DOE/ET/20279-225

BDM Corporation Final Report:

DESIGN AND FABRICATION OF A PROTOTYPE SYSTEM FOR PHOTOVOLTAIC RESIDENCES IN THE SOUTHWEST

August 1982

BDM Corporation
Under Contract No. 1-4-23550X1
with New Mexico Solar Energy Institute (NMSEI)

Under Purchase Order No. BX-554 Between
NMSEI and MIT Lincoln Laboratory

Massachusetts Institute of Technology
Lincoln Laboratory
Lexington, Massachusetts 02173-0073

Prepared for
THE U.S. DEPARTMENT OF ENERGY
UNDER CONTRACT NO. DE-AC02-76ET20279

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(3rd final report)

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Albuquerque

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ABSTRACT

This is the final report of the BDM Corporation on the design, fabrication, and maintenance of a prototype residential photovoltaic (PV) power system installed and operated at the Southwest Residential Station in Las Cruces, New Mexico. The purpose of this program is to identify and resolve engineering problems that will result from the widespread use of residential PV systems. The report documents the tasks accomplished under this contract and evaluates overall system design and performance.

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CHAPTER I
PROGRAM DESCRIPTION

A. INTRODUCTION

The U.S. Department of Energy National Photovoltaic Program is an effort to reduce the cost of photovoltaic (PV) systems to a level competitive with traditional energy sources. Under this program, the Solar Residential Project performs experiments with residential building prototypes which have integrated PV systems. Prototype PV systems have been built comprising the full-size PV array as would be used in a lived-in residence, the balance-of-system (BOS) components, and sufficient structure to support the array and house instrumentation.

Under sponsorship of the Massachusetts Institute of Technology Lincoln Laboratory (MIT LL), agent for the U.S. Department of Energy (DOE), New Mexico Solar Energy Institute (NMSEI) awarded multiple contracts for the detailed design, fabrication, and subsequent maintenance of prototype residential PV power systems installed and operated at the Southwest Residential Experimental Station (SW RES) in Las Cruces, New Mexico.

The BDM Corporation received one of the above contracts. Dean & Hunt Associates and Forrester Construction Company were subcontractors on this project. Dean & Hunt Associates supplied the architectural drawings for the full-sized residence and Prototype. Forrester Construction built the Prototype System in Las Cruces. BDM provided engineering, integration, and analysis required under the contract.

B. PURPOSE AND OBJECTIVES

The purpose of the Prototype construction is to identify and resolve engineering problems that will result from widespread use of residential PV systems. Voltage regulation, distribution line and transformer sizing, circuit breaking, and lineman safety are of key interest.

C. OVERVIEW AND SCOPE

There were six tasks to be accomplished under the contract.

(1) Preliminary design of a PV residence, including the PV system.
(2) Estimation of the energy load of the residence and the performance of the PV system.
(3) Detailed design of the Prototype System.
(4) Fabrication and installation of the turnkey Prototype System at the SW RES.
(5) Maintenance of the Prototype System for a period of 1 year from System acceptance.
(6) Reporting and participation in DOE PV program reviews, design reviews, and meetings.

The preliminary design of the full-size residence provides:

(1) Specifications on all equipment required to meet the thermal and electrical loads.
(2) A PV system that meets the JPL Block IV module design specifications, above 4 kW at peak output, and provides at least 50 percent of the annual electrical energy required.
(3) A dc-to-ac inverter that allows two-way power flow to the 120V/240V 60-Hz utility.
(4) Protection and control for automatic start-up, shutdown, and disconnect in the event of utility power interruption.
(5) Energy conservation in the design of the space heating and cooling and hot water system.
(6) Energy conservation features in the 2,073-square-foot residence as well as an aesthetic design.
(7) Adequate safety and protection by complying with building and electrical codes and standards.
(8) Drawings showing front, rear, and side building elevations, interior layout, energy conservation features, and a block diagram of the PV power system.

The estimation of annual energy performance includes the PV array power output and residence total electrical demand. The meteorological data were taken from SOLMET weather tapes. The quantities of total PV array dc output energy (kWH), total inverter ac output energy (kWH), total space heating load (kWH Thermal), and total space cooling load (kWH Thermal) were estimated.

The Prototype design is based on the full-size residence but is minimized to include only the roof area required by the array for support and four walls to enclose the structure. The Prototype also includes the full-size PV array. This provides more than the required 8-foot by 10-foot floor area for the BOS components, instrumentation, and electrical load. Insulation is provided to simulate the temperature conditions below the PV array. Provisions were made for venting the thermal load generated by the NMSEI-provided load-duplicating equipment. The south-facing windows and louvered roof windows were provided.

All applicable building and electrical codes were followed during the design and construction.

Drawings and pictures of the Prototype front, rear, and side elevation, the plan view, and the construction details are provided in chapter 3 as well as a block diagram of the PV power system and thermal system.

D. SUMMARY OF RESULTS

The objectives of the program have all been met or exceeded, and several lessons have been learned through the construction and operation of the Prototype facility.

(1) The building design has proven quite satisfactory. The excellent energy efficiency with effective passive solar gain has resulted in a projected energy consumption for the BDM residence design that will use only 60 percent of the energy of a conventional building of equal size. The construction techniques have proven satisfactory and yield an aesthetically pleasing design with very good commercial potential.

(2) The standoff array mounting has also proven an excellent design approach as it allows a very cost-effective approach to integrating the array into the building architecture while maintaining or enhancing the aesthetics of the building and providing a durable weatherproof seal with excellent insulating properties. The standoff design also facilitates very efficient installation of the array as the BDM Prototype required a total of only 28 man-hours to completely install and check out the PV array. Tests performed by MIT indicate that the cell temperature of the standoff array is not significantly different from that of standard, rack-mounted PV modules.

(3) The photovoltaic components functioned adequately. The design array rating was exceeded with the 4.4 kW rating defined by Lincoln Laboratory tests. However, module performance was actually below the manufacturer's published "typical" data by 4 percent at rated conditions. All modules were above the minimum performance specifications defined as part of the design and the array has provided excellent reliability, even under somewhat adverse conditions when the array was stored in short circuit for prolonged periods of time in a high insolation, high ambient temperature environment.

(4) The inverter proved to be a hardware item requiring significant development. The performance of the Abacus inverter in the early portions of the program proved to be unsatisfactory and several field and factory modifications or upgrades were made. Later in the project, a high frequency inverter provided by Helionetics through Sandia National Laboratories was installed at the BDM Prototype. This inverter has yielded completely satisfactory performance with excellent power quality and reliability.

CHAPTER II
PHOTOVOLTAIC RESIDENCE DESIGN

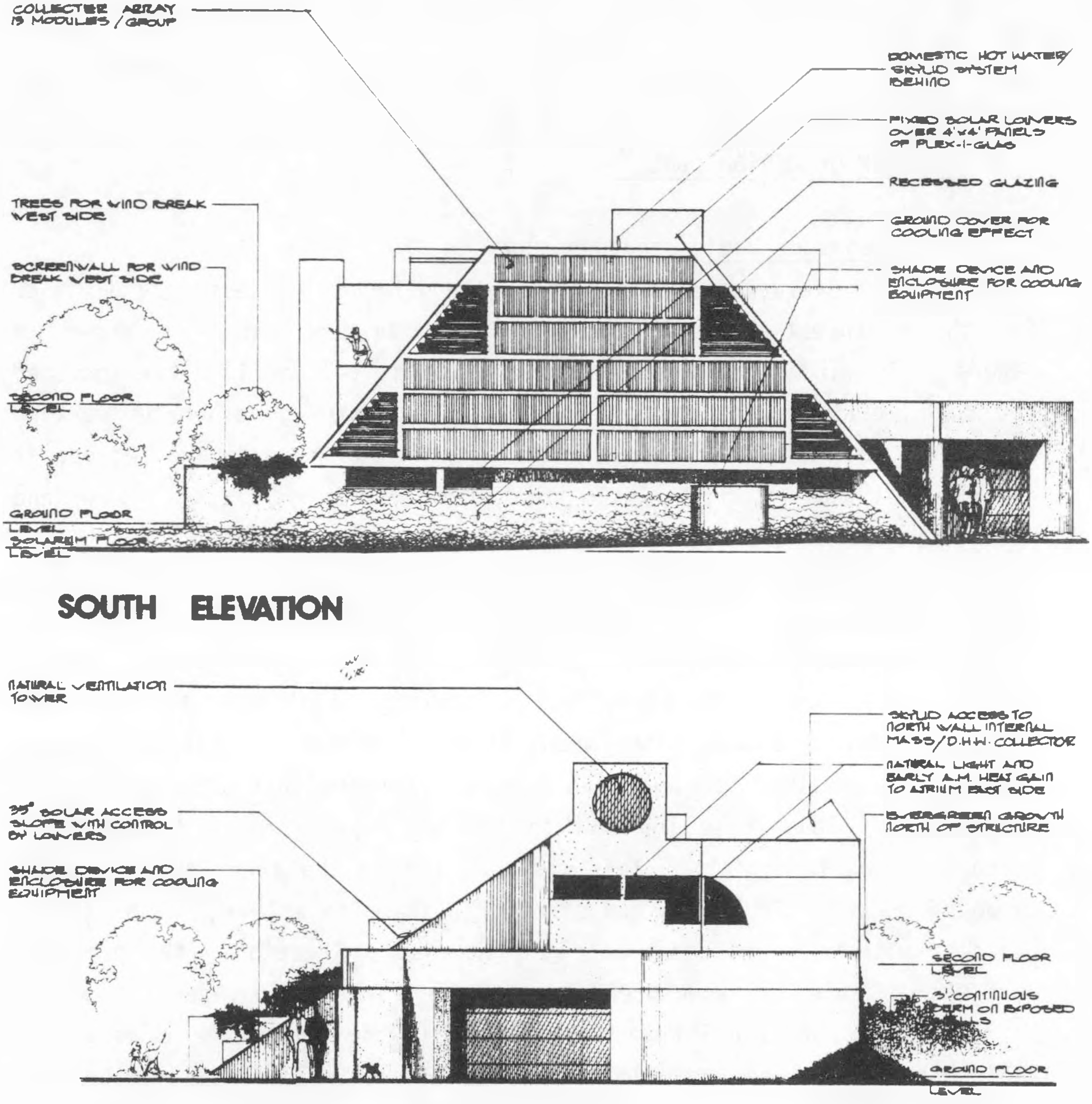
A. OVERVIEW OF DESIGN CONCEPT

1. Residence Design and Construction

The elevation of a single-family detached PV residence designed for the southwest climatic region of the United States is shown in figure II-1. The floor plans shown in figures II-2 and II-3 are included to show details of interior design. BDM chose this design in working with Dean and Hunt Associates, the architects on the program, because it accommodates the PV array while also providing many passive solar and energy conservation elements.

The house is energy efficient, requiring less than 60 percent of the energy used in current residential structures. This savings is provided by passive solar and conservation features (shell design, ventilation, etc.) and high efficiency mechanical equipment that can be integrated into the home with essentially no increase in building costs. For example, in 1980 BDM and Dean & Hunt estimated that this home could be built in Albuquerque for $40 to $45 per square foot, including an appropriate building lot. This was well within the then current market value of houses. The frame and stucco construction allows flexibility in building without significant increase in cost. Therefore, the proposed home is suitable for widespread construction in the Southwest, provides an attractive functional home, and is within the current home construction cost range. The reduced energy requirement will actually make this home more affordable than a conventional home.

This is a 2,073-square-foot frame stucco home with three bedrooms and two baths. It incorporates conventional energy conservation features to reduce thermal loads while including a variety of novel ideas addressing energy conservation, passive solar features, and consideration of house orientation relative to existing lot orientations.



ALTERNATIVE NO.1 ELEVATIONS

0 5 10

DESIGN TEAM ARCHITECT HAL DEAN ENGINEER TERRY WALKER
DEAN & HUNT ASSOCIATES LTD. WALKER BROWN ENGINEERS
BUILDING TYPE TWO STORY DETACHED LOCATION ALBUQUERQUE, NEW MEXICO
CODE DATE JULY 31, 1978 SHEET No. A-8
CLIENT: AIA RESEARCH CORPORATION FOR HUD / DOE

BDM/A-81-550-TR

Figure II-1. Photovoltaic Residence Elevation

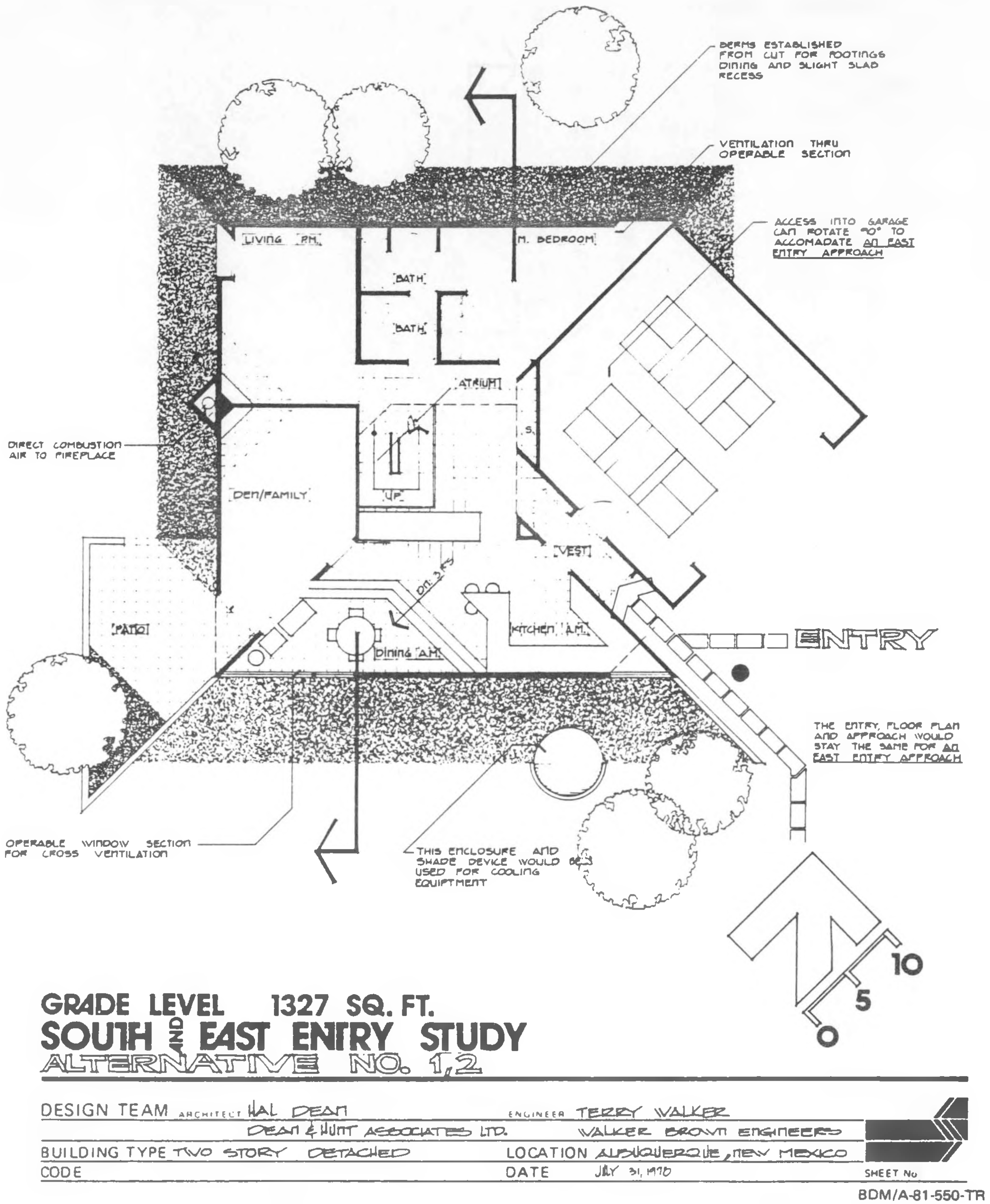


Figure II-2. Photovoltaic Residence First Level Floor Plan

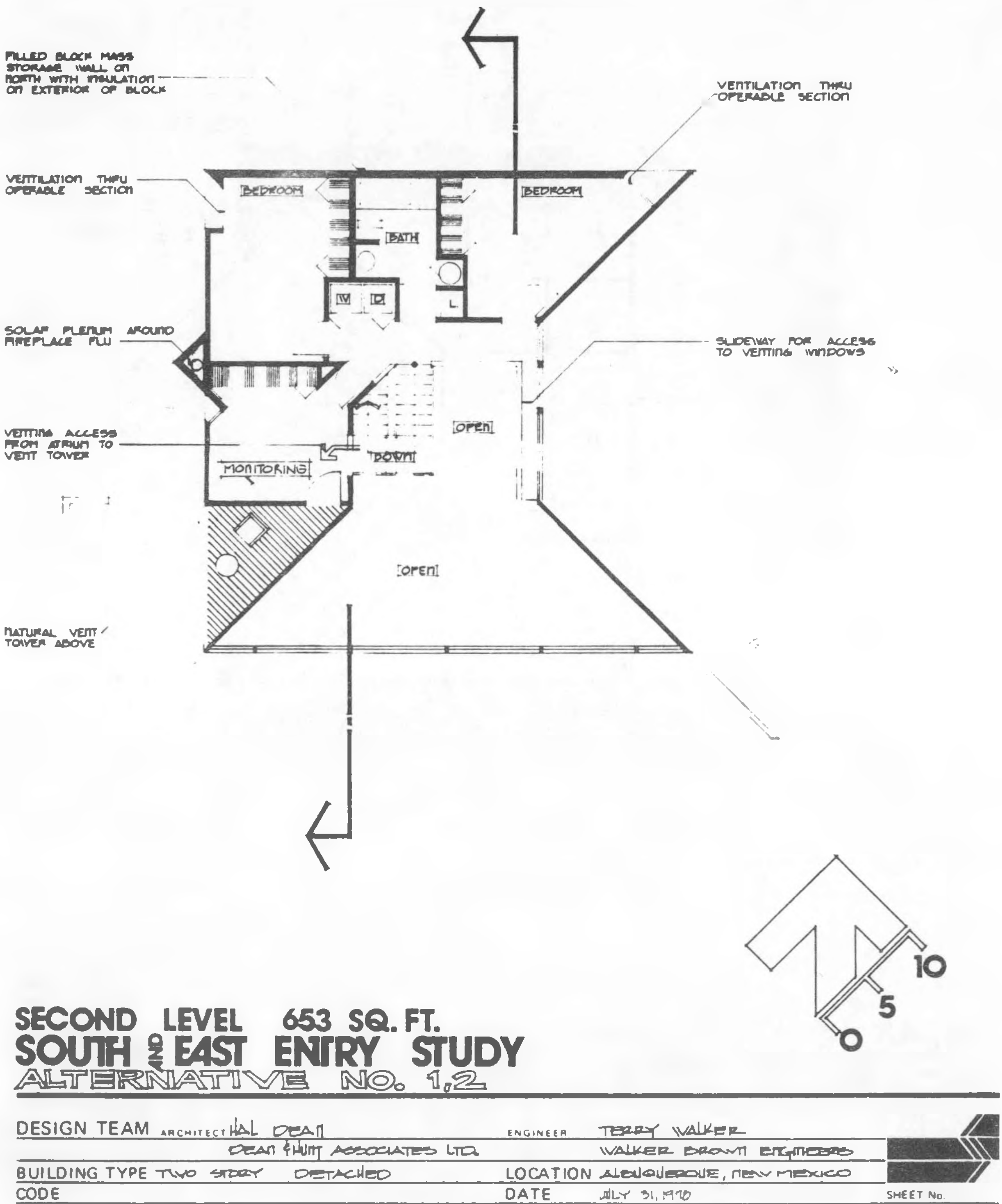


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Figure II-3. Photovoltaic Residence Second Level Floor Plan

As is evident in the rendition, the home is aesthetically pleasing. It integrates a sloping roof area into the flat roof characteristic of southwestern architecture. Rather than the obtrusiveness often characteristic of solar arrays in the past, this design allows the PV array to become an integral part of the design. The aesthetics of the PV array and its integration into the home design were given a high priority, as it is realized that the acceptance of PV residences is dependent on cost and appearance.

The array lies in the plane of the roof and is composed of two rectangular areas composing a portion of the trapezoidal, sloping, south-facing roof structure. The remaining portion of the sloping roof structure contains glazing with louvered panels that allow solar gain for heating the home during winter months. The trapezoidal shape was selected for the solar roof design for three reasons. First, it allows rectangular subarrays to be used while providing sufficient area for substantial passive solar energy collectors. Second, it provides the necessary area for the PV array and louvered passive solar windows without requiring the residence to be oversized. Finally, the home is a contemporary southwestern design for which the trapezoidal area is aesthetically well suited.

The size of the array has been carefully selected to allow effective integration into the residential structure. The louvers are a dark earth tone selected to allow attractive exterior coloring of the collector roof area. The low reflectance of the glass modules and the inherent color of the PV cells will afford a low-key, well-coordinated aesthetic presentation by the south wall and roof area.

2. Photovoltaic (PV) System Interface

The PV array and a close-up of its integration into the roof structure are shown in figure II-4. The array is made up of 117 Motorola Block IV modules encompassing 507 square feet of aperture and providing a peak power of 4,680 kW at rated conditions as defined by the individual module ratings. The vertical mounting of these modules in groups of 13 provides the best packing factor for the

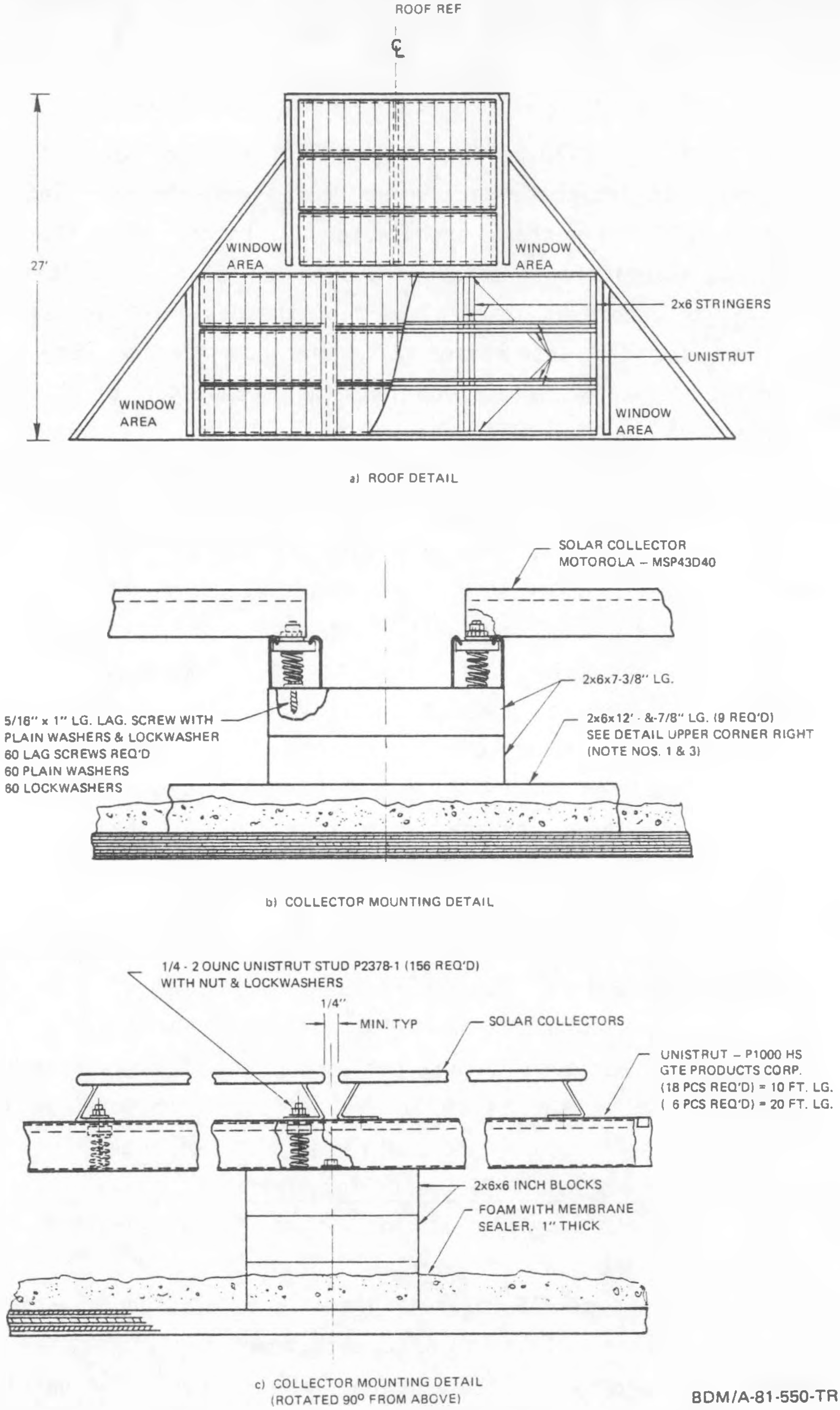

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Figure II-4. PV Array Mounting

available roof area while allowing wiring that satisfies the input requirements of the dc/ac inverter systems.

The portion of the roof on which the array is mounted slopes at 35 degrees to approximate an average latitude tilt for the southwestern United States. This angle is also one that can be built by the construction industry. The array is mounted in a standoff configuration to provide an air space behind the modules. The air space allows convective cooling of the modules while also providing good roof drainage to prevent the buildup of water and debris. Provision of the air space for module cooling is a critical design item because direct-mounted field installations have experienced excessive operating temperatures that affect not only the performance but also the safety of the system.

The module-to-roof interface standoff design for this system is also shown in the cutaway view of figure II-4. The 2 by 6 stringers are mounted directly to the roof structure, which is then sealed with 1-inch roofing foam. Pairs of 2 by 6 by 6 and 2 by 6 by 7-3/8 inch blocks are added to the stringers to provide additional spacing. Two-inch Unistrut® members are mounted to the blocks perpendicular to the 2 by 6 stringers. The PV modules are bolted to the Unistrut members.

The array wiring and interconnection are accomplished in a manner that provides a neat and easy access to maintain installation. Module wiring terminates in a junction box below the module and within its physical envelope. Wiring between modules meets the NEC code requirements. The entire array terminates in a main junction box below the roof surface. The maintenance and safety enclosure is located outside to provide easy access for public utility personnel. The inverter is located inside the garage.

3. Energy Conservative/Utilization Design

a. Residence Layout and Orientation

The primary orientation of the PV residence was presented in the first section of this chapter (figure II-1). As would be expected, the solar array is orientated facing true south. A unique aspect of this home design is its ability to be utilized on residential lots with different entry locations without affecting the south-facing capability of the sloped roof area. This capability is depicted in figure II-5 for each of four lot orientations. Note that the basic house plan remains unchanged for each lot configuration with the exception of the garage and the front door entry, which are moved to accommodate the street-side entry of the lot. The interior design of the home has been laid out to accommodate the different front door entry locations. Such a concept allows a more diversified use of the home and residential planning without the need to utilize only lots with configurations providing for a southern exposure.

Since the home does not have to be reoriented for each lot selection, the interior of the house has been designed to accommodate personal habits and usage and prevailing environmental conditions. Fresh air entry has been designed to accommodate the prevailing winds of the Southwest. Layout of each of the rooms matches room usage with passive heating and/or shading of the sun as appropriate.

Since the house orientation may be different depending on the specific lot chosen for construction, the house has been designed with a 360-degree aesthetic consideration, so that when entries are moved from one point of the house to another, the front-facing portion of the house is still aesthetically pleasing.

b. <u>Passive Solar and Energy Conservation Design Attributes</u>

Reduced energy requirements have been achieved in the residence design via building orientation, efficient shell structure design, passive solar with internal storage, unique building ventilation, and selection of very efficient mechanical equipment. Figures II-6 and II-7 identify some of the key passive solar elements and conservation techniques of the PV residence design. BDM feels that it is important to include these designs in the residence to minimize both electrical and thermal requirements. This provides a more effective energy package and allows a small PV array to provide a larger portion of the energy requirements for the structure.

