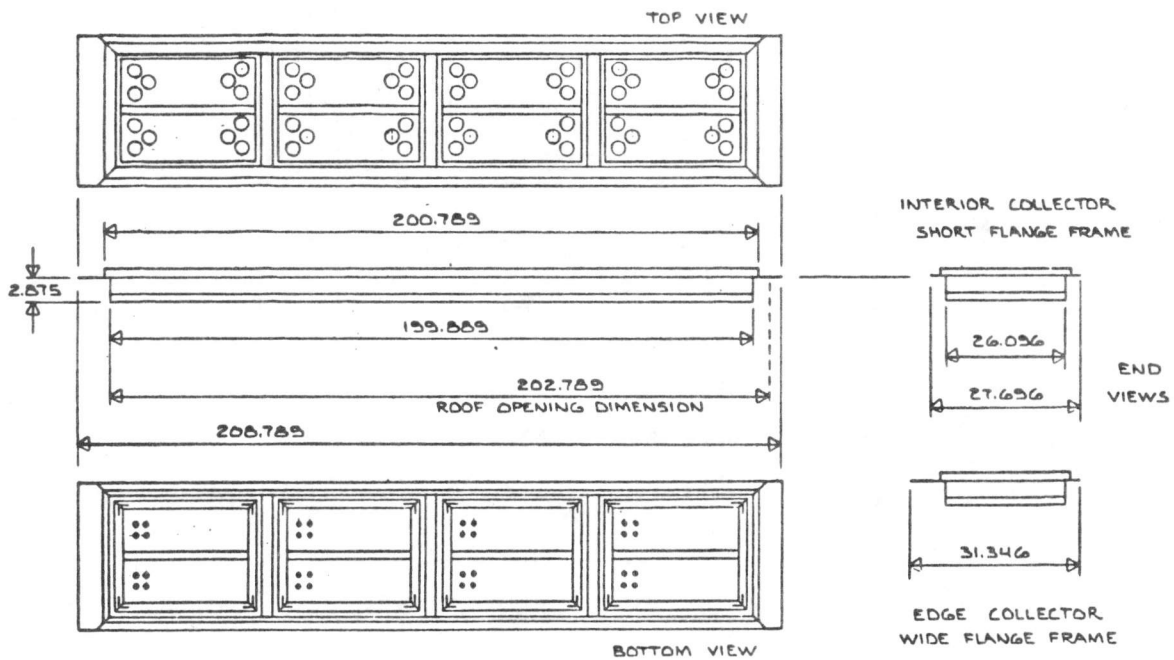
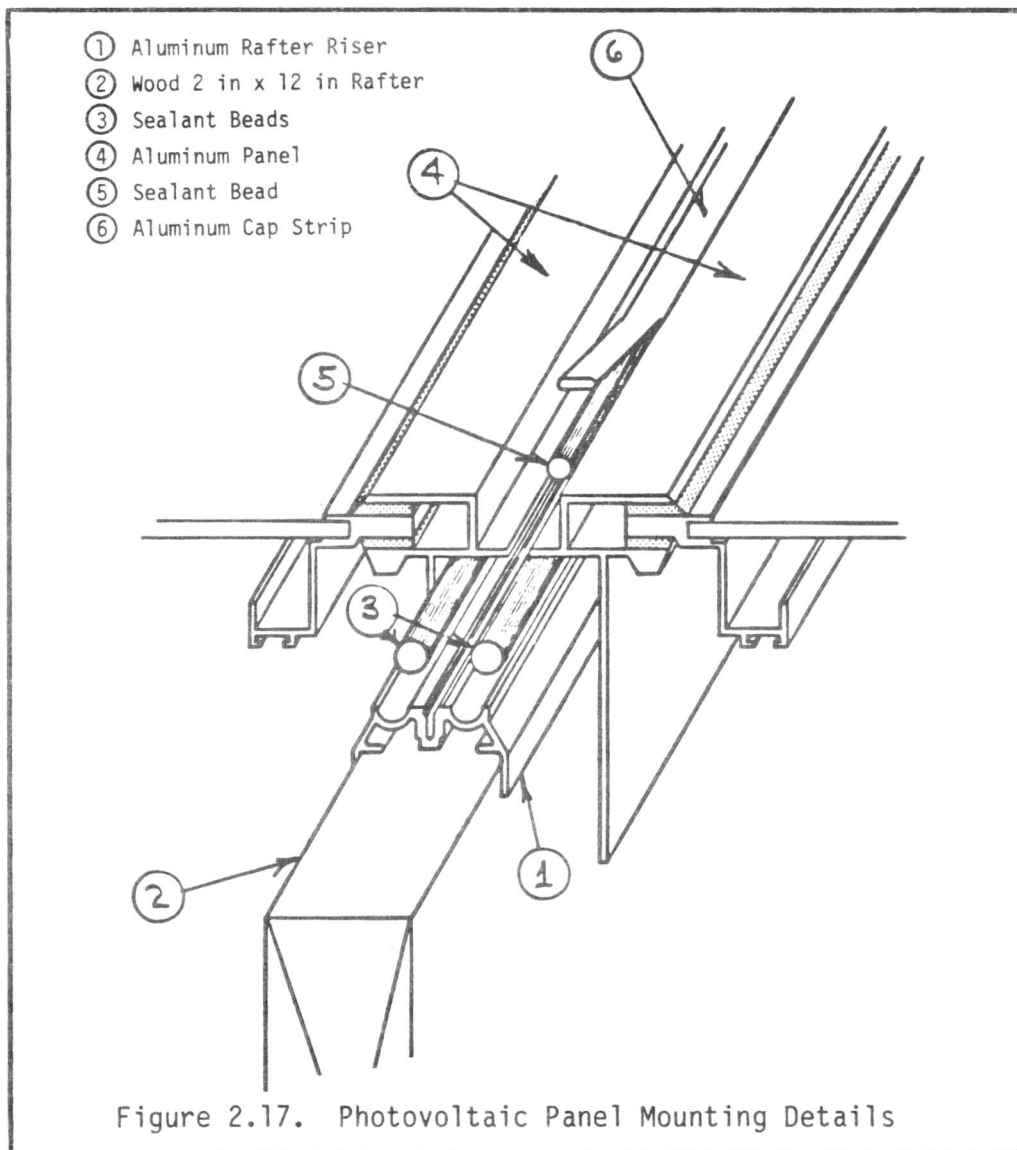


Figure 2.16. Solar Panel Details

2.2.1.4 Panel Installation

The panel installation procedure used to obtain a watertight roof seal is illustrated in Figure 2.17. Extruded aluminum rafter risers (1) were placed over the rafters (2) and nailed in place from the side. Two beads of sealant (3) were laid side by side in grooves provided in the rafter risers using a pneumatic caulking gun. Solar cell panels (4) were nested side by side between adjacent rafters with the panel side flanges touching the beads of sealant. An additional bead of sealant (5) was laid in the cavity formed by the rafter riser and the edges of the panel side flanges. An aluminum cap strip (6) was then placed over this joint and fastened with screws. This resulted in a watertight seal between the panels and the rafters.



All panels except those located at the ends were identical, and the installation procedure made it possible to start installing panels at any position within the array. Each end panel had one wide side flange that had to be located away from its adjacent neighbor. To ensure watertight seals, beads of sealant were placed beneath the top and bottom flanges of the panels before installation as well as beneath the flanges at the sides.

2.2.2 POWER CONDITIONER

Physical Details

The power conditioner, purchased from Abacus Controls, Inc., came in a rectangular metal cabinet with full-length doors on both front and back. Physical details of the power conditioner are shown in Figure 2.18. When closed, the front door covers all the switches, controls, and indicator lamps shown except for the dc breaker and three-position operating mode switch, both of which are mounted toward the bottom of the front panel. These controls can be accessed through holes in the door when the door is closed. When the back door is closed, the input and output terminal blocks shown are inaccessible.

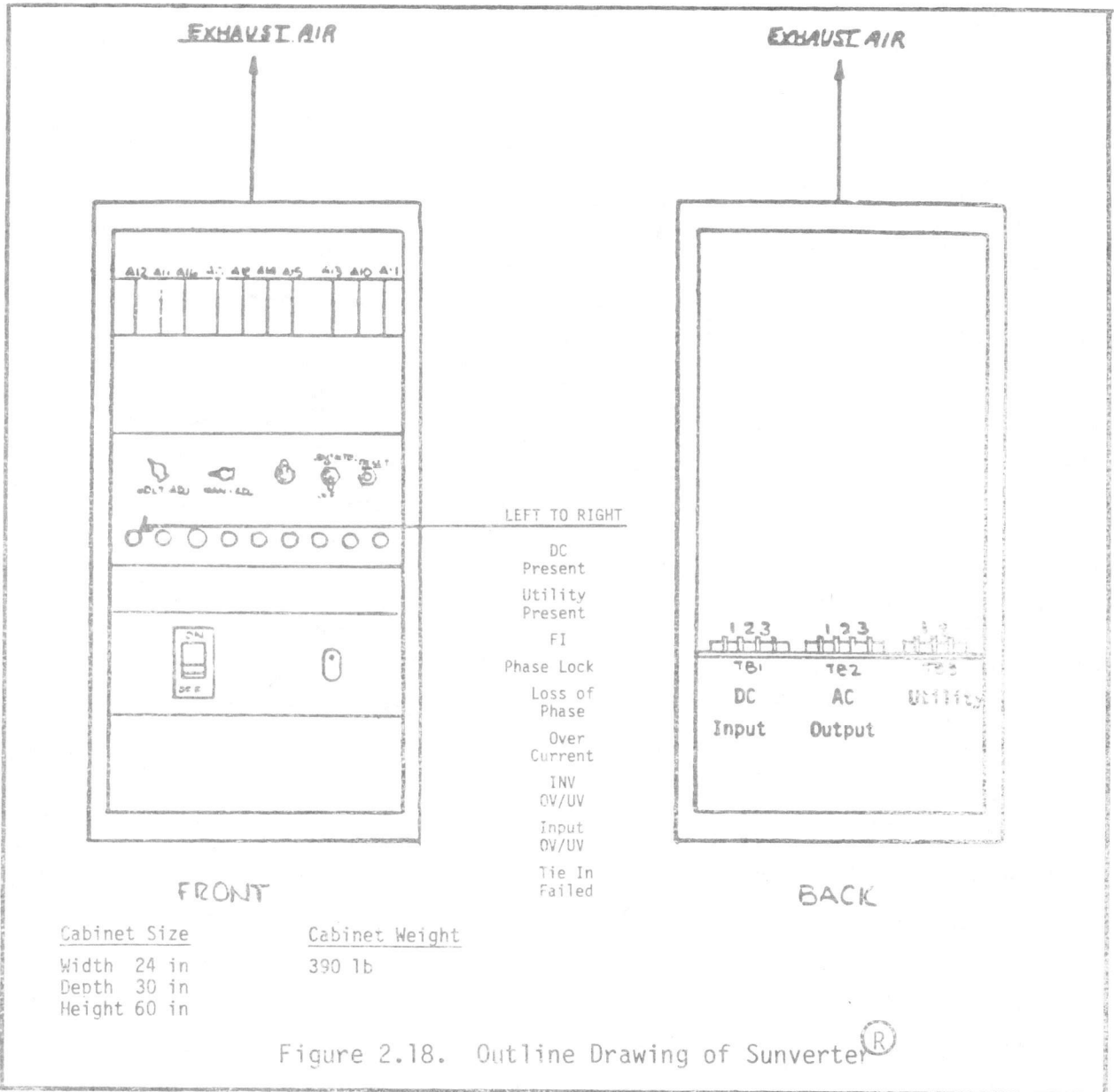
Cabinet size and weight are shown in the figure. Louvres in the rear door provide an entrance for air, which flows past the power modules and is exhausted through louvres in the top. A thermostatically controlled fan enhances natural convective airflow when the temperature of the heat sinks in the power modules exceeds a preset value.

2.3 ELECTRICAL SYSTEM DESIGN

2.3.1 SYSTEM DESCRIPTION

2.3.1.1 System Function

The electrical system of the full-size residence includes a solar PV power system that supplies the on-site loads together with the electric utility. The PV power system interacts with the utility, permitting power flow either to or from the utility depending upon conditions within the residence.



Possible power flow paths within the residential electrical system are illustrated in Figure 2.19. In path #1, power generated by the PV system flows to the on-site residential load. If the power generated by the PV system is insufficient to meet the demand of the on-site load, supplemental power will flow along path #2 until the load demand is satisfied. At night or during periods of cloudy weather, the PV system will cease producing power and all on-site load power will be provided by the utility along path #2. On the other hand, if the power generated by the PV system exceeds the demand of the on-site load, the excess will be delivered to the utility along path #3.

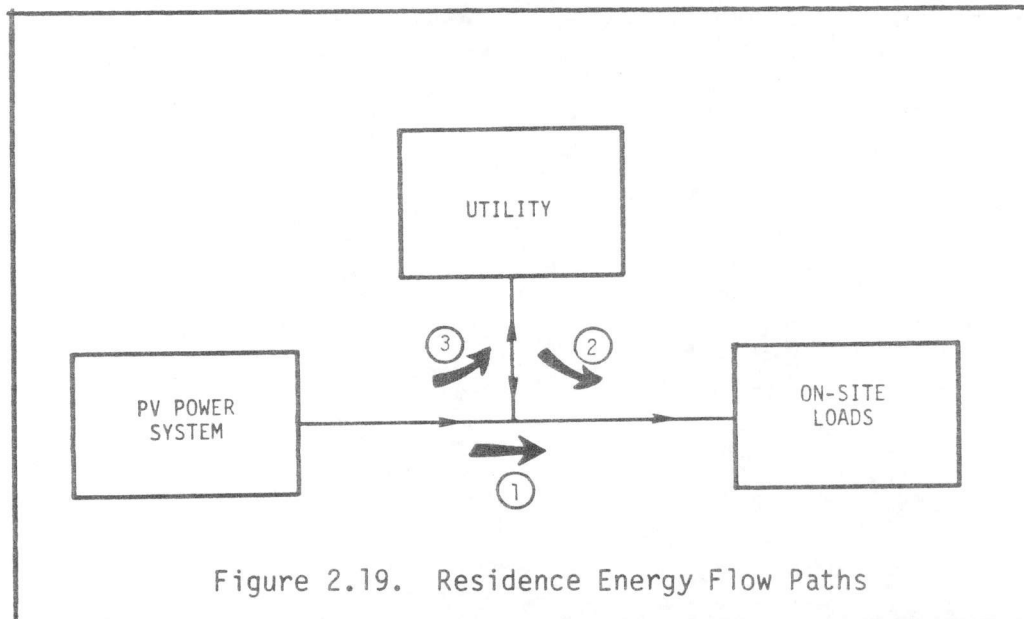


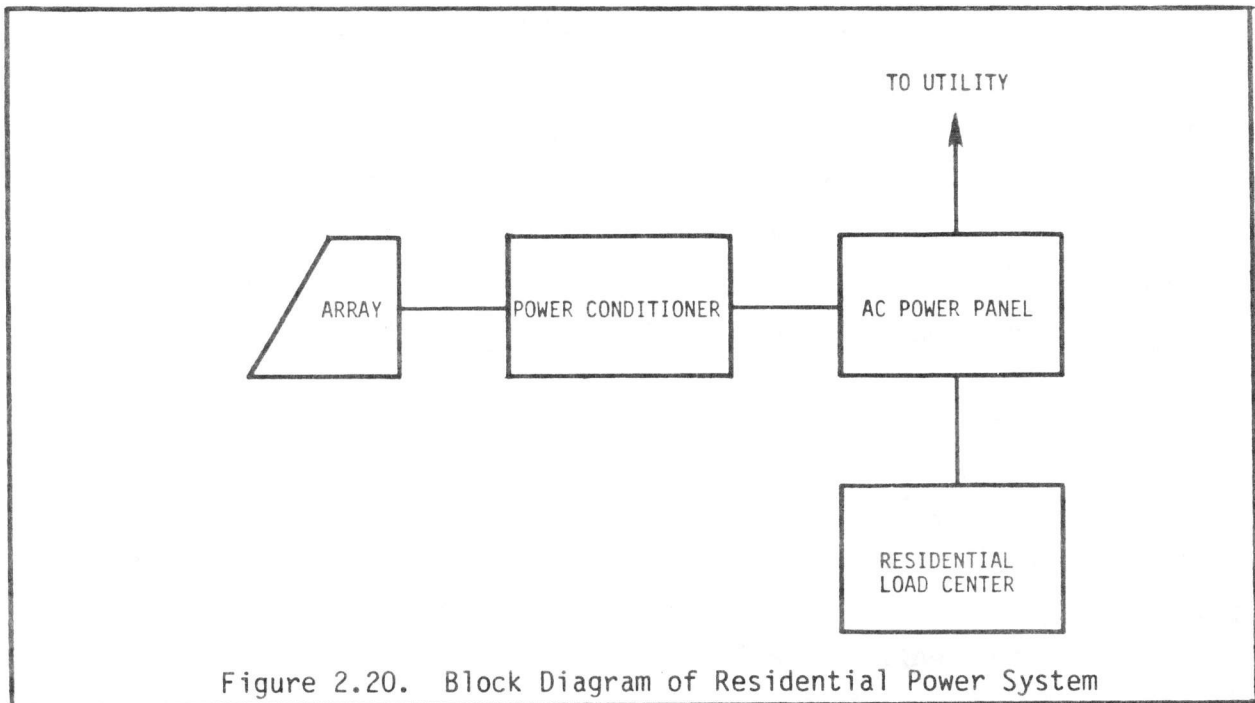
Figure 2.19. Residence Energy Flow Paths

The system contains no on-site electrical energy storage. It is a utility-interactive system that effectively utilizes the utility grid as a storage mechanism by delivering power during periods of excess generation and withdrawing power when the PV system output cannot meet the residential load demand.

2.3.1.2 Major Subsystems

The major subsystems of the PV system are shown in Figure 2.20. The array is constructed of modules containing round, single-crystal silicon solar cells mounted on glass superstrates and encapsulated with layers of organic material. The individual cells are interconnected in a series/parallel matrix that ultimately yields the desired dc bus voltage necessary for proper operation of the power conditioner.

The array output is varying dc, which is regulated and changed to utility quality, 60-Hz, sinewave ac power by the power conditioning subsystem. The power conditioner also includes a provision to vary the array loading, and by sensing output power, always seeks to withdraw the maximum power available from the array for the prevailing weather conditions. The power conditioner logic and control also provide the ability to cause the unit to "wake up" in the morning and "retire" at night as the sun rises and sets.



The ac power panel subsystem provides the interconnection between the output of the PV system, the utility grid, and the on-site loads. Included in this subsystem are breakers for protection and meters for voltage, current, power, and energy measurements.

2.3.1.3 Design Requirements

The requirements imposed upon the residential PV system design by this application are listed in Table 2.1.

2.3.2 SUBSYSTEM DESCRIPTIONS

2.3.2.1 Array

2.3.2.1.1 Solar Cell Module Laminate

The solar cell module laminate used to construct the solar panels was obtained from ARCO Solar, Inc. It is the same one used to manufacture the Type ASI 16-2300 industrial module that meets JPL Block IV requirements. A cross section of the module is shown in Figure 2.9. Photographs of the ASI 16-2300 module are shown in Figures 2.10 and 2.11.