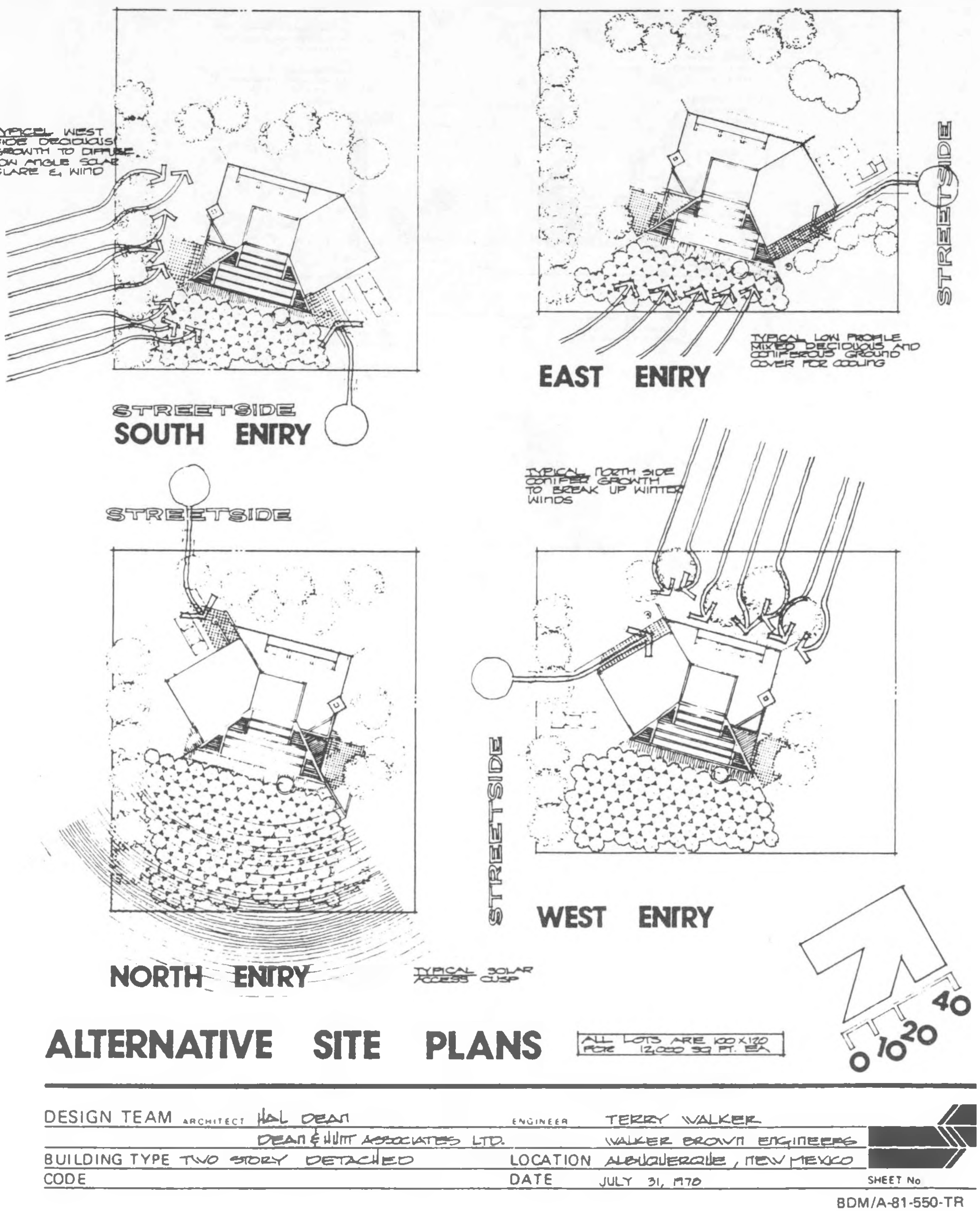

Figure II-5. Photovoltaic Residence Orientation Flexibility

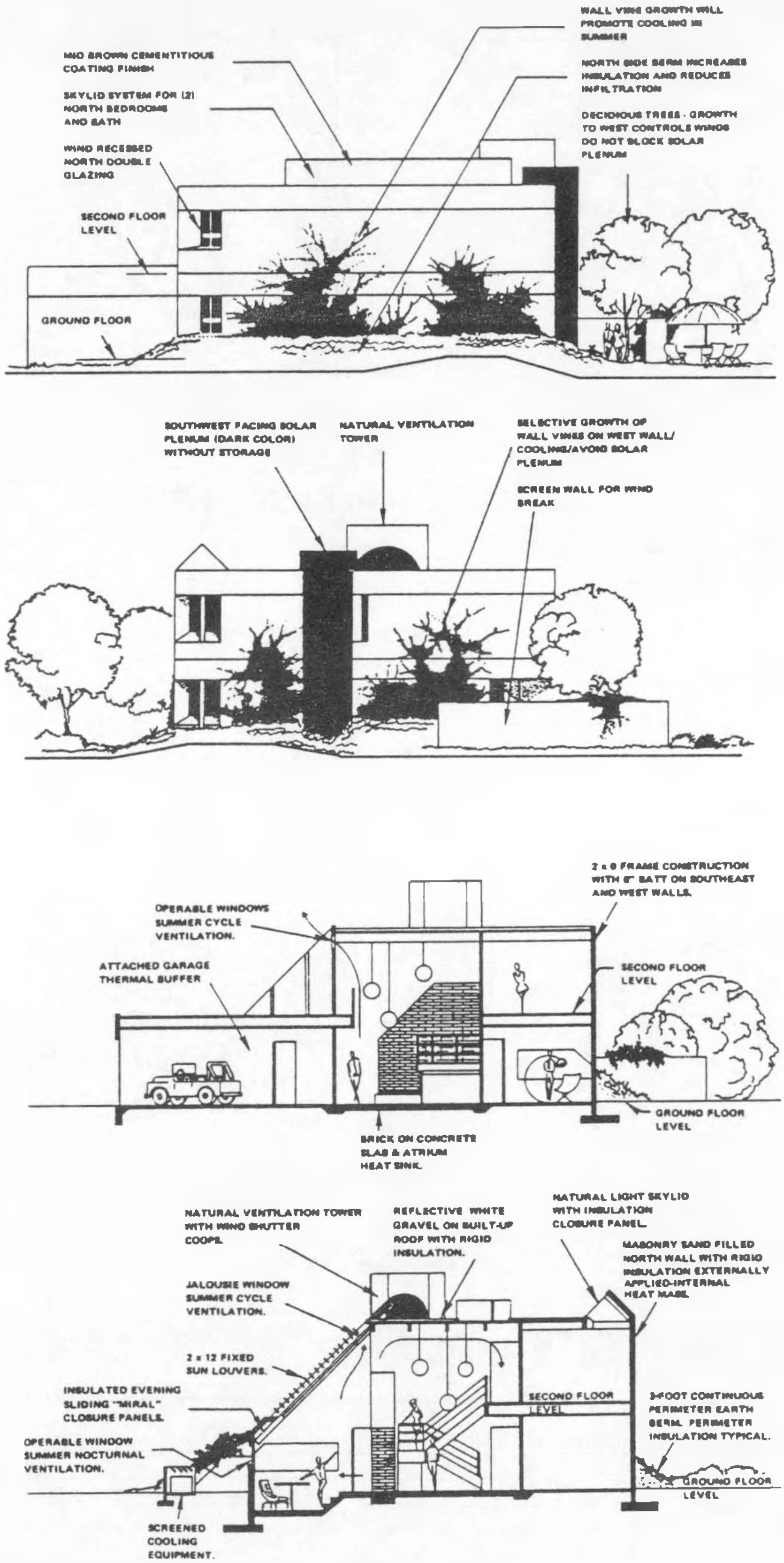

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Figure II-6. Photovoltaic Residence Energy Conservation Features

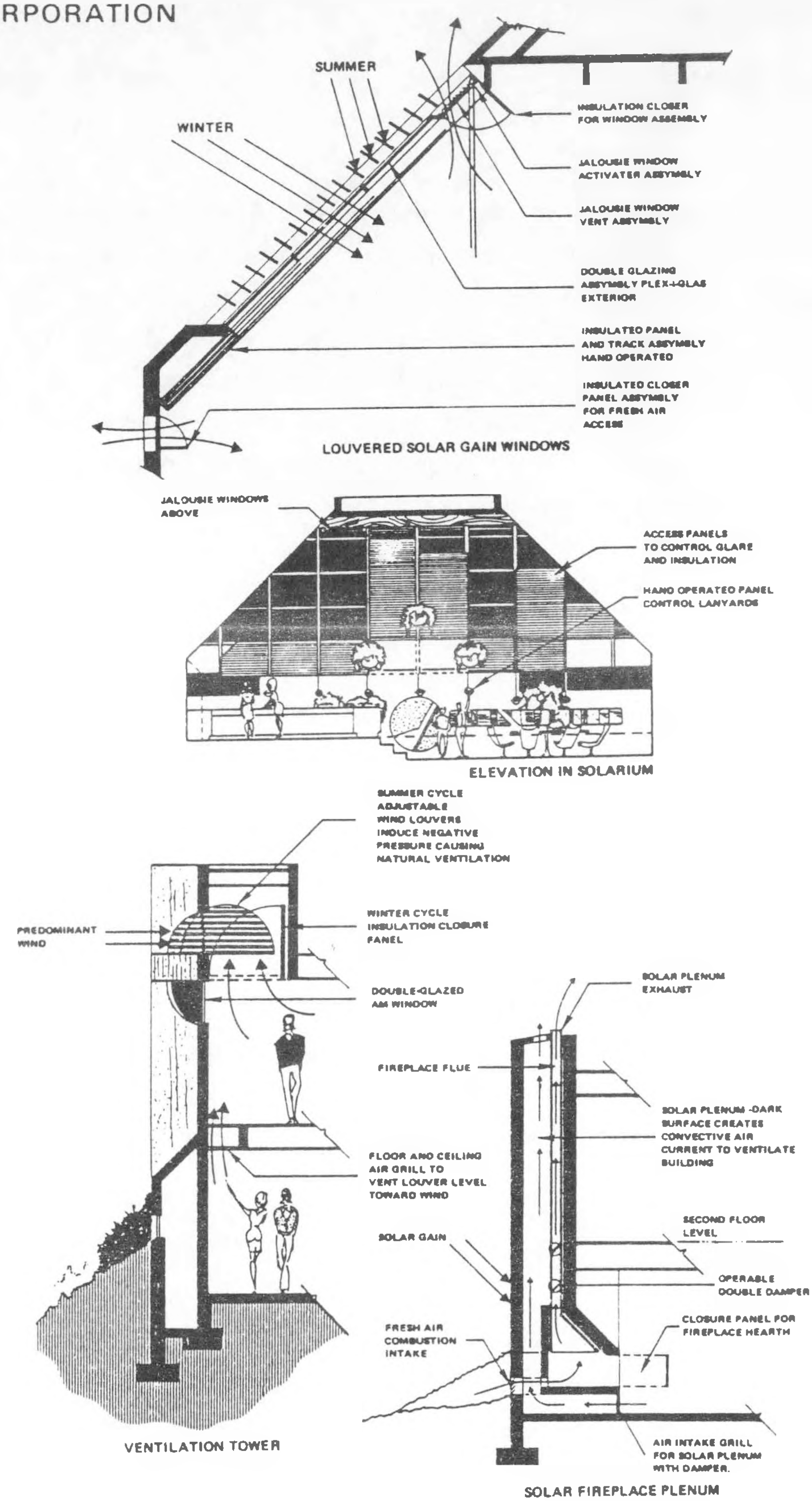

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Figure II-7. Photovoltaic Residence Energy Conservation Features

The design of this energy-efficient home begins with an analysis of the functional needs or "use patterns" of the family. The objective of the passive design is to provide temperature control for the occupied areas of the house at different times of the day. This results in the breakfast area being located in the southeast portion of the house, with the living and dining areas in the southern and southwest locations, respectively. The bedrooms are located in the northern portion of the house, allowing cool temperatures in the summer by avoiding direct sunlight gain (i.e., skylights closed). The passive ventilation tower shown in the elevation will support bedroom cooling at night by drawing air through the bedroom via the tower when outside climatic conditions are appropriate. During the winter, the skylights will heat the bedrooms and north wall, which is void of (northern) windows and has been designed as an internal thermal storage medium with heavy external insulation. This will keep the bedrooms warm throughout the night. The sloped room surrounding the PV array contains louvered windows that allow sunlight to enter the atrium during the heating months and, due to their fixed angle, shade the windows during the summer months. Roof level, south-facing windows are also provided over the northern bedrooms. Once the sunlight enters, the thermal energy is stored in the brick floor of the atrium and the rear wall (north wall) of the residence, which could be designed as a storage medium. To ensure that the northern roof skylights are energy efficient, they have been fitted with closure panels to maintain energy within the structure when desired.

Further control of the sunlight entering the atrium through the louvered windows is accomplished by internal panels in the solarium, which can be controlled from an internal point on one of the atrium walls. Also, the windows on the south walls of the home are recessed so that during the winter additional sunlight enters the atrium, but during the summer the angle of the sun prevents the sunlight from reaching the atrium.

The flat portions of the roof adjacent to the PV area are coated with a reflective white paint to provide additional passive protection from the sun's energy during the summer months.

Two additional exterior conservation techniques include the earth berm that surrounds the lower portion of the home and trees, plants, and vines, which are placed appropriately, as shown in the figure II-6, to provide wind protection and shading of certain portions of the home where the sun's rays are not desired.

Another aspect of this home's energy conservation is the natural ventilation supplied to minimize the requirement for forced convective cooling. The tower protruding from the roof of the residence is actually a ventilation shaft, which significantly aids in drawing the air flow throughout the entire residence. In addition to the ventilation tower, venting windows in the roof of the atrium area have been installed so that during the summer months hot air may escape to the exterior. Additional atrium venting is accomplished in the flat roof area, as shown in the figure II-6. Finally, at key points through the periphery of the residence, venting windows, which open to allow warm air to escape during the hot days and cool air to enter during the evenings, are installed in the walls.

Several other features are unique to this particular residence. Shown in figure II-7 is a solar fireplace plenum that utilizes the energy from both the fireplace and from solar heating on the external wall of the fireplace to heat the home. Note also that a thermal buffer has been installed to minimize heat losses between the home and the attached garage. Finally, the cooling equipment has been screened from the sun. This will allow it to reject heat to a cooler environment and improve its performance efficiency as well as protect it from weathering.

Conservation has been further enhanced by the utilization of insulation at levels consistent with current passive residence designs. In the walls, R-19 insulation will be utilized along with 6-inch studs for the construction. Because the cathedral ceiling is utilized in the atrium, R-25 insulation will be placed at the ceiling level. No attic is included in this particular design, and thus R-38 insulation, as mentioned in the original program design guidelines, is not necessary. However, the insulation above the flat portions of the roof structure will include R-25 insulation. All of the windows in the structure are double glazed. There are no northern windows. One recessed window is included on both the northeast and northwest corners of each level of the house to allow direct solar gains during winter months; these are double glazed. As previously mentioned, the northern wall is specifically designed as an internal thermal storage medium with heavy exterior insulation. Additional insulation will be included around the slab and/or foundation around floor joists and between window headers. Infiltration losses are minimized with sound, high quality construction.

B. PHOTOVOLTAIC (PV) POWER SYSTEM

1. Photovoltaic (PV) System Block Diagram with Major Components

The PV system block diagram is shown in figure II-8. The major components are

(1) The PV array
(2) The power conditioning system (dc-to-ac inverter)
(3) The maintenance and safety enclosure
(4) The utility disconnect
(5) The two watt-hour meters.

The PV array produces dc power that is routed through the maintenance and safety enclosure and into the house to the inverter. The maintenance and safety enclosure provides a disconnect for the array and a monitoring capability. The inverter converts the dc power to ac power compatible with the utility power (120/240 VAC, single phase). This output is tied in parallel with the utility. The PV system operates interactively with the utility, feeding power to the utility when the array output exceeds the residential electrical demand. One meter monitors the energy supplied by the utility. The other meter monitors the energy fed back to the utility.

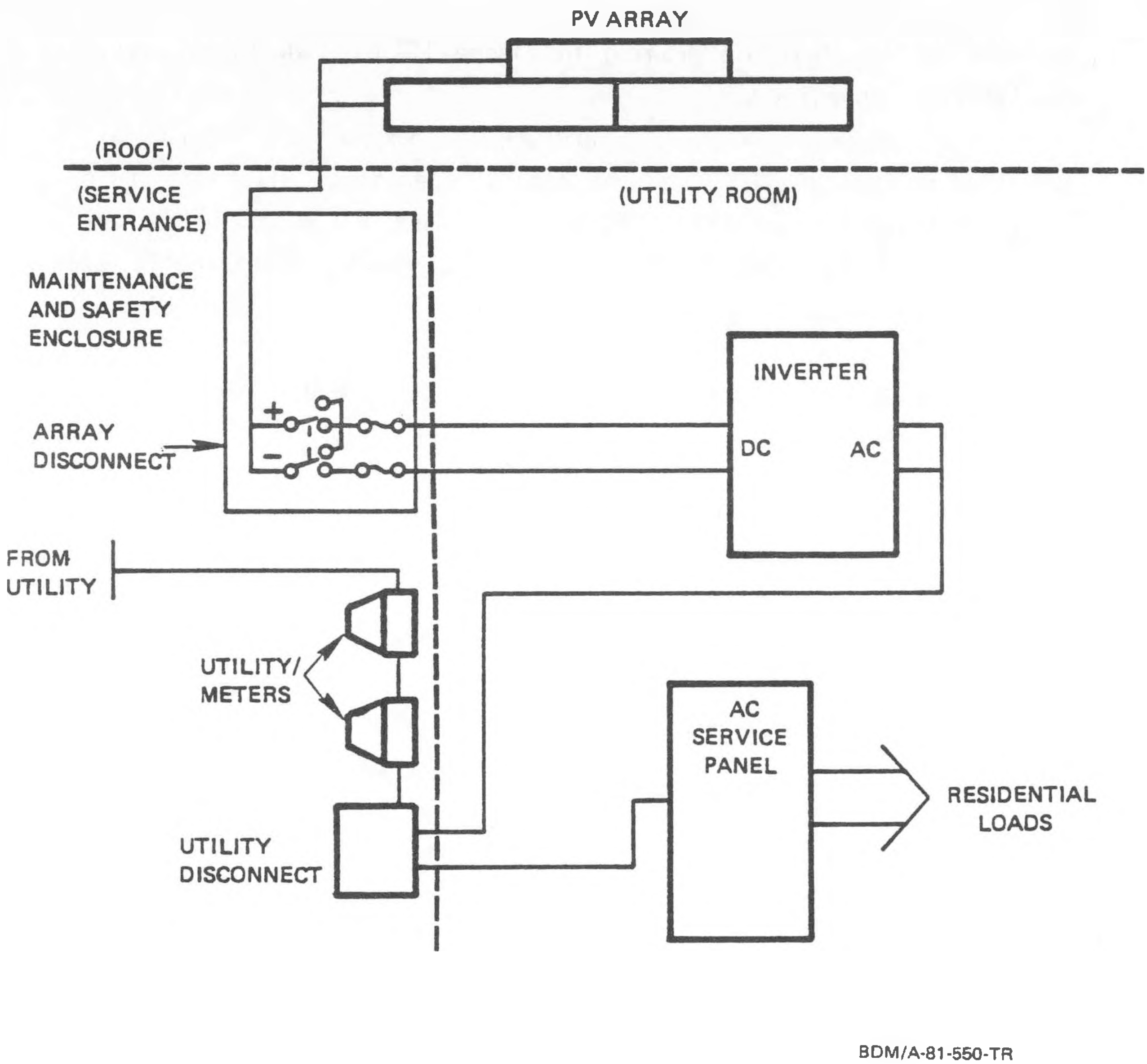

Figure II-8. Residence Power System Block Diagram

2. Photovoltaic (PV) Array

a. Photovoltaic (PV) Module

The Motorola module (P/N SSP0165, formerly MSP43D40) is a high reliability, glass-covered, JPL Block IV-tested module. A photograph of the module is included as figure II-9. Physical dimensions are included in the Motorola drawing in figure II-10. Additional data are available in Appendix C.

The module will produce a maximum of 40.0 W at an operating voltage of 14.3 V at the nominal operating cell temperature of 28°C. The packing density is 82 percent using 100 mm by 100 mm cells. Reliability is enhanced by the use of redundant cell-to-cell interconnects. Three copper ribbons across the cells reduce power loss in the event of cell cracking.

Motorola has adapted its design to our needs. The BDM module contains three bypass diodes (one per every 11 cells) instead of the one across the output. This design is illustrated in figure II-11. This is an electrical schematic and does not represent the physical layout. The bypass diodes are actually located in the module junction boxes.

b. Array Layout

The PV array is made up of 9 rows of 13 modules each. The 13 modules are connected in series to provide a voltage of between 160 and 240 VDC. The rows are connected in parallel to provide between 22 and 23.4 amps dc. Figure II-12 illustrates this arrangement.

The specific voltage output was selected to be compatible with inverter input requirements. Figure II-13 illustrates the output capability for strings of 12, 13, and 14 modules for different temperatures. Nine rows of PV modules are used to satisfy the minimum power requirement of 4 kW and to provide 50 percent of the annual energy requirements of the residence. Section II-D provides the energy load estimates for a residence of this design.

The arrangement of the array on the trapezoidal roof is illustrated in figure II-14. The roof area that is not covered by the PV array is made into louvered window area to provide heat gain in the

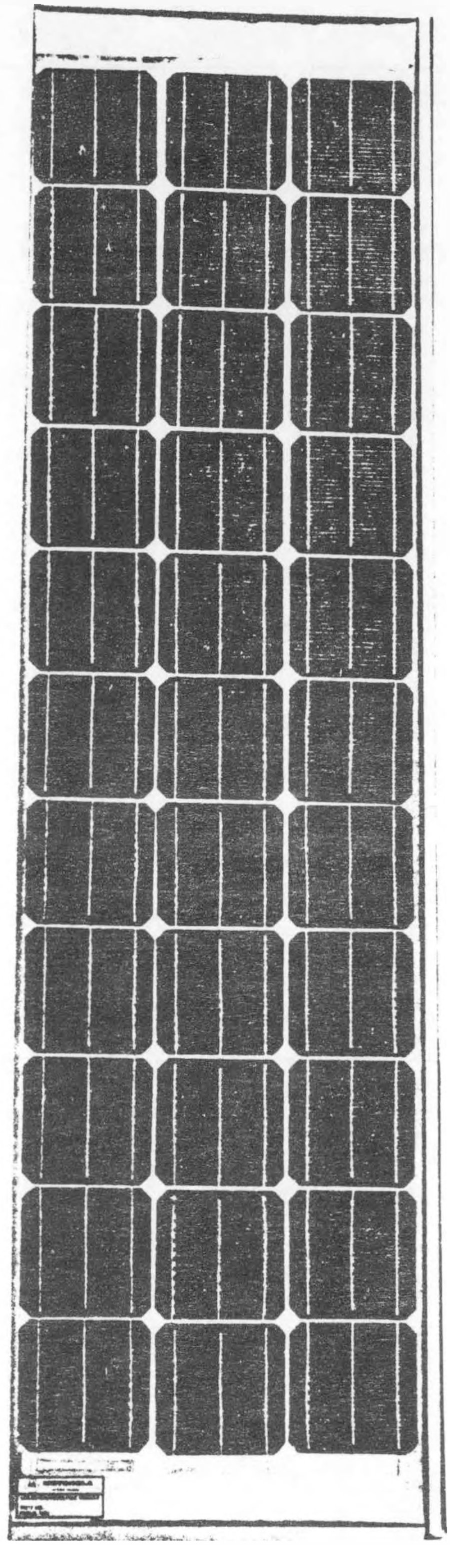

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Figure II-9. Motorola PV Module (SSP0165)

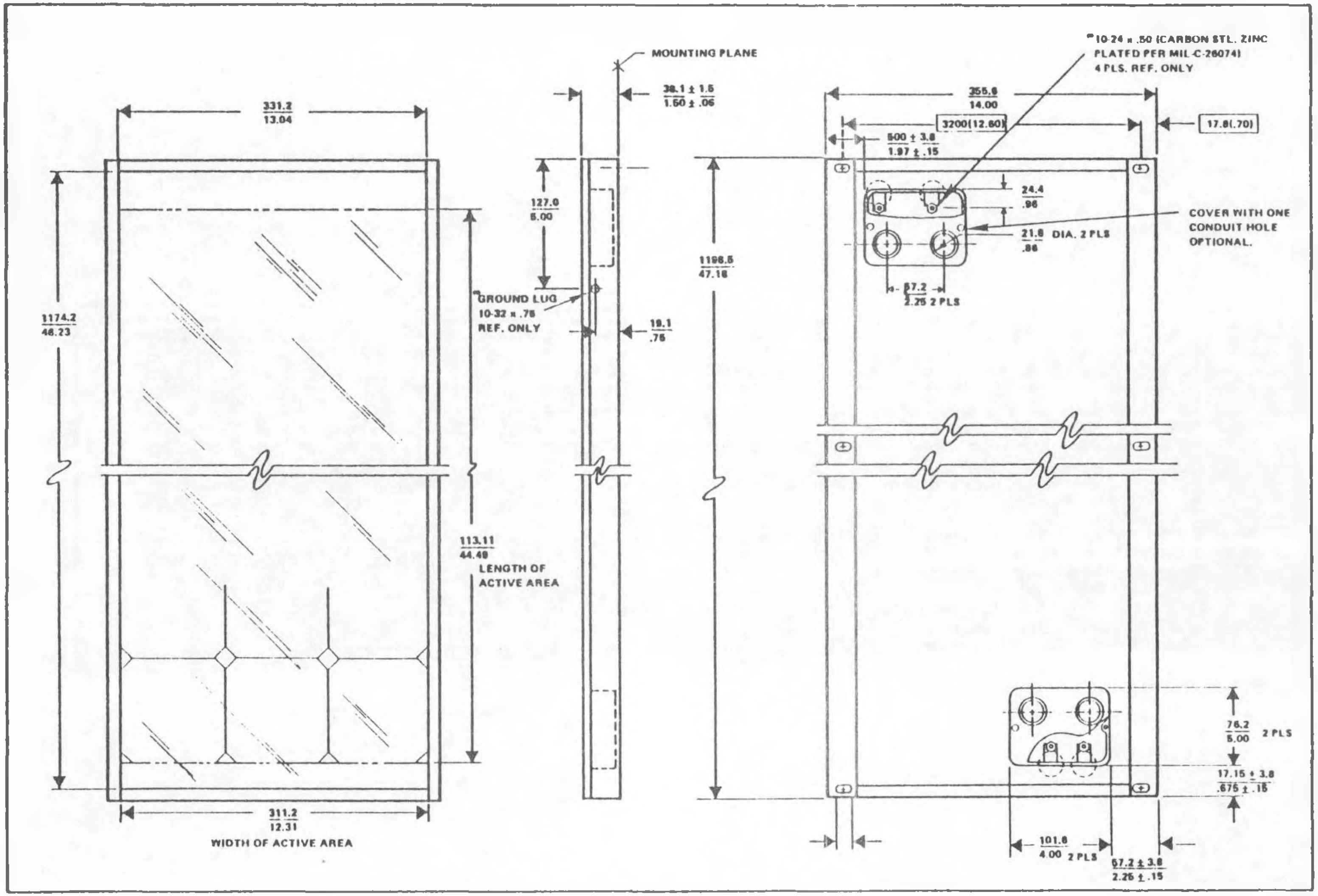

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Figure II-10. Motorola Module Drawing

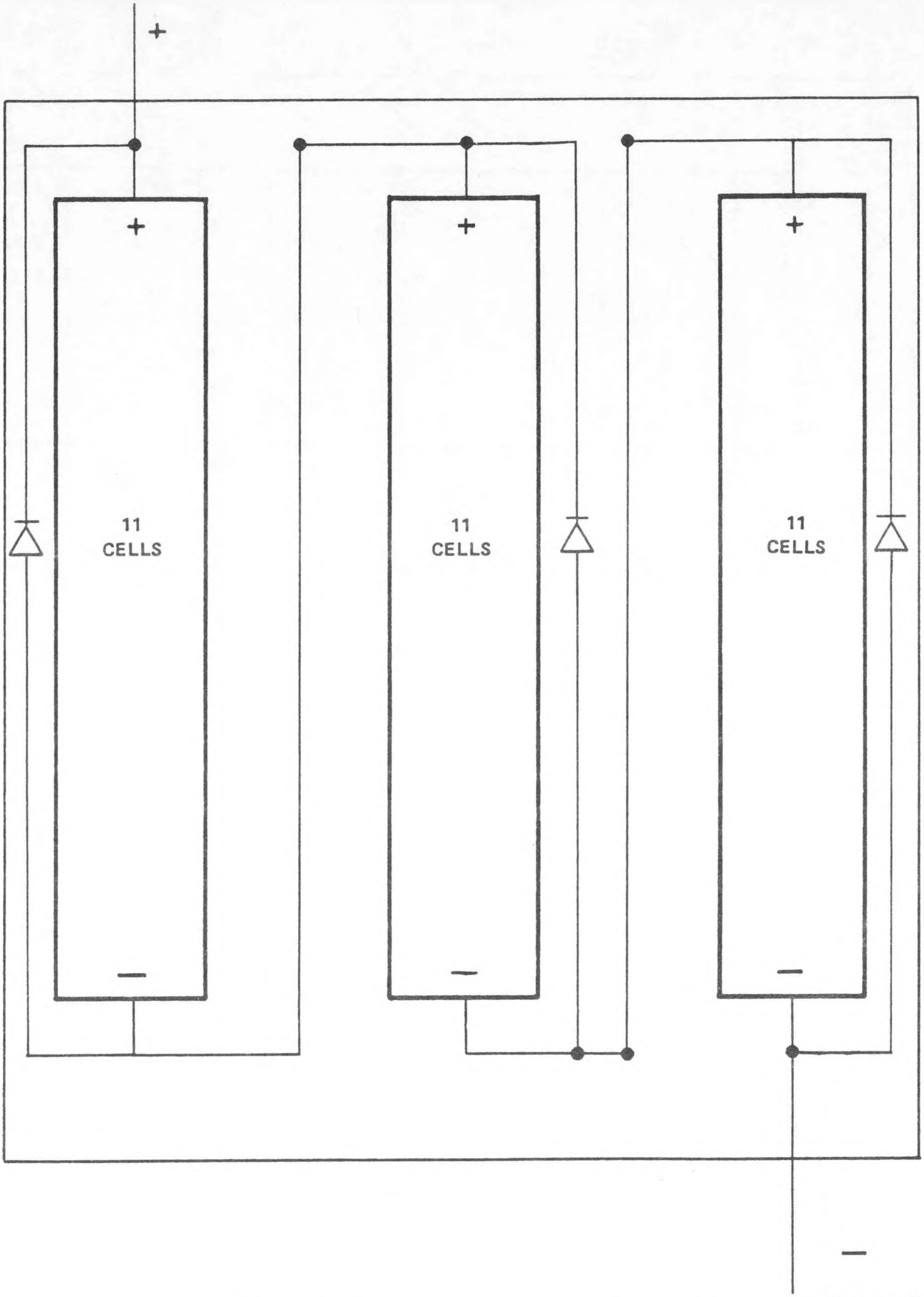
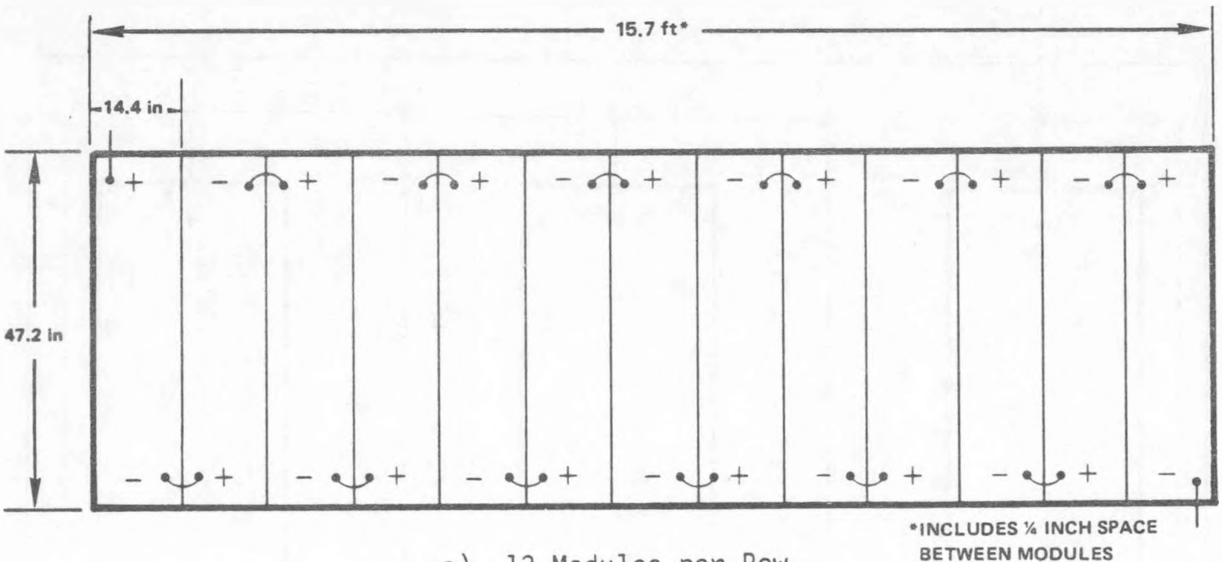
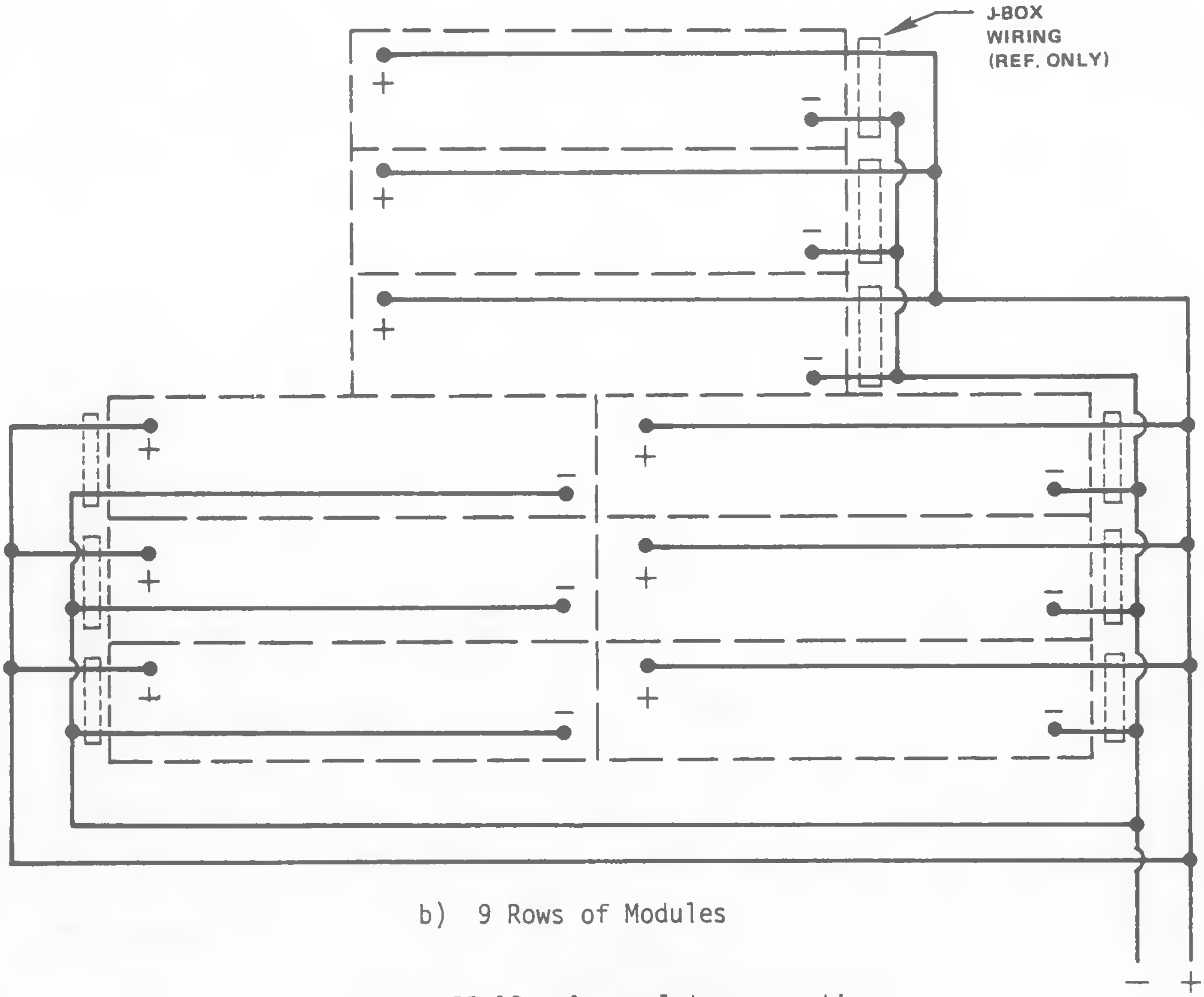


Figure II-11. Module Bypass Diode Scheme



a) 13 Modules per Row



b) 9 Rows of Modules

Figure II-12. Array Interconnection

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T_A	T_C	1 MODULE V_{NO}	1 MODULE I_M	1 MODULE P_M	12 MODULE V_{NO}	13 MODULE V_{NO}*	14 MODULE V_{NO}
-20°F(-29°C)	-29°C	19.8	2.43A	48.2W	238V	257V	277V
0°F(-18°C)	-18°C	19.1V	2.45A	46.8W	229V	248V	267V
0°F(-18°C)	0°C	17.8V	2.48A	44.2W	214V	231V	249V
0°F(-18°C)	12°C	17.0V	2.50A	42.5W	204V	221V	238V
68°F(20°C)	28°C	15.8V	2.53A	40.0W	190V	205V	221V
68°F(20°C)	50°C	14.3V	2.56A	36.6W	172V	186V	200V
105°F(40°C)	71°C	12.8V	2.59A	33.2W	154V	166V	179V
117°F(47°C)	77°C	12.4V	2.60A	32.2W	149V	161V	174V

*AS DETERMINED FROM THE MANUFACTURERS PUBLISHED DATA. PROTOTYPE FIELD EXPERIENCE INDICATES LOWER VOLTAGES CAN BE EXPECTED.

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Figure II-13. Voltage and Power of Module and Array for Various Temperature Conditions

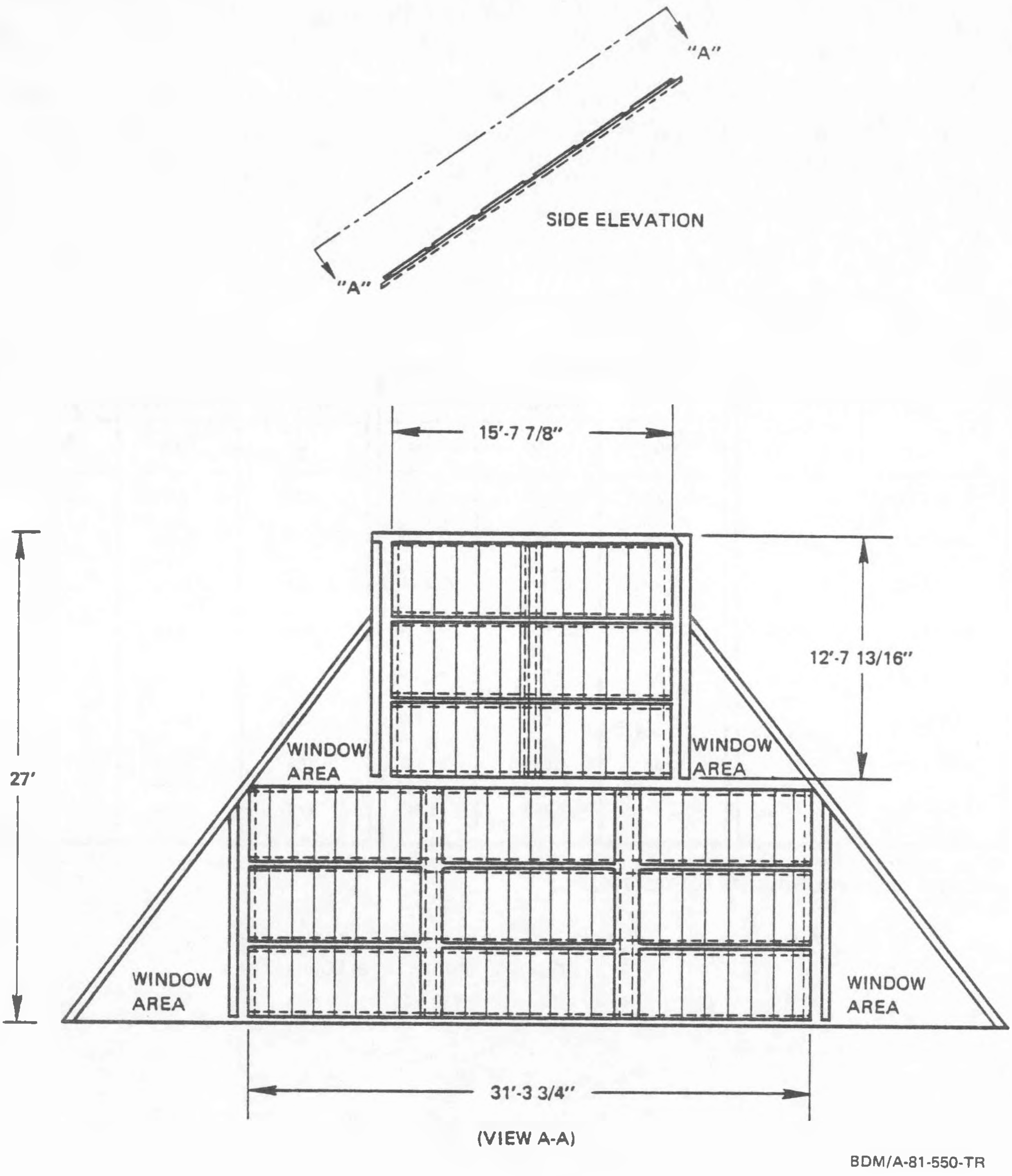


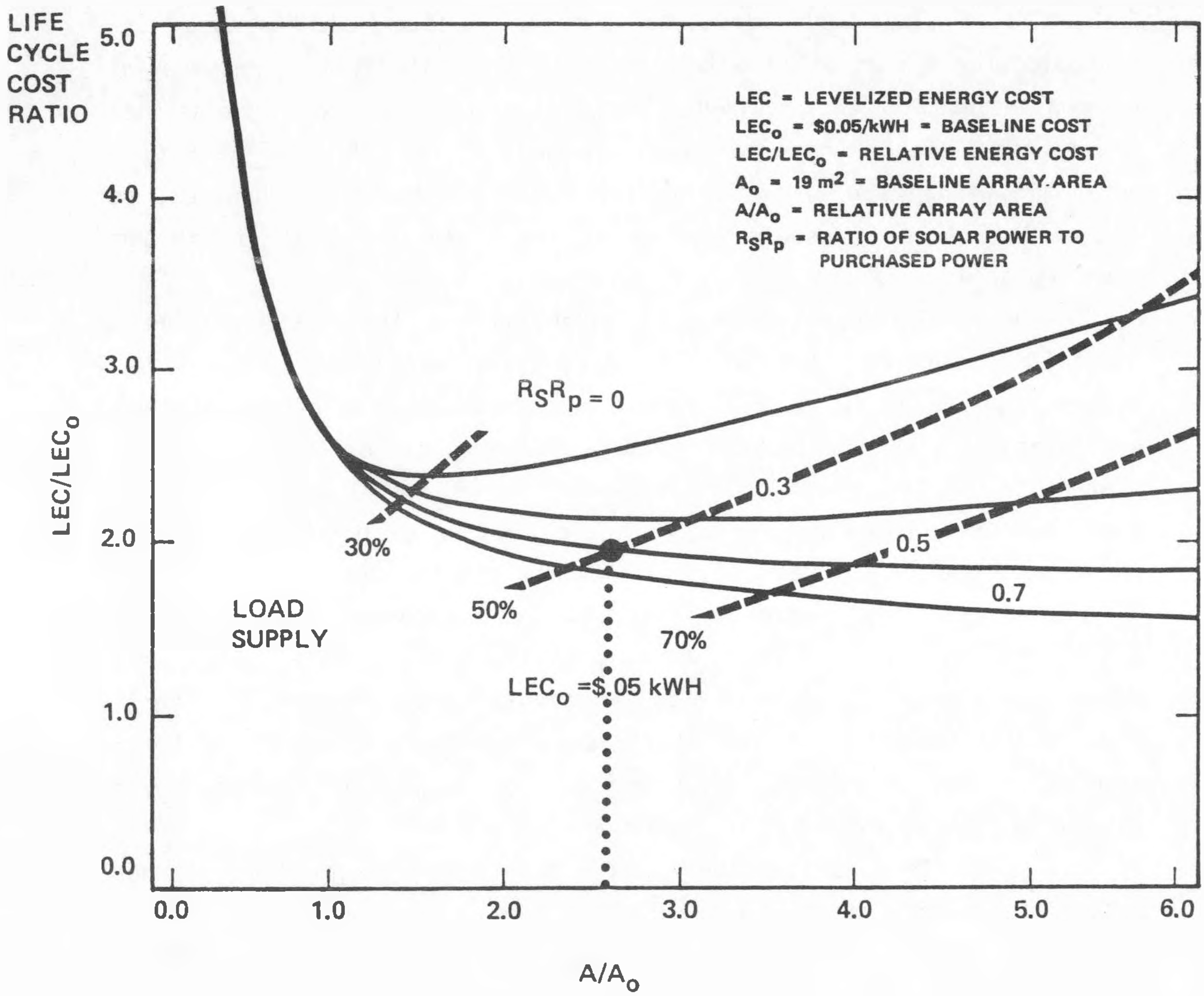
Figure II-14. Prototype PV Array Layout

winter. The roof dimensions will vary for homes in different areas that require 12 or 14 PV modules per row.

The key considerations in sizing the array (i.e., selecting the number of 13 module strings) were the physical requirements or constraints of the residential building and the overall electrical energy requirements. A total area of about 81 m^2 (872 square feet) is available within the south-facing roof of the residence. However, not all of this area is usable because of the irregular shape of the roof mounting area.

The next constraint addressed was that of supplying at least 50 percent of the total electrical energy required. About 16 MWH/YR are required for a typical Phoenix residence assuming effective energy conservation. BDM performed estimates of the electrical energy requirements of the proposed 2,073-square-foot residence. These estimates indicated that a Phoenix residence would require about 17.9 MWH/YR, and an Albuquerque or El Paso residence would require between 15 and 17.2 MWH/YR. These numbers were verified with projections performed by Sandia (SNLA) and the Public Service Company of New Mexico (PNM). SNLA estimates that energy conservation for a typical Phoenix residence (slightly under 2,000 square feet) can be reduced from the current 28 MWH/YR to between 16 and 17 MWH/YR. PNM provided corresponding figures for an Albuquerque house of 25 MWH/YR and 17 MWH/YR.

The baseline array was sized to provide at least 50 percent of the energy required for a Phoenix home. The 50 percent level was selected as the design criterion because the resultant PV array could be integrated with the residence in a manner that preserves aesthetics and allows significant use of passive solar energy. Further, the first commercial PV residence will use smaller power units that, as the costs decrease, will handle larger capabilities (i.e., as the residential PV system "matures" as a commercial product). Finally, this power level corresponded to a favorable economic system size for the designed house according to the techniques presented by Jones and Mehalick at the 14th IEEE Photovoltaic Specialists Conference. As shown in figure II-15,



A_o = 19 M^2
DIRECT USE = .68

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(Ref: "Photovoltaic System Sizing Analysis," G. J. Jones, R. M. Mehalick, SAND-80-0110C)

Figure II-15. Photovoltaic Array Sizing Analysis for Phoenix Rancher because the point defined by the 50 percent sellback credit structure and 50 percent PV load is beyond the knee of the curve, very little additional economic benefit can be gained by increasing the array size.

Given the above design criteria and constraints, and assuming the more conservative residential load of 17.9 MWH/YR, the PV array was sized to 4,680 peak watts, which included 9 module strings, each containing 13 modules. Each 13-module string is 4 feet by 15.7 feet as shown in figure II-12. These can be arranged within the trapezoid roof area as shown in figure II-14. The entire array is composed of 9 strings totaling 117 modules. The array area is 507 ft^2 and the array peak power at rated conditions of 40 W per module is 4,680 W.

c. Array Wiring

Figure II-10 shows the junction boxes located on the back of each PV module. Figure II-12 shows the daisy chain wiring for an array string. The PV modules are wired with #14 Awg wire. The wiring between the modules and between the modules and junction box is not in conduit. Instead, the wire is sheathed in "TYGON" plastic tubing to provide extra isolation and UV protection. High voltage connectors are provided to allow easy assembly and replacement of the modules. Each string has a junction box near it where the string wiring is conveniently spliced and makes the transition to conduit. The wiring for each string is brought down separately from the junction box to the maintenance and safety enclosure. This approach ensures that no wire carries more than 3 amps and that each array string can be monitored and tested individually.

The strings are tied in parallel in the maintenance and safety enclosure using blocking diodes. Lightning protection is provided via the incorporation of varistors that are also housed in the maintenance and safety enclosure. A switch enables the array to be shorted or dc power to be sent to the inverter.

d. Array Mounting Structure

A simple, inexpensive, sturdy standoff-mounting technique is incorporated for the residential design. The concept is illustrated in figure II-4. The standoff mounting promotes air flow under the modules, which helps to cool the modules and increases reliability and power output.

All boards are primed and sealed before attachment to the roof. The 12-foot by 2-inch by 6-inch boards are nailed to the plywood roof surface vertically, as shown in figure II-4. One inch of foam with a membrane sealer is applied to the roof and this provides a weather-tight roof seal. Pairs of 2-inch by 6-inch by 6-inch blocks are nailed onto the stringers to further space the array away from the roof. This provides better ventilation and therefore improved cooling. Unistrut® is bolted horizontally to the blocks. The array modules are then bolted to the Unistrut.®

This design will be implemented at very low cost and will afford:

(1) Easy module maintenance
(2) Negligible wind loading
(3) No roof leaking problems
(4) No degradation due to trapped moisture
(5) Small standoff chimney effect allowing module cooling (recommended by JPL as high temperature problems have been identified with direct mount modules)
(6) An aesthetically pleasing array design effectively integrated into the building architecture
(7) Low mounting cost.

3. Power Processing and Utility Interfacing Subsystem

The residence power processing system consists of a dc-to-ac inverter and related switches. The processing system function is to convert the roof PV array dc output to 240 VAC single phase power and to provide the necessary switches for control and system safety. Figure II-8 presents a functional diagram of the residential power processing system with key components, including the inverter switchgear to isolate the array and the inverter, and the main circuit breaker panel board.

The inverter uses a digitally synthesized wave design approach to convert 160-240 VDC power from the PV array to 6-kVA output ac power.

The inverter maintains a 0.96 - 1 power factor with a 50 percent input power, 5 percent current total harmonic distortion waveform, and the 20-100 percent load efficiency is about 87 percent. The system interties with the utility and ensures that the voltage is phase-locked with the utility voltage. Automatic start-up occurs at 180 VDC; automatic shutdown occurs when the array voltage is less than 160 VDC, more than 264 VDC, during output overcurrents, phase-lock loss, or utility loss.

The switchgear consists of array row disconnects and two manual disconnects to isolate the inverter from the utility and/or to isolate the entire array from the inverter. The disconnects are necessary to allow installation and maintenance of the array and inverter without exposure to ac or dc power levels. Each of the 9 PV rows has disconnects to allow electrical isolation and has blocking diodes for array protection.

The main circuit breaker panel board is standard for homes, and the two-wire output of the inverter connects to the bus between the main and branch feeder breakers. The inverter 240 VAC connects to the two secondary coil leads from the utility stepdown transformer, and the transformer center tap provides the return leg for both the utility and inverter power. For imbalance conditions across the two transformer secondary coils and center tap, the transformer acts like an autotransformer to the inverter.

4. <u>Power Conditioning System</u>

The Abacus inverter uses a dual bridge digitally synthesized wave design approach. Figure II-16 is an inverter functional diagram showing the digital controller, dual bridge inverter, filter, and phase-locked loop blocks. The inverter provides high quality output power and includes safety and protection features.

The digital controller provides the switching signals to the inverter block to control amplitude, frequency, phase, peak power tracking, and safety. The controller synthesizes sine waves by storing patterns of positive and negative pulses on programmable read only memories (PROM). The PROMs are cycled at a frequency 360 times the 60-Hz

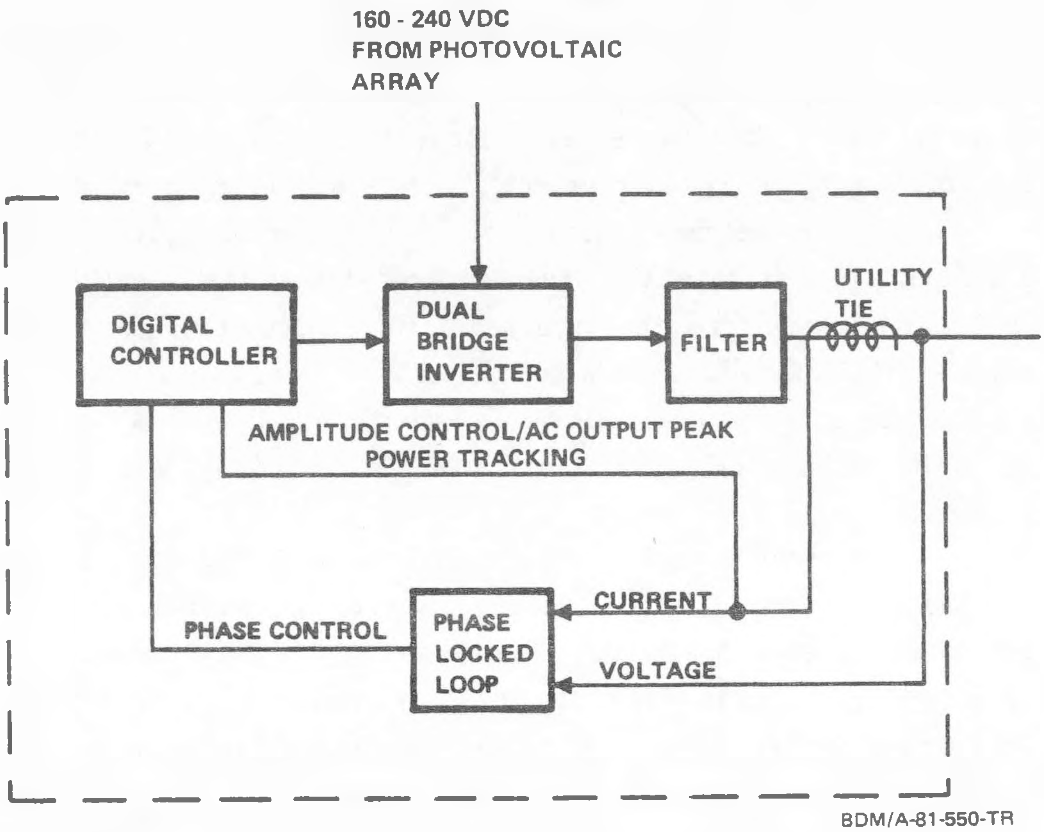

Figure II-16. Inverter Functional Block Diagram operating rate, thus producing one degree resolution. The PROM outputs trigger the dual bridge transistors, and this output is filtered to provide a low harmonic sine wave. The output sine wave phase is locked to the utility via the phase-locked loop circuitry, and the output voltage is regulated by increasing the time that the pulse pattern stays at zero. The peak power tracking mode monitors the output ac current and shifts the dc input impedance as required to obtain peak power from the array.

The digital controller also monitors input dc, output ac, utility power, and transistor temperature to determine when to automatically start-up, shutdown, or disconnect the array and/or utility from the inverter.

The dual bridge inverter converts the array dc to a pulsed ac output, which is then filtered to obtain a low harmonic content sine wave. The array dc is switched in transistors, which are triggered by the digital controller output signals.

The filter is a simple LC (inductive capacitive) network that reduces the high order harmonics. The low order harmonics are reduced by selecting an appropriate programmable read-only-memory (PROM) pulse pattern. The LC filter is physically small since the switching frequency in the dual bridge inverter is high.

The phase-locked loop monitors the output ac power current and voltage to obtain phase control signals for the digital controller. The phase-locked loop ensures the power factor is as close as possible to 1, which provides the best energy transfer to the utility grid.

The ac power output contains no more than 5 percent current total harmonic distribution, less than 3 percent voltage total harmonic distortion, and a power factor greater than 0.96. This quality is important to ensure transfer of usable energy to the utility and to reduce heat generation in components that accept harmonic dominant currents.

The inverter safety and protection features allow automatic start-up, shutdown, and disconnect when various conditions are sensed by the digital controller. The features include automatic start-up at

180 VDC (wake-up in morning), automatic shutdown when the array voltage is less than 160 VDC (clouds or night) or more than 240 VDC (high open circuit voltage) or during transistor overtemperature, and automatic output disconnects when utility values are less than 216 VDC or more than 264 VDC, during output overcurrents, phase-lock loss, or utility loss. The inverter also includes fuses on both input and output lines and a dc on-off switch that isolates the inverter from the array.

5. Photovoltaic (PV) System Control and Protection

Figure II-17 illustrates the key elements associated with control and protection of the PV system.

The array power is routed into the maintenance and safety enclosure as shown in figure II-18. The positive side of each row is brought through a blocking diode and a switch before being tied together. The blocking diodes protect the rows by preventing energy from flowing into a row should it become shaded or fail. The switches allow open-circuiting of individual rows for testing purposes and maintenance. A resistor divider network on each row provides a low-voltage monitor point. A varistor is connected between the tie point and earth ground to protect the array from nearby lightning strikes.

The negative side of the rows have a monitor jack and a series 0.1-ohm resistor before the tie point. This allows the current from each row to be monitored as a voltage. A varistor-to-earth ground provides lightning protection for the negative side.

From the tie points, the positive and negative sides go to a switch that is "ganged" to five circuits. This switch either provides array power to the dc-to-ac inverter or shorts the array. One set of contacts of the "five-ganged" switch turns on a light located above the array to indicate that it is qualified to do maintenance on the roof array.

PV power is routed to the inverter from the maintenance and safety enclosure. The inverter provides an on-off switch and automatic or manual operation. Normal operation is automatic. The inputs and outputs of the inverter are protected by fuses. The inverter automatically shuts down for the following conditions:

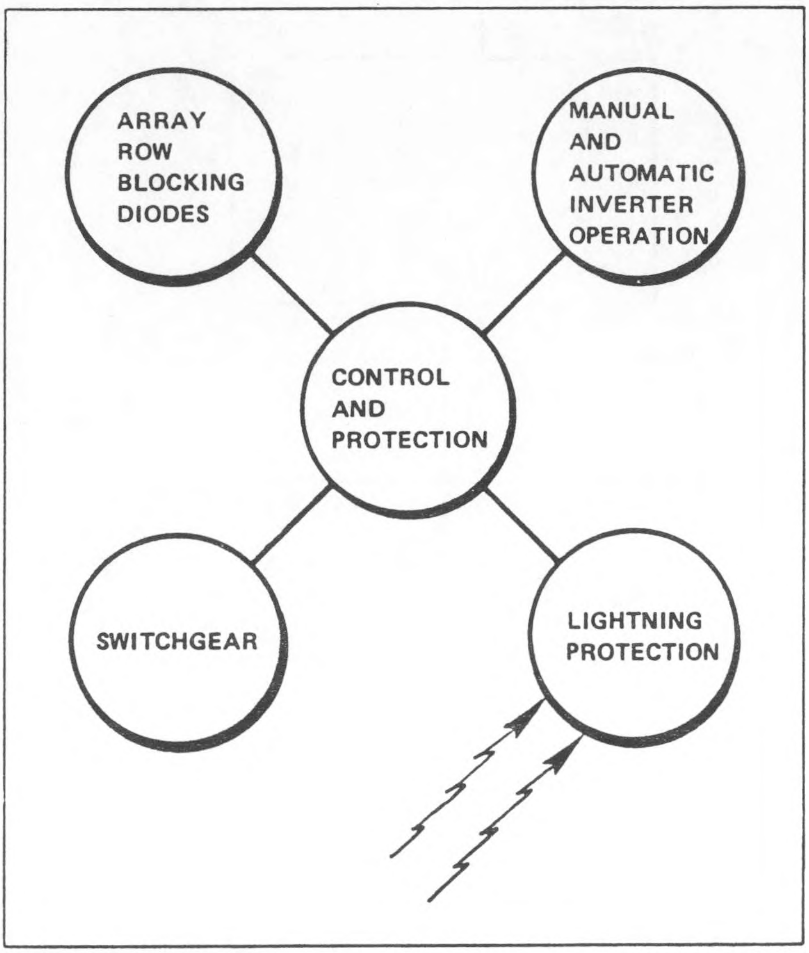

Figure II-17. Photovoltaic System Control and Protection

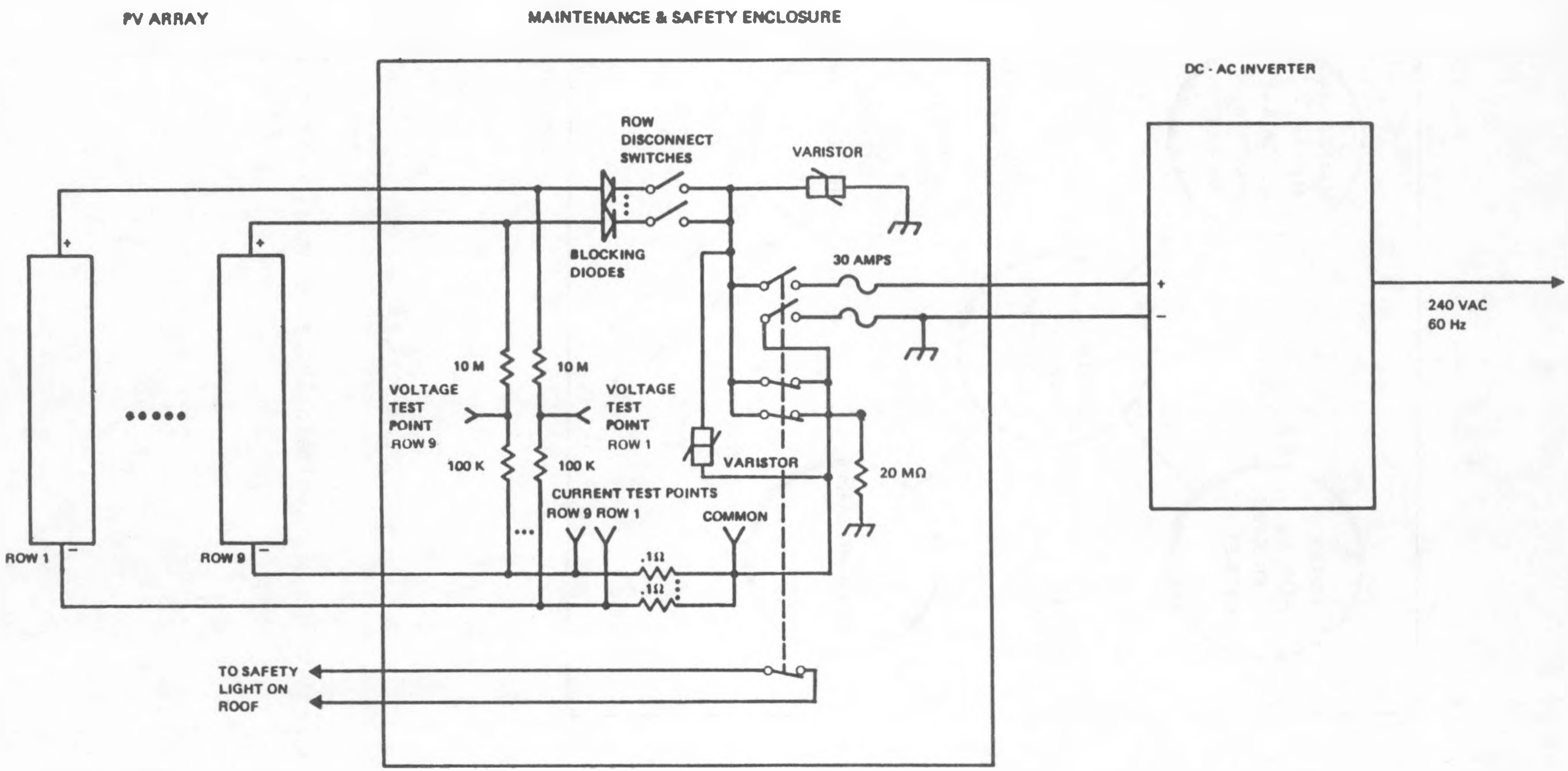

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Figure II-18. Photovoltaic System dc Schematic

(1) dc input less than 160 VDC
(2) dc input greater than 240 VDC
(3) Transistor overtemperature
(4) Utility voltage less than 216 VAC
(5) Utility voltage greater than 264 VAC
(6) Output over current
(7) Loss of phase lock

The ac output of the inverter is connected to the utility by going to the load side of a 30-amp circuit breaker.