TABLE 2.1
RESIDENTIAL SYSTEM DESIGN REQUIREMENTS

1. The system must produce utility-quality power and its output must interface with the utility line and on-site loads.
2. The system must operate unattended and must automatically wake up, synchronize, connect to the utility line, and retire.
3. The system shall not include on-site storage.
4. Power generated in excess of that required by the on-site load shall be delivered to the utility.
5. The system shall automatically disconnect itself from the utility line in the event of a loss of utility voltage.
6. The output of the system shall be current limited and fused.
7. The power conditioner shall load the array so that maximum power is extracted from it at all times.
8. The system shall be designed to function in the following ambient conditions:
 - o Ambient Temperature -22° to 42°C
 - o Relative Humidity 0 to 99%
 - o Wind 0 to 113 KMPH (70 MPH)
 - o Hail Up to 1.90 cm (0.75-in) diameter
9. The array module design shall not include any provision to recover and use thermal energy.
10. All exposed metal parts shall be grounded.

The solar cell module laminate was purchased as a catalog item with no additional parameter screening. Data sheet parameters describing the module laminate as purchased are shown in Figure 2.21. Each module laminate was serialized and flash tested by the vendor at standard test conditions (1,000 W/m², AM 1.5, and T_c = 28°C) during the production final test. A copy of the flash test data was supplied for each module laminate purchased. A typical I-V characteristic obtained from such a test is shown in Figure 2.22.

2.3.2.1.2 Electrical Connection Considerations

Because the basic solar cell module used produced a peak power of only 37 W at standard test conditions, many modules were connected together in a series/parallel configuration to form the array rated at 5.7 kW. The number connected in series was chosen to yield a dc bus voltage that provided the best match to the power conditioner input voltage requirements, while the number in parallel was selected to yield the desired array output power. The task of choosing the number to be connected in series was complicated because solar cell module electrical characteristics change with cell temperature and because solar cell modules are exposed to the elements with temperatures varying in both daily and seasonal cycles.

2.3.2.1.3 Thermal Considerations Relating to Module Position

The array is configured with 160 solar cell modules 4 high by 40 across. The module mounting technique created a 10.16-cm (4-in.) air space behind the modules, permitting airflow by natural convection into a vent at the soffit and out of a vent at the ridge. As the air behind the array moves upward, its temperature increases owing to the thermal energy contribution of each module. Therefore, the temperature of the solar cells in the top row of modules is higher than that of the bottom row, as illustrated in Figure 2.23.

Because the module electrical characteristics vary with cell temperature, any partitioning scheme that arranged groups of modules in series or parallel arrangements had to be chosen to ensure that the average cell temperature in each group was the same. Such a combinatory arrangement minimizes mismatch losses.

Power Specifications

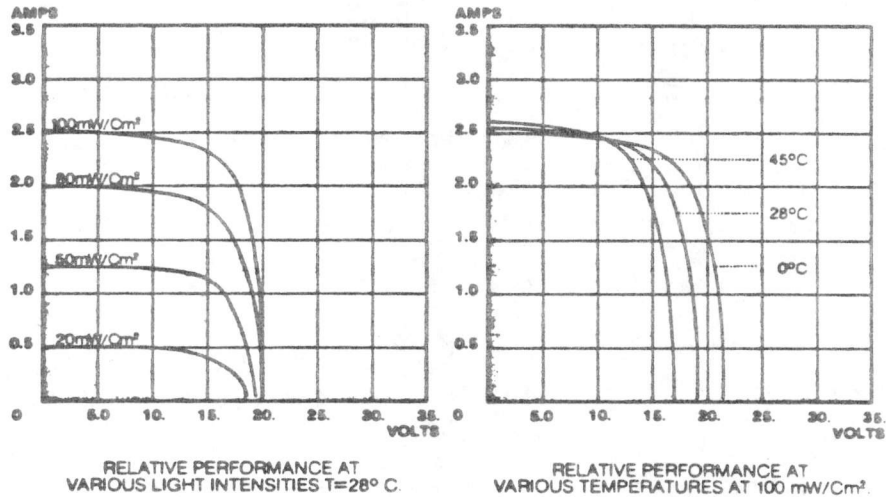


Table 1. Output specifications at various test conditions

	100mW/cm ² & 28°C	100mW/cm ² & 45°C (NOCT)
Open Circuit Voltage	20.3	18.9
Short Circuit Current	2.5	2.5
Voltage at Peak Power	16.1	14.6
Current at Peak Power	2.3	2.3
Watts of Peak Power	37	34

Explanation of terms and test conditions:

The specifications in Table 1 at the right were determined at two different temperatures. 28°C (82°F) is a test temperature widely used by the industry for production line testing. In recent years, however, the U.S. Department of Energy has favored testing at a higher temperature—one which corresponds to the annual average operating conditions. Therefore, we also show power ratings at Nominal Operating Cell Temperature (NOCT), which is 45°C for our modules.

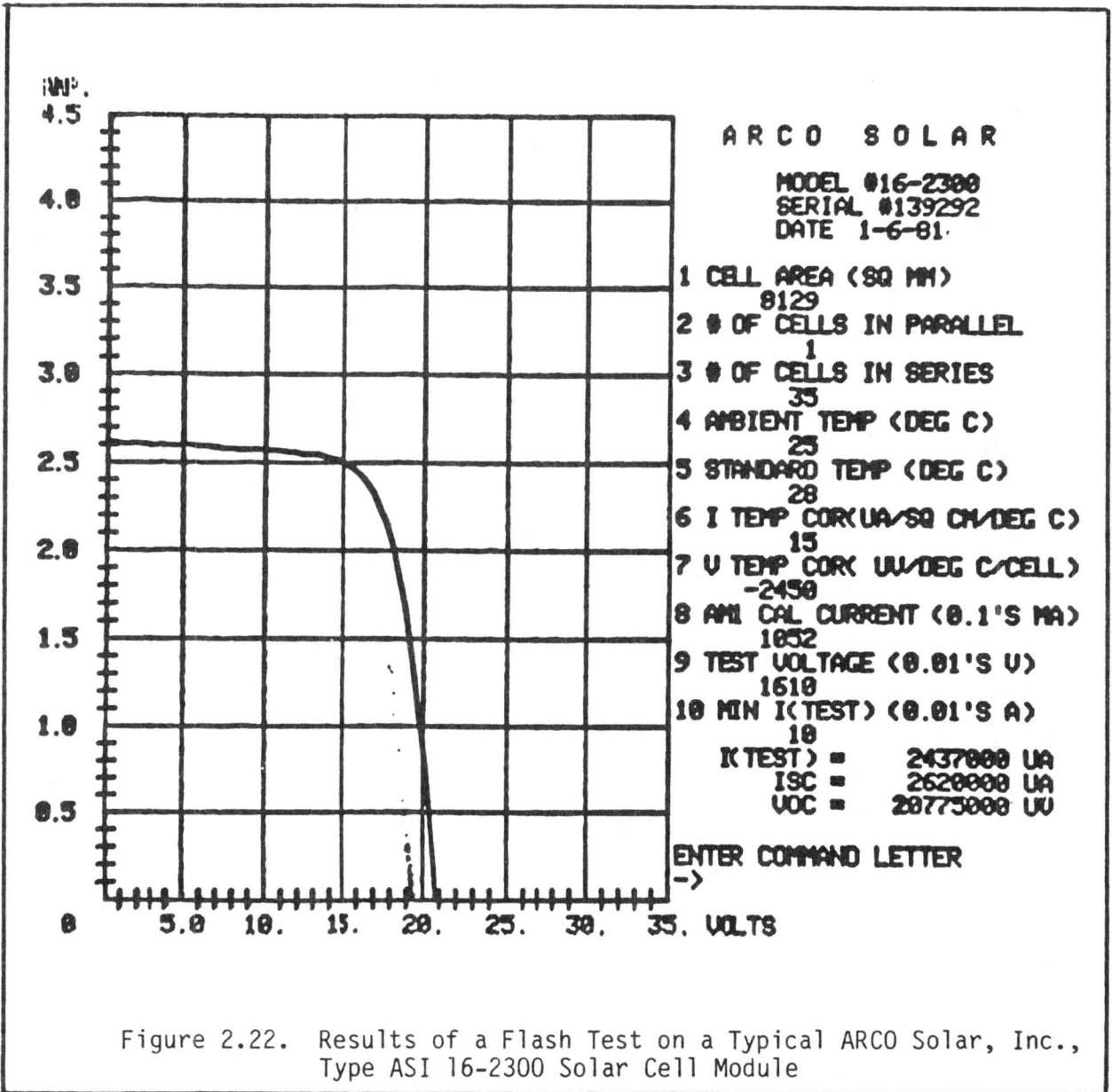
NOCT is defined as cell temperature measured under these conditions:

- Insolation = 80mW/cm²
- Air Temperature = 20°C
- Wind Velocity = 1 meter/second
- Mounting = Tilted, with open back.

Once determined, NOCT can be used as a test temperature for power measurement under 100mW/cm² light intensity (equivalent to noonday sun).

All specifications shown in Tables 1 and 2 are nominal values. Actual production units may show a variation of ± 10%.

Figure 2.21. Data Sheet Describing ARCO Solar Type ASI 16-2300 Solar Cell Module Characteristics



As a result, the electrical connection chosen involved the parallel connection of each group of four modules going vertically up the roof from soffit to ridge. Because the average temperature of each group was the same, further series and parallel connections could be made without violating the previously stated thermal requirement to keep equal the average temperature of series- and parallel-connected groups.

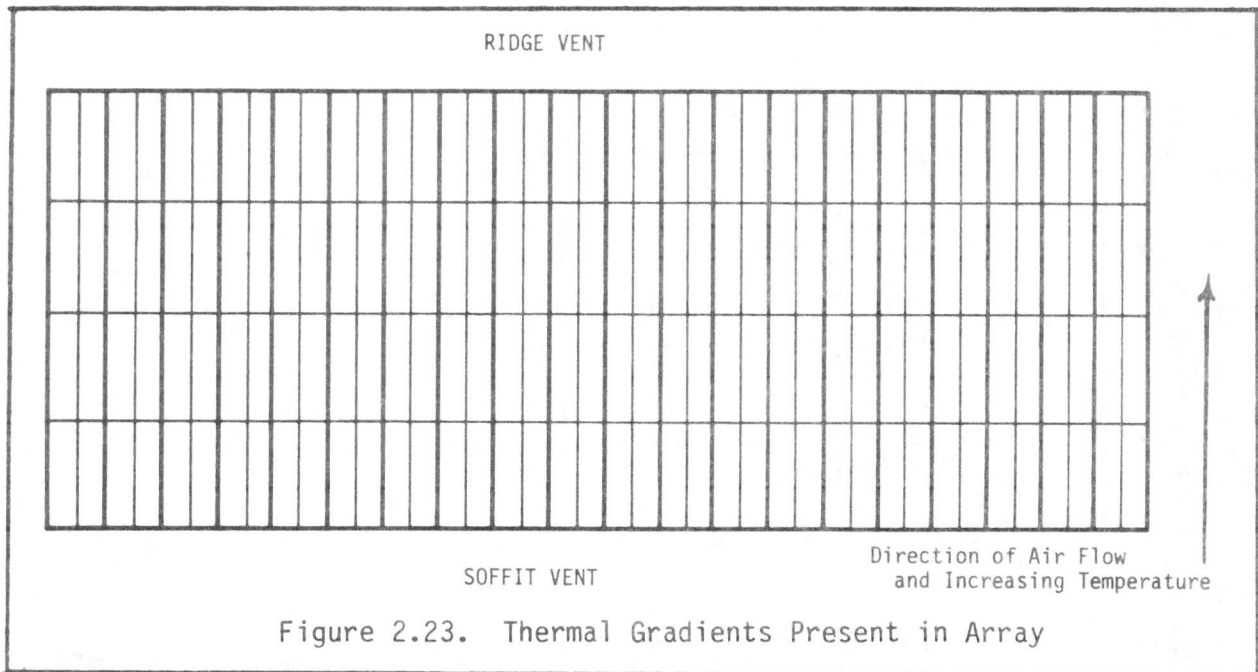


Figure 2.23. Thermal Gradients Present in Array

2.3.2.1.4 Variation of Maximum Power Point with Temperature

The maximum-power-point voltage of a module, and thus of the array, varies with solar cell temperature in a predictable manner; approximately $-0.5\%/^{\circ}\text{C}$. Solar cell temperature varies with ambient air temperature and with the level of the sun's radiation, part of which is absorbed and converted to thermal energy dissipated in the cell.

Figure 2.24 shows plots of array maximum-power-voltage variations with both ambient and average cell temperatures for three different numbers of series-connected modules in the array. The vertical lines at ambient temperatures of -22°C and 42°C define the extremes of the operating ambient temperature range. Where they intersect the lines defining the variations of the maximum-power-point voltages with temperature for the given numbers of series-connected modules, they define the required array-voltage operating ranges.

Shown also in the figure are the upper and lower operating voltage limits of the power conditioner. As can be seen by inspection of the figure, the curve for an array of 13 series-connected modules yields the range of maximum-power-point variations most compatible with the power conditioner operating range. For this reason, an array configuration of 13 modules in series was used.

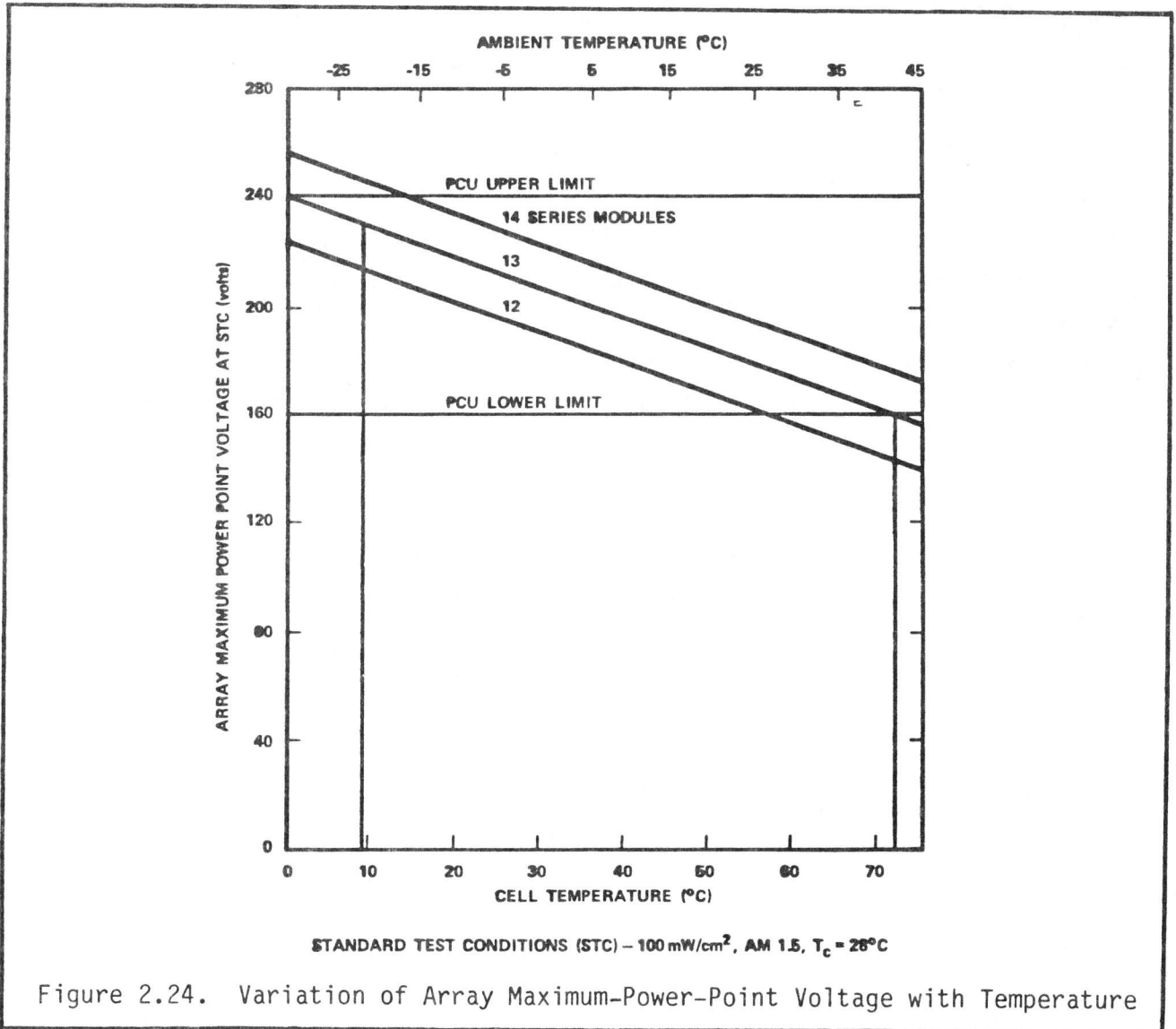


Figure 2.24. Variation of Array Maximum-Power-Point Voltage with Temperature

2.3.2.1.5 Module Series/Parallel Interconnection

In section 2.3.2.1.4, the rationale for selecting the number of series-connected modules was presented. The interrelationship between the input operating voltage range of the power conditioner and the voltage of a single module yielded 13 as the optimum number of series-connected modules.

No such relationship constrains the choice of the number of modules to be connected in parallel. This choice must then be made using some other criterion, such as electrical connection based on symmetry for thermal reasons, economics, or power output.

Shown in Table 2.2 are array output power values for parallel-connected modules ranging from 1 to 16. In addition, those values marked with asterisks can be physically realized using interconnections of four module groups as discussed in section 2.3.2.1.3. The number of modules chosen for parallel connection in the Prototype array was 12, as indicated in the table. Such an array uses 156 (13 x 12) electrically connected modules, although the array contains 160 modules due to geometrical considerations. The total module output power at standard test conditions is 5,775 W. A 12 parallel-connected-module array was chosen over one using 16 for economic reasons and because the 156-module array should produce 50 percent of the required annual electrical load.

TABLE 2.2 ALLOWABLE ARRAY TOTAL POWER OUTPUT (Standard Test Conditions)		
Number of Modules in Parallel	Total Number of Modules in Array	Array Total Power Output (watts)
1	13	481
2	26	962
3	39	1,443
4*	52	1,924
5	65	2,405
6	78	2,886
7	91	3,367
8*	104	3,848
9	117	4,329
10	130	4,810
11	143	5,291
1	12*	5,775
	13	6,253
	14	6,734
	15	7,215
	16*	7,696

*Interconnection arrangements that can utilize groups of four parallel-connected modules

Note 1 - Configuration Selected

Overall I-V characteristics of the 13-by-12 module array based upon published module vendor's data are shown in Figure 2.25. The two curves are for different thermal conditions. The upper curve is for a cell temperature of 28°C and is the standard test condition used by module vendors for production final tests. The lower curve is for nominal operating conditions where the standard thermal environment is used and the cell temperature is allowed to rise to the NOCT value as defined in Section 2.3.2.1.1.