The utility power is brought in through a main disconnect switch. This allows the utility to disconnect the house completely. From the disconnect switch two meters are installed. One records the energy the residence uses from the utility. The other measures the energy the residence supplies to the utility. A surge arrestor is installed there to protect the utility and inverter from transients.

6. Photovoltaic (PV) System Grounding and Safety Design

System safety is an important issue in the design of a PV system. Personnel safety is critical and, along with hardware protection, can also directly influence the commercialization of PV systems through the cost of insurance premiums.

The standoff mounting of the collectors to the roof provides electrical isolation from the roof. One disconnect switch to completely isolate each collector row and quick disconnect plugs minimizes the hazard of electrical shock when servicing the collectors. The inverter has a disconnect switch activated by the opening of the ac service panel to prevent inadvertent shock of personnel during servicing and maintenance. Two other disconnect switches are provided in the system to isolate the inverter from the PV array and to isolate the inverter from the utility company. Lightning and surge protection are provided by blocking diodes and varistors for the PV array, and transient protection is provided at the power conditioning equipment. The PV system is grounded through the maintenance and safety enclosure to the building service ground for further personnel safety and hardware protection.

C. HEATING, COOLING, AND HOT WATER SYSTEM BLOCK DIAGRAM

1. Overview Block Diagram

Block diagrams for the heat pump configuration and the solar-assisted water heater designed for the PV residence are presented in figures II-19a and b. The heat pump is a package unit located on the outside of the facility. The air handling equipment, liquid air heat exchanger, and backup electric heater are contained within an air plenum located within the residence.

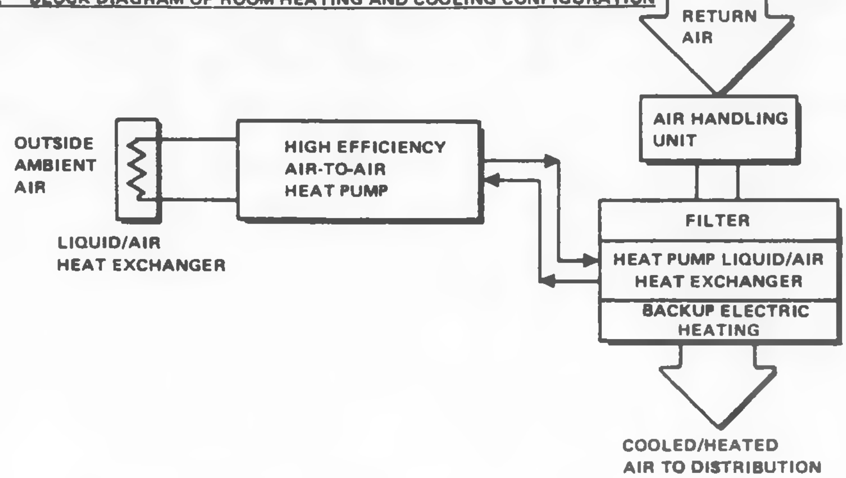
The major components which will be included in these systems designs are illustrated in figure II-19. The heat pump within the conceptual design calls for a General Electric BWC030B100B or equivalent heat pump unit. The system is a packaged heat pump with a cooling capacity of 37,000 BtuH and a heating capacity of 40,000 BtuH. This unit operates at a nominal 1,200 CFM with a high temperature heating coefficient of performance of 2.3 and a cooling energy effectiveness ratio of 6.8 BtuH/W.

2. Room Heating and Air Conditioning

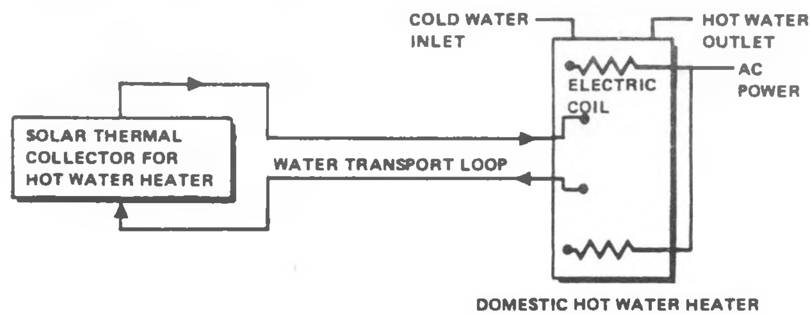
The proposed PV residence has been configured to allow the use of several different room heating and air-conditioning configurations. This is considered appropriate because within the southwestern United States climatic conditions can warrant selection of different types of hardware. The baseline configuration selected is a high efficiency air-to-air heat pump system. This system was selected for the baseline design because it is applicable throughout the southwestern region and because its inherent high efficiencies minimize the total electrical requirement of the residence.

The conceptual design of the heat pump system is shown in figure II-20. The heat pump will be housed on the outside of the residence in a shaded enclosure. A liquid-to-air heat exchanger will act as the exchange mechanism between the working fluid and the ambient air. The working fluid is then circulated to the liquid-to-air heat exchanger within the atrium on the first floor of the residence. A 1/2-hp air

a. BLOCK DIAGRAM OF ROOM HEATING AND COOLING CONFIGURATION



b. BLOCK DIAGRAM OF SOLAR ASSISTED DOMESTIC HOT WATER SYSTEM



c. SPECIFICATIONS OF MAJOR HEATING, COOLING AND HOT WATER SYSTEM COMPONENTS

HVAC

1. HEAT PUMP: G.E. BWC030B100B (OR EQUIVALENT)
   - 31,500 BTUH COOLING; 33000 BTUH HEATING
   - 1000 CFM
   - HEATING COP = 2.3 (HIGH TEMPERATURE)
   - COOLING ENERGY EFF RATIO = 6.8 BTUH/W

   (SEE APPENDIX B FOR DETAILED PERFORMANCE DATA.)
2. AIR HANDLING UNIT: ½ HP CAGE FAN (G.E. BWCO30B-B or EQUIVALENT)
3. CHARCOAL FILTER
4. CENTRAL ELECTRIC HEATER (G.E. BAY96X259C, 1 RACK)

HOT WATER

5. HOT WATER SOLAR FLAT PLATE THERMAL COLLECTORS (METALLIC HELIOSYSTEMS MT200C)
6. HOT WATER SOLAR THERMAL TRANSPORT MEDIA: WATER (DRAIN DOWN)
7. HOT WATER HEATER: (HELIO SYSTEMS DHW MODEL 120)

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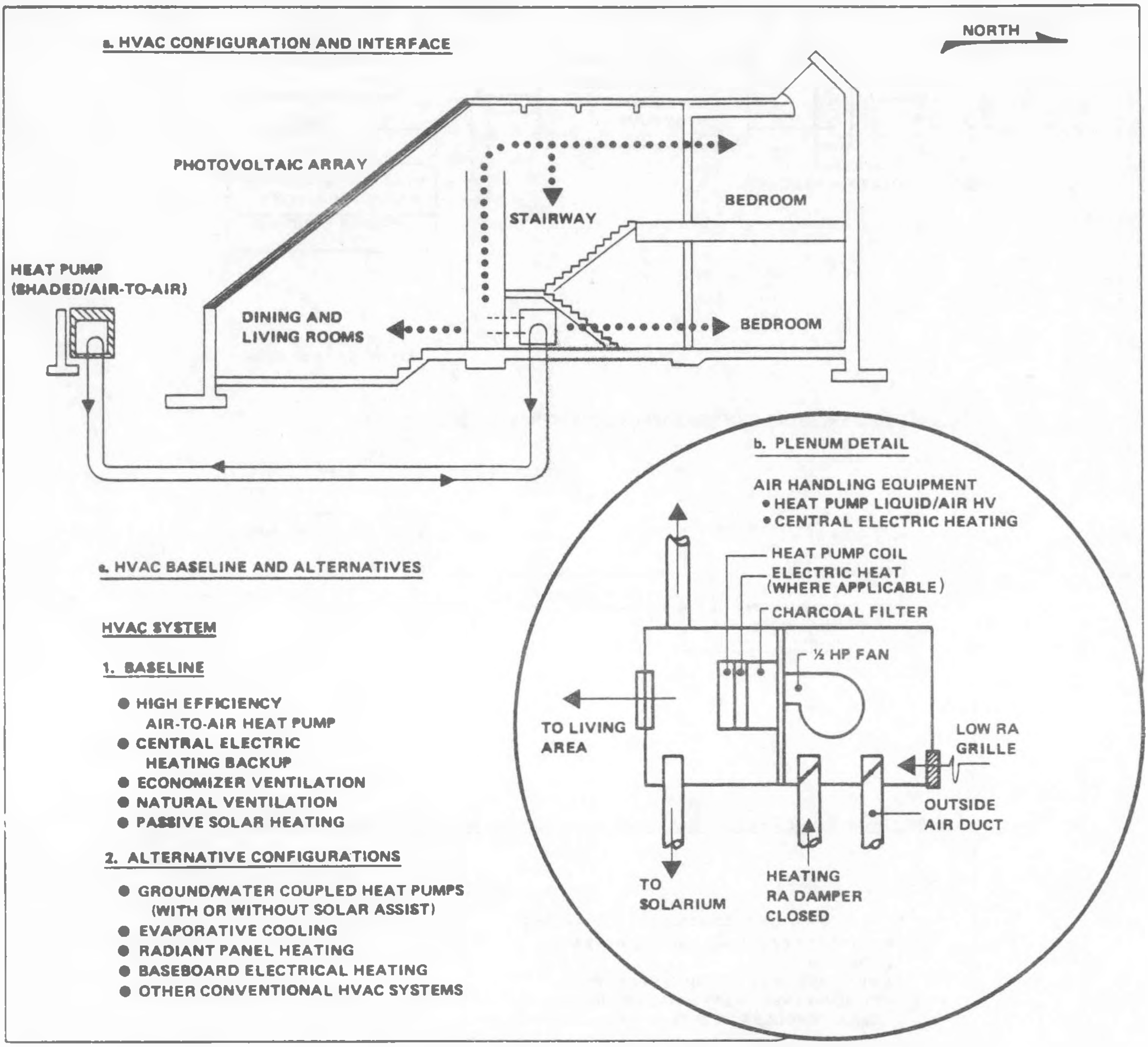
Figure II-19. Heating and Cooling Systems Block Diagrams and Component Specifications



NOTE:
DAMPERS FOR LOW RA AND OUTSIDE AIR SHALL OPERATE ON AN ENTHALPY ECONOMIZER CYCLE.

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Figure II-20. Residential Heating, Ventilation, and Air-Conditioning (HVAC) Equipment circulating fan then circulates the air through the heat exchanger, providing the necessary heating or cooling, and the air is then circulated to the periphery of the residence. The heat pump is designed to work in both the heating and air-conditioning modes, but electrical coils are provided in the air plenum to provide auxiliary or backup central electric heating for the residence.

A detailed diagram of the plenum is shown in figure II-20. The plenum includes inlets for recirculated air as well as outside air with the necessary dampers for control. Air pumped by the air handling equipment is first forced through a charcoal filter and then through the heating coil and the liquid-to-air heat exchanger from the heat pump unit. The air is then forced through the plenum to the north rooms, living area, or solarium.

The heat pump HVAC configuration will include an economizer cycle that will allow outside air to be circulated through the house when refrigeration is not required. In addition, natural ventilation and passive solar heating will augment the cooling and heating systems. Hot air outlets are provided at the top portion of the atrium and through the ventilation tower as part of the residence design. Passive solar heating is provided through windows located around the PV array and windows located at the roof level of the northern periphery of the building. As previously mentioned, a high-efficiency heat pump was selected as the baseline because of its high performance characteristics and general applicability throughout the Southwest. Heat coefficients of performance (COP) on the order of 2.3 (as minimum for air-to-air heat pumps) are currently quoted by manufacturers. When compared with direct electric heating where the COP would be unity, substantial savings in electrical energy required for heating are achieved. Likewise, the cooling energy efficiency ratio of 6.8 BtuH/W provides for efficient air cooling when required. Heat pumps couple to other heat sink/ sources such as the ground (via tanks, etc.) or available large volumes of water (ground water table, ponds, domestic water source, etc.) can provide significantly improved efficiencies (COPs of more than 3). These systems can be used in the full-size residence.

It is also recognized that different locations within the Southwest may be able to gain significant economies by utilizing evaporative cooling. Areas of southern New Mexico, Arizona, and other more arid climates can, and do, currently utilize evaporative cooling. The use of evaporative cooling substantially decreases power requirements for room cooling. The configuration presented in the BDM proposal allows the use of evaporative cooling systems that can be combined with either central electric or baseboard electric or even electric radiant panels for heating purposes. Evaporative coolers would require that the air handling equipment be located at ground level on the outside of the building, and air would be circulated through the residence in the same pattern as that illustrated in figure II-20.

The conceptual design of the PV residence for the Southwest allows for substantial flexibility in each HVAC system design. Depending on the specific location, the most cost-effective and efficient HVAC equipment can be utilized to minimize the electrical energy requirements. Further, no redesign is required when different room heating and cooling systems are applied to the residence.

The air handling unit is a 1/2-hp cage fan (General Electric BWC030B-B or equivalent utilizing a charcoal filter). A one-rack central electric heater will be utilized to supplement the room heating when necessary. A General Electric BAY96X259C or equivalent will be used.

3. Domestic Hot Water

The domestic hot water will be heated in part with solar energy. Solar thermal collectors located on the flat roof portion of the building will heat the domestic water before it is stored in an electrically powered water heater on the first level of the residence. Electrical coils within the water heater will be used only when required, and, in fact, only the top coils should be used during periods of inclement weather for quick recovery purposes.

A low-temperature, flat-plate thermal solar collector will be utilized to provide the solar energy to augment the domestic water heating requirements. The conceptual design includes a Heliosystem metallic solar collector with maximum operating temperature of 180°F. The water heater will be a 120-gallon, quick-recovery water heater also provided in the Heliosystem package. Insolation will be provided and solar energy will be introduced directly into the hot water by circulating water from the tank through the collectors and back to the tank.

The most cost-effective and energy-efficient heating and cooling components have been selected for the conceptual design. Maximum use will be made of both passive heating and cooling designs within the building, which have been described earlier in this chapter. The overall energy envelope design will provide the minimum requirement for both electrical and thermal energy within a Southwest residential design.

D. ENERGY PERFORMANCE ESTIMATES

1. Photovoltaic (PV) System Performance

The array consists of 117 modules. Figure II-21 illustrates the expected power out of the array based on Motorola's specifications.

The performance estimates were determined by using two techniques. The first technique was to simply utilize the manufacturer-specified value and multiply by the total number of modules (117) in the array. These values are presented in figure II-21 for the typical and minimum performance state for each of three cell temperature conditions. Specification values for this module are provided in Appendix C. It was determined that the manufacturer's "typical" module power more closely represented an actual maximum than it did an average or nominal value.

The second prediction technique used to estimate the performance of the array was to use a computer code called Photovoltaic Transient Analysis Program (PV-TAP). This code was developed by BDM for Sandia National Laboratories and was used to determine array performance based upon cell photocurrent variations resulting from known manufacturing distributions.

	CELL TEMPERATURE		
	28° C	50° C (NOCT)	70° C
POWER SCALED FROM SPEC. SHEET			
TYPICAL	4,680 W	4,282 W	3,908 W
MINIMUM	4,271 W	3,896 W	3,562 W
POWER CALCULATED USING PV-TAP			
UNMATCHED MODULES	4,653 W	4,275 W (PV-TAP)	3,927 W
MATCHED MODULES	4,702 W	4,313 W (PV-TAP)	3,949 W

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Figure II-21. Array Output Power

The distribution of module performance was modeled after the following sorting procedures used by the module manufacturer. The cells are tested and sorted into one of three bins based upon cell current: (1) 2.4 to 2.6 amps, (2) 2.6 to 2.8 amps, (3) more than 2.8 amps. Historical experience was that approximately 30 percent of the cells were in the lowest bin, 60 percent in the middle bin, and 10 percent in the highest bin (see figure II-22). Analysis was performed using PV-TAP in which it was postulated that the 13 modules strings were assembled using (a) matched modules and (b) modules selected at random. Results from this analysis are listed on the bottom of figure II-21 and indicate that about a 1-percent loss of power can be expected due to not matching the modules during the selection process. This is viewed as a negligible loss and therefore probably does not warrant the effort of sorting and matching prior to assembly in the field.

The SOLCEL computer program was used to estimate the energy that the array and inverter would supply over an average year as defined by the SOLMET weather data. See figure II-23 for the SOLCEL results.

2. Energy Load Estimates

The heating load is discussed first using the degree-day method. This takes into account the heat lost through the building structure and infiltration. Figure II-24 lists the building dimensions used in the subsequent calculations. Figure II-25 shows the calculation of the U-values for the major exterior surfaces. The different exterior surface areas are shown in figure II-26 as well as the design temperatures. Figure II-27 lists the heat load for the residence.

Solar gain will help to offset the heating requirements. Solar gain is calculated using the ASHRAE bin method. The equation for this technique is illustrated in figure II-28. Figure II-29, II-30, and II-31 divide up the day into 5-degree bins that require heating. The number of hours that the temperature is in each range is written into the appropriate row. Day and night are tracked to separate the time when solar gain is possible. Each figure illustrates one day in the indicated months. Figure II-32 is a composite of figures II-29, II-30, and II-31.

PURPOSE — ASSESS LOSS IN ARRAY POWER DUE TO VARIATIONS IN PHOTOCURRENT

- DISTRIBUTIONS APPROXIMATED FROM MOTOROLA SORTING PROCEDURES
  - — 3 BINS ON I_{MP} — (2.4 — 2.6A), (2.6 — 2.8A), (2.8A AND ABOVE)
  - — 30 PERCENT FROM LOW BIN; 60 PERCENT FROM MIDDLE BIN

    $\therefore I_{SC}$ (AVE) $\approx$ 2.75A; I_{SC} (1σ) $\approx$ 2.65A
- STRINGS WITH MODULES MATCHED AND UNMATCHED

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Figure II-22. PV-TAP Calculations

	LAS CRUCES	PHOENIX
ARRAY dc	10,707 kWH/YR	10,281 kWH/YR
INVERTER ac	9,240 kWH/YR	8,843 kWH/YR

- SOLMET TMY DATA FOR EL PASO AND PHOENIX USED
- INVERTER EFFICIENCY
  - 90 PERCENT — FULL LOAD (PROJECTED)
  - 86 PERCENT — 40 PERCENT LOAD (PROJECTED)

TARE POWER — 160 W (PROJECTED)

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Figure II-23. PV Power System Annual Energy Production Calculated with SOLCEL

ROOM	EXTERIOR WALL AREA Ft²		WINDOW AREA Ft²	BERM AREA Ft²	CEILING AREA Ft²	DOOR (Exterior) Ft²	FLOOR AREA Ft²
LIVING ROOM	16' 6" x 9' 0" 13' 0" x 9' 0"	265	3' 6" x 4' 0' = 14	(16' 6" + 13' 0") = 88.5	UNDER SOLAR PANELS		HEATED CONCRETE FLOOR
BATH	10' 9" x 9' 0"	96.8	0	10' 9" x 3' 0" = 32.3	648		1462
MASTER BEDROOM	13' 6" x 9' 0" 4' 0" x 9' 0" 14' 6" x 9' 0"	288	3' 6" x 4' 0" = 14	16' 6" x 3' 0" = 49.5	PLASTICRAFT 198		
DEN	17' 6" x 9' 0" 5' 6" x 9' 0"	207	0	17' 6" x 3' 0" = 52.5	FLAT CEILING 1041	6' 8" x 3' 0" =20	
DINING ROOM	28' 0" x 9' 0"	252	9' 0" x 1' 6" 18.8 3' 6" x 1' 6"	28' 0" x 5' 0" = 140			
KITCHEN	16' 0" x 9' 0" 16' 0" x 9' 0"	288	7' 0" x 1' 6" = 10.5	16' 0" x 3' 0" = 48			
VESTIBULE AND CLOSET	7' 6" x 9' 0" 10' 0" x 9' 0" 4' 0" x 9' 0"	193.5	0	0		3' 0" x 6' 8" = 20	
BEDROOM	12' 0" x 9' 0" 13' 6' x 9' 0"	229.5	0	0		3' 0" x 6' 8" =20	
BEDROOM	16' 6" x 9' 0" 13' 0" x 9' 0"	265.5	3' 6" x 4' 0" = 14	0			
BATH	10' 9" x 9' 0"	96.8	0	0			
BEDROOM	13' 6" x 9' 0" 4' 0" x 9' 0" 14' 6" x 9' 0"	288	3' 6" x 4' 0" $\frac{\pi \times (3' 8'')^2}{4}$ 23.6	0			
HALL	16' 0" x 9' 0"	144	3 each: 2' 0" x 3' 6" = 21	0			
ATRIUM	$\frac{(13 \times 10)}{2}$ 2 each	130	0	0			
TOTAL	2744.1		115.9	410.8	AS ABOVE	60	1462

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Figure II-24. Building Dimensions

WALL U–VALUES
(EXTERIOR) $\frac{\text{BTU}}{(\text{hr})(\text{ft}^2)(^\circ\text{F})}$

COMPOSITE	R
OUTSIDE AIR FILM	.17
STUCCO	.10
SHEATHING	1.32
R–19 INSULATION	19
STUDS	7.47
GYPSUM BOARD	.45
INSIDE AIR FILM	.68

$$U = \frac{1}{\Sigma R}$$

10 % OF WALL IS 6" STUDS
90% OF WALL IS R-19 INSULATION

U = .0098 + .041
U = .051

U = .06 FOR WALLS BELOW GRADE

GLAZING UNITS U – VALUES
TRIPLE U = .47

CEILING U–VALUES

COMPOSITE	R
OUTSIDE AIR FILM	.17
B/U ROOT	.62
R–25 INSULATION	25
12" STUDS	15
GYPSUM BOARD	.45
INSIDE AIR FILM	.61
5 1/2" AIR SPACE	1

$$U = \frac{1}{\Sigma R}$$

U = .006 + .034
U = .04

CEILING U-VALUES
(UNDER SOLAR PANELS)

COMPOSITE	R
OUTSIDE AIR FILM	.17
POLYURETHANE FOAM	7.68
PLYWOOD	.93
INSULATION	19
DRYWALL	.45
INSIDE AIR FILM	.61
12" STUDS	15
5 1/2" AIR SPACE	1

U = .034

CEILING – PLASTICRAFT

U = .58

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Figure II-25. Building Characteristics

JOB SOUTHWEST PHOTOVOLTAIC RESIDENCE		NUMBER OF OCCUPANTS 3
LOCATION LAS CRUCES		
INDOOR TEMPERATURE, T_R,	68°F	
DESIGN WINTER OUTDOOR TEMPERATURE, T_o,	21°F	
DESIGN TEMPERATURE DIFFERENCE	47°F	
DESIGN DEGREE-DAY, 65 - T_o,	44°F	

EXTERIOR WALL AREA:	2,744.1 – 60 (doors) -- 155 (windows) – 410.8 (beam) = 2,157.4 ft^2
WINDOW AREA:	155 ft^2
DOOR AREA:	60 ft^2
NET EXTERIOR WALL AREA:	2, 118 ft^2
	410.8 ft^2 with berm
CEILING AREA:	648 ft^2 under solar panels, 1041 ft^2 flat, 198 ft^2 under plasticraft
FLOOR AREA:	1,462 ft^2, 184 ft perimeter
BASEMENT WALL AREA:	0

HEATING DEGREE-DAYS:*	January	685	°F-DAYS
	Annual	2700	°F-DAYS

Figure II-26. Building Heat Load Characteristics

		U $\frac{\text{Btu}}{(\text{hr})(\text{ft}^2)(^\circ\text{F})}$	A	ΔT °F ($T_R - T_o$)	$h = UA\ \Delta T$ BtuH
EXTERIOR WALLS (NET)		.051	2118	47	5,077
BASEMENT WALLS	BERM	.06	410.8	47	1,158
	BELOW GRADE			•	
WINDOWS AND SLIDING PATIO DOORS	SINGLE				
	DOUBLE				
	TRIPLE	.47	155	47	3,424
	STORM				
EXTERIOR SLAB DOORS		.49	60	47	1,382
FLOORS $q = F_2 P(t_1 - t_o)$	OVER CRAWLSPACE				
	CONCRETE SLAB ON GRADE	.55	184	47	4,756
CEILING	FLAT	.04	1,041	47	1,957
	SOLAR PANEL	.034	648	47	1,036
	PLASTICRAFT	.58	198	47	5,397
SUBTOTAL (WALLS, WINDOWS, DOORS, FLOORS, CEILING)					24,187
INFILTRATION: (0.018) x 23392 ft^3 x 47°F (ASHRAE)					19,790
DUCT = 10 PERCENT OF SUBTOTAL (IF DUCTS NOT IN INSULATION ENVELOPE)					
DESIGN HEATING LOAD: BtuH					43,977
DESIGN HEATING LOAD: Btu/DD — DESIGN HEATING LOAD (BtuH) x (24 hr/Design TD)					22,456
JANUARY HEATING LOAD: m Btu — (Btu/DD) x (January DD)	(SOLAR POSSIBLE 13.4 for January)				15.4
ANNUAL HEATING LOAD: m Btu — (Btu/DD) x (Annual DD)	(ANNUAL SOLAR POSSIBLE 67.2)				60.6

• $\Delta T = T_R - 45^\circ$

DOMESTIC HOT WATER LOAD (NOT SOLAR)

NUMBER OF OCCUPANTS x 16,680 Btu/day	50,040
JANUARY LOAD (m Btu) (Btu/day) x 31 x 10^{-6}	1.6
ANNUAL LOAD (m Btu) (January load x 12)	18.6

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Figure II-27. Building Heat Load Calculations

$$\sum_{T=1}^{N\ BINS} \left(\text{HOURS IN 5°F BIN}\right)_T \times \left(\frac{\text{LOAD}}{\text{HIP CAPACITY}}\right)_T \times \left(\text{POWER @ CAPACITY}\right)_T$$

MODIFY TO REFLECT

PASSIVE SOLAR GAIN

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Figure II-28. ASHRAE Bin Technique

DAY/NIGHT DISTRIBUTION OF WEATHER OCCURRENCES
5th DAY
(3 DAY/MO. SAMPLE)

BIN RANGE °F	TEMP HIGH °F	BIN RANGE OK	OCT D	OCT N	NOV D	NOV N	DEC D	DEC N	JAN D	JAN N	FEB D	FEB N	MAR D	MAR N	APR D	APR N	TOTAL D	TOTAL N	
65-69	67	293.6 291.3	1	2	6	3					4	1	10	3	4	7	28 60%	19 40%	HRS %
60-64	62	290.8 288.6			1	1	4	1			1	2	1	3	0	4	7 39%	11 61%	HRS %
55-59	57	288.0 285.8			1	6	2	5	1		1	1	2	5	0	1	7 28%	18 72%	HRS %
50-54	52	285.2 283.0			2	5	1	8	2	4	1						6 26%	17 71%	HRS %
45-49	47	282.4 280.2				2			2	3	1						3 37%	5 63%	HRS %
40-44	42	279.7 277.4							1		1						2 100%		HRS %
35-39	37	276.9 274.7							2			2					2 50%	2 50%	HRS %
30-34	32	274.1 271.9							1		1	5					2 29%	5 71%	HRS %
25-29	27	271.3 269.1							1	2							1 34%	2 66%	HRS %
20-24	22	268.6 266.3								5								5 100%	HRS %
15-19	17	265.8 263.6																	
10-14	12	263.0 260.8																	

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Figure II-29. Weather Occurrence Distribution

DAY/NIGHT DISTRIBUTION OF WEATHER OCCURRENCES
15th DAY
(3 DAY/MO. SAMPLE)

BIN RANGE °F	MID TEMP °F	BIN RANGE OK	OCT D	OCT N	NOV D	NOV N	DEC D	DEC N	JAN D	JAN N	FEB D	FEB N	MAR D	MAR N	APR D	APR N	TOTAL D	TOTAL N	
65-69	67	293.6 291.3	4										4		4		12 100%	0 0%	HRS %
60-64	62	290.8 288.6	2	2					4		6	2	3		1	3	16 67%	8 33%	HRS %
55-59	57	288.0 285.8	3	3	4	2	5		2		4	6	1	1	1	2	20 59%	14 41%	HRS %
50-54	52	285.2 283.0	2	4	5	12	2	3	2			6	1	4	2	2	14 31%	31 69%	HRS %
45-49	47	282.4 280.2	1	3		1	1	5	1	1			1	2		5	4 19%	17 81%	HRS %
40-44	42	279.7 277.4					2	5	1	1			1	3			4 31%	9 69%	HRS %
35-39	37	276.9 274.7								3			1	2			1 17%	5 83%	HRS %
30-34	32	274.1 271.9							1	8							1 11%	8 89%	HRS %
25-29	27	271.3 269.1																	
20-24	22	268.6 266.3																	
15-19	17	265.8 263.6																	
10-14	12	263.0 260.8																	

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Figure II-30. Weather Occurrence Distribution

DAY/NIGHT DISTRIBUTION OF WEATHER OCCURRENCES
25th DAY
(3 DAY/MO. SAMPLE)

BIN RANGE °F	TEMP HIGH °F	BIN RANGE °K	OCT D	OCT N	NOV D	NOV N	DEC D	DEC N	JAN D	JAN N	FEB D	FEB N	MAR D	MAR N	APR D	APR N	TOTAL D	TOTAL N	
65-69	67	293.6 291.3	0	9									9	2	2	3	11 44%	14 56%	HRS %
60-64	62	290.8 288.6		4	6	1					3		3	1		3	12 57%	9 43%	HRS %
55-59	57	288.0 285.8		1	1	5					2	3		3			3 20%	12 80%	HRS %
50-54	52	285.2 283.0			1	3	3				2	1		1			6 55%	5 46%	HRS %
45-49	47	282.4 280.2			2	4	3		5	1	2	2					12 63%	7 37%	HRS %
40-44	42	279.7 277.4				1	3		3	3	3	4		3			9 45%	11 55%	HRS %
35-39	37	276.9 274.7					5		1	7		2		2			6 35%	11 65%	HRS %
30-34	32	274.1 271.9					2	6	1	3							3 25%	9 75%	HRS %
25-29	27	271.3 269.1					1										1 100%	0 -	HRS %
20-24	22	268.6 266.3																	
15-19	17	265.8 263.6																	
10-14	12	263.0 260.8																	

Figure II-31. Weather Occurrence Distribution

TOTAL COMPOSITE

DAY/NIGHT DISTRIBUTION OF WEATHER OCCURRENCES
DAY
(3 DAY/MO. SAMPLE)

BIN RANGE °F	MID TEMP °F	BIN RANGE OK	OCT D	OCT N	NOV D	NOV N	DEC D	DEC N	JAN D	JAN N	FEB D	FEB N	MAR D	MAR N	APR D	APR N	TOTAL D	TOTAL N	
65-69	67	293.6	5	11	6	0	3	0	0	0	4	1	23	5	10	10	51	27	HRS
		291.3															65%	35%	%
60-64	62	290.8	2	6	7	2	4	1	4	0	10	4	7	4	1	10	35	27	HRS
		288.6															56%	44%	%
55-59	57	288.0	3	4	6	13	7	5	3	0	7	10	3	9	1	3	30	44	HRS
		285.8															41%	59%	%
50-54	52	285.2	2	4	8	20	6	11	4	4	3	7	1	5	2	2	26	53	HRS
		283.0															33%	67%	%
45-49	47	282.4	1	3	2	7	4	5	8	5	3	2	1	2	0	5	19	29	HRS
		280.2															40%	60%	%
40-44	42	279.7			0	1	5	5	5	4	4	4	1	6			15	20	HRS
		277.4															43%	57%	%
35-39	37	276.9					5	0	3	10	0	4	1	4			9	18	HRS
		274.7															33%	67%	%
30-34	32	274.1					2	6	3	11	1	5					6	22	HRS
		271.9															21%	79%	%
25-29	27	271.3					1	0	1	2							2	2	HRS
		269.1															50%	50%	%
20-24	22	268.6							0	5							0	5	HRS
		266.3															0	100%	%
15-19	17	265.8															0	0	HRS
		263.6																	%
10-14	12	263.0															0	0	HRS
		260.8																	%

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Figure II-32. Weather Occurrence Distribution

Figure II-33 reiterates these results and also makes allowance for loss of 10 percent of the daylight time. Figure II-34 calculates the heat gain at 8:00 am on January 21. This indicates that during the day the solar heat gain can generally take care of the heating requirements so only the percentage of non-solar time must be taken care of by conventional means.

Figures II-35 and II-36 show the energy demands for different outside temperatures. Each figure is based on the capability of a different heat pump. At the bottom is the total electrical demand for heating, taking into account the solar gain. The heat demand in this figure is taken from the U.S. Weather Bureau. Figure II-37 compares the results from these two methods.

Figure II-38 shows the cooling requirements for a residence in Las Cruces and one in Phoenix. Note that an evaporative cooler would only require 1.5 MWH/YR.

The hot water load was calculated in two ways. The first method was based on the RFP. The second came from the ASHRAE handbooks. The results are in figure II-39. Some of this requirement is picked up by solar heating of the water. The specifications for the solar heater is in figure II-40.

Figure II-41 summarizes the total electrical load for the residence that the utility and PV array will supply.

3. Summary of Residence Supply/Load

Figure II-42 summarizes the energy supply and load requirements for the proposed residence. The PV array supplies an equivalent of half of the annual energy for a Las Cruces residence. It should be noted that the PV-generated energy is supplied to the utility when it exceeds the building load. Neglecting time differences between generation and consumption, the net energy required from the utility is less than a tenth that of the average non-solar residence. For a Phoenix residence, the comparable figure is 20 percent.

TEMPERATURE BIN	100% AVAILABILITY DAY	100% AVAILABILITY NIGHT	90% AVAILABILITY DAY	90% AVAILABILITY NIGHT
62	56%	44%	51%	49%
57	41%	59%	36%	64%
52	33%	67%	30%	70%
47	40%	60%	36%	64%
42	43%	57%	39%	61%
37	33%	67%	30%	70%
32	21%	79%	19%	81%
27	50%	50%	45%	55%
22	-	100%	-	100%
17	-	100%	-	100%
12	-	100%	-	100%

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Figure II-33. Distribution of Weather Occurrences Versus Solar Availability

JANUARY 21 - 8:00 AM - EL PASO/LAS CRUCES

FENESTRATION			JANUARY 21 HEAT LOAD @ 8:00 AM (TYPICAL)	
SLOPE (SOUTH) WINDOWS	= 16,463 BTUH		$T_{AMB} = 45^{0}F$	....16,660 BTUH
SOUTH VERTICAL	= 2,420 BTUH		$T_{AMB} = 32^{0}F$	....27,489 BTUH
EAST VERTICAL	= 2,923 BTUH			
N-E VERTICAL	= 706 BTUH			
S-E VERTICAL	= 1,644 BTUH			
TOTAL	24,156 BTUH			

CONCLUSION/ASSUMPTION: SOLAR GAIN VIA FENESTRATION CAN EFFECTIVELY OFFSET HEATING LOAD

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Figure II-34. Early Morning Heat Gain Analysis (ASHRAE)

				HEAT PUMP ALONE GE/BWC030B-B (1000CFM)							SUPPLEMENTARY HEAT		
OUTDOOR TEMP (5° INCREMENTS)	BTUH LOSS PER 1°F (HEAT LOSS ÷ TD)	OUTDOOR TEMP BELOW 65°F (65-COLUMN A)	HEAT LOSS (BTUH) B x C	HEAT PUMP HEATING CAPACITY (BTUH) MFR DATA	HEAT PUMP RUNNING TIME (%) D ÷ E	HEAT PUMP INPUT (KW) MFR DATA	SEASONAL HEATING HRS U.S. W.B.	NON-SOLAR FRACTION	NET CONVENTIONAL HEATING HOURS	SEASONAL HEAT PUMP INPUT (KWH) F x G x H'	RESISTANCE HEAT INPUT (BTUH) D MINUS E	RESISTANCE HEAT INPUT (KW) J-3413	SEASONAL RESISTANCE HEAT INPUT (KWH) H x K
A	B	C	D	E	F	G	H	-	H'	I	J	K	L
62	↑	3	2,499	42,850	.06	4.5	749	.49	367	99.1			
57		8	6,664	40,200	.17	4.4	760	.64	486	363.5			
52		13	10,829	37,000	.29	4.2	687	.70	481	585.9			
47		18	14,994	33,900	.44	4.1	611	.64	391	705.4			
42		23	19,159	30,750	.62	3.9	494	.61	301	727.8			
37	833 BTUH/°F	28	23,324	27,700	.84	3.8	369	.70	258	823.5			
32		33	27,489	24,600	1.00	3.65	233	.81	189	689.9	2,899	.85	160.0
27		38	31,654	21,700	1.00	3.5	104	.55	57	199.5	9,954	2.92	166.2
22		43	35,819	18,850	1.00	3.35	34	1.00	34	113.9	16,969	4.97	169.2
17		48	39,984	16,100	1.00	3.25	10	1.00	10	32.5	23,884	7.00	70.0
12	↓	53	44,149	14,350	1.00	3.1	2	1.00	2	6.2	29,799	8.73	17.5
										4,347	TOTALS		583

GE/BWC030B-B

- 1,000 CFM
- HEATING CAPACITY = 33,000 BTUH
- COOLING CAPACITY = 31,500 BTUH

- TOTAL ELECTRICAL USE = 4.93 MWH/YR

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Figure II-35. Heat Pump Energy Calculations

HEAT PUMP ALONE GE/BWC036B-C (1200CFM)											SUPPLEMENTARY HEAT		
OUTDOOR TEMP (5° INCREMENTS) A	BTUH LOSS PER 1°F (HEAT LOSS ÷ TD) B	OUTDOOR TEMP BELOW 65°F (65-COLUMN A) C	HEAT LOSS (BTUH) B x C D	HEAT PUMP HEATING CAPACITY (BTUH) MFR DATA E	HEAT PUMP RUNNING TIME (%) D ÷ E F	HEAT PUMP INPUT (KW) MFR DATA G	SEASONAL HEATING HRS U.S. W.B. H	NON-SOLAR FRACTION -	NET CONVENTIONAL HEATING HOURS H'	SEASONAL HEAT PUMP INPUT (KWH) F x G x H' I	RESISTANCE HEAT INPUT (BTUH) D MINUS E J	RESISTANCE HEAT INPUT (KW) J-3413 K	SEASONAL RESISTANCE HEAT INPUT (KWH) H x K L
62	↑	3	2,499	51,900	.05	5.45	749	.49	367	100.0			
57		8	6,664	48,750	.14	5.25	760	.64	486	357.2			
52		13	10,829	44,800	.24	5.05	687	.70	481	583.0			
47		18	14,994	41,100	.36	4.90	611	.64	391	689.7			
42		23	19,159	37,600	.51	4.70	494	.61	301	721.5			
37	833 BTUH/°F	28	23,324	34,150	.68	4.55	369	.70	258	798.3			
32		33	27,489	30,650	.90	4.40	233	.81	189	748.4			
27		38	31,654	27,500	1.00	4.20	104	.55	57	239.4	4,154	1.21	69.0
22		43	35,819	24,350	1.00	4.00	34	1.00	34	136.0	11,469	3.36	114.2
17		48	39,984	21,750	1.00	3.90	10	1.00	10	39.0	18,234	5.34	53.4
12	↓	53	44,149	18,900	1.00	3.70	2	1.00	2	7.4	25,249	7.40	14.8

<u>GE/BWC036B-C</u>

- 1200 CFM
- HEATING CAPACITY = 40,00 BTUH
- COOLING CAPACITY = 37,000 BTUH

- TOTAL ELECTRICAL USE = 4.67 MWH/YR

4,420	TOTALS	251.4

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Figure II-36. Heat Pump Energy Calculations

	Las Cruces/El Paso		Phoenix	
	THERMAL LOAD	ELECTRICAL LOAD	THERMAL LOAD	ELECTRICAL LOAD
1. DEGREE-DAY METHOD	60.6 MMBTU/YR	3.86 MWH/YR	39.6 MMBTU	2.52 MWH/YR
(WITH 50% SOLAR &	(30.3 MMBTU @ 50% SOLAR)		(19.8 MMBTU @ 50% SOLAR	
COP = 2.3)	43,997 BTUH - DESIGN		COP = 2.3)	
			29,006 BTUH DESIGN	
2. MODIFIED ASHRAE BIN METHOD				
HIGH VENTILATION - 23,000 FT³/HR	-	4.67 MWH/YR	-	3.05 MWH/YR
LOW VENTILATION - 6,000 FT³/HR	-	3.10 M	-	2.02 MWH/YR
(RECOMMENDED PRACTICE)				

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Figure II-37. Heat Load Summary

	Las Cruces/El Paso		Phoenix	
	Tin = 75°F	Tin = 78°F	Tin = 75°F	Tin = 78°F
1. PEAK/DESIGN LOAD (Q = U•A•CLTD)	-	23,837 BTUH	35,024 BTUH	32,442 BTUH
2. COOLING DEGREE DAYS	-	360	1,688	1,271
3. ANNUAL COOLING LOAD	-	9.8 MMBTU/YR	41.7 MMBTU/YR	31.9 MMBTU/YR
4. EEF(ENERGY EFFECTIVENESS RATIO)	-	6.7 BTUH/W	6.7 BTUH/W	6.7 BTUH/W
5. ANNUAL ELECT. LOAD (D.D)	-	1.46 MWH/YR	6.2 MWH/YR	4.76 MWH/YR
• FVAP COOLING	1.5 MWH/YR	-	-	-
6. EQUIV. FULL LOAD HOURS	1000 HRS	750 HRS	1200 HRS	900 HRS
7. HEAT PUMP POWER	5.5 kW	5.5 kW	5.5 kW	5.5 kW
8. ANNUAL ELEC. LOAD (EFCH)	5.5 MWH/YR	4.12 MWH/YR	6.6 MWH/YR	4.95 MWH/YR

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Figure II-38. Cooling Load Summary (ASHRAE Recommended Practices)

1. 60 GAL/DAY; $60^{o}F$ - $140^{o}F$; 40,032 BTU/DAY = 14.6 $\frac{MBTU}{YR}$

2. 16,680 $\frac{BTU}{DAY\text{-}OCCUPANT}$ x 3 OCCUPANTS; 50,040 BTU/DAY = 18.3 $\frac{MBTU}{YR}$

3. THERMAL COLLECTORS; 48 FT^2; 38% AVG. ANNUAL PERFORMANCE = 13.6 $\frac{MBTU}{YR}$

4. ELECTRICAL DEMAND = 0.38 MWH/YR TO 1.46 MWH/YR

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Figure II-39. Domestic Hot Water Load Requirements

HELIOSYSTEMS CORP

TECHNICAL SPECIFICATIONS

Type: Potable water, recirculation or draindown

Collector: Heliosystems MT 200C, flat plate; copper absorber plate and waterways

Standard collector area: 48 ft^2

Standard storage tank type: Rheem-Ruud glasslined steel tank

Standard tank capacity: 82 or 120 gallon

Tank insulation: R-5

Recommended heat transfer fluid: Water

Heat exchanger: None

Components not supplied for installation: Pipe and pipe insulation

Pump manufacturer and horsepower: Grundfos, 1/35 hp

Differential controller manufacturer and model: Heliotrope General, DTT 200

PRODUCT DESCRIPTION

These kit-form hot water systems include two 3-ft x 8-ft solar collectors, a stainless steel pump, automatic temperature controller, collector mounting brackets, valving and fittings, and an 82- or 120-gallon storage tank with heating element and thermostat.

Features: Recirculation or draindown freeze protection for warm or cold climates.

Options: Size; kit form.

Installation Requirements: Southern exposure for collector; protected area for tank and pumps

Maintenance Requirements: Acid wash collector every 5 years; clean pump filter twice a year; drain tank sediment every 3 months.

Guarantee/Warranty: 5-year limited warranty on panel, tank and controller, 18-month warranty on pump.

Suggested List Price: Model 82, $1,575.
Model 120, $1,675.

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Figure II-40. Hot Water Equipment

	LAS CRUCES		PHOENIX	
	RANGE	EXPECTED	RANGE	EXPECTED
1. BASE ELECTRICAL LOAD (MWH/YR)	5.5 - 7.1	5.5	5.5 - 7.1	5.5
2. AIR-CONDITIONING ELECTRICAL LOAD (MWH/YR)	1.5 - 4.1	1.5	5.0 - 6.6	5.0
3. DOMESTIC HOT WATER ELECTRICAL LOAD (MWH/YR)	0.4 - 1.5	0.4	0.4 - 1.5	0.4
4. HEATING ELECTRICAL LOAD (MWH/YR)	3.1 - 4.7	3.9	2.0 - 3.1	2.5
TOTAL ELECTRICAL LOAD (MWH/YR)	10.5 - 17.4	11.3	12.9 - 18.3	14.4

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Figure II-41. Residential Electrical Load Summary

		LAS CRUCES	PHOENIX
1.	PV SYSTEM OUTPUT (NET ac)	9,240 kWH/YR	8,843 kWH/YR
2.	BUILDING ELECTRICAL LOAD		
	- RANGE	10,500-17,400 kWH/YR	12,700-18,300 kWH/YR
	- EXPECTED	11,300 kWH/YR	13,200 kWH/YR
3.	PERCENT OF LOAD PROVIDED BY PV SYSTEM *		
	- RANGE	88% - 53%	70% - 48%
	- EXPECTED	82%	67%

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*These figures are strictly algebraic results obtained by dividing annual PV production by annual residence load (x 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.

Figure II-42. Summary of Load Provided by PV System

CHAPTER III
PROTOTYPE PHOTOVOLTAIC RESIDENCE

A. OVERVIEW OF PROTOTYPE

The PV residence Prototype System is shown in figure III-1. This structure is based on the full-size residence design. It is a structure that has been minimized to provide support for the full-size PV array. No attempt was made to duplicate the heat loss or gain of the full-size residence.

The prototype building is, in effect, a section taken out of the full residence design with all but the portion of the house under the array roof structure eliminated. The only passive solar energy elements of the full-size residential design included in the Prototype structure were the louvered solar gain windows, which form an integral portion of the array roof structure. The conservation elements include the use of the exterior wall and of ceiling insulation that has the same R-value as the full-size residence, as well as the use of double-glazed windows.

Although much of the house is removed for the Prototype design, the aesthetics of the PV array are still addressed by the Prototype, as the entire roof area surrounding the array is similar to the full-size residence.

The Prototype fits into the volume envelope provided at the test site. The lowest module is well above the 3-foot vertical requirement at the south grade. Access has been provided by a double-width standard door, and windows have been included to allow for natural light.

It should be noted that the PV array, the power processing subsystem, and the PV system control and protection that were provided in the Prototype System are identical to the design in the full-size residence.

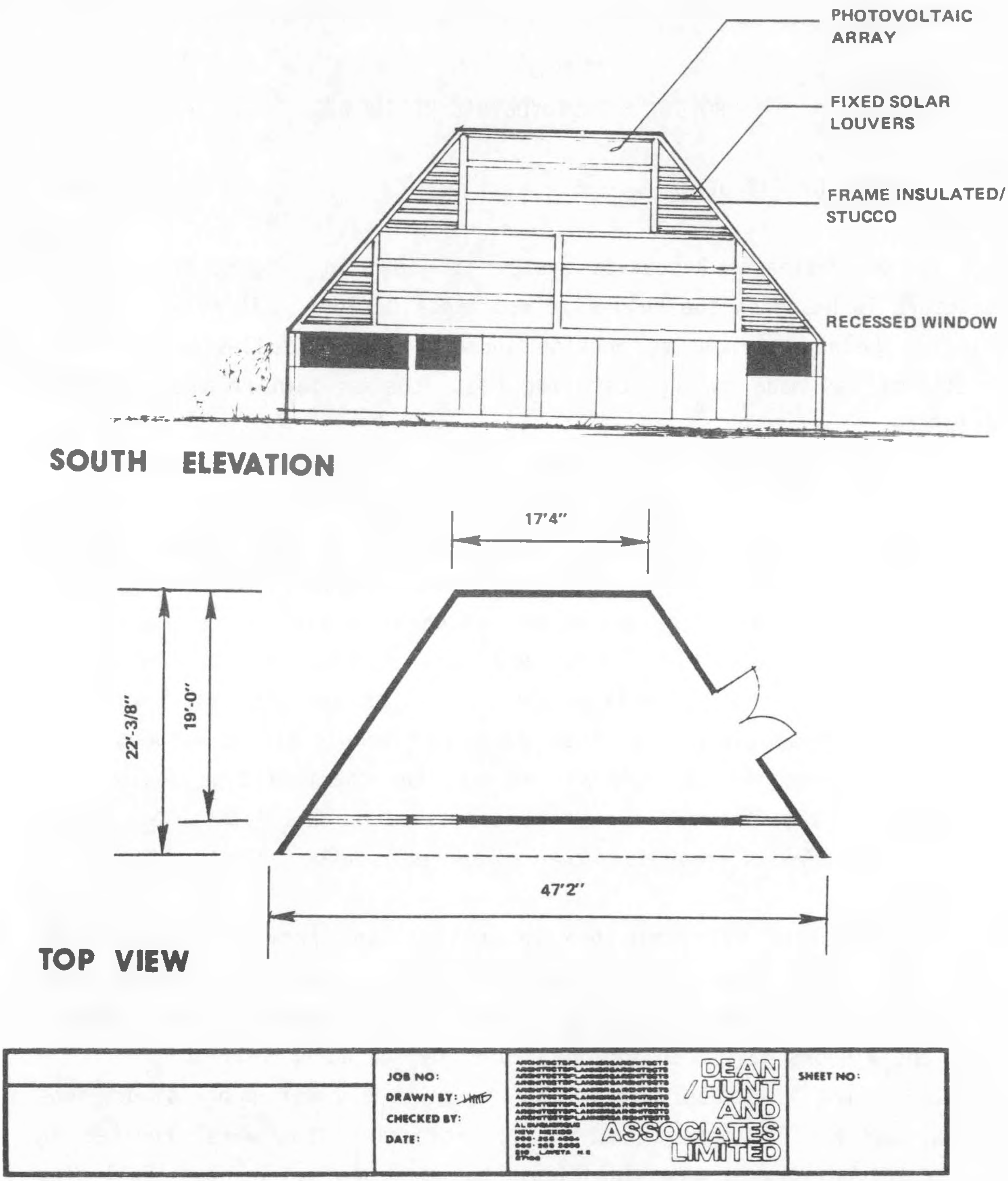

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Figure III-1. Photovoltaic Residence Prototype

B. PROTOTYPE PHOTOVOLTAIC (PV) SYSTEM

1. Prototype Array Design

The Prototype array design, sizing, layout, and mounting procedure is identical to the residential array design as discussed in sections II-B-2-c and II-B-2-d of this report; figure III-2 lists the salient design points of the Prototype array design and figure III-3 provides the diagram of array layout, wiring, and mounting.

The Motorola units are configured in 9 parallel 13 module strings, and the temperature effects have been studied to ensure that array dc outputs are compatible with the inverter input voltage requirements of 160 VDC-240 VDC. The peak power output of the array at ideal rated conditions is 4.68 kW. The 9 rows of 13 modules each will fit within the dimensions of the south-facing roof, and the modules are mounted using a simple, inexpensive standoff technique that consists of Unistruts attached to the roof. The modules are secured to the Unistrut® using spring-loaded quick release screws, and the 6-inch clearance between the module and roof facilitates array assembly and disassembly and promotes air flow under the modules for improved cooling and increased power output. Each row has a disconnect for row isolation and blocking diodes for reverse current protection. The array has varistors for lightning surge protection. This circuitry is installed in the maintenance and safety enclosure located outside on the north wall.

2. Prototype Power Processing

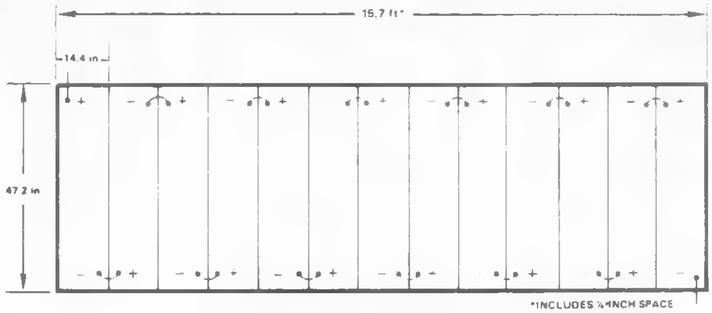
The Prototype residential power processing approach is identical to the full-size residence design with the following exceptions: (1) additional disconnects are provided to allow flexibility in testing through various interconnection schemes involving the utility, load, and inverter and (2) a simulated residence load is connected to the inverter and utility power. Figure III-4 illustrates the functional blocks of the Prototype power processing system.

The main circuit breaker panel board and switchboard are installed inside the home, next to the inverter for testing convenience.

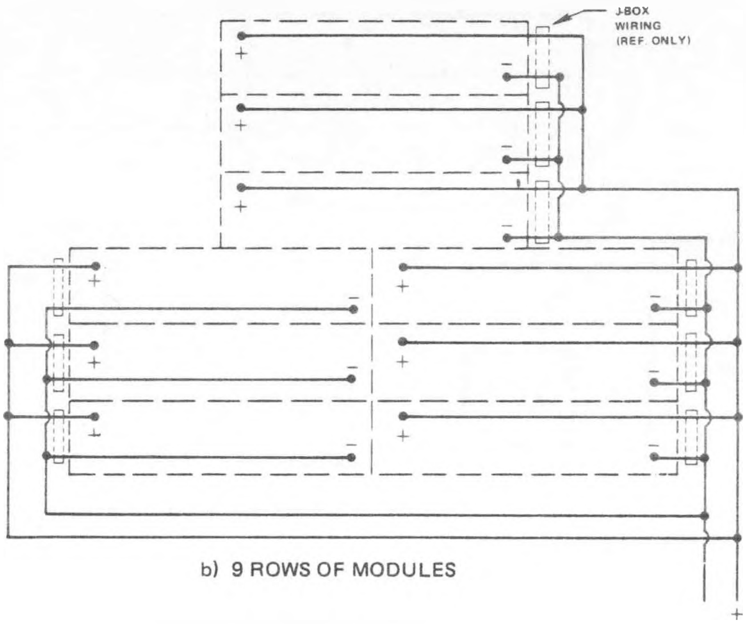
- MOTOROLA MODULES
- NINE PARALLEL 13 MODULE STRINGS
- 4.4-kW ARRAY ACTUAL PEAK POWER OUTPUT AT RATED CONDITIONS
- FITS WITHIN DIMENSIONS OF THE SOUTH-FACING ROOF
- MOUNTED ON INEXPENSIVE UNISTRUT STANDOFF STRUCTURE
- ROWS INCLUDE DISCONNECTS, BLOCKING DIODES, AND VARISTORS

BDM/A-81-550-TR

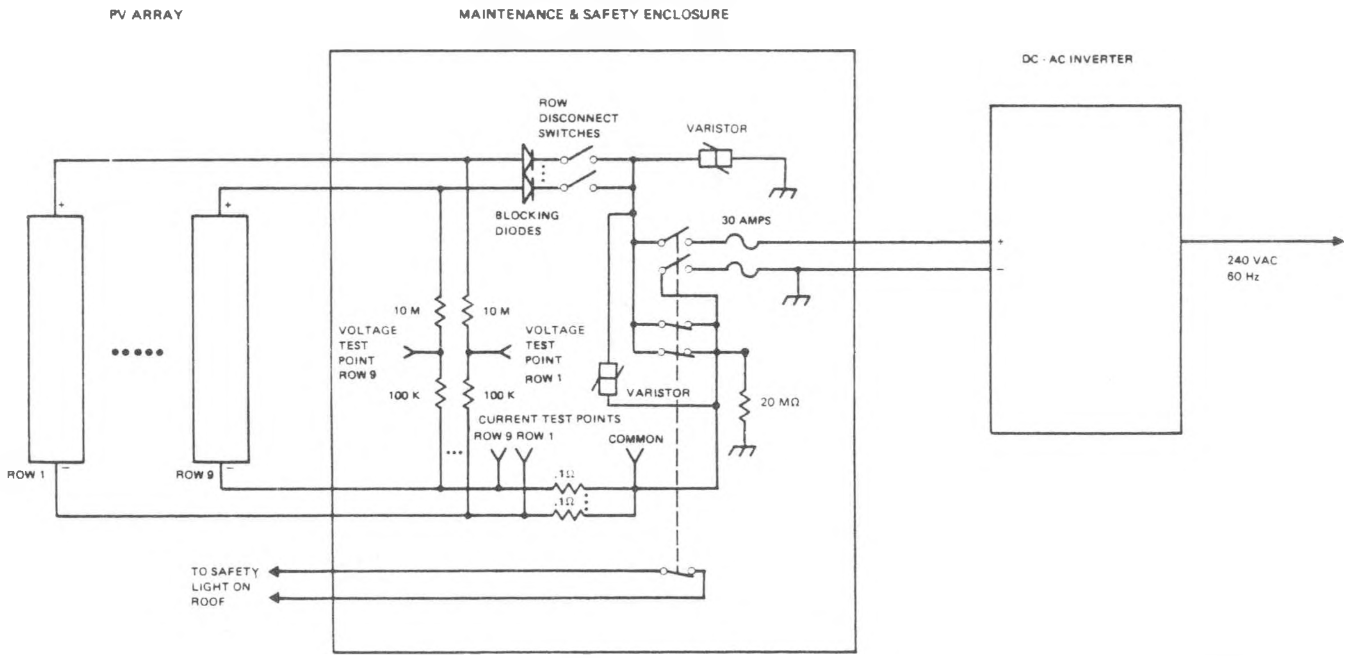
Figure III-2. Prototype Array Design Salient Points Summary



a) 13 MODULES PER ROW



b) 9 ROWS OF MODULES



c) DC SCHEMATIC

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Figure III-3. Array Layout, Wiring, and Mounting

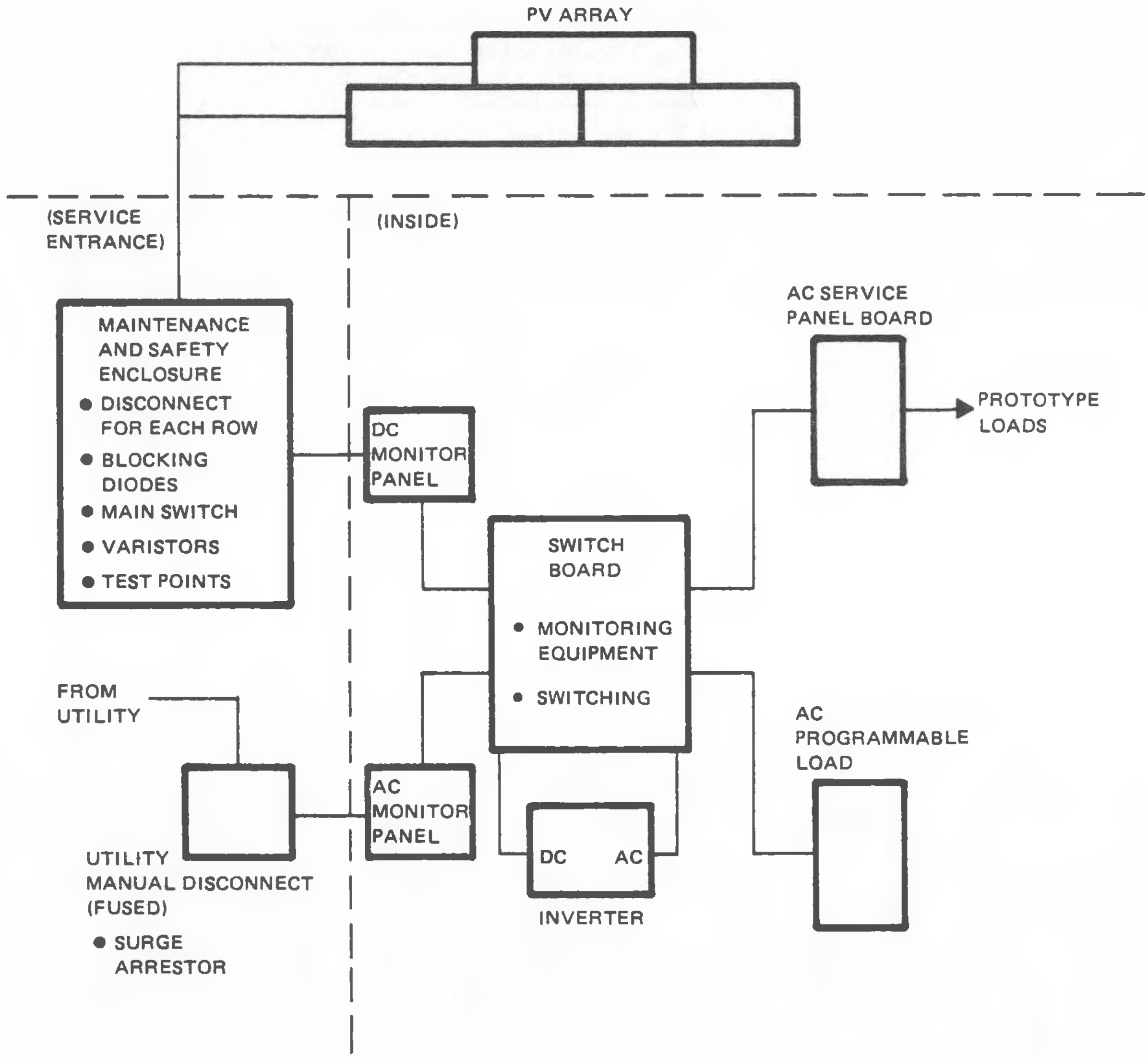

Figure III-4. Prototype Power Processing Functional Diagram

The roof-mounted PV array provides dc power to a 6 kVA Abacus inverter with a 240-VAC single phase, two wire output. The utility provides power for the heat pump, ac outlets, lighting, and for a test branch that is connected in parallel with the inverter via switchgear to a residence load simulator.