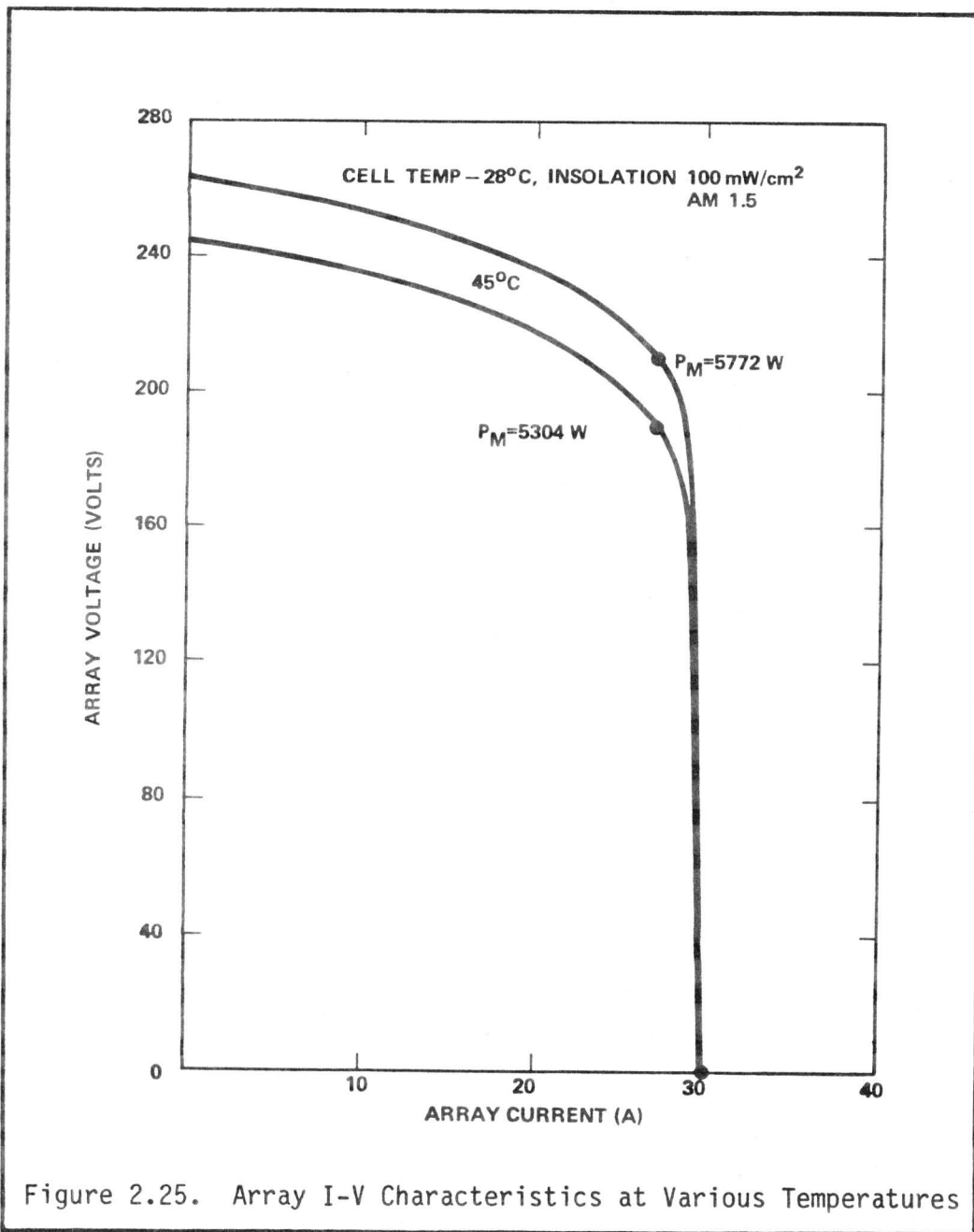
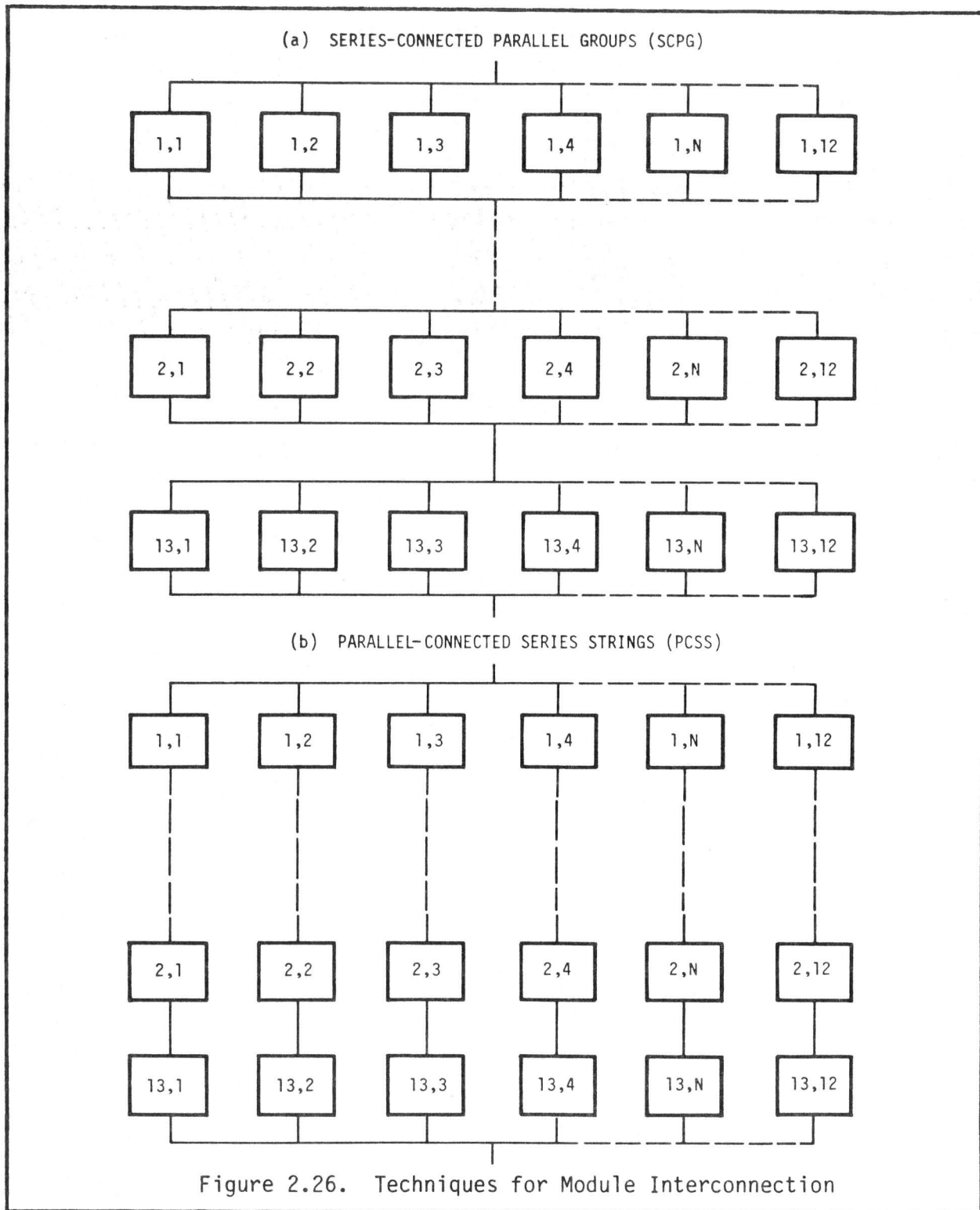


Figure 2.25. Array I-V Characteristics at Various Temperatures

2.3.2.1.6 Choice of Array Configuration Used

Two module interconnection schemes are possible for the selected 13-by-12 module array, illustrated in Figure 2.26. The first interconnection, called



"Series-Connected Parallel Groups (SCPG)" is shown in Figure 2.26(a). In a given row, all 12 modules are connected in parallel, with successive parallel groups connected in series until all 13 module groups are series connected. The other interconnection technique, called "Parallel-Connected Series Strings (PCSS)" is shown in Figure 2.26(b). In a given row, all 13 modules are connected in series and then connected to the dc bus. The remaining 11 series-connected module columns are also connected in parallel across the dc bus.

Early in the design phase, it was decided that standard Type ASI 16-2300 modules would be purchased having permissible parameter variations of ± 10 percent. It was also decided that modules would be placed in the array at random to avoid the cost of added selection and handling. Because the variation in module voltage at a fixed current is generally less than the variation of current at a fixed voltage, the Series-Connected Parallel Group technique was chosen as the one that would result in a minimum mismatched loss. The mismatch loss was later estimated using an array simulation technique, having a computer randomly select groups of modules to form arrays 500 times. The power output distributions of the resulting arrays were then plotted so that a statistical distribution could be obtained. The distribution for the output power of the SCPG arrays was narrow, and the mean was only 50 W less than could be obtained by an optimized, non-random module placement of modules.

2.3.2.1.7 Bypass Diodes

When series-connected strings of modules are connected in parallel across the dc bus, a bypass diode rated at the module current can be connected across each individual module. However, when parallel groups of modules are connected in series, as in the case of the Prototype array, a single bypass diode is needed for each parallel group, and the diode current rating must be equal to the total current produced by all modules in a parallel-connected group.

The bypass diode connection used is shown in Figure 2.27. Each 12-module parallel-connected group is shown divided into three parts, illustrating it is composed of 3 four-module parallel groups, as discussed in section 2.3.2.1.3. As shown in the figure, each parallel-connected module group has a single bypass diode.

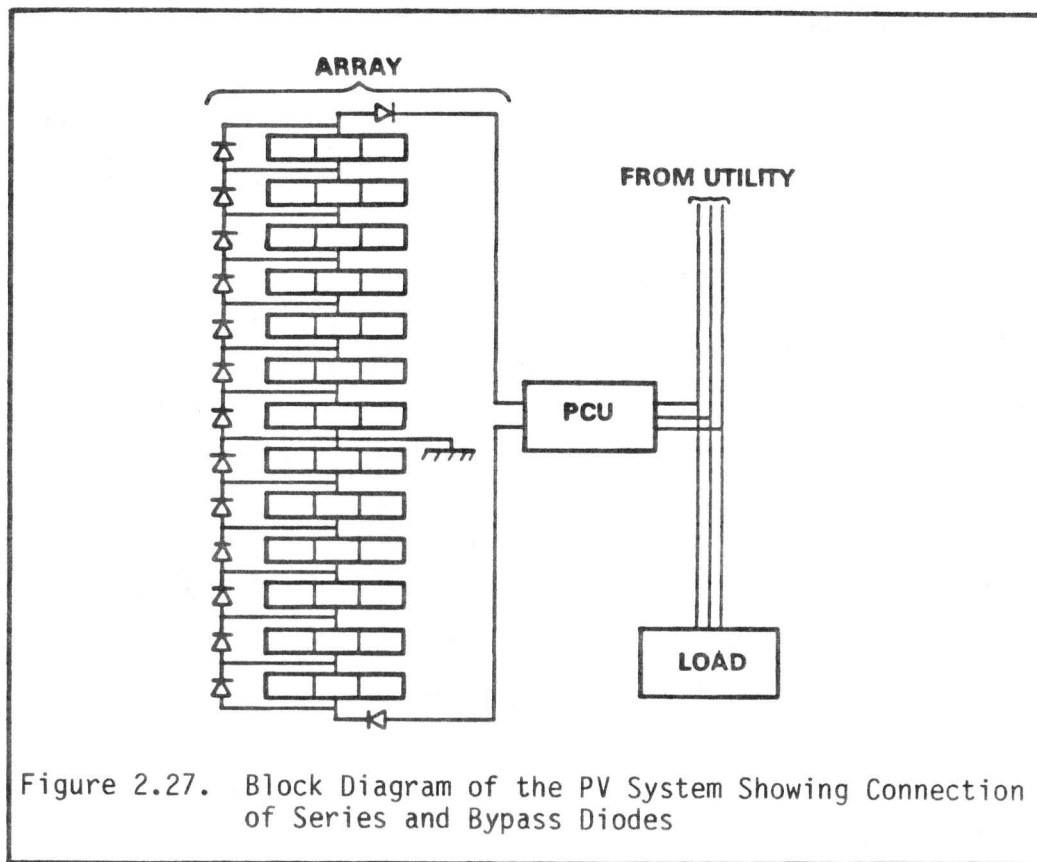
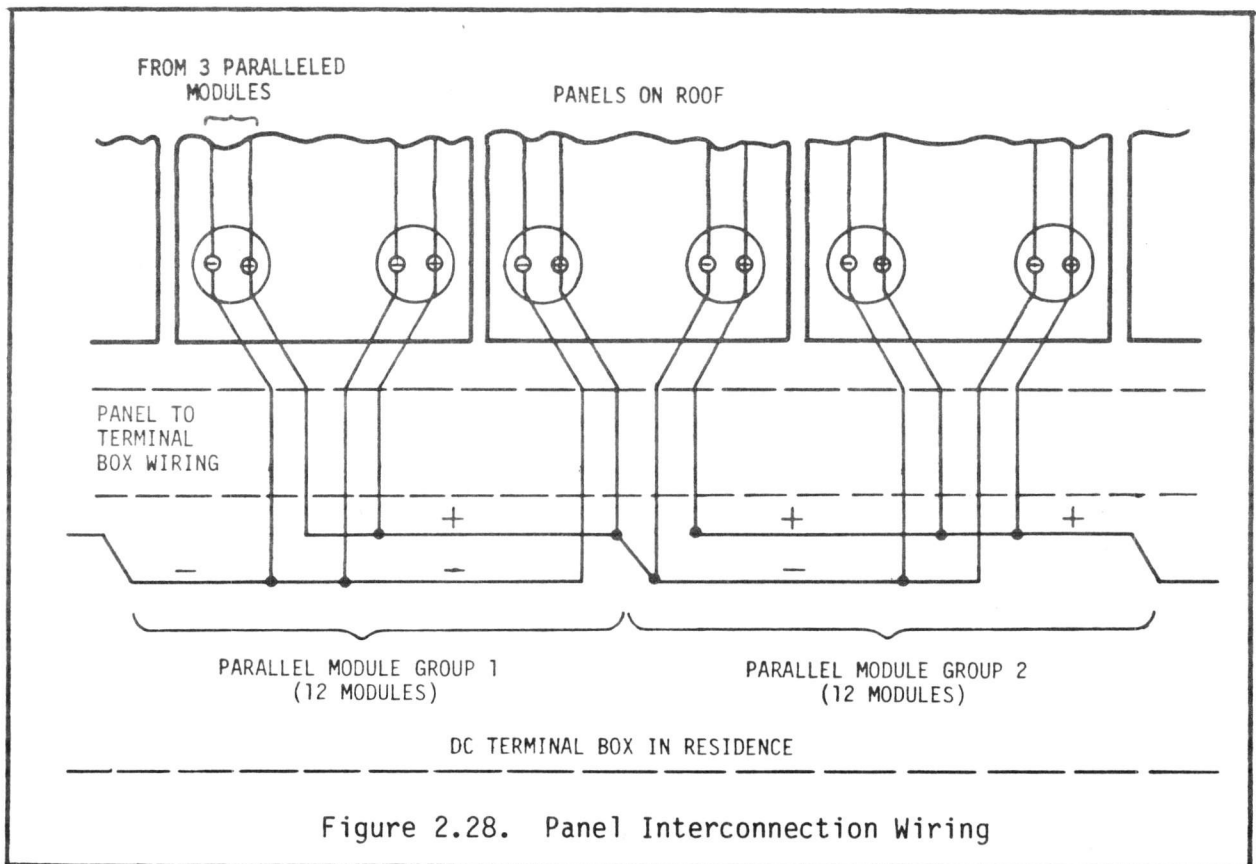


Figure 2.27. Block Diagram of the PV System Showing Connection of Series and Bypass Diodes

2.3.2.1.8 Panel Wiring

Each of the 20 solar panels contained eight solar cell modules mounted two wide by four high. As discussed in section 2.3.2.1.3, the modules in each group of four running from soffit to ridge were connected in parallel. The output of each group of four parallel-connected modules was then connected to a dc terminal box located within the Prototype structure where array series/parallel connections are easily made and changed. The use of a centrally located dc terminal box makes possible electrical measurements on each group of four modules from inside the structure at floor level.

The wiring technique used is illustrated in Figure 2.28 where the upper circular terminal boxes of the groups of four modules are shown. A cable containing four conductors runs from each panel to the dc terminal box within the Prototype structure. As shown in the figure, the outputs of three groups of four paralleled modules are connected in parallel in the dc terminal box. Successive groups of three sets of four paralleled module groups are then connected in series at the dc terminal box. This connection yields the full dc bus voltage.



2.3.2.1.9 Wire Size

Because this Prototype installation was one of the first of its kind, it was important to design it for ease of measurement and repair. Therefore, instead of making all series connections between paralleled groups of modules in the ceiling, the output of each four-module parallel group was brought down to the dc terminal box located inside the Prototype structure. In this box, all series and parallel connections were made using quick-disconnect terminations.

Each panel contained 2 four-module groups, and a single cable containing four conductors was run from each panel to the dc terminal box. Wire size was chosen based on power loss considerations using the following rationale.

The 20 panels making up the array were located side by side on the roof, while the dc terminal box was centrally located inside the building directly beneath the array. An average cable run between the array panels and dc terminal box

was estimated to be 7.3 m (24 ft). Assuming 20 panels and four single conductors per panel, the total length of single conductor wire became 585 m (1,920 ft).

Shown in Table 2.3 are the wiring losses of 585 m (1,920 ft) of cable using three different size conductors; #14, #10, and #8. Assuming a 5,772-W-peak array output, the percentage wiring losses become 8.5, 3.4, and 1.3 percent, respectively. The 8.5-percent loss resulting from the use of #14 wire is excessive considering the cost of the solar cell modules to produce it. The 1.3-percent loss obtained using #8 wire was attractive, but the quick-disconnect, crimp-on lugs used to make series/parallel interconnections inside the dc terminal box would not accommodate this size wire. The use of #10 wire appeared to be the best choice.

In addition to the loss in the panel due to dc terminal box wiring, power is lost in the back-panel wiring connecting the eight modules of each panel into two groups of four modules in parallel. These interconnections were made with #14 wire. The total back-panel wiring power loss of all 20 panels was calculated to be 96 W.

	Wire Size			
	Units	#14	#10	#8
Loss In Single Conductor	W/m	0.845	0.335	0.130
	W/ft	0.257	0.1018	0.0395
Loss in 585 m (1,920 ft) of Single Conductor	W	493	195	75.8
Loss Percentage of Peak Output	%	8.5	3.4	1.3
Cost of Single Conductor Wire	¢/m	22.56	45.62	80.16
	¢/ft	6.86	13.87	24.37

The total dc wiring loss then becomes $195 \text{ W} + 96 \text{ W} = 291 \text{ W}$. The percentage power loss is then 5.0 percent of the peak array output. The percentage of annual energy lost, however, would be less than 5.0 percent because power loss increases as the square of array current. Because peak power is attained only for a relatively short time, the annual energy loss is estimated to be roughly half of the percentage power loss of the peak, or about 2.5 percent. Such a loss was felt to be a justifiable selection based upon a cost/performance trade-off.