The main switchgear allows the utility, load, and inverter to be interconnected or isolated for test flexibility, and another disconnect isolates the array from the inverter. The switchboard hardware is contained in one panel board, separate from the main circuit breaker panel board, and is mounted on the wall next to the main board and inverter. In addition to the test circuit, one 240 circuit, two 120-VAC lightning circuits are provided in the main ac J-box. The main ac J-box also contains a lightning protection surge arrestor just before the main circuit breaker. The maintenance and safety enclosure transient suppressors on both the positive and negative array dc power lines provide lightning surge protection for the inverter and array. Also in this enclosure is the 30-amp dc disconnect switch, which shorts the array and isolates it from the inverter.

The simulated residential load is wired via a fused disconnect to the utility and inverter ac power. The utility/inverter line provides 240-V single phase, three wire service to the load to allow 240- or 120-VAC operation. Metering and data acquisition of that load was performed by NMSEI and was not accomplished under this contract.

C. PROTOTYPE BUILDING DESCRIPTION

1. Prototype Building Layout and Size

The layout of the Prototype residence is presented in figure III-5. All of the equipment and instrumentation is along the north wall. Heat from the electrical load is ducted outside through the equipment vent in the north wall.

The floor plan of the Prototype fits within the site envelope required, as it measures 22 feet by 47 feet. Due to the trapezoidal

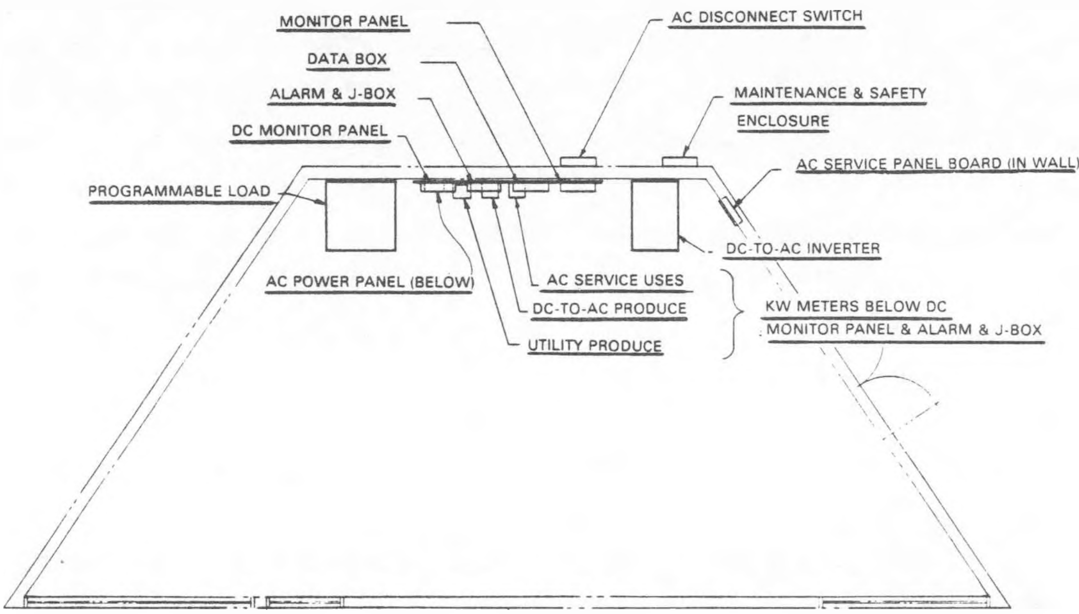

Figure III-5. AC-DC Electrical Component Layout No Scale geometry of the residence roof design, the roof extends with an overhang on the south side. This space is required to exactly simulate the full-size residence roof and PV array. The prototype height is approximately 21 feet, which is well within the 26-foot limitation and therefore causes no shadowing of other prototype projects.

Entry to the building is through a set of standard height double doors in the east wall. Windows are provided in the south wall, with additional natural lighting being provided by the window area in the roof structure.

The HVAC system is provided by an exterior G.E. heat pump on the east side of the building and an air handler unit inside the facility. Ducting is accomplished within the floor concrete slab, with three floor vents along the south wall. Thermostatically controlled vents at the rear of the east and west walls near the ceiling allow venting of heat during the summer months.

The overall interior lighting is provided by two neon light fixtures in the lower end of the cathedral ceiling and three incandescent units in the upper portion of the ceiling. The neon fixtures are aesthetically more pleasing and far more efficient than standard, four-bulb units. Wall plugs are located along the interior of the west and north walls.

2. Prototype Building Construction Details

Typical construction details of the Prototype facility are shown in Appendix E. The construction materials and approach were the standard frame stucco generally used in Southwest construction. This construction is typical in the Las Cruces area and provided no problems to the construction firm (Forrester Construction Company).

The frame structure is on a standard residential concrete slab. The basic frame consists of 2-inch by 6-inch studs on 2-foot centers. The roof joists are 4-inch by 12-inch beams on 4-foot centers with a plywood decking on the exterior. The 2 by 6 stringers are mounted to the plywood decking. Additional 2 by 6 blocks are nailed to the stringers to provide additional spacing for the array. Finally, a 2-inch

Unistrut® is mounted crosswise from the stringers onto which the array is mounted. Sealing of the roof was accomplished with a 1-inch foam layer over the deck with a membrane sealer.

Although all of the energy conservation techniques of the full-size home were not included, the Prototype building is insulated in the same manner as that described for the full-size residence. This is necessary not only to present pleasant working conditions within the prototype but also to provide a representative environment below the cathedral type ceiling on which the PV array is mounted. R-19 insulation is in the walls, with R-25 insulation at the ceiling. The interior walls of the Prototype building were finished with textured dry walls, which were painted. This protects the insulation bats and prevents interior dust build-up, which would occur if the interior walls were left open. Several alternatives were considered, but the standard texturing and painting was found to be the most cost effective.

The internal floor area is covered with indoor-outdoor carpet. This approach provides an attractive interior and a more acceptable work surface than bare concrete floor. The exterior of the prototype is fully representative of the external decor of the full-size residence and is similarly colored with a basic mid-brown color. The trim was painted in a matching manner.

D. BUILDING UTILITIES

As indicated in figure III-6, the building utilities include a heat pump/air handler system for heating and cooling, three-tube fluorescent fixtures for lighting, ac power for the heat pump, lights, ac outlets, and testing, ventilation vents, and an external water faucet for array cleaning.

The heat pump/air handler system is a G.E. model BWC024V100A 25.5K BtuH cooling 25K BtuH heating unit with a 2.4- kW supplementary heater located in the air handler. The supplementary heater is controlled by the heat pump and is used to augment heating if required. The floor

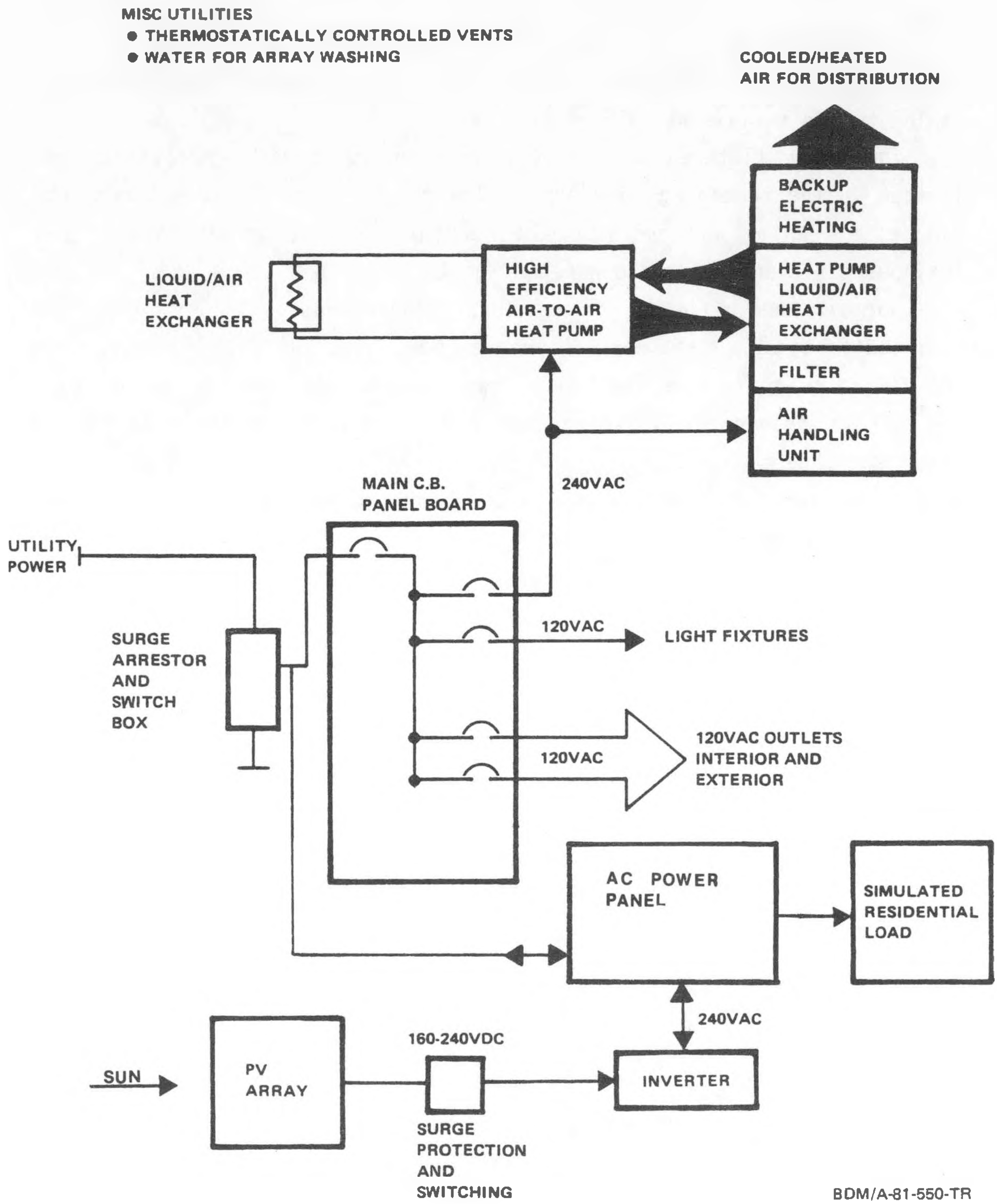

Figure III-6. Building Utilities Block Diagram vents located near the south wall provide air distribution and the return is located on the air handler.

The light fixtures are located over the test work area; three are located in the remaining home area. The fixtures are 48-inch three-tube flourescent units and contribute to energy savings, providing a higher luminous efficiency than incandescent units.

Normal home 240-VAC three-wire, single-phase utility power is distributed using a main circuit breaker box. The circuits include: one 240-VAC circuit for the heat pump, two 120-VAC branches for ac outlets, one 120-VAC branch for lighting, one 240-VAC branch connected to the PV power switchgear for testing, and one 120-VAC circuit as a spare. Five wall ac outlets are located inside the home and two exterior outlets are available for array test equipment.

CHAPTER IV

PROTOTYPE CONSTRUCTION AND INITIAL OPERATING EXPERIENCE: LESSONS LEARNED

A. SCHEDULE AND STATUS

The schedule for construction of the Prototype facility called for construction to begin on January 5, 1981, with completion on April 15, 1981. These two milestones were met; however, many of the intermediate steps differed from the proposed schedule. The two major factors that compressed so much activity into the final weeks were (1) delays in getting the foamed roof completed and (2) delays in receiving the junction box covers for the PV modules.

Approximately one week after the completion of Prototype construction, and PV system installation and operation, an incident occurred during a manual start-up of the power conditioning system in which the utility power was switched on after the dc array was switched to the power conditioning system. This caused a malfunction of the inverter, which resulted in the temporary shutdown of the system. The inverter was repaired onsite by manufacturer personnel and the system was subsequently accepted by NMSEI on May 12, 1981.

B. BUILDING CONSTRUCTION EXPERIENCE

The building construction proved to be satisfactory and it was completed on schedule and within cost. However, minor difficulties in framing were observed because of the unusual angles imposed by the roof design and the unique Prototype characteristics of the building constructed at the Southwest Residential Experiment Station. Some minor difficulties were encountered during forming of the roof due to wind conditions at the time of installation and the 35-degree roof slope. Neither of these problems is considered an inherent design defect; both can be alleviated with proper construction scheduling and field experience.

1. Building Geometry

The combination of the trapezoidal shape of the structure in its plan view plus the 35-degree slope of the roof created a difficult geometry problem during the framing portion of the construction. The most difficult task was cutting the roof rafters in the areas where they intersect the side walls of the building.

2. Foam Roof and Colored Membrane

In view of maintaining an April 15 completion date, the most serious construction problem related to the foam roof. The prime problems were delays due to the weather. The foam should be applied in winds of less than 10 mph. Spring in Las Cruces is typically a windy time and therefore does not offer the best of conditions. Delays encountered here affected completion of the building interior.

The second problem encountered was the application of the foam and sealer on the 35-degree sloped roof. This was possible only because the standoff material for the modules was available for footholds. This difficulty plus wind conditions exceeding 10 mph resulted in an uneven application of the foam.

Delays were encountered due to the use of a colored membrane sealer that had to be specially blended at the factory and was not available until April. After application, it requires 30 days to cure to its ultimate strength. The combination of insufficient curing time (3 days) before working on the surface plus the shearing action imparted by walking on the 35-degree slope resulted in several damaged areas. These areas were repaired by applying more Diathon membrane sealer with a brush.

C. PHOTOVOLTAIC SYSTEM CONSTRUCTION/INSTALLATION EXPERIENCE

The use of 2 by 6 runners and blocks as standoff mounts for the unistrut worked quite nicely. As mentioned previously, they provided footholds for traversing the 35-degree sloped roof.

The Unistrut® rails were changed to P1000 from P2000-HS because of their immediate availability in pregalvanized finish. The rails were mounted on the standoffs with little difficulty. Only one rail had to be adjusted for proper module fit during installation.

Module installation progressed very rapidly with all modules being mounted in 28 man-hours. This was done in spite of wind conditions exceeding 20 mph all during the second day. The 28 man-hours also included time to remove three modules to correct a voltage reversal and find an open connection in row #4.

D. PHOTOVOLTAIC SYSTEM CHECKOUT AND PERFORMANCE

1. Photovoltaic (PV) Modules

Individual I-V power plots were obtained from Motorola for each module for cell temperatures of 28°C and 50°C. In all cases the module performance was better than the minimum specification, but only a few met or exceeded the typical performance values that were advertised by the manufacturer. The average power output at 28°C cell temperature for the 117 modules was approximately 38.4 W, or about 4 percent below the manufacturer's "typical" value of 40.0 W. At 50°C the average value for the lot was 34.5 W, or approximately 6 percent below the "typical value" of 36.6 W. No modules were damaged in shipment and all are functional as of the origination of this report.

Figure IV-1 indicates the power out of row one compared to the sum of the peak power from each module. This data is based on the I-V curves supplied by Motorola for 50°C and shows a 2 percent loss of power. This compares to the 1 percent loss anticipated as a result of a preinstallation analysis using the computer code, PV-TAP.

2. Array

Once the array was installed, BDM measured the open-circuit voltage and the short-circuit current of each row to verify proper wiring and module functionality.

MODULE SERIAL NUMBER	POWER @ 2.52 amps 50°C AND 100 mW/cm^2	PEAK POWER
4205	36.8	37.1
4097	34.0	34.0
4203	34.5	35.2
4102	32.8	34.0
4228	36.0	36.1
4222	30.2	35.7
4204	35.3	35.8
4206	36.5	36.5
4098	35.0	35.1
4105	35.3	35.3
4218	36.0	36.5
4223	34.0	34.3
4220	36.3	36.5
TOTALS	452.7	462.1

$$\frac{462.1 - 452.7}{462.1} \times 100 = 2.0 \text{ percent}$$

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Figure IV-1. Photovoltaic (PV) Mismatch Losses for Row 1

The module serial numbers in each row were recorded when the array was installed on the Prototype. This location information coupled with the module I-V curves provided by Motorola and the I-V curves taken onsite by MIT LL have enabled some limited analysis of array performance. Figure IV-2 summarizes the data resulting from measurements taken on April 16, 1981. These values were corrected to cell temperature condition of 50^{o}C and 100 mW/cm^2. The resultant adjusted row values are then summed to a total output of 3,848 W at the cell temperature existing during the test. This represents approximately a 10 percent difference (9.5 percent after correction for wire losses) as compared to the expected "typical" value of 4,282 W at the same cell temperature.

Figure IV-3 delineates a row-by-row analysis of the module I-V curves taken at 50^{o}C operating conditions as measured on April 16, 1981. Using these recorded currents for the operating conditions as a constant for each respective string, the operating voltages were extracted from each module curve and summed to obtain the row voltage. The expected row power and total array power is computed and displayed in the third column of this figure. This value is 3,915 W, down approximately 9 percent compared to the expected "typical" value of 4,282 W obtained through computation of specification sheet values. It is, however, 0.5 percent above the minimum specified value. Backup data for the summarized numbers on figures IV-2 and IV-3 are provided in the appendix.

A 9 percent to 9.5 percent decrease in expected array performance has been observed when analyzing the limited test data. As described earlier, approximately 6 percent degradation can be attributed to the performance of the manufactured lot and approximately 2 percent is due to the mismatch of modules in a row. A specific explanation for the remaining 1 percent to 1.5 percent degradation is not clear. It is likely that it is due to a combination of reasons. However, clear insight is not possible without additional testing. The following is a description of potential contributors:

The temperature was measured by a probe in contact with the Tedlar backing. Obviously there will be some temperature difference from

	MODULE VOLTAGE CORRECTED TO 50°C		MODULE CURRENT ADJUSTED TO 1 SUN		STRING POWER AT 50°C	MFG "TYPICAL" EXPECTED ROW OUTPUT AT 50°C*	PERCENTAGE DEFICIENCY IN MEASURED VERSUS EXPECTED POWER FOR ROW
Row 1	171 Volts	X	$\frac{2.39 \text{ AMPS}}{.948}$	=	431.1 Watts	(475.8W)	- 9.0%
Row 2	(170 + .9)	X	$\frac{2.33}{.954}$	=	417.40	(475.8W)	-12.0%
Row 3	(172 + 1.8)	X	$\frac{2.39}{.954}$	=	435.41	(475.8W)	- 8.0%
Row 4	(169 + .9)	X	$\frac{2.39}{.954}$	=	425.64	(475.8W)	-11.0%
Row 5	(175 + .9)	X	$\frac{2.33}{.954}$	=	429.61	(475.8W)	-10.0%
Row 6	(174 + .9)	X	$\frac{2.39}{.954}$	=	438.17	(475.8W)	- 8.0%
Row 7	(170 + 0)	X	$\frac{2.39}{.963}$	=	421.9	(475.8W)	-11.0%
Row 8	(170 + .9)	X	$\frac{2.39}{.963}$	=	424.14	(475.8W)	-11.0%
Row 9	(174 + .9)	X	$\frac{2.34}{.963}$	=	424.99	(475.8W)	-11.0%
Total Array:					3,848.36 W	4,282.26 W	-10.0%

April 16, 1981
Corrected for 50°C   Wire loss = 0.5%

Conclusion: Power generated at 50°C is approximately 9.5% lower than manufacturer's specification.

Notes:
*"Typical" expected row output at 50°C cell temperature.
P_{ROW} = 13 modules x 36.6 W/module = 475.8 W

Figure IV-2. Comparison of Measured Power Generated Versus Expected "Typical" Power Per Manufacturer's Specification Sheet

	VOLTAGE IN VOLTS		CURRENT IN AMPS		POWER IN WATTS	POWER LOSS	POINT OF COMPARISON
Row 1	178.7	X	2.52	=	450.3	- 5.3%	475.8 W
Row 2	182.2	X	2.44	=	444.6	- 6.6%	
Row 3	166.3	X	2.51	=	417.4	-12.3%	
Row 4	163.6	X	2.51	=	410.6	-13.7%	
Row 5	167.5	X	2.51	=	420.4	-11.6%	
Row 6	177.2	X	2.51	=	444.8	- 6.5%	
Row 7	181.0	X	2.48	=	448.9	- 5.7%	
Row 8	172.2	X	2.48	=	427.1	-10.2%	
Row 9	185.5	X	2.43	=	450.8	- 5.3%	
April 15, 1981 Corrected for 50°C					3,914.9	- 8.5% (4282.2 W)	

+0.4% of minimum specification (3896.1 W). Wire loss already taken into account.

Figure IV-3. Expected Array Power as Calculated from IV Curves

	April 15	April 16	August 11
Row 1	+1.1 V +0.6%	+7.7 V +4.3%	+7.4 V +4.0%
Row 2	+4.0 V +2.0%	+12.2 V +6.7%	+5.1 V +2.9%
Row 3	-15.8 V -8.7%	-5.7 V -3.4%	+1.9 V +1.0%
Row 4	+3.1 V +1.6%	-5.6 V -3.4%	+2.6 V +1.5%
Row 5	+3.1 V 1.6%	-7.5 V -4.5%	+2.6 V +1.5%
Row 6	+9.2 V +3.9%	+2.2 V -1.2%	+6.1 V +3.4%
Row 7	+8.8 V +4.3%	+11.0 V +6.0%	+7.4 V +4.1%
Row 8	+4.7 V +2.4%	+2.2 V +1.2%	N/A
Row 9	-6.2 V -3.4%	+11.5 V -6.2%	N/A

The values are the predicted voltage minus the measured voltage.

N/A = not available

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Figure IV-4. Error Data

the cell junction to the Tedlar outside surface. The temperature difference will vary with wind conditions and insolation. Also, each row temperature was not measured, so there may be error associated with a temperature gradient from row to row.

Although Motorola used 100 mW/cm^2 of insolation in its test, it did not use sunlight. There are some spectral differences between artificial light and sunlight.

The predicted data were taken from a graph, which introduces some human error in reading the numbers.

Using the graph implies that the module probably does not have any cells in reverse bias. In the series rows, this may not be the case.

One possibility that does not appear very likely, but would explain the large variance, is that the row numbering has been confused, so that predicted data from one row is being compared to empirical data from another. Again this has been deemed very unlikely.

3. Power Conditioning Subsystem

Following the checkout of the array on April 15, the 6-kW Abacus inverter was tested. Initially the inverter was run in the stand-alone mode. Following the stand-alone test, the inverter was run tied to the utility. The inverter functioned fine for both tests and achieved the manufacturer's specifications for efficiency.

The 6-kW inverter failed three times. The first two times, the inverter was repaired onsite by Abacus personnel. The third time the inverter was shipped back to Abacus and a 10-kVA Abacus inverter was borrowed from Sandia National Laboratories and put in use temporarily. The 10-kW unit failed once, but it is operational as of this report.

All Abacus inverters at both the SW RES and the NE RES have had operational problems. An intensive effort was undertaken by Abacus Control to overcome these problems. As of this writing, the cycling problems at start-up and shutdown have been fixed by using a pilot cell by the array for reference in the peak power mode.

The second failure of the inverter led to a failure in the maintenance and safety enclosure. Fuses blew out, but they did not have sufficient contact separation to break the arc. To fix this problem, 600-V fuses were substituted. No other problems with the BDM equipment were encountered.

4. Overall System Performance

The following information is extracted from the Data Report for the Southwest Residential Experiment Station, March-September 1981, dated October 30, 1981, and also from the November 16, 1981, edition for the month of October. These reports summarize the PV prototype operational experience.

> The BDM Prototype System was initially activated at 1225 MST on 15 April 1981. It has since been plagued with failures of its Abacus inverter. First failure occurred at 0800 MST on 24 April during a "restoration of utility" test. The unit was repaired and reactivated on 12 May. It again failed on Saturday, 23 May. Repaired and reactivated on 11 June, it again failed on Saturday, 20 June. Following this failure, the unit was shipped to Abacus for diagnosis and was replaced by a 10-kilowatt unit for further diagnostic work at the SW RES. The larger unit was installed and activated on 1500 MDT on 8 July; it failed on 15 July. On 4 August the decision was made, in concert with Lincoln Laboratory and Abacus Controls, Inc., to cease routine operation of Abacus units. The 10-kilowatt unit was operated for brief intervals in late August and early September for diagnostic purposes.

E. CONCLUSION AND RECOMMENDATIONS

The typical PV module supplies approximately 9 percent less power than is indicated by the manufacturer's specifications. The power conditioning systems were actually in a state of developmental engineering. After several attempts to correct the deficiencies in the Abacus inverters, the unit was replaced with a new 6-kVA inverter manufactured by Helionetics. After several months of operation, the Helionetics inverter has performed very well - excellent reliability and waveform quality as reported by the S.W. Residential Experiment Station.

	Las Cruces	Phoenix
1. PV System Output (Net ac)	8,270 kWH/YR	7,914 kWH/YR
2. Building Electrical Load		
- Range	10,500-17,400 kWH/YR	12,700-18,300 kWH/YR
- Expected	11,300 kWH/YR	13,200 kWH/YR
3. Percent of Load Provided by PV System *		
- Range	78% - 48%	62% - 43%
- Expected	73%	60%

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*These figures are strictly algebraic results obtained by dividing annual PV production by annual residence load (x 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.

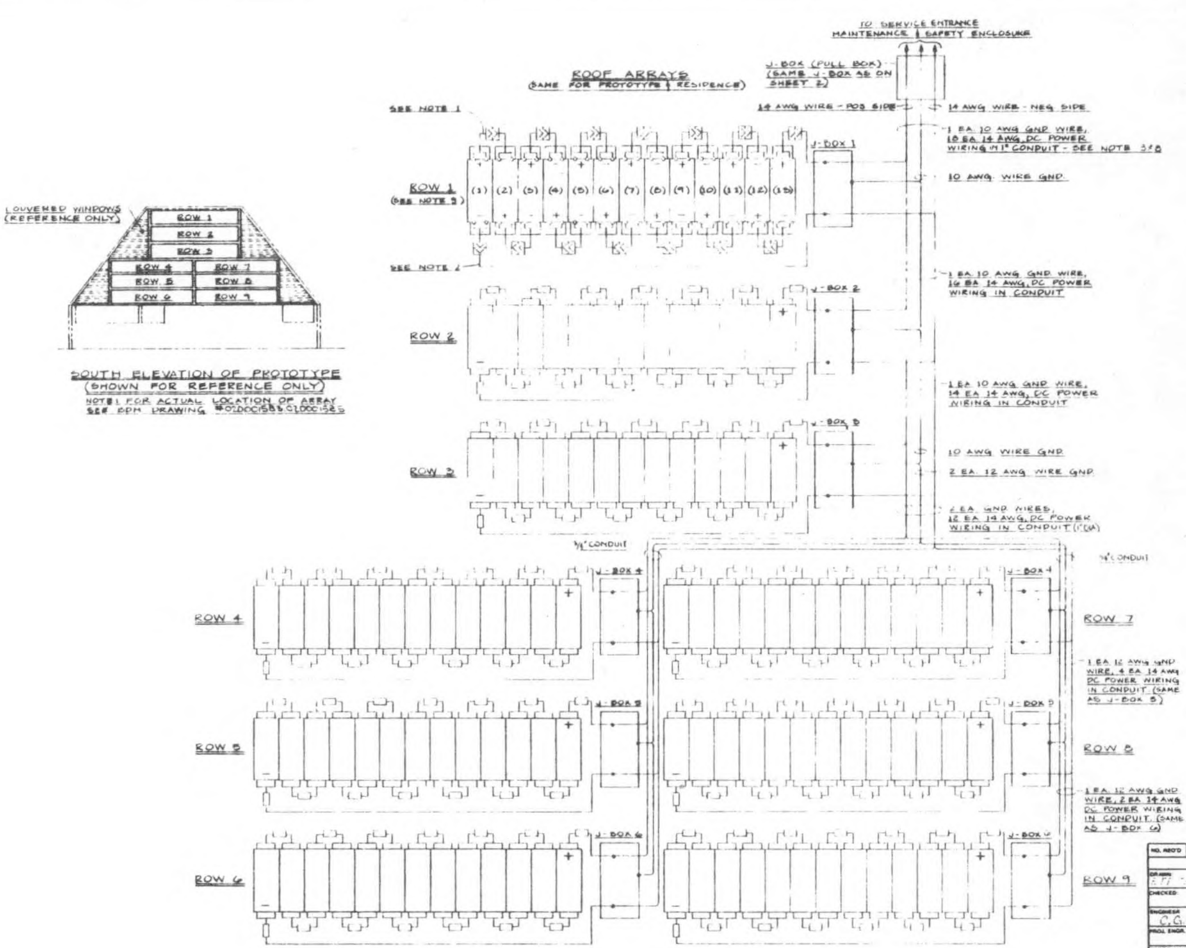
Figure IV-5. Summary of Load Provided by Derated Photovoltaic (PV) System

The detailed energy estimates for the full-size residence indicate that the PV array should have no problem supplying energy equivalent to 50 percent of the annual energy consumed. This is taking into account the lower array power. Figure IV-5 depicts applying a conservative 10.5 percent reduction in energy output to the numbers generated by the SOLCEL computer analysts.

The PV array, wiring, and maintenance and safety enclosure worked well and should be duplicated for the full-size residence.

Framing details should also be considered prior to the installation of construction. The objective of this exercise is to ensure smooth integration of the 35-degree roof slope into the structure of the full-size residence. Horizontal stringers should also be considered to facilitate easier application of the roof foaming and to provide a better working surface for the roof fabrication and module installation. Adequate curing time for the roof foam should be provided in the construction schedule of the full-size residence to avoid unnecessary damage to the roof membrane.

APPENDIX A
AS-BUILT DRAWINGS



NOTES:

1. WIRE FROM MODULE TO MODULE IS 2' LONG WITH HOOK-UP WIRE AND ONE PAIR OF SURE-SEAL CONNECTORS.
2. WIRE FROM END MODULE TO J-BOX IS 16' LONG WITH ONE PAIR OF SURE-SEAL CONNECTORS.
3. ALL OUTSIDE WIRING FROM J-BOX WILL BE IN LIQUID-TIGHT CONDUIT IN ACCORDANCE WITH NEC. ALL CONDUIT CONNECTORS SHALL BE COMPRESSION TYPE ONLY, ALL CONDUIT WILL BE 3/4" OR 1" DIA. AS NOTED ON DRAWING.
4. ALL WORK SHALL BE EXECUTED IN A GOOD WORKMANLIKE MANNER.
5. THE INSTALLATION SHALL COMPLY WITH ALL LOCAL AND STATE CODES APPLYING TO ELECTRICAL INSTALLATIONS AND WITH THE LATEST ISSUE OF NATIONAL ELECTRICAL CODES. AT COMPLETION OF WORK, THE CONTRACTOR SHALL FURNISH THE CERTIFICATE OF FINAL INSPECTION AND APPROVAL FROM THE LOCAL ELECTRICAL INSPECTION DEPARTMENT.
6. ALL PARTS AND MATERIAL SHALL WITHSTAND 290 VDC and 3 AMPS.
7. ALL DC AND AC SERVICE INSIDE HAS TO BE IN CONDUIT, EXCEPT LIGHTING AND OUTLET. CONDUIT WILL BE 3/4" DIA.
8. ALL WIRING HAS TO BE TYPE TW BUILDING WIRE.
9. EACH ROW CONSIST OF:
   - 13 EACH MODULES.
   - 14 EACH CABLES.
   - 1 EACH J-BOX.
10. SEE SHEET 2 THIS DRAWING FOR SERVICE ENTRANCES AND INSIDE WIRING.
11. SEE SHEET 3 FOR DETAILS ON MAIN SAFETY ENCLOSURE.
12. ALL CONDUIT ON ROOF MOUNTED AT SAME LEVEL AND ATTACHED TO UNISTRUT AS REQUIRED.
13. ALL WORK DONE AS DIRECTED BY THIS DRAWING TO BE APPROVED BY BDM.
14. THIS DRAWING TO BE USED IN CONJUNCTION WITH BDM DRAWING NUMBERS 02D001588, 02D001586.
15. FOR PHYSICAL ARRAY LOCATION SEE BDM DRAWING NUMBERS 02D001582, 02D001583.

1 EA. 12 AWG GND WIRE, 4 EA. 14 AWG DC POWER WIRING IN CONDUIT (SAME AS J-BOX 5)

1 EA. 12 AWG GND WIRE, 2 EA. 14 AWG DC POWER WIRING IN CONDUIT (SAME AS J-BOX 6)

NO. REQ'D	PART NO.	MATERIAL	DESCRIPTION	ITEM NO.

LIST OF MATERIAL

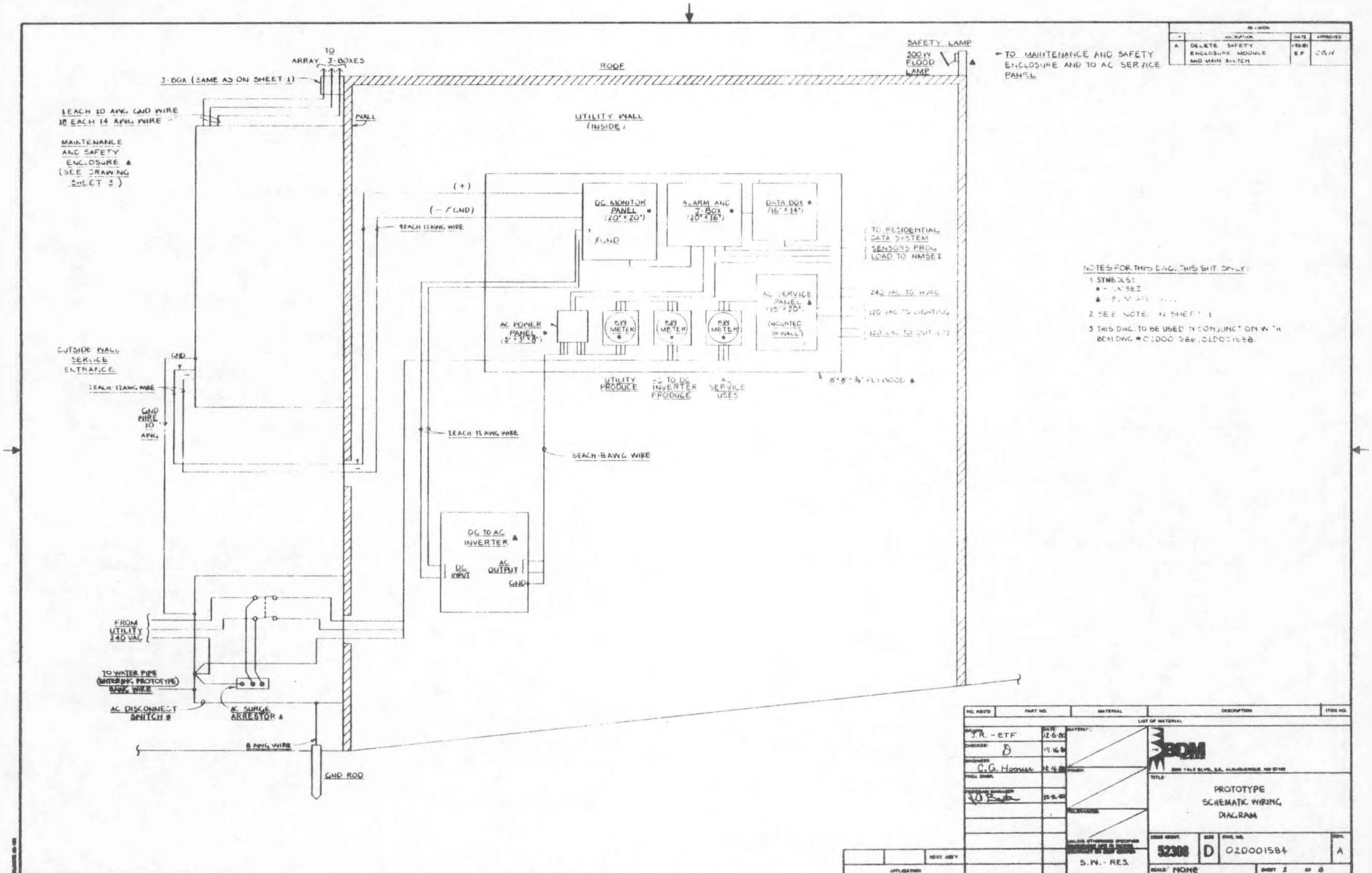
DRAWN ETT	DATE 12-3-80	MATERIAL
CHECKED	12-16-80	
ENGINEER C.G. Hoover	12-16-80	FINISH
PROJ. ENGR.		
PROGRAM MANAGER	12-16-80	TOLERANCES
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES		CONTRACT OR COST CENTER: S.W. RES.
NEXT ASSY		APPLICATION

BDM — 2600 YALE BLVD. S.E. ALBUQUERQUE, NM 87106

TITLE: PROTOTYPE SCHEMATIC WIRING DIAGRAM

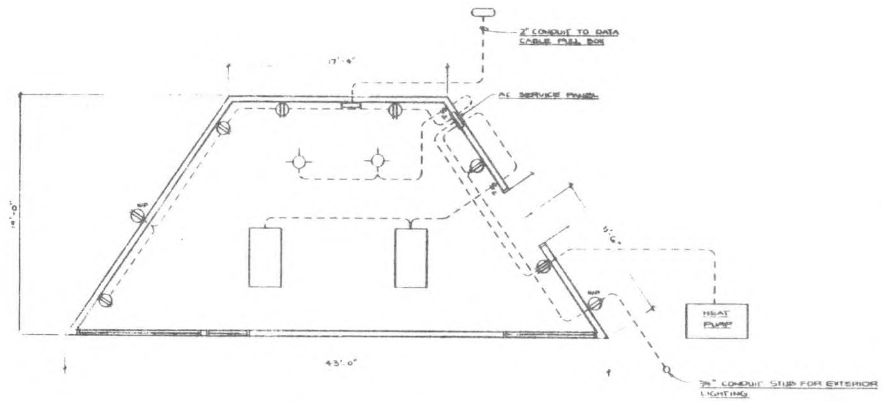
CODE IDENT.	SIZE	DWG. NO.	REV.
52308	D	02D001584	B
SCALE NONE		SHEET 1 OF 4	

SHEET 17

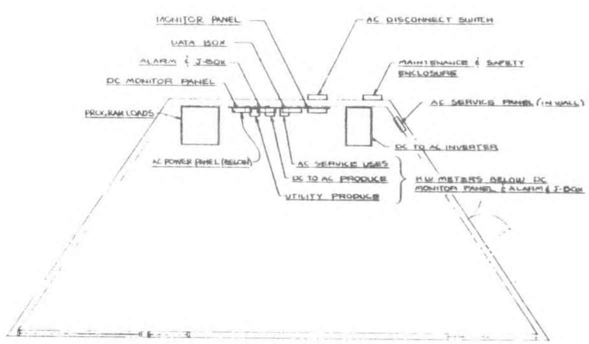

TO ARRAY J-BOXES
J-BOX (SAME AS ON SHEET 1)
ROOF
SAFETY LAMP
300 W FLOOD LAMP
← TO MAINTENANCE AND SAFETY ENCLOSURE AND TO AC SERVICE PANEL
1 EACH 10 AWG GND WIRE
18 EACH 14 AWG WIRE
WALL
UTILITY WALL (INSIDE)
MAINTENANCE AND SAFETY ENCLOSURE ▲ (SEE DRAWING SHEET 3)
(+)
(− & GND)
DC MONITOR PANEL (20" × 20")
ALARM AND J-BOX (20" × 16")
DATA BOX (16" × 14")
TO RESIDENTIAL DATA SYSTEM SENSORS FROM LOAD TO NMSEI
AC POWER PANEL
AC SERVICE PANEL ▲ (15" × 20") (MOUNTED IN WALL)
240 VAC TO HVAC
120 VAC TO LIGHTING
120 VAC TO OUTLETS
KWH METER
KWH METER
KWH METER
UTILITY PRODUCE
DC TO AC INVERTER PRODUCE
AC SERVICE USES
OUTSIDE WALL SERVICE ENTRANCE
GND
GND WIRE 10 AWG
2 EACH 12 AWG WIRE
8' × 8' × 3/4" PLYWOOD ▲
2 EACH 12 AWG WIRE
5 EACH 8 AWG WIRE
DC TO AC INVERTER ▲
DC INPUT
AC OUTPUT
GND
FROM UTILITY 240 VAC
TO WATER PIPE (EXISTING PROTOTYPE) 8 AWG WIRE
AC DISCONNECT SWITCH ●
AC SURGE ARRESTOR ▲
8 AWG WIRE
GND ROD
NOTES FOR THIS DWG. THIS SHT. ONLY:
1. SYMBOLS:
2. SEE NOTE ON SHEET 1
3. THIS DWG. TO BE USED IN CONJUNCTION WITH BDM DWG # 02000 1586, 02000 1588.
REVISION
A DELETE SAFETY ENCLOSURE MODULE AND MAIN SWITCH EF CGH
NO. REQ'D
PART NO.
MATERIAL
DESCRIPTION
ITEM NO.
LIST OF MATERIAL
DRAWN J.R. - ETF 12-6-80
CHECKED 12-16-80
ENGINEER C.G. Hoover
PROGRAM MANAGER
NEXT ASSY
APPLICATION
S.W. - RES.
BDM
2600 YALE BLVD., S.E., ALBUQUERQUE, NM 87106
TITLE: PROTOTYPE SCHEMATIC WIRING DIAGRAM
CODE IDENT. 52308
SIZE D
DWG. NO. 020001584
REV. A
SCALE: NONE
SHEET 1 OF 8

SHEET 1B

REV	DESCRIPTION	DATE	APPROVED
A	DELETE STATEMENT	1-13-81	CGH
B	AS BUILTS	4/24/81	4-24-81



ELECTRICAL LAYOUT
NO SCALE



AC-DC ELECTRICAL COMPONENT LAYOUT
NO SCALE

NOTES:

1. THIS DWG TO BE USED IN CONJUNCTION WITH BDM DWGS 02D001586, 02D001588. SEE DEAN/HUNT FLOOR PLANS, SHEET [illegible]
2. DIMENSIONS GIVEN THIS DWG ARE FOR REF ONLY
3. INTERIOR WALL COMPONENTS TO BE MOUNTED ON 8'×8'×3/4" (2-4'×8'×3/4" SHTS) PLYWOOD

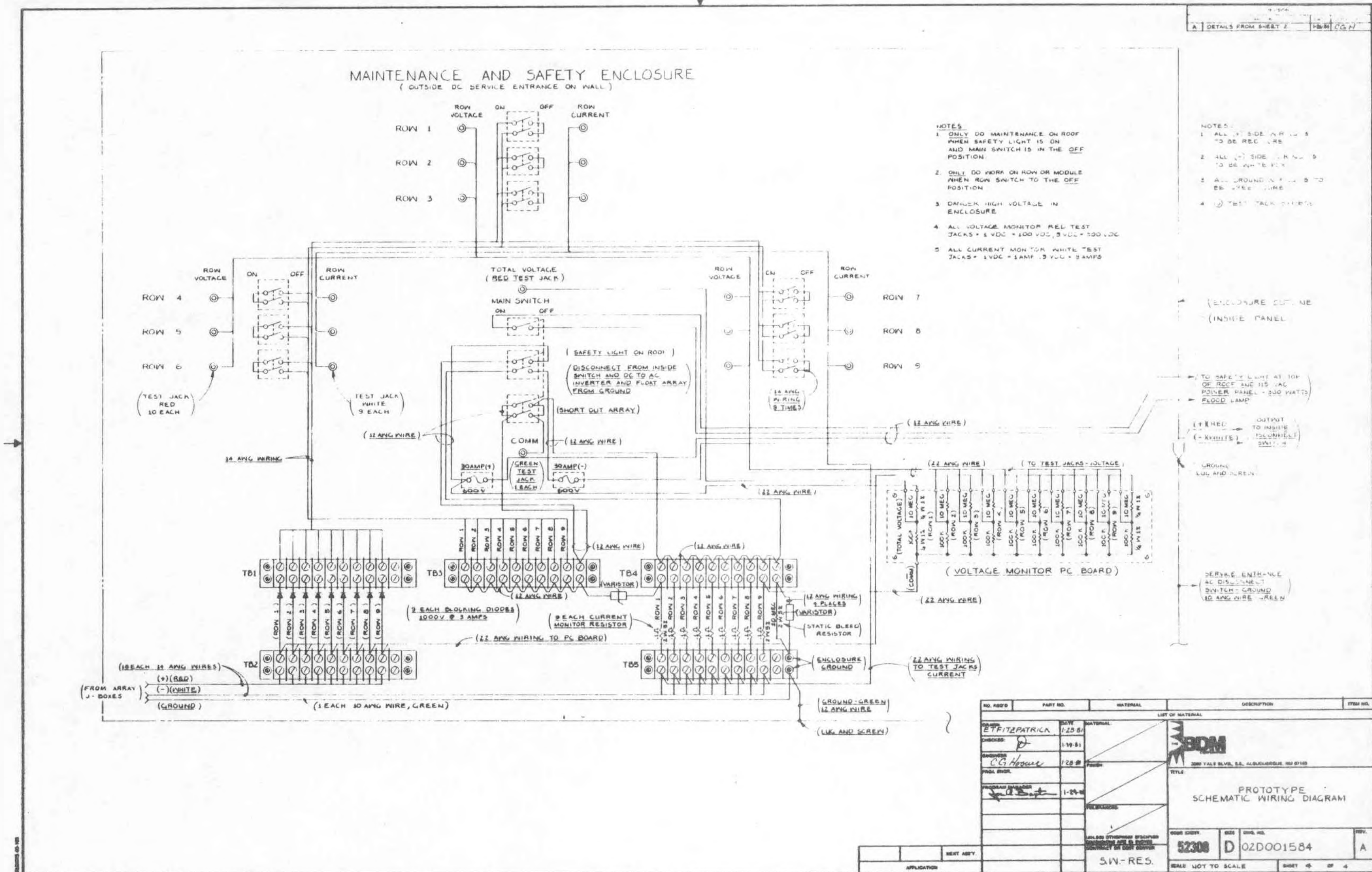
NO. REQ'D	PART NO.	MATERIAL	DESCRIPTION	ITEM NO.
LIST OF MATERIAL				

DRAWN: K. COX — DATE: 12/14/80
CHECKED: [signature] — 12-16-80
ENGINEER: C.G. Hoouse — 12-16-80
PROGRAM MANAGER: J.D. Baxter — 12-18-80
FINISH: S.W. RES.

THE BDM CORPORATION — 2600 YALE BLVD., S.E., ALBUQUERQUE, NM 87106

TITLE: PROTOTYPE SCHEMATIC WIRING DIAGRAM

CODE IDENT. 52308 | SIZE D | DWG. NO. 02D001584 | REV. B
SCALE: NONE | SHEET 3 OF 4


MAINTENANCE AND SAFETY ENCLOSURE
(OUTSIDE DC SERVICE ENTRANCE ON WALL)
ROW VOLTAGE
ON
OFF
ROW CURRENT
ROW 1
ROW 2
ROW 3
ROW 4
ROW 5
ROW 6
ROW 7
ROW 8
ROW 9
TOTAL VOLTAGE (RED TEST JACK)
MAIN SWITCH
(SAFETY LIGHT ON ROOF)
(DISCONNECT FROM INSIDE SWITCH AND DC TO AC INVERTER AND FLOAT ARRAY FROM GROUND)
(SHORT OUT ARRAY)
COMM
(TEST JACK RED 10 EACH)
(TEST JACK WHITE 9 EACH)
14 AWG WIRING
NOTES
1. ONLY DO MAINTENANCE ON ROOF WHEN SAFETY LIGHT IS ON AND MAIN SWITCH IS IN THE OFF POSITION
2. ONLY DO WORK ON ROW OR MODULE WHEN ROW SWITCH TO THE OFF POSITION
3. DANGER HIGH VOLTAGE IN ENCLOSURE
(ENCLOSURE OUTLINE (INSIDE PANEL)
(VOLTAGE MONITOR PC BOARD)
TB1
TB2
TB3
TB4
TB5
(VARISTOR)
(9 EACH BLOCKING DIODES 1000V @ 3 AMPS)
(9 EACH CURRENT MONITOR RESISTOR)
(22 AWG WIRING TO PC BOARD)
(STATIC BLEED RESISTOR)
(ENCLOSURE GROUND)
(22 AWG WIRING TO TEST JACKS CURRENT)
(18 EACH 14 AWG WIRES)
(+)(RED)
(-)(WHITE)
(GROUND)
(FROM ARRAY J-BOXES)
(1 EACH 10 AWG WIRE, GREEN)
(GROUND-GREEN 12 AWG WIRE)
(LUG AND SCREW)
PROTOTYPE SCHEMATIC WIRING DIAGRAM
52308
D
02D001584
A
S.W.-RES.
NOT TO SCALE

SHEET 20

APPENDIX B

STRUCTURAL LOAD DATA

MEMORANDUM

January 29, 1981

TO: J. A. Baxter (83, 110-3)

FROM: W. E. Kuchar (83, 202-2)

SUBJECT: Structural Analysis of PV Module Installation on Roof of S.W PV Residence (Update No. 1)

REFERENCE: Memorandum BDM/A-WEK-0416-81

Per our conversation subsequent to the issuance of the reference memo we have investigated allowable lengths of three of the Unistrut steel support tubes which span across the support blocks and support the PV modules. The table below shows two allowable lengths: (1) based on a yield strength of 25000 psi (per Unistrut catalog) and (2) based on a deflection at midspan of L/240.

Section Number	L (ft) (1)	L (ft) (2)
P1000	7.7	5.5
P2000	6.0	4.8
P5500	10.3	7.7

Stress levels above 25000 psi (Unistrut guideline) and deflections above L/240 (building code) will not be exceeded if Unistrut spans are limited to approximately 5 feet.

MEMORANDUM BDM/A-WEK-0416-81

January 12, 1981

TO: J. A. Baxter (83,110-3)

FROM: W. E. Kuchar (83,202-2) WEK

SUBJECT: Structural Analysis of PV Module Installation on Roof of S.W. PV Residence

REFERENCES: (1) Timber Construction Manual, American Institute of Timber Construction (AITC, John Wiley and Sons, 2nd Edition, 1974).
(2) Block IV Solar Cell Module Design and Test Specification for Residential Applications, DOE/JPL-1012-78/14.

The installation analyzed consisted of two rectangular arrays of PV modules on a trapazoidal roof, sloped at approximately 36 degrees, which constitutes one roof section of the prototype Photovoltaic Residence in the Southwest. Two basic arrangements of roof construction were considered - one with 4" X 12" roof beams on 4' centers unsupported between eaves and crown, and covered with 3/4" plywood decking under the PV arrays, and the other identical, except with 2" X 12" roof beams on 2' centers. In both cases the PV modules were 14" X 47.18" modules, manufactured by Motorola Corporation, with each module weighing 13.2 pounds. For an initial design the modules were attached to steel brackets mounted to 2" X 6" wood beams attached to the plywood roof deck. Later, the steel brackets were replaced by wood blocks but the roof weight loading used in the analysis of the roof beams contains the bracket weights so the analysis is conservative to that extent. A layer of foam covered the plywood deck and the 2" X 6" beams. Details of the current roof installation are shown on BDM Drawing 02D001582.

Analysis of the PV module installation included streses and deflections of the primary roof support beam and plywood decking, and deflection and fastener loads of the PV modules - for roof system and module weight loads, occupied ladder loads, wind loads, and snow loads.

Stress and deflection results for the 4" X 12" roof beams are given in Table 1. These results show adequate margins of safety for beam bending stress for individual and combined load cases for weight, ladders wind, and snow when using beams of construction grade Douglas Fir. Maximum deflection of the 4" X 12" roof beams was found to be 1.0 inches which is less than the guidelines of 1.25 inches allowed by reference 1 and based on a deflection criteria of L/240, where L is the beam length.

J. A. Baxter
BDM/A-WEK-0416-81
January 12, 1981
Page 2

For the configurations using 2" X 12" beams on 2' centers the load per foot of beam length will be one-half, and the beam stiffness very nearly double, that for 4" X 12" beams on 4' centers, so the results of Table 1 also apply to 2" X 12" beams on 2" centers.

Results for the plywood deck are shown in Table 2 for roof beams on 4' and 2' centers. These results show adequate margins of safety for weight, wind, and snow loads, when using Group 1, exterior grade, plywood. Group 2 or 3, exterior grade, plywood would be marginal for use with roof beams on 4' centers but acceptable with roof beams on 2' centers.

Analysis of the 8' long Unistrut steel tube members which support the PV modules showed the P2000 series Unistrut to be overstressed during uplift wind conditions. The Unistrut manufacturer lists an allowable stress of 25000 psi, and the calculated bending stress during wind uplift (based on Reference 1 coefficients) was 52448 psi. Using the P5500 series Unistrut steel tube members which are 13/16" deeper in cross-section will reduce the bending stress during wind uplift to 19657 psi for a margin of safety of ±.27. The P5500 Unistrut member is recommended.

One other area of the roof installation which will probably present problems over the long term (say 1 year), are the nailed block supports for the Unistrut members. Wind induced vibrations of the PV modules will eventually cause the nails in the support blocks to withdraw and it is conceivable that PV modules could be damaged. Through-bolts or metal straps could be used instead of nails for the 2" X 6" support blocks.

Regarding deflection of support members, the distortion of PV modules during wind, weight, and snow loading was calculated to be less than the deviation from true flat of ±1/4" per foot, allowed by Reference 2.

Please contact me if you have any questions concerning the analysis or need additional information.

WEK/dgq

Attachments: (1) Table 1. Stresses and Deflections in Roof Beams
(2) Table 2. Stresses and Deflections in Plywood Decking

cc:

H. T. Webster
M. G. Semmens
W. R. Kauffman

TABLE 1. STRESSES AND DEFLECTIONS IN ROOF BEAMS

	A UNIFORM WT. (1)	B LADDER LOADS (2)	C DOWNWARD WIND LOAD	D UPWARD WIND LOAD	E SNOW LOAD	A&B (M.S.)	A&C (M.S.)	A,E, & 1/2 OF C (M.S.)
BENDING STRESS (PSI)	418.	471.	95.	-349.	438.	889.	513.	903.
						(+.18)	(+1.05)	(+.16)
SHEAR STRESS (PSI)	15.	9.	5.	-33.	19.	24.	20.	37.
						(+2.96)	(+3.75)	(+1.57)
DEFLECTION (IN.)	0.5	0.4	0.1	-1.0	0.5	0.9	0.6	1.0
						(*)	(*)	(*)

(1) Uniformly distributed wts. of PV modules, 3/4" plywood deck, 2" X 6" support blocks, 4" X 12" roof beams, and steel support brackets.

(2) Assuming two ladders, one across each array of PV modules, each ladder weighing 200 lbs., and two 200 lbs. persons at the center of the roof.

(3) Margins of safety (M.S.) are based on allowable stresses for construction grade Douglas Fir (F_b = 1050, F_v = 95 psi).

* Allowable deflection based on L/240 is 1.25 inches.

TABLE 2. STRESSES AND DEFLECTIONS IN PLYWOOD DECKING

	A UNIFORM WT. (1)	B LADDER LOADS	C DOWNWARD WIND LOADS	D UPWARD WIND LOADS	E SNOW LOADS	A&C	A,E, & 1/2C
BENDING STRESS (PSI)							
4' SPAN	442.	(2)	170.	-1193.	682.	612.	1209.
					(+1.93)	(+2.27)	(+.65)
2' SPAN	110.	(2)	43.	-299.	170.	153.	302.
					(+10.8)	(+12.1)	(+5.62)
DEFLECTION (IN.)	.13	(2)	.05	-.35	.20	.18	.35
					(*)	(*)	(*)
2' SPAN	.01	(2)	.00	-.02	.01	.01	.02
					(**)	(**)	(**)

(1) Uniformly distributed wts. of PV modules, 3/4" plywood deck, 2" X 6" support blocks, and steel support brackets.

(2) Assume ladder loads carried by roof beams.

(3) Margins of safety are based on Group 1, exterior grade plywood (F_b = 2000 psi, F_v = 250 psi).

(4) Shear stresses are negligible since max. shear stresses are approx. 5 psi and allowable is 53 psi.

* Allowable deflection based on L/240 is 0.20 inches for L = 48 in.

** Allowable deflection based on L/240 is 0.10 inches for L = 24 in.

APPENDIX C
PV MODULE DATA

C.1 MANUFACTURER'S SPECIFICATION SHEET

C.2 ROW I-V PARAMETERS

APPENDIX C.1

MODULE MANUFACTURER'S SPECIFICATION SHEET

SOLAR SYSTEMS

MSP43A40

PHOTOVOLTAIC PRODUCTS

40 WATT HIGH DENSITY SOLAR MODULE

The MSP43A40 utilizes advanced technology 100 mm X 100 mm (4" X 4") square cells to provide maximum power in minimum space. The 33 series cell module provides more 12 volt battery charging current per watt of module power than modules with a higher number of cells. Both analysis and tests have proven that the 33 cell configuration provides ample charging voltage in all climates. Balance-of-system costs are reduced by increased packing density. All materials and construction techniques have a proven history of reliability.

FEATURES

- High Packing Density (82% of total area) using 100 mm X 100 mm square cells
- High Reliability due to Redundant Interconnects
- Across-The-Cell Contacts Eliminate Potential Power Loss Due to Cracked Cells
- 33 Cells in Series
- 40 Watts Peak Power
- Maintenance Free Construction. Tempered Glass Superstrate. Stainless Steel Frame
- Low Cell Temperature. NOCT = 45C
- Metric Dimensions. 340 mm by 1200 mm
- Designed to Exceed JPL Block 4 Requirements
- Exceeds National Electrical Code

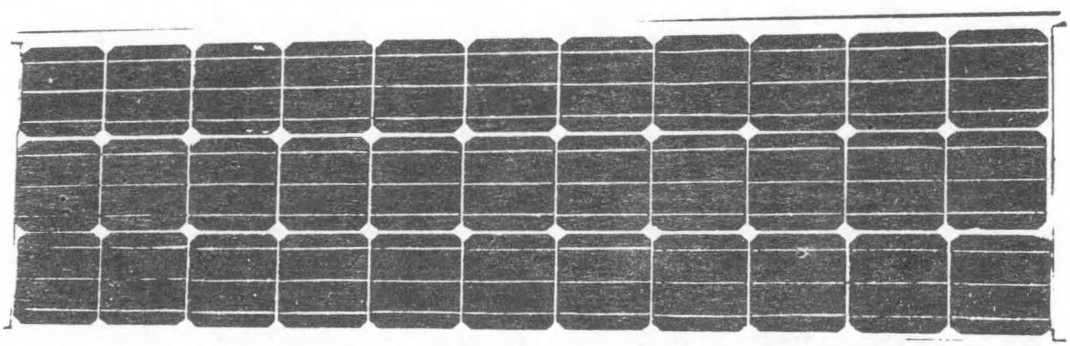
APPLICATIONS

Village Power
Remote Communications
Offshore Equipment
Cathodic Protection
Forestry Equipment
Boats
Instrumentation
Water Pumping
Microwave Relays
Navigational Aids
Portable Equipment
Emergency Phones
Cabins
Remote Refrigerators

SYSTEMS ENGINEERING

In addition to photovoltaic modules, we can supply other system components, including voltage regulators, steel support structures, batteries and related wiring.

Our staff of application engineers is available to assist you in system definition and system sizing.



 DS 2205

BDM/A-81-550-TR

MSP43A40

ELECTRICAL

CONDITIONS AIR MASS 1.5	I_{SC} TYP	I_M AT MIN	V_{NO}	V_{OC} TYP	P_M MIN	P_M TYP
T_C = 28C, 100 mW/cm^2	2.6	2.3	15.8	19.5	36.5	40.0
T_A = 20C, T_C = 50C, 100 mW/cm^2	2.6	2.3	14.3	17.9	33.3	36.6
T_A = 20C, T_C = 45C, 80 mW/cm^2	2.1	1.9	14.4	17.9	26.9	29.5
T_A = 40C, T_C = 65C, 80 mW/cm^2	2.1	1.9	13.0	16.4	24.6	27.1

I_{SC} = Short Circuit Current, Adc

I_M = Current, Adc, Measured at V_{NO}

V_{NO} = Nominal Operating Voltage, Vdc, is the Reference Voltage Level at which the Modules are Designed to Provide Maximum Power Output at Specified Operating Conditions.