2.3.2.2 Power Conditioner

2.3.2.2.1 Power Circuit Technology

The power conditioners available in the market for use in utility-interactive PV systems involve the use of one of two basic power circuit technologies. The voltage-fed, self-commutated technology is utilized in the Abacus Controls Sunverter[®] which uses a transistorized power stage driven by programmed waveform, pulse-width-modulated logic. The current-fed, source-commutated technology is utilized in the Windworks Gemini power conditioner, which utilizes a thyristor bridge in the power circuitry.

The attributes of the Abacus Controls, Inc., Sunverter[®] are low harmonic distortion and near unity power factor. Its disadvantage is that it is expensive. On the other hand, the major attribute of the Windworks Gemini power conditioner is that it is less expensive than the Abacus Sunverter[®], but its disadvantages are its higher harmonic distortion and lower power factor. The Abacus Controls Sunverter[®] was selected because of the higher output power quality, which justified the higher cost.

As initially purchased, the Abacus Sunverter[®] included maximum-power-point tracking implemented in closed-loop fashion by sensing the real power delivered at its output. A later modification installed by the manufacturer changed the method of implementing maximum-power-point tracking from closed-loop power sensing to open-loop power control using a pilot cell separate from the solar cell array.

All the necessary supervisory control features were incorporated in the control circuits of the power conditioner. These involved turn-on in the morning with automatic synchronization prior to line-tie and turn-off at night.

2.3.2.2.2 Performance

The performance of the Abacus Sunverter[®] is summarized in Table 2.4. The input voltage range was specified by the manufacturer and was a criterion used during the design of the array interconnection configuration. The output voltage of 240 V ac was also specified by the manufacturer. Harmonic distortion is principally in the ac output voltage, and the total is less than 4 percent. The unit features include maximum-power-point tracking, automatic startup and shutdown, and overcurrent protection. In addition, it includes dc isolation between input and output, and connections to the ac lines are made using a contactor providing a positive disconnect when turned off.

Appendix B contains a portion of the technical manual that explains the installation and operation of the Abacus Sunverter[®].

2.3.3 GROUNDING

On the dc side of the system all metal parts associated with the array are grounded. This includes the doublet frames, which are connected to adjacent doublet neighbors and then to the main panel frame, and the main panel frames, which are connected to their adjacent panel neighbors. A single ground wire near the center of the array then connects the panel frames to earth ground.

● Input Voltage Range	160-V to 240-V dc
● Output Voltage.	240-V ac
● Power Rating.	6-kW max
● Voltage THD	<4%
● Utility Paralleling	Included
● Maximum Power Tracking.	Included
● Automatic Startup and Shutdown.	Included
● Output Overcurrent Protection	Included

The center point of the array is grounded to establish a dc side ground point, which minimizes the peak dc voltage stress to ground. The ground connection is made at the array using the same wire that grounds the main panel frame. A #10 wire is used for the array and panel frame connection to ground.

The metal cabinet of the power conditioner and all other metal enclosures within the building are also grounded.

On the ac output side, the three-wire utility service brought into the Prototype includes a neutral wire that by code must be earth grounded at the load center. This is the only ground on the ac side of the system.

The power conditioner used includes internal dc isolation, making it possible to establish independent grounds on the dc and ac sides. As discussed, the dc ground is at the center of the array, while the ac ground is at the neutral line of the utility service.

Although the array would most likely not survive a direct lightning strike, the system is protected against possible damage due to currents induced from nearby strikes. Two zinc oxide resistors are connected between the positive and negative buses and ground to absorb induced transient energy. In addition, all exterior roof ridge flashing is also earth grounded.

2.3.3.1 DC Grounding

Because the power conditioner used provides dc isolation between input and output, it is possible to ground any point on the dc circuitry. In order to minimize the peak dc voltage stress to ground, the center of the array was grounded as shown in Figure 2.29. Using this technique, the positive bus is nominally 117 V above ground while the negative bus is nominally 100 V below ground.

2.3.3.2 Use of Series Blocking Diodes

Series blocking diodes are necessary to prevent the backfeed of energy from the power conditioner to the solar array. Because the center point of the array is

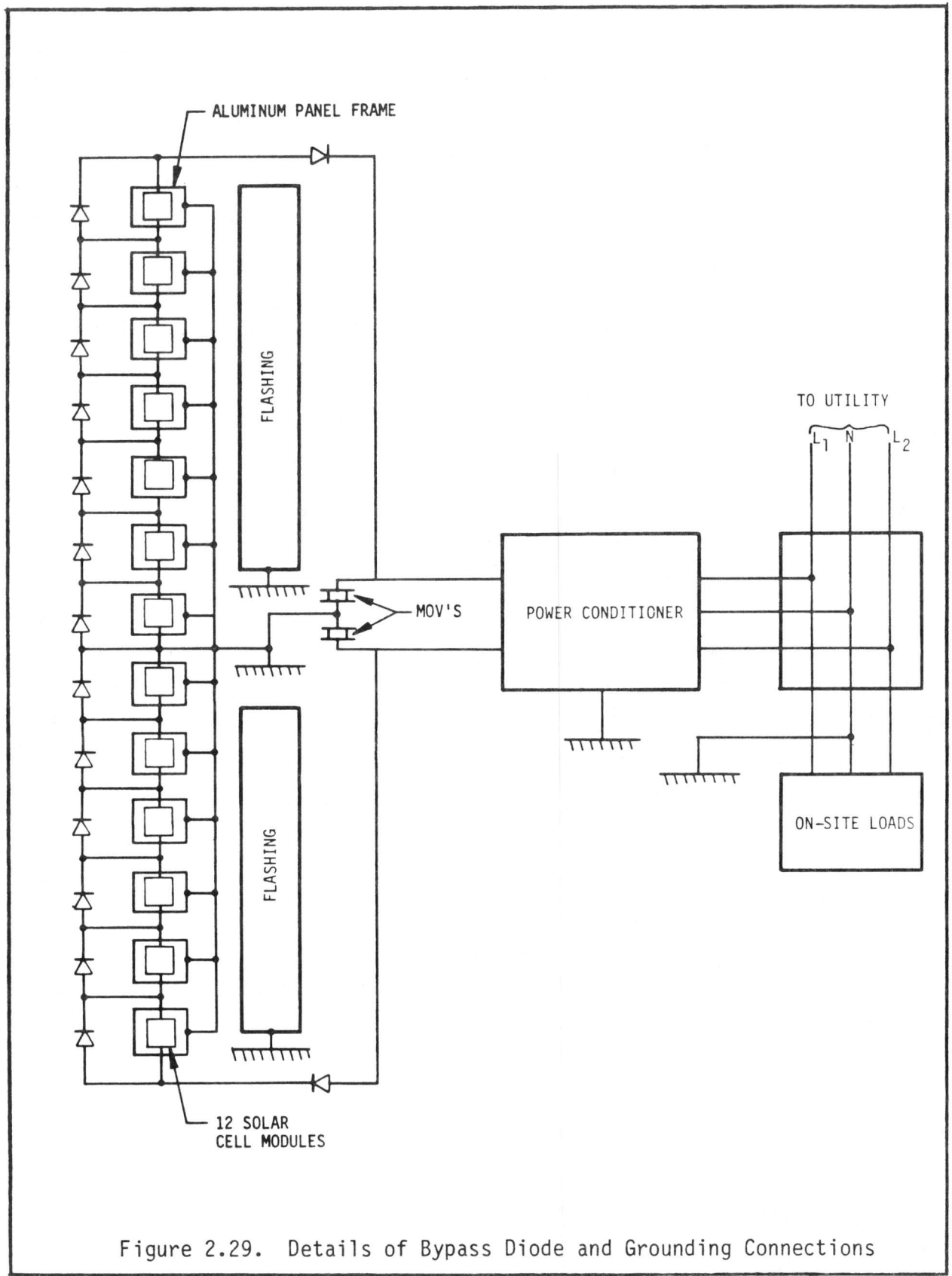


Figure 2.29. Details of Bypass Diode and Grounding Connections

grounded, series blocking diodes are used in both the positive and negative dc buses as shown in Figure 2.29.

2.3.3.3 Surge Suppressors

Nearby lightning strikes induce voltage surges that could present excessive voltages between the solar cell strings within the modules and the grounded doublet frames. They could also introduce transients into the input of the power conditioner that could be destructive. As shown in Figure 2.29, metal oxide varistors are connected from each dc bus to ground to dissipate surges under transient voltage conditions.

2.3.3.4 AC Grounding

The three-wire incoming 120/240 V residential ac service contains a neutral wire, and the codes require that the neutral be earth grounded at the residential load center. This connection establishes the ac ground as shown in Figure 2.29.

2.3.3.5 Grounding of Exposed Metal Parts

Pairs of modules are housed in aluminum doublet frames mounted between insulating rubber gaskets in larger aluminum panel frames holding four doublets. During panel fabrication, ground wires were connected between each of the four doublet frames within a panel and then to the panel frame. After installation, all panel frames were wired together and connected to the ground wire run to the center of the array. The metal flashing at the ridge was also grounded.

All metal cabinets, boxes, and conduits are grounded in all locations inside and outside of the Prototype.

2.3.4 POWER CONDITIONER INSTALLATION

In installing the Abacus Sunverter[®], the power conditioner was placed free-standing in a room near but not up against a wall. Electrical connections were made to the power conditioner using flexible BX metal sheathed cable. Two separate BX cables were run, one to carry the dc input wires, and the other for the output wires.

3.0 PROTOTYPE FABRICATION HISTORY

This PV system is the second of its kind to use the panel system developed by General Extrusions to mount PV modules. As a result, problems solved during design and fabrication of the first system simplified installation of this system. Future systems utilizing this basic design can be produced much more efficiently making use of the experience gained from these programs.

3.1 ARRAY

3.1.1 MODULE PROCUREMENT

The type of solar cell module used was a variation of the ARCO Solar, Inc. industrial version, which included a glass superstrate surrounded by an aluminum mounting frame. The aluminum frame was fastened to the glass superstrate using butyl rubber applied hot. The butyl rubber served two purposes. It acted as an adhesive to hold the aluminum frame onto the glass while permitting differential expansion, and secondly it served as an edge sealant to prevent the penetration of moisture into the edge of the solar cell laminate between the glass and the various organic materials applied to the back surface of the glass.

The first problem encountered was that a standard module with a frame could not conveniently be incorporated into the aluminum panel system. Therefore, it was decided that laminates without frames would be used. After an unsuccessful attempt to remove the aluminum frame from a standard production module, the vendor was asked to supply modules taken from the production line before the edge seal was applied. The vendor was concerned about long-term degradation of modules shipped without edge sealing. The solution agreed upon was to ship individual module laminates in sealed plastic bags to the General Extrusions plant where Goodyear Pliogrip would be applied to seal the edges.

The panel system used was developed by General Extrusions for solar thermal panel construction. In such an applications, double rubber gaskets hold flat plates of glass or plastic material that serve as the watertight seals of the array. To properly seal such joints, at least 1.6 cm (5/8 in.) of glass edging must be clear and available for the gaskets to seal against.

The ARCO solar cell modules used, however, were designed to permit the edges of the solar cells to come within 0.6 cm (1/4 in.) of the edge of the glass. To alleviate this problem, a doublet frame was designed to serve two purposes. It held two modules in a frame that included a 1.6 cm (5/8 in.) aluminum projection suitable for normal gasketing, and secondly, the solar cell modules were fastened into the doublet frame with Pliogrip adhesive, which served to provide an edge seal preventing the intrusion of moisture into the laminate.

The ARCO industrial module includes a thin steel foil as one of the layers of the laminate to minimize the penetration of moisture through the back into the solar cells. Because the foil runs to the edge of the glass, the possibility that it might come into contact with the aluminum doublet frame and thus present a ground plane within a few mils of the backs of the solar cells was considered. Such a module might then exhibit a low breakdown voltage between the solar cells and ground.

Since there appeared to be no simple way to eliminate this possibility, it was decided that the doublets and panels would be assembled in the normal way and then tested for breakdown strength. A sample of five doublets was tested for isolation to ground to a voltage of 1,500 V, and all passed the test showing no evidence of breakdown. The remaining doublets were tested to a voltage of 250-V dc and all passed without difficulty. In view of the fact that 125 V is the highest dc voltage stress to ground in the system, 250 V appeared to be a good compromise between ensuring a sufficient voltage withstand capability and possibly causing a doublet to short to ground during the test at a voltage far in excess of that which will normally occur in the system. In residential application where excessive moisture is not a problem, the metal foil can be eliminated from the laminate, removing the source of the potential problem.

The panel was designed around the size of the ARCO industrial module because a special module made to our dimension would have been quite expensive. As a result, the panel design arrived at called for a rafter center-to-center spacing of 71.1 cm (28 in.). Because it is not a standard rafter spacing commonly used in the construction industry, it appears that this might be an impediment to the use of this concept. Therefore, if a module 55.6 cm (21.5 in.) wide could be obtained, a panel suitable for mounting on rafters spaced 60.9 cm (24 in.) on center, which is an industry standard, could be made.

Other minor manufacturing problems noticed included chips in the edges of the glass superstrate, varying spacing between the cell edge and glass edge, and varying laminate thickness near the edge of the glass. On just a few of the modules, loose terminal posts and loose terminal junction boxes were found.

Modules were purchased to the manufacturer's data sheet parameter tolerances, which were ± 10 percent. No additional parameter screening was performed. Modules were then selected randomly for placement in panels during fabrication. Array performance measurements showing minimal mismatch loss appear to verify computer estimates mentioned earlier.

3.1.2 PANEL FABRICATION

All back panel wiring that interconnects the eight modules contained in a panel into two groups of four was performed at the General Extrusions, Inc., plant where the panels themselves were fabricated and the solar cell modules installed. The layout of the back-panel wiring is shown on Westinghouse Drawing Number 103E039 contained in Appendix A. All back-panel wiring cables were supplied to General Extrusions by Westinghouse precut to length with lugs crimped on the ends ready for installation.

All module-to-module jumper cables were made longer than necessary to facilitate doublet replacement from the outside in the field. When a doublet is replaced, the exterior gasket is removed and the doublet lifted out of its position by a distance sufficient to provide access to the back so that the electrical connections can be loosened and the wires removed. All

module-to-module interconnection cables were made sufficiently long to provide such access.

In addition to the interconnection cables that joined the outputs of the modules in the desired fashion, the back-panel wiring included means to ground the metal doublet frames. This was accomplished by connecting a ground wire from doublet to doublet and then connecting it to the main panel frame as shown in Drawing Number 103E039. The doublet grounding wires were secured to the doublet aluminum frames by bolts threaded into rivnuts inserted into the doublets during fabrication.

3.1.3 SHIPPING

Modules were shipped from the vendor's plant to the General Extrusions plant in standard cardboard shipping cartons four to a box, side by side, separated by polyurethane foam edge separators in each of the four corners. Each module was sealed in its own plastic bag before being placed in a shipping carton.

A number of cartons were then metal-banded to a wood fork truck pallet, and the pallets were shipped by motor freight. Although a few bumps and dents were noticed on the outsides of the boxes when they arrived at the General Extrusions plant, none of the modules was damaged.

Finished panels were shipped to the job site using a motor freight hauler. The 20 panels were built into two wooden support structures, which were loaded into a conventional trailer. No damage was incurred during panel shipment. The array shipping cost between Youngstown, Ohio, and Las Cruces, New Mexico, was \$4,804.00.

3.1.4 INSTALLATION TASK/TIME BREAKDOWN

The 20 panels fabricated at the General Extrusions plant were shipped by truck to the job site, where they were installed in May 1981. The installation was completed without difficulty within one working day utilizing workmen who had no experience with solar panels. The procedure followed during installation is shown in the series of photographs in Figures 3.1 through 3.7.

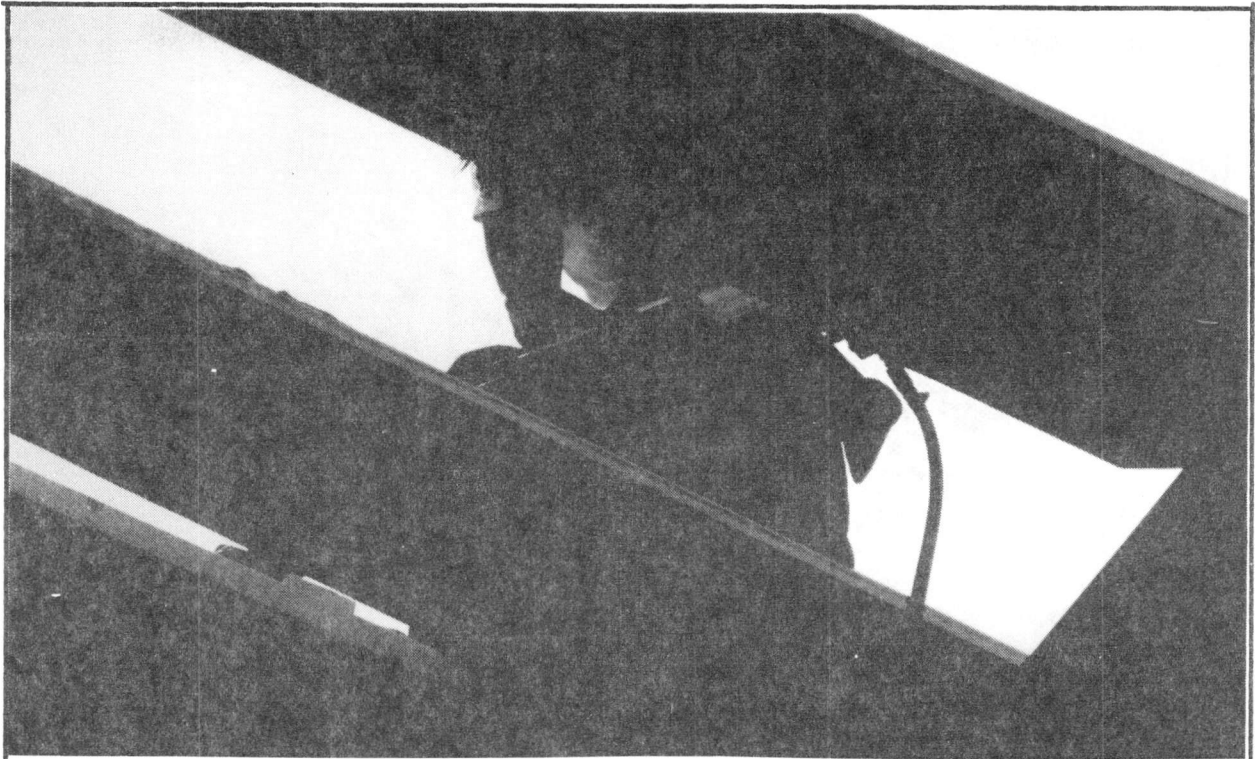


Figure 3.1. Caulking of Rafter Riser

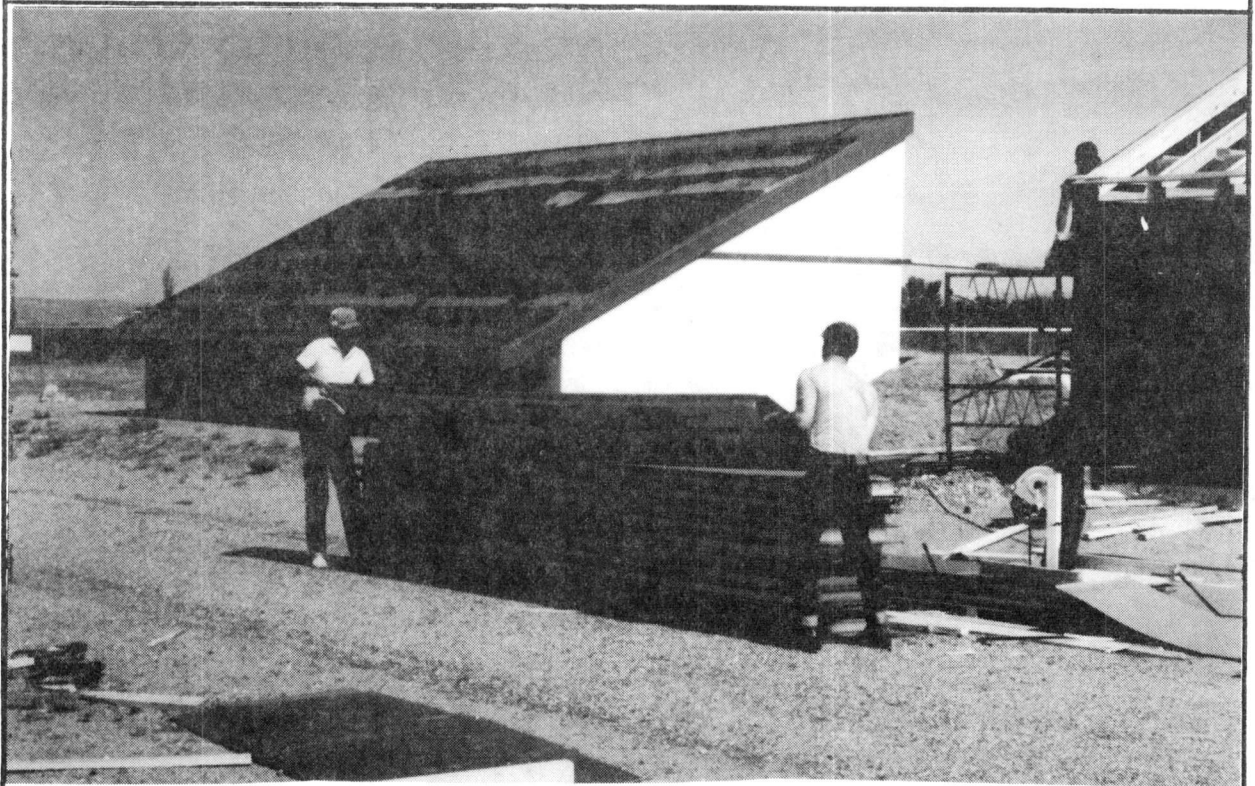


Figure 3.2. Lifting First Panel From Uncrated Stack

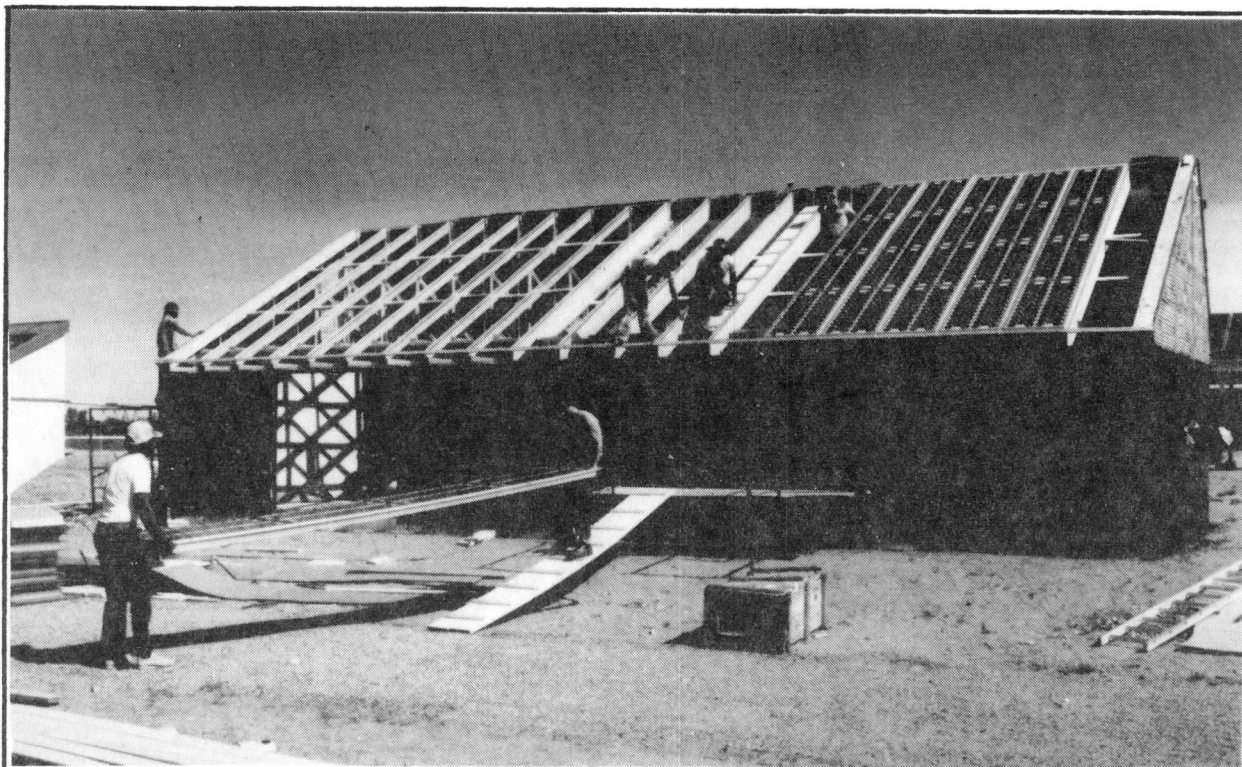


Figure 3.3. Panel Being Carried from Stack to Structure

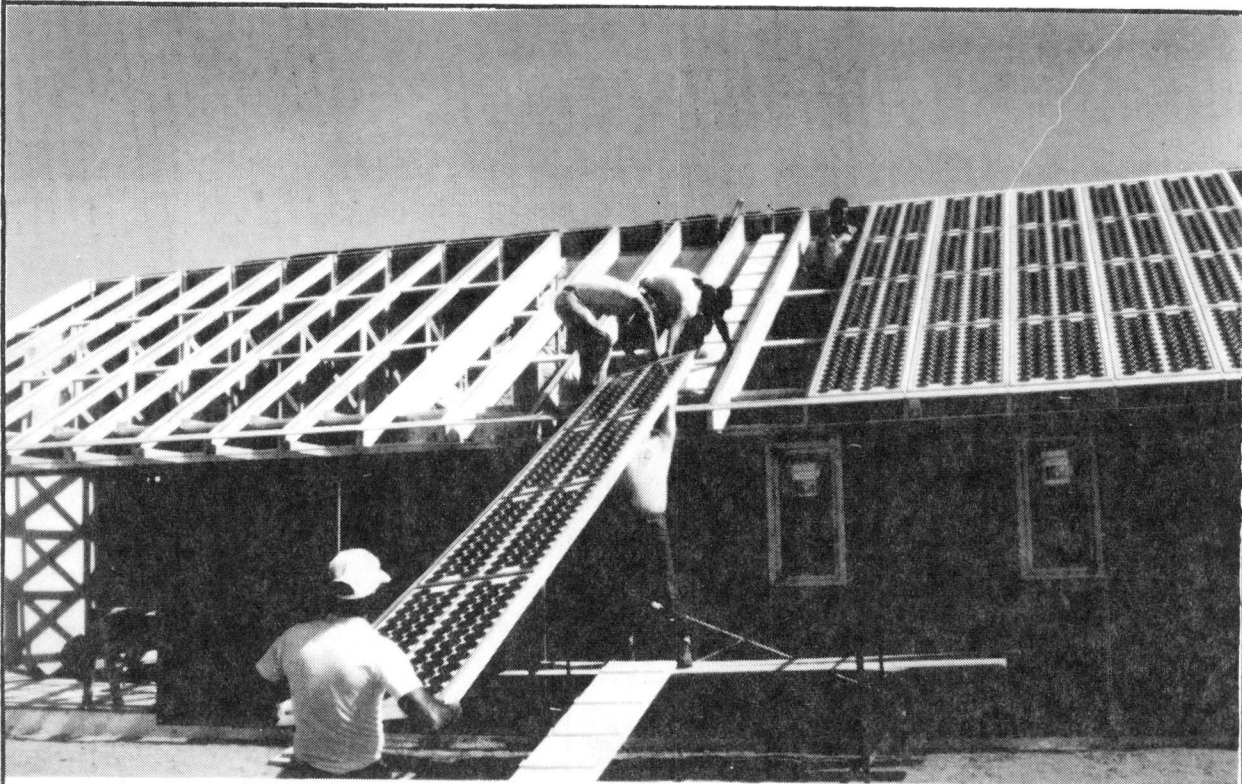


Figure 3.4. Panel Being Hoisted to Roof

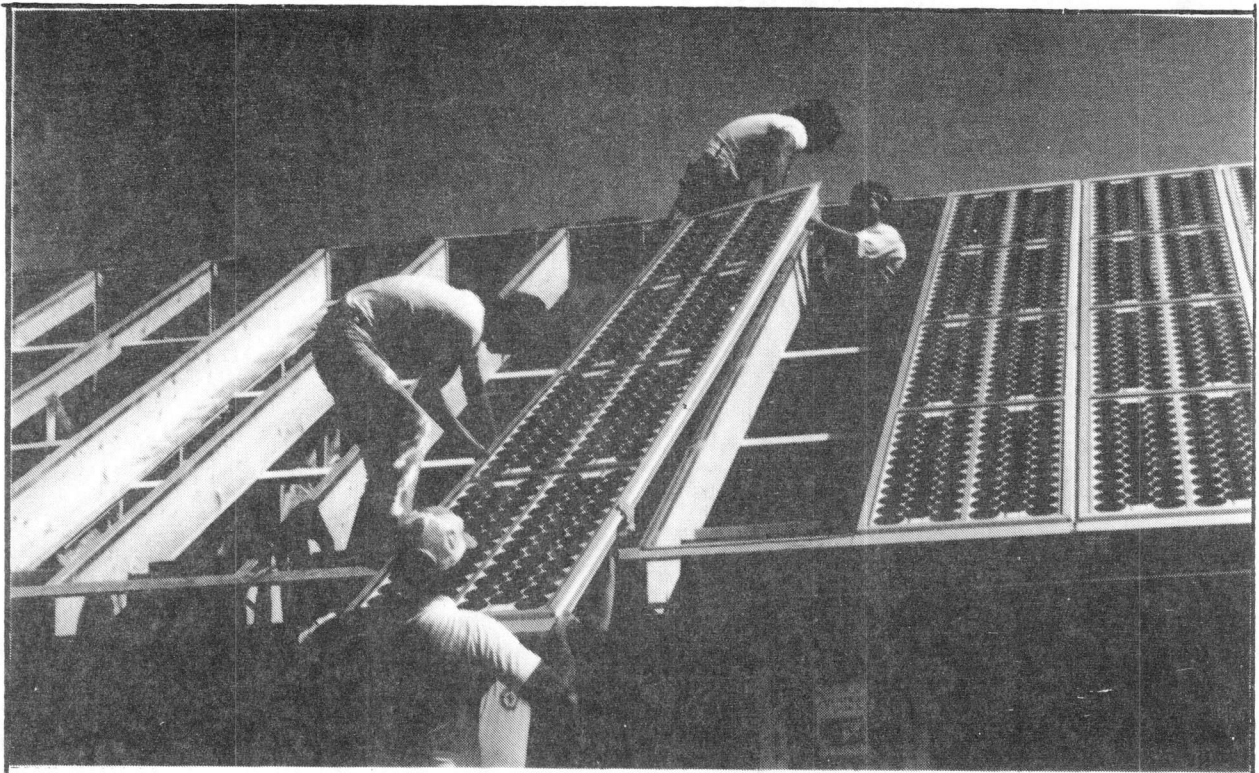


Figure 3.5. Panel Being Aligned for Installation

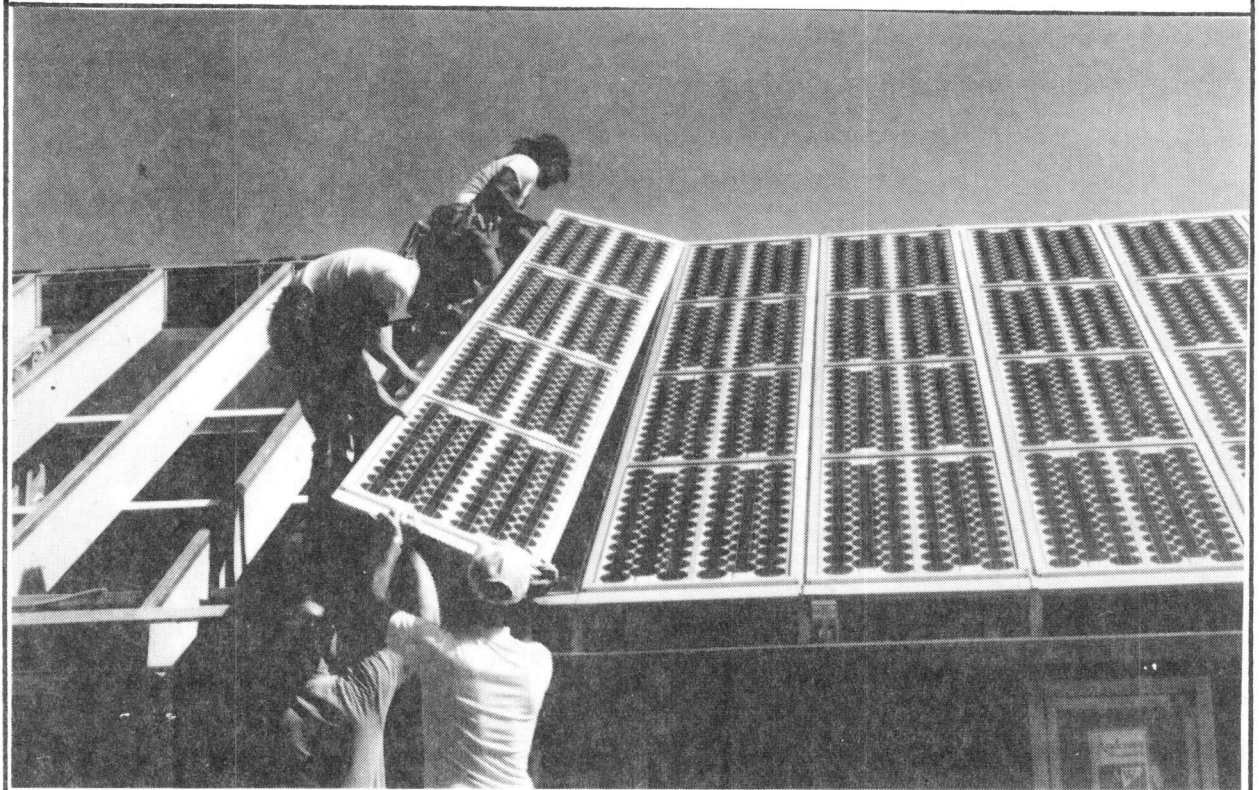


Figure 3.6. Panel Being Installed Between Rafters

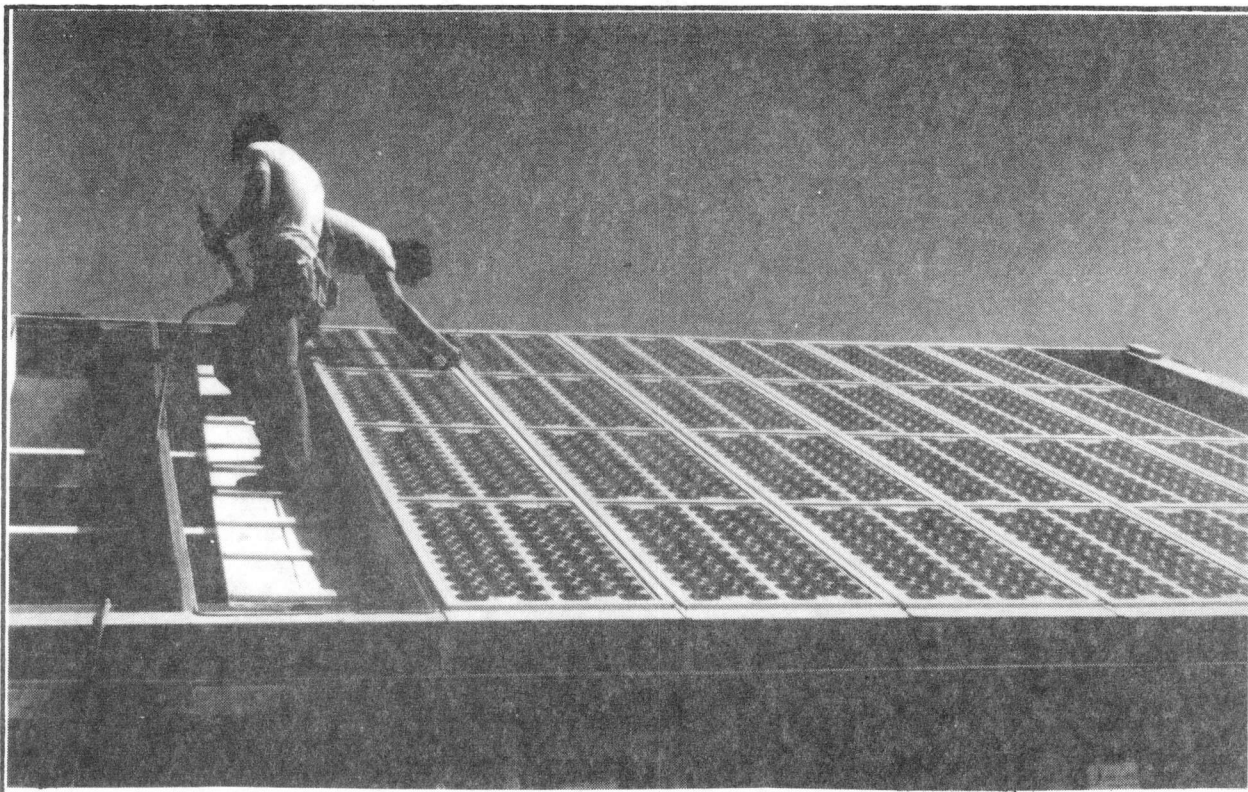


Figure 3.7. Panel Cap Strips Being Installed

Array installation included mounting on the roof 20 panels, each containing eight solar cell modules. Shown in Figure 3.8(a) through (d) are the serial numbers of all modules identified by panel letter designation and by position in the panel. Panel letter code designations are identified on Westinghouse Drawing Number 103E075 contained in Appendix A.

Array wiring consists of module-to-panel wiring, panel-to-dc terminal box wiring, and dc terminal box interior wiring. Each of these was accomplished as described in the following paragraphs.

The outputs of each of the two groups of four paralleled modules in each panel were connected to the dc terminal box within the Prototype using a four-conductor cable with #10 wires. A photograph of the interconnections made in the module junction box where the four-conductor cable from the dc terminal box connects to the panel is shown in Figure 3.9. The four-conductor cable has a black sheath while the connections from the two other groups of paralleled modules are made with the two other entering cables, which have white sheaths. Details of the connections made in the junction box are shown schematically on Westinghouse Drawing Number 103E039 contained in Appendix A.

PANEL A		PANEL B		PANEL C		PANEL D		PANEL E	
139310	139376	139444	139396	139384	139394	139277	139340	139382	139429
139279	139255	139383	139377	139312	139331	139453	139463	139357	139333
139421	139420	139370	139281	139374	139398	139468	139354	139301	139353
139397	139356	139344	139355	139426	139285	139286	139365	139389	139433

Figure 3.8(a). SW Panel (A-E) Locations - Inside View

PANEL F		PANEL G		PANEL H		PANEL J		PANEL K	
139321	139346	139257	139419	139253	139300	139366	139343	139278	139269
139325	139339	139367	139342	139315	139299	139263	139256	139334	139280
139309	139298	139276	139249	141881	141873	139335	139329	139369	139289
139439	139341	139316	139360	139348	139405	139446	139372	139358	139364

Figure 3.8(b). SW Panel (F-K) Locations - Inside View

PANEL L		PANEL M		PANEL N		PANEL P		PANEL R	
139266	139248	139415	139379	139359	139339	139271	139409	139351	139268
139363	139375	141867	141891	139246	139297	139292	139295	139291	139254
139401	139319	139330	139403	139461	139473	139250	139245	139332	139449
139290	139269	139296	139304	139404	139424	139381	139322	139244	139317

Figure 3.8(c). SW Panel (L-R) Locations - Inside View

PANEL S		PANEL T		PANEL U		PANEL V		PANEL W	
139287	139273	139302	139252	139392	139393	141897	141870	SPARE 139399	139320
139904	139921	139428	139412	139294	139293	139371	139347	SPARE 139270	139288
139458	139265	139489	139407	139452	139378	139350	139324	SPARE 139272	139284
139251	139337	139259	139283	139274	139275	139328	139349	SPARE 139442	139425

Figure 3.8(d). SW Panel (S-W) Locations - Inside View

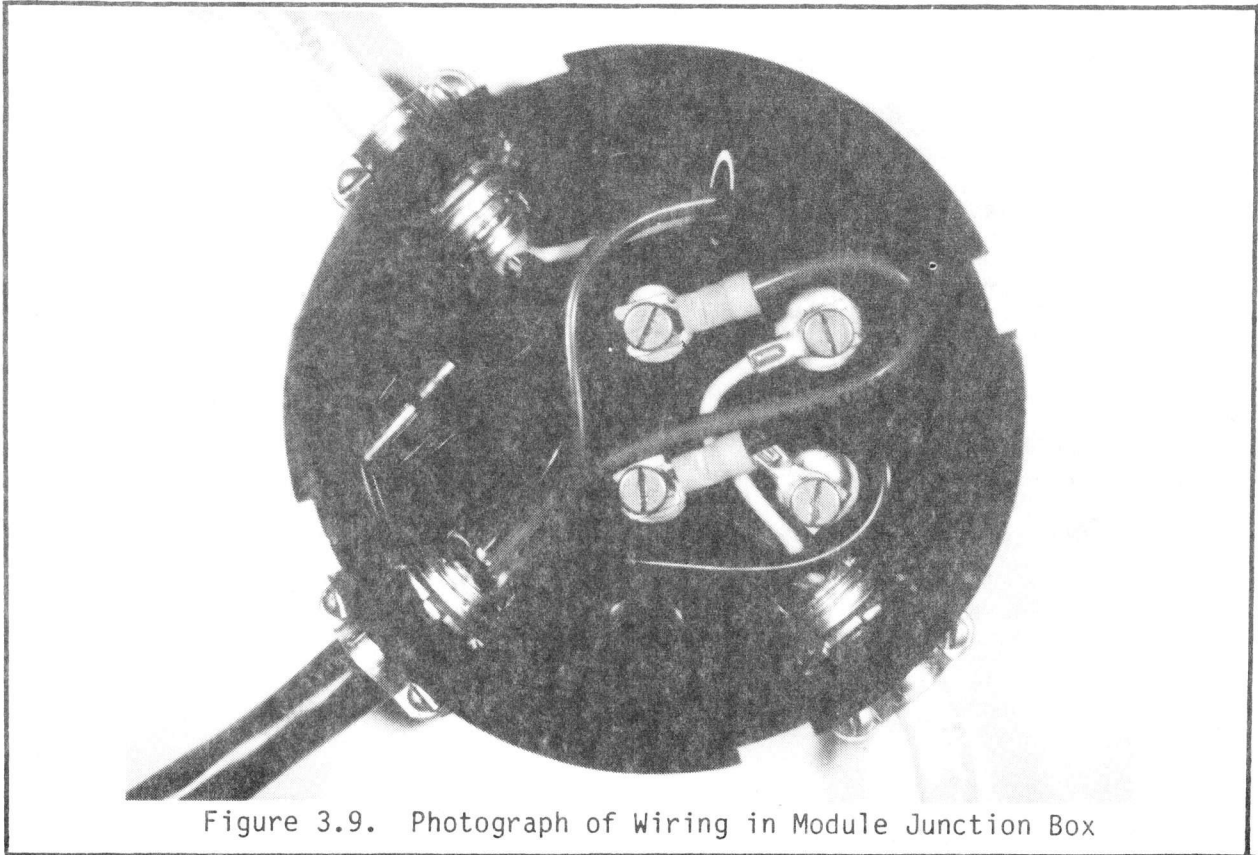


Figure 3.9. Photograph of Wiring in Module Junction Box

The four wire cables from all panels run to the dc terminal box, where they are connected to positive and negative terminal strips using quick-disconnect, push-on connectors.

A schematic diagram showing details for panel-to-dc terminal box wiring is shown in Westinghouse Drawing Number 103E075. With this connection, the output of each four module parallel group is accessible at the dc terminal box for tests or any modification to array wiring.

The dc terminal box provides a convenient terminal point for the outputs of all 40 groups of paralleled modules. The necessary parallel and series connections that form the module groups into the full array were made in this box as well. Another function performed by the dc terminal box is to serve as a location where the heat sinks for the bypass diodes are mounted.

A mechanical drawing of the dc terminal box is shown in Westinghouse Drawing Number 103E087, and a photograph of the finished terminal box is shown in Figure 3.10. The ventilation grills on top and bottom in line with the bypass diode heat sinks were added after worst-case thermal tests on the box without ventilation showed that the diode junction temperature rise would be excessive without some form of ventilation.

All wiring necessary to parallel and series connect the module groups and to connect the bypass diodes was done on the terminal strips. Modular group paralleling was accomplished with solid metal jumpers formed to interconnect terminals side by side on a terminal strip. Series connections of paralleled module groups were made with #12 wire jumpers running from one terminal strip to another using push-on, quick-disconnect connectors. Connections from all bypass and series diodes were made using #12 wire, with push-on, quick-disconnect connectors at the terminal strips.

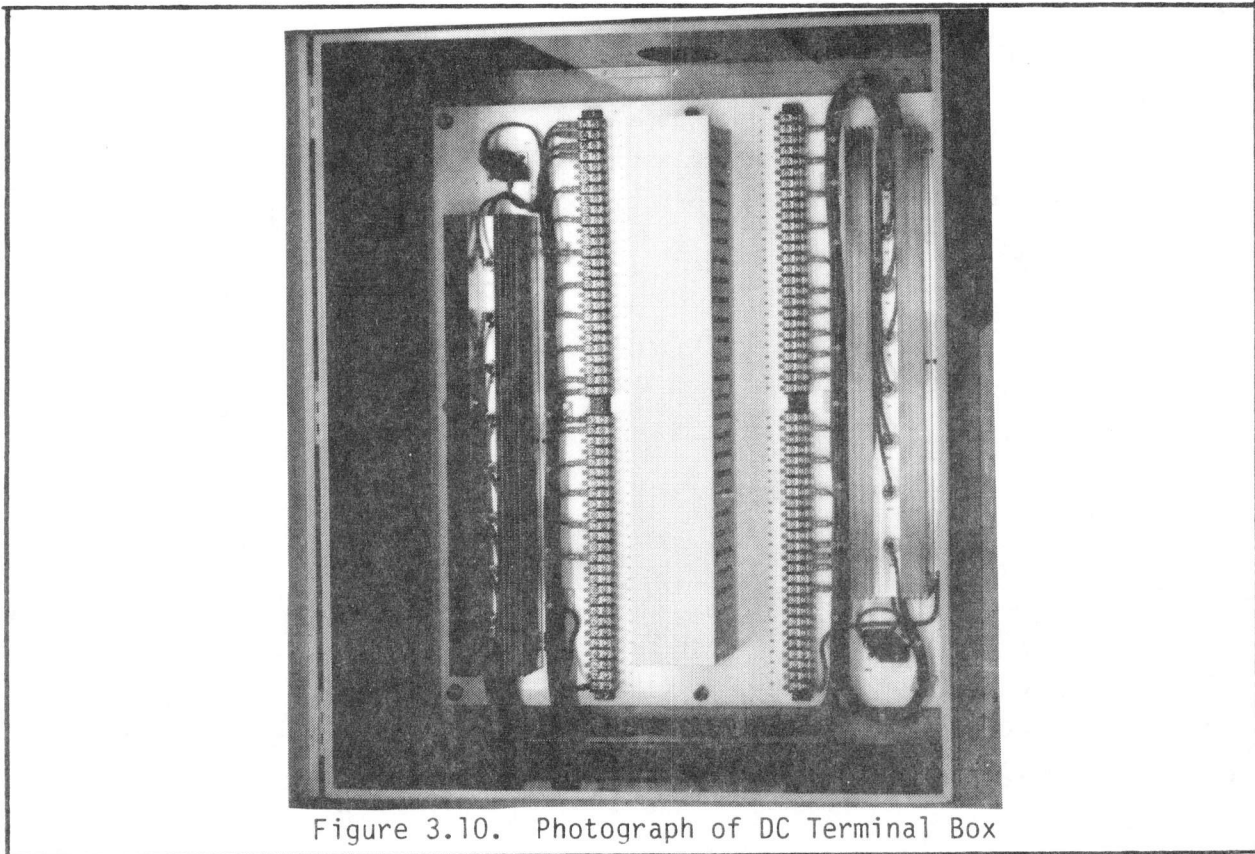


Figure 3.10. Photograph of DC Terminal Box

The array installation and wiring costs are as follows:

Array Installation Material	\$ 7,985
" " Labor	3,204
Displaced Labor Credit	- 314
" Material "	- 575
Array Wiring Material	819
" " Labor	<u>2,187</u>
 Total	 \$13,306

After installation of the array and completion of all panel wiring, the building interior was finished. The last portion of the interior to be completed was the ceiling behind the array. Rigid Styrofoam insulation was cut and pressed into place behind the array while care was taken not to impede the flow of air through the 15.2 cm (6 in.) channel formed between the back surface of the array and Styrofoam. Finally, conventional wallboard was attached to the back surface and finished.

Site visits by the design architects and engineers as well as the contractor and local architect's representatives indicate that the watertight membrane is still intact. Due to the double and triple redundancy associated with the panel and array design, violation of the watertight integrity is felt to be quite unlikely to happen.

3.2 POWER CONDITIONER

3.2.1 MANUFACTURER/PROCUREMENT

No problems of any significance were encountered during manufacture or procurement.

A subsystem interface problem identified during testing of the Northeast Residential Experiment Station (RES) Prototype completed earlier but still present at the Southwest Residential Experiment Station (RES) Prototype involved the dc operating voltage range. The power conditioner vendor specified the dc voltage operating range as 160 V to 240 V. The power conditioner automatically turns off and stays off as long as the dc voltage is outside this range.

The solar cell array was designed so that as the array maximum-power-point voltage varies with ambient temperature, its variation is symmetrically centered about the power conditioner operating voltage range.

However, what was neglected was the fact that the array open-circuit voltage is roughly 1.3 times its maximum power voltage. Therefore, on cold days when the maximum-power-point voltage is close to the high end of the operating voltage range, the open-circuit voltage was out of range, making it impossible to start the system. This problem has been solved by Abacus by introduction of a modification that permits higher voltage startup.

A second subsystem interaction problem discovered during testing at the NE RES Prototype was that of on/off cycling of the power conditioner early in the morning and late in the evening or at other times of marginal insolation. The process was as follows. Even though the insolation level was low, the input voltage reached the turn-on limit of 190 V, causing the power conditioner to begin the turn-on sequence. The logic power supplies turned on, initiating a 30-second time delay. When the time delay expired, the logic caused the ac line contractor to close, causing a minimum ac current to flow into the ac line/on-site load connection. The current caused a corresponding minimum dc current to be drawn by the input of the inverter. Because the level of insolation was low, the array could not provide this current, so it was drawn from the large input filter capacitor connected at the dc input of the power conditioner. As the input filter capacitor continued to provide the necessary current, its voltage decreased until the dc lower limit of 160 V was reached. At this point, the power conditioner turned off, causing its dc input current to go to zero. The small current from the array then began to charge the input filter capacitor, causing its voltage to rise toward 190 V and initiating another cycle. At dawn and dusk, oscillations of this form could persist for 30 minutes or more. At the time that this cyclic behavior was first noticed, it was felt that such oscillations would eventually be harmful to component reliability. This conclusion was eventually shown to be valid.

This cyclic behavior of the power conditioner was eventually eliminated by a vendor retrofit that kept the power conditioner from turning on until sufficient insolation was present to enable the array to provide the minimum dc current. The array current capability determination needed for this turn-on decision was detected by sensing the short-circuit current capability of an independent pilot cell. As part of the same retrofit, the vendor changed from closed-loop maximum power tracking, by sensing the response of the ac output power to changes in array loading, to the use of an independent pilot cell as an open-loop constant-voltage sensor.

The power conditioner installation costs were:

Installation Material	\$36
" Labor	<u>17</u>
Total	\$53

3.2.2 SHIPPING

The power conditioner was shipped to the job site via motor freight. It was housed in a plywood box during shipment and arrived without incident.

3.2.3 INSTALLATION TASK/TIME BREAKDOWN

The power conditioner required very little installation. It was designed to stand free on the floor and was easily moved because it rode on casters. For ease of access, the dc and ac wiring were connected through flexible BX conduits that entered the power conditioner near the floor through the back of the unit. When connected in this manner, both the front and back doors could easily be opened, and both side panels could be removed if required.

3.3 SYSTEM

3.3.1 INSTALLATION

The electrical system installed in the Prototype is shown in block diagram form in Figure 3.11 and in schematic form in Westinghouse Drawing Number 103E089 included in Appendix A. Certain parts of the system were furnished by Westinghouse while others were provided by NMSEI, as described in the following paragraphs.

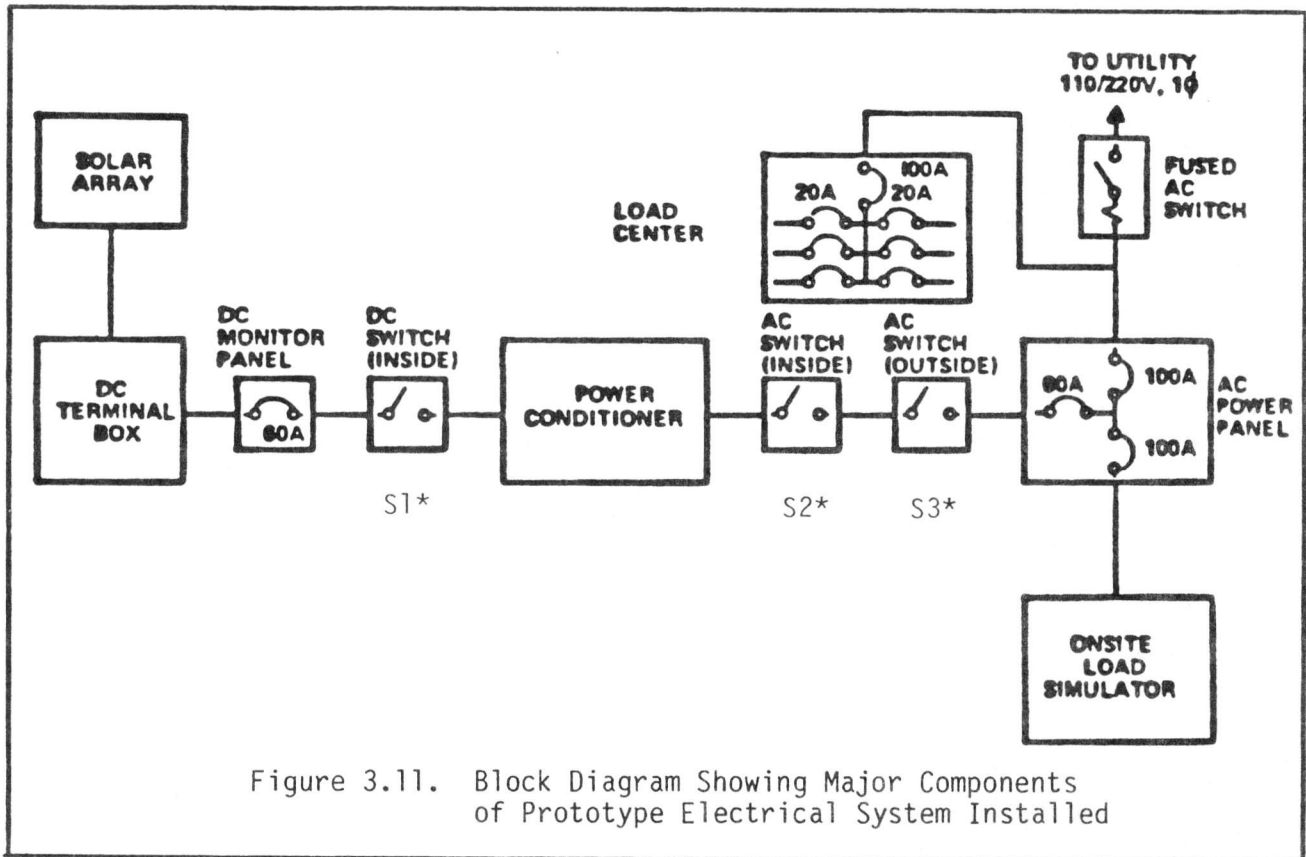


Figure 3.11. Block Diagram Showing Major Components of Prototype Electrical System Installed

Referring to Drawing Number 103E089, the solar array including both modules and panels was supplied by Westinghouse as were the dc switch and both ac switches. The power conditioner was also furnished by Westinghouse as was the load center.

The remaining items of electrical equipment were furnished by NMSEI. Included were the dc monitor panel, the ac power panel, the load simulator, and the main disconnect switch.

Three positive disconnect switches were included in the system as shown in Figure 3.11. One is located in the dc bus and the other two in the ac output bus. The disconnects used are Westinghouse Type GU322N for indoor installation and Westinghouse Type RGF422N for outdoor installation.

The purpose of the disconnects located indoors is to provide positive and visible removal of all power to the power conditioner when the unit must be opened for servicing. Therefore, near to and visible from the location of the power conditioner are the positive disconnects in both the dc bus and in the ac bus.

The third positive disconnect is located on an outside wall of the Prototype. It is connected in the ac line running to the PCU and can be locked in the "off" position. The purpose of this disconnect is to make it possible for the utility to remove the output of the PV system from the utility grid in the event of an emergency.

Shown in Figure 3.12 is a photograph of the interior of the Prototype, illustrating the physical location of a number of pieces of the PV system equipment. Shown in the figure are the dc monitor box, the dc terminal box, the ac power panel, and several data collection boxes. All pieces of equipment are wall mounted except for the power conditioner and the load simulator. A photograph of the power conditioner is shown in Figure 3.13.

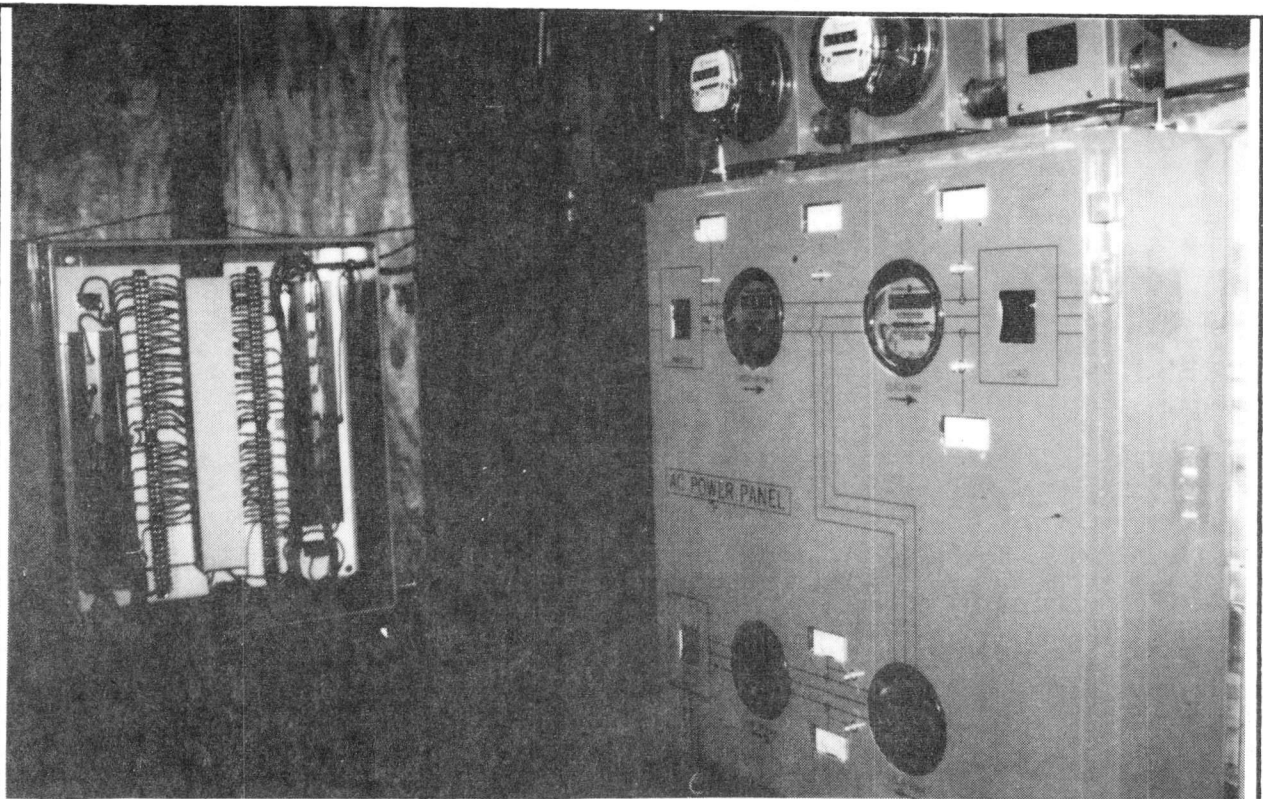


Figure 3.12. Photograph Showing Location of PV Subsystems

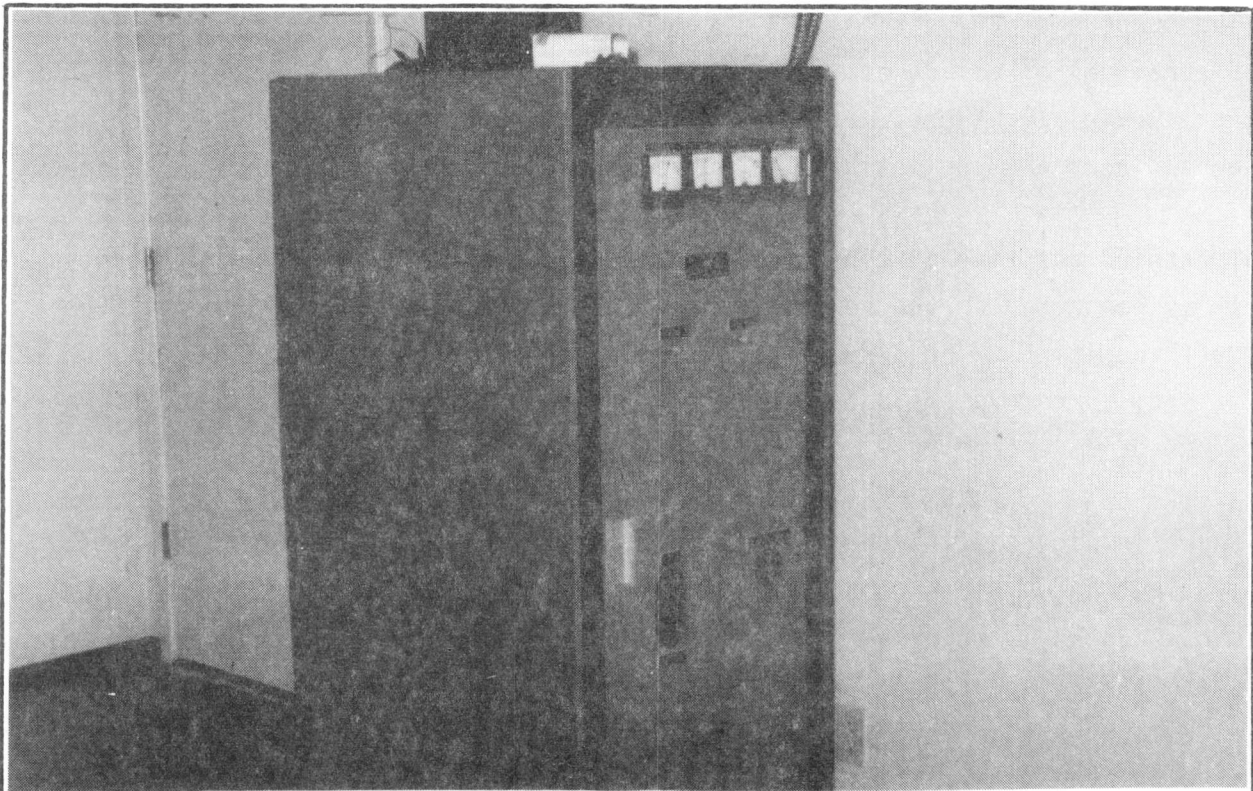


Figure 3.13. Photograph of Abacus Sunverter[®] Power Conditioner

3.3.2 SYSTEM FINAL CHECKOUT

Operation of the complete Prototype electrical system was verified by checking first the performance of the array and then that of the array and power conditioner together.

Array performance was verified by making measurements of the open-circuit voltages and short-circuit currents of each of the 13 groups of 12 modules in parallel before the series jumpers were installed. When the results of these measurements showed all 13 groups to be similar in performance, the groups were placed in series by connecting jumpers in the dc terminal box. Voltage measurements were then made at all points in the series connection to verify that all connectors were properly made. An open-circuit dc bus voltage measurement was then made to verify that resulting array voltage fell within the operating range of the power conditioner.

When array performance was verified, dc voltage was applied to the power conditioner with a 5-kW load connected to TB2 and with the utility connection removed. The power conditioner was then energized in the "Stand Alone" mode in accordance with Section 3.2 of the Sunverter[®] technical manual in Appendix B.

When satisfactory performance was found in the "Stand Alone Mode," the system was then deenergized and the 5-kW load removed. The system was then energized in the "Phaselock" mode with both dc from the array and ac from the utility in accordance with Section 3.3 of the Sunverter[®] manual. The indicator lamps on the power conditioner were then scanned to look for any out-of-tolerance alarm conditions.

If none was found, the output contactor switch was turned off and the mode control switch turned to "Utility" in accordance with Section 3.1 of the Sunverter[®] manual. If no alarm occurred, the output contactor switch was closed, placing the power conditioner in full operation.

After the system was in full operation maximum power tracking on a clear day, voltage measurements were made on each of the 13 series-connected groups of 12 modules to verify that they shared voltage equally.

Acceptance tests, which included array I-V characteristic measurements as well as power conditioner operating and out-of-limit tests, were performed by NMSEI.

3.3.3 NORMAL OPERATION

The Sunverter[®] is designed to operate unattended once turned on. The following operating procedures pertain to normal startup and shutdown (see Figure 3.11).

3.3.3.1 Initial Conditions

1. Array Terminal Box - All 12 series jumpers installed.
2. DC Monitor Panel - CB1 and CB2 set to OFF .
3. DC Voltage Bus Switch - S1^{*} set to OFF .

4. AC Power Panel - CB1, CB2 and CB3 set to OFF .
5. AC Voltage Bus Switches - S2* and S3* (located outside on east side of front door) set to OFF .
6. Power Conditioner - Input power switch (S1) set to OFF .

3.3.3.2 Startup-Normal

1. DC Monitor Panel - Set CB1 to ON . Note that DC voltmeter reads total array voltage.
2. DC Monitor Panel - Set CB2 to ON .
3. DC Voltage Bus Disconnect Switch - Set S1* to ON . Note that power conditioner "DC PRESENT" light is ON .
4. AC Power Panel - Set CB1 and CB2 to ON . Push RESET button (S1).
5. AC Voltage Bus Switches - Set S3* and S2* to ON. Note that power conditioner UTILITY PRESENT light is ON .

The power conditioner may be operated in the STAND ALONE , PHASE LOCK , or UTILITY mode of operation. Since UTILITY is the mode of operation that should normally be used, it will be described in this procedure. The other modes of operation are described in the Abacus Sunverter[®] technical manual.

3.3.3.3 Startup Following Loss of Utility Feed to Power Conditioner

1. Power Conditioner - Set input power switch to the OFF position for approximately 30 seconds.
2. AC Power Panel - Re-establish utility power to Power Conditioner.
3. Power Conditioner - Set mode switch to the PHASE LOCK position.

4. Power Conditioner - Set input power switch to the ON position.
5. Power Conditioner - Set mode switch to the UTILITY position.

3.3.3.4 Power Conditioner Normal Operation - Utility Mode

1. Set MODE switch (S2) to the UTILITY position.
2. Set MAX POWER TRACK/MANUAL I ADJ (S7) to the MAX POWER TRACK position.
3. Set CONTACTOR switch to ON .
4. Set INPUT POWER switch (S1) to the ON position.
5. When the solar array generates sufficient voltage to overcome the undervoltage cutout circuits, a 5-second time delay before turn-on is initiated. At the end of the time delay and providing the array voltage remains continuously above the cutout value, the Sunverter[®] turns on. Phase lock occurs at turn on. Note that the PHASE LOCK light is on.
6. After an additional 10-second delay to ensure that no alarm conditions are present, the utility tie-in contactor closes to connect the Power Conditioner output to the utility line. Note that no Power Conditioner alarm lights are ON and that ac power panel inverter current meter (M1) is indicating.

3.3.3.5 Shutdown

1. Power Conditioner - Input Power Switch (S1) - Set to OFF .
2. Deenergize ac bus to AC Power Panel - Set S2* to OFF .
3. Deenergize dc bus to PC - Set S1* to OFF .

4. Deenergize dc bus to S1* - Set dc monitor panel CB1 or CB2 to OFF .
5. Deenergize utility ac power to S2* - Set ac power panel CB1 or CB2 to OFF.

3.3.4 MODULE FAILURE DETECTION AND REPLACEMENT

A failed module can best be detected by a comparison of the voltage drops across all 12-module parallel groups while the array flows current. Because each module group flows the same current, a change in the characteristics of one module in a group will cause an uneven voltage distribution within the series string.

When the group containing the malfunctioning module has been identified, the current distribution between the three or four-module parallel groups can easily be measured at the dc terminal to find which group contains the malfunctioning module. From this point, shadowing tests on the modules within this group should make possible positive identification of the malfunctioning module.

A module that fails because of thermal stress or as the result of the impact of a hard object can easily be detected by a visual inspection of the array from outside.

When a module doublet has been identified as the one containing a malfunctioning module, it can be replaced as follows:

1. Remove all series jumpers at the dc terminal box.
2. Remove the outer Tremco gasket by pulling it out from under the aluminum flange.
3. Remove the panel frame cross piece(s) by unhooking them.
4. Joggle the doublet out far enough to provide access to the terminal boxes on the backs of the modules.

5. Loosen and remove all electrical connections to the doublet.
6. Remove the malfunctioning doublet and replace it with a good one.
7. Reconnect all wires in the module junction boxes.
8. Joggle the connected doublet in place in the panel.
9. Clean the gasket and module edge with mineral spirits.
10. Replace panel frame cross piece(s).
11. Force the front gasket back in its place.
12. Replace all series jumpers in the dc terminal box.

3.3.5 MAINTENANCE

The array may require periodic washing or cleaning to remove accumulated dirt that is not removed because of minimal rainfall in the dry climate of the Southwest.

The power conditioner has no motors or air filters used routinely. Therefore, unless it is located in a very dirty atmosphere, no routine maintenance is required.

3.3.6 REPAIR

The subsystem most likely to need repair in the power conditioner. It can be serviced using standard equipment and techniques applicable to solid state power electronic equipment.

3.3.7 SYSTEM CONSTRUCTION AND INSTALLATION COST

A summary of the cost of all purchased material as well as fabrication and installation labor needed to build the PV system installed in the Prototype structure is shown in Table 3.1.

TABLE 3.1 - SYSTEM CONSTRUCTION AND INSTALLATION COSTS

<u>Purchased Items</u>	
Modules	\$59,200
Array Installation (Panel Material)	7,410
Array Wiring	819
Power Conditioner	12,430
Positive Disconnects (3)	170
Other Misc. Electrical Components	<u>1,662</u>
Total Material	\$81,691
<u>Labor</u>	
Array Installation (Panel Fabrication and Job Site Installation Less Roofing Credit)	\$2,890
Array Wiring	2,187
Power Conditioner Installation	17
DC Terminal Box Assembly	<u>1,468</u>
Total Labor	\$6,562
<u>Summary</u>	
Total Purchased Items	\$81,691
Total Labor	6,562
Shipping	<u>4,804</u>
Total	\$93,057

4.0 CONCLUSIONS, RECOMMENDATIONS, AND LESSONS LEARNED

4.1 CONCLUSIONS

1. A solar PV system can be designed to be integrated into a single-family residence that is both energy conservative and aesthetically attractive.
2. A prototype system duplicating system installation and operation in a full-size residence can be constructed at less cost than that of constructing a full-size residence.
3. The open interior Prototype structure makes it easier to work on a developmental system than it would be if the system were in a complete full-size residence.
4. The solar panel system, although used here for only the second time as part of a solar PV system, worked well with little difficulty.
5. The solar panel system provided an integral array mounting that is water-tight and showed no tendency to leak.
6. The panels were installed in the roof of the Prototype structure in a very short time compared with the installation times for other array mounting techniques.
7. Modules can be purchased to data sheet parameter specifications without requiring additional screening and can be randomly placed in the array with minimum mismatch loss when the array interconnection technique employed in the Prototype system is used.
8. The use of a centrally located dc terminal box where access to all groups of four paralleled modules is available is convenient for measurements and

diagnostics for early developmental systems, but the added wiring results in excessive losses.

9. Solar cell module problems were minimal. No array module degradation was observed over the first year of operation.
10. Module cracking is not a significant problem. One module cracked, apparently from built-in stress.
11. Cracked modules can be replaced from the outside using the procedure described. This was verified by the replacement of a doublet containing a module that cracked from internal stress at the Northeast Residential Experiment Station.
12. Cracked modules can maintain normal electrical output indefinitely if the solar cells are not cracked.
13. Solar cell shorting to ground through the metal foil is not a problem.
14. Power conditioner cycling at low insolation was a problem that was solved by use of a different control technique.
15. Power quality of the pulse-width-modulated inverter is acceptable and meets most proposed utility standards.
16. Power can be fed from the PV system to the utility grid without difficulty through connections made at the RES Prototype site.

4.2 RECOMMENDATIONS

1. Additional work should be done immediately to improve power conditioner reliability and to reduce power conditioner cost while maintaining high power quality.

2. More residential PV systems should be constructed and operated in many different climatic regions of the United States to obtain system operating experience in different climates.
3. Modules with higher efficiency should be obtained to minimize installation cost.
4. Power conditioner efficiency should be increased.
5. Effort should continue to reduce the costs of all PV system components and subsystems, as well as the cost of installation.

4.3 LESSONS LEARNED

1. Power conditioner problems were underestimated.
2. Concerns regarding module and array problems were overestimated.
3. Modules with laminates incorporating metal foils should not be used in such a panel system.
4. The power conditioner dc voltage operating range must be wide enough to accommodate both open-circuit and maximum power point voltages that occur throughout the different seasons of the year as the ambient air temperature varies.
5. The centrally located dc terminal box concept, while extremely useful, is too lossy to be used except for a few very early developmental systems.
6. In order to design a solar panel consistent with standard 60.9 cm (24 in.) spacing rafters, a solar cell module of 54.6 cm (21.5 in.) width - with cells held back 1.59 cm (5/8 in.) from the edges must be used. No such module is available or under development.

7. Because of wasted area between panels and between modules within panels, array overall area efficiency for this panel type array is lower than that for many other array mounting techniques.
8. Residential construction tradesmen have no difficulty understanding PV system installation requirements and can readily install the panels and power conditioner without incident.
9. Larger areas of soffit and ridge vents should be used to obtain a larger airflow for module-back surface cooling.

Appendix A

Westinghouse Drawings

103E089 - Schematic Diagram

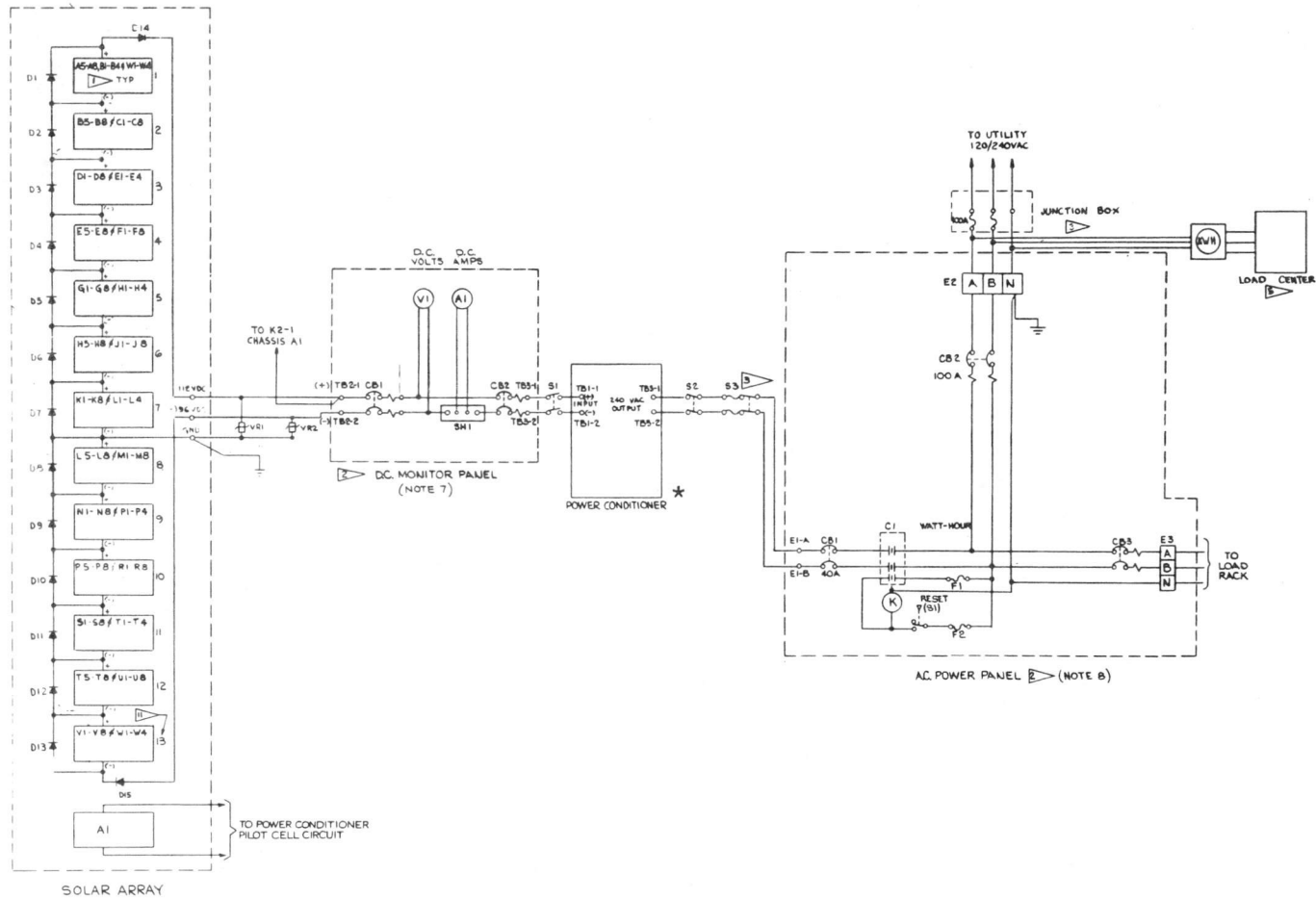
103E075 - Array Terminal Box Wiring Diagram

103E039 - Solar Panel Wiring Diagram

103E087 - Terminal Box Layout

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Ed. Note: S1 on the dc side and S2 and S3 on the ac side are shown for distinguishing clarity as S1*, S2* and S3* in Figure 3.11 (block diagram) and throughout Section 3.3.3 (normal operation).



- ① SUB-ARRAY IDENTIFICATION NUMBERS.
- ② FOUR PHOTOVOLTAIC MODULES CONNECTED IN PARALLEL.
- 5. REFERENCE MIT DRAWINGS D755G7 & C75153.
- 6. REFERENCE MIT DRAWING S755G9.
- 7. REFERENCE MIT DRAWING D755G6.
- 6. REFERENCE DRAWINGS: 103E039, 103E075 & 103E007.
- ⑤ SUPPLIED BY WESTINGHOUSE
- 4 ALL VOLTAGES SHOWN ARE NOMINAL VALUES.
- ③ LOCATED OUTSIDE PROTOTYPE.
- ② SUPPLIED BY NMS&I
- ① TWELVE PHOTOVOLTAIC MODULES CONNECTED IN PARALLEL EXCEPT A1 WHICH IS A SINGLE MODULE USED AS A P.C. PILOT CELL.

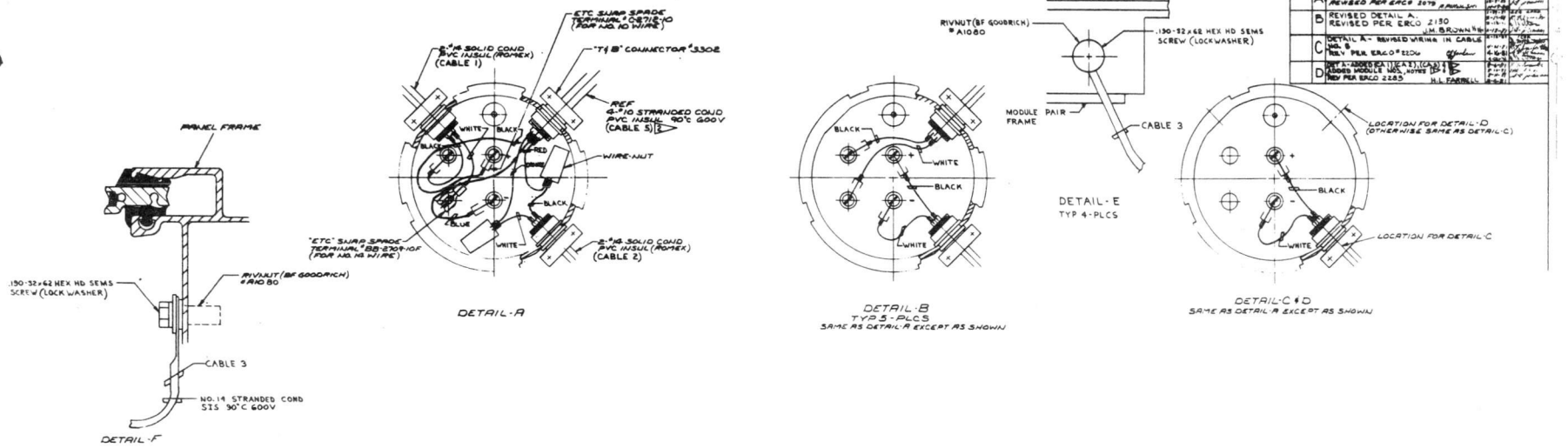
REVISIONS	
NO.	DESCRIPTION
E5	DELETED "CHASSIS POWER CONDITIONER" FROM DC MONITOR PANEL. SEE FIG. 3.11
D418	AC POWER PANEL WAS:
A	ADDED NOTES 1, 5 & 9
G7	ADDED CONTACT KE-1 & DIODE DMS
CT	ADDED WIRING FROM SOLAR ARRAY TO CHASSIS A1
ED	ADDED TBA-1 THRU TBA-5 & WIRING TO CHASSIS A1 FROM THE POWER CONDITIONER. ADDED NOTE 10 & 11
E5	NOTE 1 - ADDED EXCEPT A1 WHICH IS A SINGLE MODULE USED AS A P.C. PILOT CELL. DELETED NOTE 10.
E2	POWER CONDITIONER WAS:
C	TBA-1 TBA-2 TBA-3 TBA-4 TBA-5 TBA-6 TBA-7 TBA-8 TBA-9 TBA-10 TBA-11 TBA-12 TBA-13 TBA-14 TBA-15 TBA-16 TBA-17 TBA-18 TBA-19 TBA-20 TBA-21 TBA-22 TBA-23 TBA-24 TBA-25 TBA-26 TBA-27 TBA-28 TBA-29 TBA-30 TBA-31 TBA-32 TBA-33 TBA-34 TBA-35 TBA-36 TBA-37 TBA-38 TBA-39 TBA-40 TBA-41 TBA-42 TBA-43 TBA-44 TBA-45 TBA-46 TBA-47 TBA-48 TBA-49 TBA-50 TBA-51 TBA-52 TBA-53 TBA-54 TBA-55 TBA-56 TBA-57 TBA-58 TBA-59 TBA-60 TBA-61 TBA-62 TBA-63 TBA-64 TBA-65 TBA-66 TBA-67 TBA-68 TBA-69 TBA-70 TBA-71 TBA-72 TBA-73 TBA-74 TBA-75 TBA-76 TBA-77 TBA-78 TBA-79 TBA-80 TBA-81 TBA-82 TBA-83 TBA-84 TBA-85 TBA-86 TBA-87 TBA-88 TBA-89 TBA-90 TBA-91 TBA-92 TBA-93 TBA-94 TBA-95 TBA-96 TBA-97 TBA-98 TBA-99 TBA-100
E2	TO CHASSIS A1 SEE DMS 103E075 DELETED LINES 10-15 P. 16
CT	MODULE WIRING:
D768	MODULE WIRING:
D1	REVERSED PERIOD 241E

PARTS LIST		SPECIFICATION	
QTY	DESCRIPTION	QTY	DESCRIPTION
1	WATT-HOUR METER	1	WATT-HOUR METER
1	RESET SWITCH	1	RESET SWITCH
1	CONTACT KE-1	1	CONTACT KE-1
1	DIODE DMS	1	DIODE DMS
1	TBA-1 THRU TBA-5	1	TBA-1 THRU TBA-5

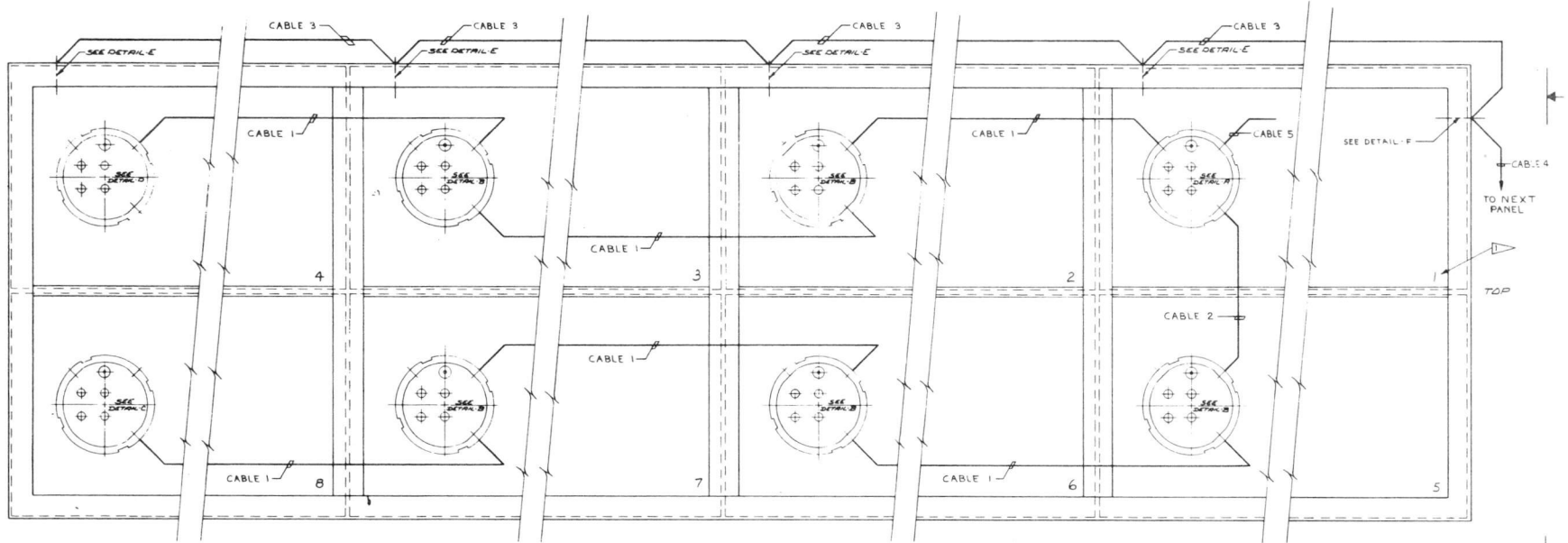
SCHEMATIC DIAGRAM
SW RESIDENCE
PHOTOVOLTAIC PROTOTYPE

103E089 C

A-5



REV	DATE	BY	CHKD	DESCRIPTION
A	11/11/70	P. B. GALL	J. M. BROWN	REVISED PER EREC 2150
B	11/11/70	P. B. GALL	J. M. BROWN	REVISED PER EREC 2150
C	11/11/70	P. B. GALL	J. M. BROWN	REVISED PER EREC 2150
D	11/11/70	P. B. GALL	J. M. BROWN	REVISED PER EREC 2150



BLACK & BLUE CONDUCTORS CONNECT LEFT SIDE MODULES (1 THRU 4).
 ORANGE & RED CONDUCTORS CONNECT RIGHT SIDE MODULES (5 THRU 8).
 MODULE NUMBERS

CONTRACT NO. 103E039	WESTINGHOUSE ADVANCED ENERGY SYSTEMS DIVISION
PROJECT NO. 14683	PRODUCTION, PROVISIONS
SOLAR PANEL WIRING DIAGRAM	
DATE 11/11/70	REV. 103E039 D
BY P. B. GALL	CHKD J. M. BROWN
DATE 11/11/70	DATE 11/11/70
SCALE NTS	BY DATE

Appendix B


Abacus Sunverter[®] Technical Manual (Abstracted)

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APPLICATION		REVISIONS			
NEXT ASSY	USED ON	LTR	DESCRIPTION	DATE	APPROVED

TECHNICAL MANUAL
 MODEL 763-4-200
 SUNVERTER

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON FRACTIONS DECIMALS ANGLES $\pm 1/64$ $\pm .005$ $\pm 1/2^\circ$	CONTRACT NO.	 abacus controls inc. 90 READINGTON ROAD BOMERVILLE, N. J. 08876
	DRAWN 12-2-80 ps	
MATERIAL	CHECKED	TECHNICAL MANUAL MODEL 763-4-200 SUNVERTER
	ENGINEER P. S. Main	
FINISH	APPROVAL	SIZE A 54241 1 0 6 7 3
		B-3 SHEET 1

SECTION 1. GENERAL INFORMATION

The Model 763-4-200 Sunverter accepts input of 160 to 240VDC from an array of solar cells and converts it to 240 volts AC at 60-Hz nominal. Output power rating is 6 kW.

There are three operating modes for the 763-4-200 Sunverter: Stand-Alone, Phaselock, and Utility. In the Stand-Alone mode, the unit supplies power to a connected load with locally adjustable frequency. For the Phaselock mode, output frequency is locked to that of the utility line. During operation in the Utility mode, the output is phaselocked to the utility line and voltage is locally adjustable to supply up to 6 kilowatts of power into the utility lines.

Maximum power tracking permits operating the equipment at the maximum power point on the I-V curve of the connected solar array, with automatic start-up, phaselock and line-tie features.

Safety circuits sense any improper current, phase, or voltage condition and cause shut down for any combination of circumstances which are potentially dangerous to the equipment.

The majority of the circuitry is located on ten printed circuit modules and eight dual-bridge output power modules. The printed circuit modules are notched and keyed to prevent improper installation.

Because of the high efficiency of the 763-4-200, cooling fans are connected through thermal switches which turn the fans on during high ambient temperature conditions. Cooling air exits at the top of the unit.

SECTION 2. INSTALLATION

There are no particular mechanical installation requirements for the 763-4-200 Sunverter. The cabinet should be located in an area which has enough space for opening the front and rear doors. The unit is mounted on casters for easy movement.

Sheet 1 of drawing 40768 shows the electrical connection points. Refer also to the outline drawing and make connections as follows:

CAUTION

Be sure to OBSERVE POLARITY when making connections from the solar array.

TB1-1 POSITIVE DC lead from solar array
TB1-2 NEGATIVE DC lead from solar array
TB1-3 Chassis Ground

TB2-1 240-volt SUNVERTER output
TB2-2 240-volt SUNVERTER output
TB2-3 Chassis Ground

NOTE: TB2 is intended for testing purposes. To assure continuous operation, any loads to be operated by the SUNVERTER must be connected at UTILITY terminal block TB-3.

TB3-1 UTILITY 240-volt connection
TB3-2 UTILITY 240-volt connection

NOTE: Since the SUNVERTER automatically phaselocks its output to the utility voltage, there is no incorrect way to make connections at TB3

SECTION 3. OPERATING INSTRUCTIONS

- 3.1 The normal operating mode of the Model 763-4-200 Sunverter is automatic and unattended. To set up the controls for fully automatic startup, perform the following steps before the sun rises:
- 3.1.1 Set INPUT POWER switch S1 to the ON position.
- 3.1.2 Set MODE switch S2 to the UTILITY position. Be sure that the utility line is connected at UTILITY terminal block TB3.
- 3.1.3 Set MAX POWER TRACK/MANUAL I ADJ. S7 to the MAX POWER TRACK position.
- 3.1.4 The sequence of events during automatic startup is as follows:
- a. Solar array generates sufficient voltage to overcome the undervoltage cutout circuits. This initiates a five-second delay before turn-on. At the end of the delay and providing the array voltage remains continuously above the cutout point, the delayed 5-volt signal is released to the driver modules and the Sunverter turns on. Phaselock occurs at turn-on.
 - b. After a 10-second delay to make sure that no alarm conditions are present, the utility tie-in contactor closes to connect the Sunverter output to the utility line.
 - c. Following line-tie, the Maximum Power Tracker adjusts the output of the Sunverter so that the greatest possible amount of power is fed into the utility line for any given conditions of sunlight intensity and temperature.
 - d. To manually adjust current into the utility line, set MAX POWER TRACK/MANUAL I ADJ. switch S7 to I ADJUST potentiometer R17, which is located on the control indicator panel.

NOTE

If the DC voltage at the output of the solar array falls below 155 volts, the Sunverter turns off. When the voltage recovers to 190 volts, another turn-on delay is initiated.

NOTE

To open the UTILITY contactor, set CONTACTOR ON-OFF switch S5 to OFF. To restore the connection, depress CONTACTOR RESET switch S6, then set CONTACTOR ON-OFF switch S5 to ON.

3.2 Operating in STAND ALONE Mode

- a. With INPUT POWER switch off, set MODE SELECT switch to STAND ALONE.
- b. Connect load to STAND ALONE terminal block TB2.
- c. Set INPUT POWER switch on.
- d. During STAND ALONE operation, output voltage is adjusted by potentiometer R11, located on the control and indicator panel.

3.3 Operating in PHASELOCK Mode

- a. With INPUT POWER switch off, set MODE SELECT switch to PHASELOCK.
- b. Connect utility line to UTILITY terminal block TB3.
- c. Connect load to STAND ALONE terminal block TB2.
- d. Set INPUT POWER switch on.
- e. Adjust output voltage by varying potentiometer R11 on the control and indicator panel. Frequency is controlled by the phaselock circuit.