V_{OC} = Open Circuit Voltage, Vdc

P_M = Maximum Power, Watts

T_A = Ambient Temperature, C

T_C = Cell Temperature, C

Temperature Coefficients:

TC V_{OC} = -0.0022 V/C/Cell (Series)

TC V_{NO} = -0.00213 V/C/Cell (Series)

TC I_{SC} = 0.00159 A/C/Cell (Parallel)

TC I_M = 0.00159 A/C/Cell (Parallel)

Voltage Changes: V_{OC} decrease 2% when irradiation decreases from 100 mW/cm^2 to 80 mW/cm^2

V_{NO} does not change appreciably with changes in irradiation level

MECHANICAL

Outside Dimensions (Nominal): 336 mm x 1200 mm (13.2 in. X 47 2 in. X 1.5 in.)
Weight (Nominal): 5.7 Kg (12.5 lb.)
Shock: 0.4 m (15 inch) drop per MIL-STD-810B, Method 516, Procedure V
Snow Loading: 290 Kg/m^2 (60 lb/ft^2) maximum
Vibration: per MIL STD 810B, Method 514, Procedure X

CONSTRUCTION

Cover Glass: 0.125 in. tempered Solatex® 91.6% transmittance
Encapsulant: Polyvinyl Butyral
Cells: 33 in Series, 100 mm X 100 mm Square Single-Crystal Silicon, Part No. MSPC2300S
Back: Aluminized Tedlar® (Polyvinyl Fluoride)
Edge Sealant: Butyl Rubber
Frame: Type 304 Stainless
Interconnect (Cell): Three Continuously Bonded Copper Ribbons Across Top and Bottom of Cells
Connection (External): Junction Box with Binding Posts

ELECTRICAL INSULATION TO FRAME

1600 Vdc minimum

OPERATIONAL CONDITIONS

Temperature (Ambient): -40C to 60C

Nominal Operating Cell Temperature: 45C at T_A = 20C, 80 mW/cm^2, Wind at 1 m/s, Module Tilted

Wind: Constant Velocity, 160 Km/hr (100 mph) maximum
Gust Velocity, 200 Km/hr (125 mph) maximum

STORAGE TEMPERATURE

-40C to +60C

MOTOROLA *Semiconductor Products Inc.*

BOX 20912 • PHOENIX, ARIZONA 85036 • A SUBSIDIARY OF MOTOROLA INC

4/26/79

APPENDIX C.2
ROW I-V PARAMETERS
(EXTRACTED FROM MODULE DATA)

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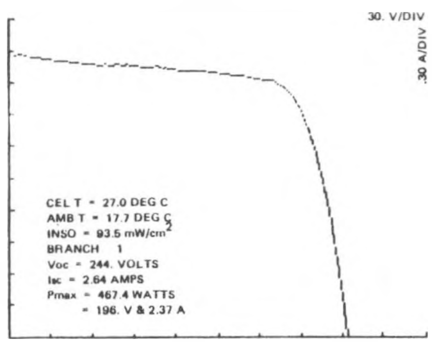
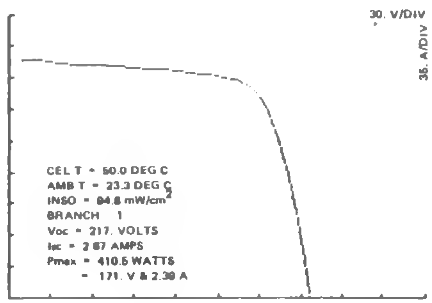
SERIES STRING/ROW #1



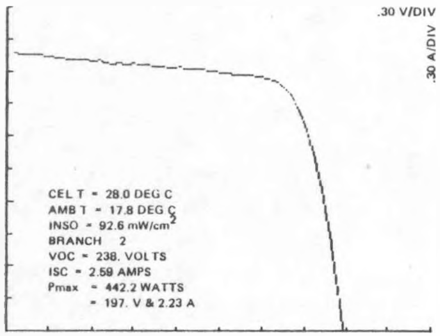
ROW #1



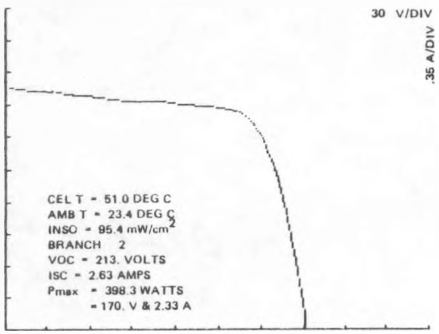
PARAMETER		1	2	3	4	5	6	7	8	9	10	11	12	13
MODULE SERIAL NUMBER		4205	4097	4203	4102	4228	4222	4204	4206	4098	4105	4218	4223	4220
V_{OC}	28°C	19.2	20.0	19.9	19.2	19.2	19.6	19.1	19.0	19.4	19.9	19.9	19.4	19.8
	50°C	17.5	17.3	17.50	17.50	17.6	17.9	17.5	17.5	17.4	17.4	17.9	17.6	17.5
I_{SC}	28°C	2.82	2.9	2.74	2.82	2.78	2.71	2.86	2.90	2.92	2.77	2.75	2.84	2.76
	50°C	2.8	2.82	2.74	2.70	2.75	2.68	2.86	2.90	2.85	2.71	2.72	2.85	2.76
$I_{(14v)}$	28°C	2.55	2.4755	2.448	2.455	2.468	2.395	2.46	2.56	2.541	2.55	2.47	2.403	2.518
	50°C	2.6	2.50	2.49	2.42	2.54	2.45	2.51	2.60	2.50	2.51	2.53	2.45	2.57
$P_{(14v)}$	28°C	40.29	39.11	38.67	38.78	38.99	37.84	38.86	40.44	40.14	40.21	39.02	37.96	39.78
	50°C	36.1	33.8	34.9	33.90	35.6	34.3	35.1	36.4	35.5	35.1	35.4	34.3	36.0
V_{MAX}	28°C	16.3	15.7	16.0	15.9	16.2	16.0	16.1	15.7	16.5	16.5	16.4	15.3	16.1
	50°C	15.0	13.50	14.5	14.2	14.6	15.2	14.6	14.3	14.3	14.3	14.9	14.4	14.6
I_{MAX}	28°C	2.53	2.57	2.45	3.50	2.47	2.35	2.44	2.57	2.52	2.51	2.47	2.5	2.54
	50°C	2.5	2.55	2.41	2.40	2.45	2.38	2.46	2.59	2.50	2.48	2.45	2.42	2.51
P_{MAX}	28°C	41.24	40.35	39.2	39.75	40.01	39.95	39.28	40.35	41.58	41.42	40.51	38.25	40.89
	50°C	38.0	34.4	34.95	34.08	35.8	36.2	35.9	37.0	35.8	35.5	36.5	34.8	36.6
I_{TEST}	50°C	2.52	2.52	2.52	2.52	2.52	2.52	2.52	2.52	2.52	2.52	2.52	2.52	2.52
V_{TEST}	50°C	15.00	13.50	13.80	12.9	14.1	12.0	13.9	14.5	14.0	14.0	14.4	13.6	14.5
P_{TEST}	50°C	37.80	34.00	34.78	32.51	35.5	30.2	35.03	36.54	35.28	35.28	36.29	34.27	36.54

BDM/A-81-550-TR

SERIES STRING/ROW #2



ROW #2



PARAMETER		1	2	3	4	5	6	7	8	9	10	11	12	13
MODULE SERIAL NUMBER		4224	4231	4121	4186	4139	4184	4189	4194	4190	4104	4125	4106	4128
V_{OC}	28°C	19.5	19.5	19.1	18.9	19.3	18.7	18.5	19.0	18.6	19.7	18.9	19.2	19.0
	50°C	17.9	17.9	17.5	17.5	17.5	17.4	16.9	17.5	17.4	17.5	17.1	17.6	17.1
I_{SC}	28°C	2.84	2.76	2.77	2.64	2.71	2.7	2.66	2.76	2.63	2.83	2.75	2.91	2.79
	50°C	2.85	2.75	2.75	2.64	2.63	2.71	2.66	2.74	2.65	2.71	2.73	2.82	2.75
$I_{(14v)}$	28°C	2.546	2.434	2.379	2.349	2.35	2.37	2.357	2.419	2.358	2.507	2.37	2.59	2.37
	50°C	2.57	2.49	2.38	2.4	2.38	2.45	2.42	2.45	2.4	2.45	2.38	2.53	2.4
$P_{(14v)}$	28°C	40.22	38.45	37.58	37.11	37.13	37.44	37.24	38.22	37.25	39.61	37.44	40.85	37.52
	50°C	35.98	34.86	33.32	33.6	33.32	34.30	33.88	34.30	33.6	34.3	33.32	35.42	33.6
V_{MAX}	28°C	16.5	17.0	15.6	15.7	15.6	15.3	15.8	16.0	16.0	16.3	15.4	16.4	15.4
	50°C	15.4	15.4	14.4	14.4	14.0	14.5	14.3	14.6	14.5	14.1	14.2	14.7	13.8
I_{MAX}	28°C	2.52	2.38	2.51	2.36	2.44	2.49	2.37	2.43	2.34	2.53	2.47	2.57	2.48
	50°C	2.5	2.4	2.36	2.38	2.41	2.41	2.4	2.43	2.37	2.45	2.39	2.47	2.46
P_{MAX}	28°C	41.58	40.46	39.16	37.05	38.06	38.10	37.45	38.88	37.44	41.24	38.04	42.15	38.19
	50°C	38.5	36.96	33.98	34.27	33.74	34.95	34.32	35.48	34.37	34.55	33.94	36.31	33.95

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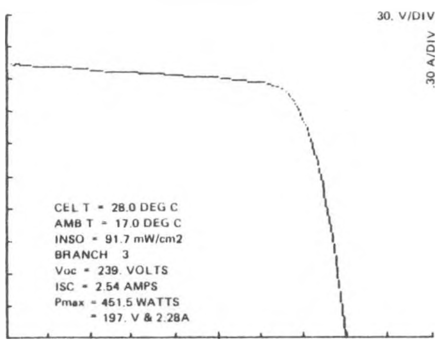
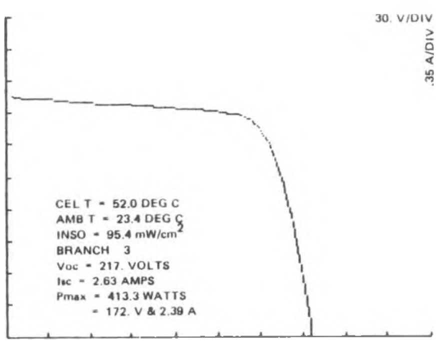
SERIES STRING/ROW #3

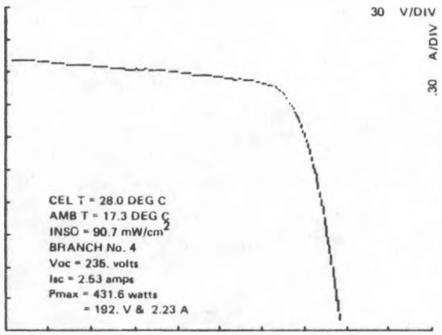


ROW #3

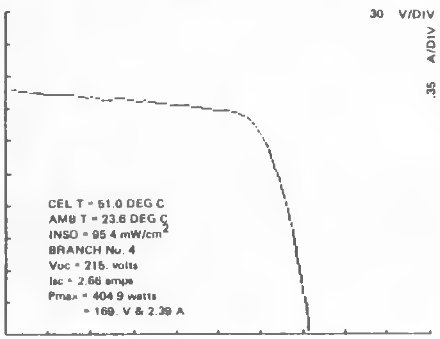


PARAMETER		1	2	3	4	5	6	7	8	9	10	11	12	13
MODULE SERIAL NUMBER		4129	4123	4152	4117	4138	4126	4133	4216	4200	4207	4213	4195	4191
V_{OC}	28°C	19.4	19.5	19.3	19.4	19.0	19.5	19.3	19.4	19.3	19.0	19.4	19.0	19.1
	50°C	17.5	17.5	17.5	17.4	17.2	17.5	17.4	17.7	17.6	17.3	17.6	17.1	17.5
I_{SC}	28°C	2.74	2.66	2.65	2.83	2.71	2.68	2.72	2.75	2.78	2.74	2.76	2.71	2.74
	50°C	2.69	2.67	2.64	2.72	2.72	2.65	2.72	2.76	2.78	2.73	2.74	2.7	2.75
$I_{(14v)}$	28°C	2.39	2.45	2.40	2.45	2.398	2.37	2.359	2.373	2.481	2.417	2.358	2.462	2.5
	50°C	2.38	2.48	2.45	2.42	2.44	2.4	2.45	2.4	2.51	2.5	2.42	2.5	2.54
$P_{(14v)}$	28°C	37.76	38.71	37.95	38.78	37.88	37.44	37.27	37.49	39.19	38.18	34.25	38.89	39.50
	50°C	33.32	34.72	34.3	33.88	34.16	33.6	34.3	33.95	35.14	35.0	33.88	35.0	35.56
V_{MAX}	28°C	16.2	16.3	16.8	16.3	15.8	15.6	16.2	17.0	16.3	15.5	16.5	16.3	16.0
	50°C	14.2	14.3	15.0	14.2	14.4	14.1	15.0	15.4	15.0	14.4	15.3	14.4	14.5
I_{MAX}	28°C	2.39	2.44	2.34	2.45	2.42	2.44	2.38	2.31	2.47	2.5	2.33	2.45	2.49
	50°C	2.41	2.49	2.36	2.4	2.44	2.39	2.35	2.36	2.44	2.48	2.34	2.49	2.51
P_{MAX}	28°C	38.72	39.77	39.31	39.94	38.24	38.06	38.56	39.27	40.26	38.75	38.45	39.94	39.84
	50°C	34.22	35.61	35.4	34.08	35.14	33.7	35.25	36.34	36.6	35.71	35.80	35.86	36.4

SERIES STRING/ROW #4



ROW #4



PARAMETER		1	2	3	4	5	6	7	8	9	10	11	12	13
MODULE SERIAL NUMBER		4215	4099	4101	4100	4124	4202	4196	4192	4208	4214	4140	4212	4183
V_{OC}	28°C	19.2	20.1	19.4	19.1	19.0	19.1	18.8	19.1	19.2	19.3	19.2	19.3	19.2
	50°C	17.5	17.6	17.4	17.1	17.4	17.6	17.4	17.5	17.5	17.4	17.7	17.5	17.5
I_{SC}	28°C	2.75	2.84	2.76	2.87	2.71	2.77	2.65	2.74	2.76	2.81	2.85	2.71	2.7
	50°C	2.75	2.76	2.66	2.75	2.62	2.76	2.65	2.75	2.75	2.79	2.84	2.7	2.69
$I_{(14v)}$	28°C	2.35	2.46	2.41	2.43	2.38	2.41	2.379	2.49	2.369	2.354	2.469	2.445	2.481
	50°C	2.40	2.49	2.38	2.40	2.38	2.45	2.44	2.5	2.41	2.41	2.55	2.5	2.51
$P_{(14v)}$	28°C	37.12	38.93	38.14	38.31	37.67	38.08	37.58	39.31	37.43	37.19	39.01	38.63	39.19
	50°C	33.6	34.86	33.32	33.6	33.32	34.3	34.16	35.14	33.74	33.74	35.70	35.0	35.14
V_{MAX}	28°C	15.9	16.3	15.6	15.6	15.4	16.9	15.4	16.5	16.3	17.3	15.6	16.4	16.1
	50°C	14.4	14.2	14.3	14.1	14.4	15.5	14.5	14.5	14.3	15.1	14.6	14.4	14.5
I_{MAX}	28°C	2.39	2.45	2.48	2.51	2.5	2.35	2.48	2.47	2.37	2.29	2.52	2.44	2.47
	50°C	2.36	2.46	2.35	2.4	2.36	2.35	2.40	2.5	2.4	2.32	2.49	2.48	2.5
P_{MAX}	28°C	38.00	39.94	38.69	39.16	38.5	39.72	38.19	40.76	38.63	39.62	39.31	40.02	39.77
	50°C	33.98	34.93	33.61	33.84	33.98	36.43	34.8	36.25	34.32	35.03	36.35	35.71	36.25

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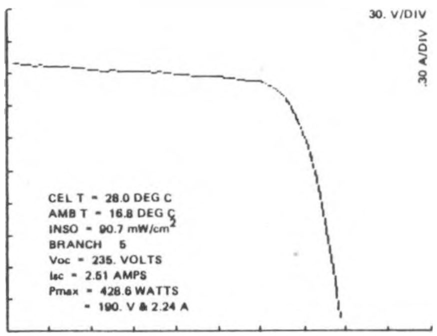
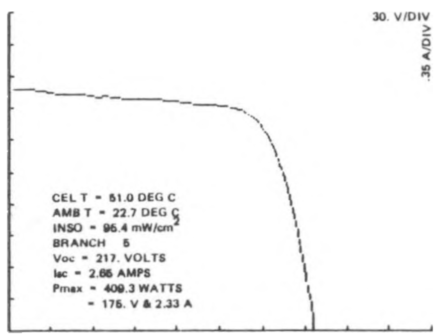
SERIES STRING/ROW #5



ROW #5



PARAMETER		1	2	3	4	5	6	7	8	9	10	11	12	13
MODULE SERIAL NUMBER		4211	4219	4217	4209	4108	4115	4116	4112	4103	4135	4122	4168	4156
V_{OC}	28°C	19.0	19.5	19.4	19.4	19.5	19.1	19.0	18.8	19.6	19.0	19.5	19.0	19.0
	50°C	17.4	17.8	17.6	17.6	17.3	17.1	17.1	17.0	17.6	17.4	17.6	17.4	17.4
I_{SC}	28°C	2.74	2.66	2.79	2.8	2.79	2.65	2.75	2.73	2.76	2.73	2.74	2.66	2.65
	50°C	2.76	2.67	2.77	2.76	2.72	2.66	2.7	2.75	2.71	2.72	2.74	2.66	2.65
$I_{(14v)}$	28°C	2.317	2.376	2.545	2.407	2.556	2.4	2.39	2.39	2.403	2.347	2.35	2.39	2.43
	50°C	2.45	2.43	2.6	2.451	2.5	2.45	2.4	2.44	2.38	2.39	2.41	2.45	2.48
$P_{(14v)}$	28°C	36.6	37.54	40.21	38.03	42.38	37.92	37.76	37.76	37.96	37.08	37.13	37.76	38.39
	50°C	34.3	34.02	36.4	34.31	35.0	34.3	33.6	34.16	33.32	33.46	33.94	34.3	34.72
V_{MAX}	28°C	16.2	17.0	16.3	15.1	16.3	16.3	16.0	16.2	15.5	16.1	15.1	15.6	16.0
	50°C	14.2	15.4	14.4	14.3	13.9	14.4	14.2	14.3	13.9	14.4	14.0	14.3	14.4
I_{MAX}	28°C	2.33	2.34	2.56	2.54	2.57	2.4	2.4	2.37	2.51	2.35	2.5	2.45	2.46
	50°C	2.42	2.36	2.56	2.45	2.53	2.44	2.4	2.44	2.45	2.37	2.49	2.41	2.46
P_{MAX}	28°C	37.75	39.78	41.73	38.35	41.89	39.12	38.40	38.39	38.91	37.84	37.75	38.22	39.36
	50°C	34.36	36.34	36.86	35.04	35.17	35.14	34.08	34.89	34.06	34.13	34.86	34.46	35.42

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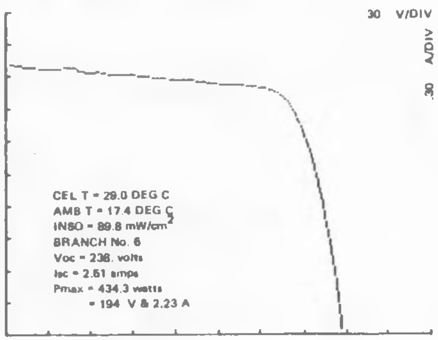
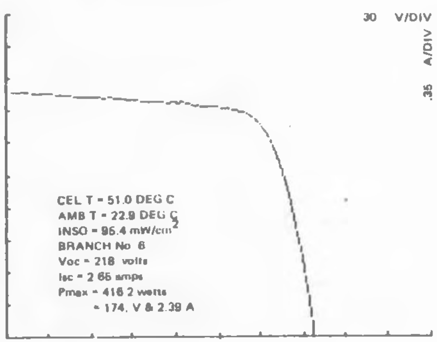
SERIES STRING/ROW #6



ROW #6



PARAMETER		1	2	3	4	5	6	7	8	9	10	11	12	13
MODULE SERIAL NUMBER		4120	4141	4109	4166	4130	4136	4165	4127	4142	4111	4107	4114	4173
V_{OC}	28°C	19.3	19.0	19.4	19.1	19.3	18.7	18.7	19.1	19.5	19.4	19.5	19.4	19.0
	50°C	17.2	18.0	17.3	17.5	17.5	17.4	18.6	17.3	17.7	17.4	17.4	17.3	17.4
I_{SC}	28°C	2.77	2.75	2.81	2.64	2.76	2.7	2.65	2.74	2.84	2.9	2.81	2.79	2.71
	50°C	2.70	2.76	2.77	2.64	2.75	2.67	2.65	2.73	2.84	2.83	2.75	2.7	2.71
$I_{(14v)}$	28°C	2.505	2.459	2.58	2.402	2.49	2.342	2.367	2.38	2.438	2.557	2.588	2.495	2.456
	50°C	2.43	2.53	2.5	2.45	2.52	2.38	2.49	2.42	2.54	2.52	2.55	2.46	2.51
$P_{(14v)}$	28°C	39.57	38.85	40.7	37.95	39.34	39.0	37.54	37.6	39.23	40.4	40.89	39.49	38.8
	50°C	34.02	35.42	35.0	34.3	35.28	33.32	34.86	33.88	35.56	35.28	35.70	34.44	35.14
V_{MAX}	28°C	15.6	16.3	15.5	16.5	15.5	16.0	16.2	15.4	16.1	15.5	16.1	16.3	15.6
	50°C	14.2	14.9	14.0	14.4	13.7	14.6	15.6	14.2	14.7	14.0	14.5	14.1	14.4
I_{MAX}	28°C	2.6	2.45	2.65	2.38	2.57	2.35	2.35	2.46	2.49	2.66	2.60	2.5	2.5
	50°C	2.43	2.49	2.54	2.43	2.57	2.35	2.4	2.42	2.49	2.56	2.5	2.45	2.49
P_{MAX}	28°C	40.56	39.935	41.08	39.27	39.84	37.6	38.07	37.88	40.09	41.23	41.86	40.75	39.0
	50°C	34.51	37.10	35.56	34.99	35.21	34.31	37.44	34.36	36.60	35.84	36.25	34.55	35.86

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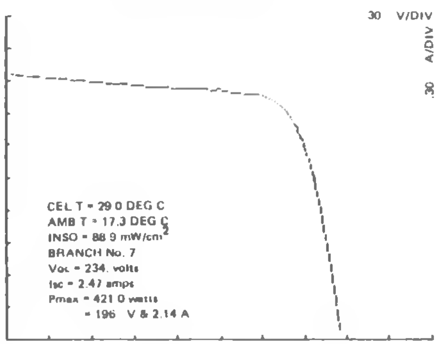
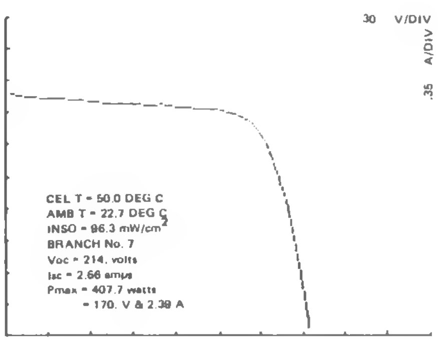
SERIES STRING/ROW #7



ROW #7



PARAMETER		1	2	3	4	5	6	7	8	9	10	11	12	13
MODULE SERIAL NUMBER		4118	4182	4131	4113	4193	4197	4198	4199	4221	4230	4227	4210	4185
V_{OC}	28°C	19.5	19.4	19.3	19.4	19.1	18.6	19.0	18.7	19.3	19.4	19.5	19.2	18.9
	50°C	17.6	18.0	17.4	17.5	17.4	17.0	17.3	17.2	17.5	17.7	17.9	17.5	17.1
I_{SC}	28°C	2.8	2.73	2.75	2.74	2.71	2.66	2.8	2.65	2.75	2.77	2.74	2.82	2.65
	50°C	2.7	2.71	2.75	2.65	2.73	2.66	2.75	2.65	2.75	2.72	2.72	2.8	2.66
$I_{(14v)}$	28°C	2.59	2.48	2.41	2.35	2.498	2.319	2.357	2.411	2.431	2.462	2.442	2.518	2.353
	50°C	2.55	2.51	2.46	2.38	2.55	2.4	2.38	2.45	2.457	2.42	2.5	2.52	2.4
$P_{(14v)}$	28°C	40.92	39.19	38.07	37.06	39.46	36.63	37.24	38.08	38.4	38.89	38.57	39.78	37.17
	50°C	35.70	35.14	34.44	33.3	35.7	33.6	33.32	34.3	34.39	33.88	35.0	35.28	33.6
V_{MAX}	28°C	16.3	16.0	16.2	15.6	16.0	15.2	15.5	15.5	16.0	16.2	16.0	15.7	15.2
	50°C	15.0	15.3	14.2	14.4	14.5	13.7	14.0	14.4	14.9	14.4	14.7	14.4	14.2
I_{MAX}	28°C	2.58	2.5	2.4	2.4	2.5	2.5	2.45	2.45	2.45	2.47	2.45	2.55	2.47
	50°C	2.5	2.4	2.45	2.35	2.53	2.5	2.38	2.43	2.4	2.4	2.44	2.56	2.39
P_{MAX}	28°C	42.05	40.0	38.88	37.44	40.0	38.0	37.98	37.98	39.2	40.01	39.2	40.04	37.54
	50°C	37.5	36.72	34.79	33.84	36.69	34.25	33.32	34.99	35.76	34.56	35.87	36.86	33.94

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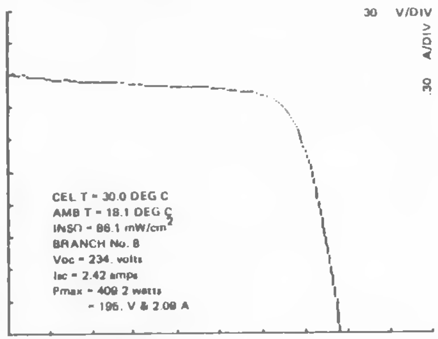
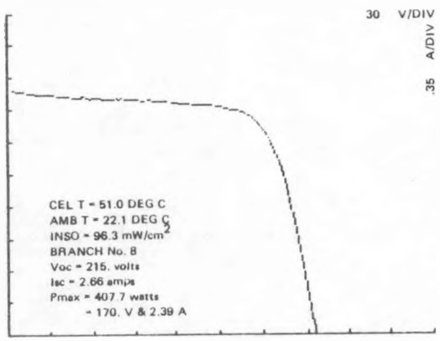
SERIES STRING/ROW #8



ROW #8



PARAMETER		1	2	3	4	5	6	7	8	9	10	11	12	13
MODULE SERIAL NUMBER		4158	4169	4170	4163	4164	4143	4132	4180	4155	4148	4134	4110	4119
V_{OC}	28°C	19.0	19.0	18.9	18.7	19.2	19.0	19.2	19.0	19.0	18.9	19.3	19.4	19.2
	50°C	17.4	17.4	18.3	17.0	17.5	17.3	17.5	17.4	17.3	17.3	17.5	17.4	17.0
I_{SC}	28°C	2.74	2.7	2.71	2.65	2.65	2.6	2.8	2.68	2.65	2.7	2.71	2.92	2.82
	50°C	2.73	2.73	2.72	2.67	2.65	2.63	2.81	2.7	2.66	2.69	2.66	2.81	2.75
$I_{(14v)}$	28°C	2.5	2.443	2.311	2.384	2.393	2.38	2.446	2.437	2.454	2.34	2.42	2.536	2.51
	50°C	2.55	2.5	2.4	2.42	2.45	2.42	2.52	2.48	2.5	2.38	2.45	2.48	2.47
$P_{(14v)}$	28°C	39.5	38.59	36.5	37.67	37.8	37.63	38.64	38.51	38.77	36.97	38.25	40.06	39.58
	50°C	35.7	35.0	33.6	33.88	34.3	33.88	35.28	34.72	35.0	33.32	34.3	34.72	34.58
V_{MAX}	28°C	15.6	16.0	16.3	15.6	16.0	16.0	15.3	16.0	16.0	16.1	16.2	15.5	15.3
	50°C	14.4	14.3	16.2	14.4	14.6	14.4	13.9	14.3	14.3	14.4	14.4	14.0	14.3
I_{MAX}	28°C	2.53	2.45	2.29	2.44	2.4	2.38	2.57	2.45	2.45	2.34	2.42	2.6	2.6
	50°C	2.53	2.49	2.25	2.4	2.4	2.42	2.57	2.48	2.47	2.38	2.45	2.5	2.45
P_{MAX}	28°C	39.47	39.2	37.33	38.06	38.4	38.08	39.32	39.2	39.2	37.67	39.20	40.3	39.78
	50°C	36.43	35.61	36.45	34.56	35.04	34.85	35.72	35.46	35.32	34.27	35.28	35.0	35.04

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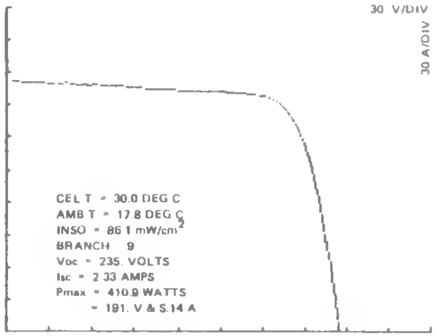
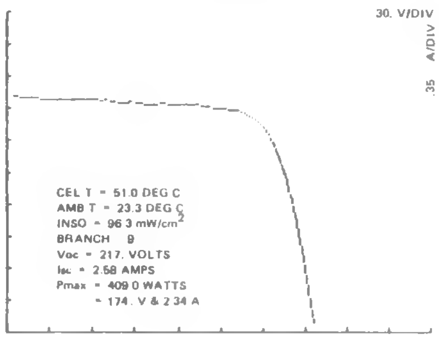
SERIES STRING/ROW #9



ROW #9



PARAMETER		1	2	3	4	5	6	7	8	9	10	11	12	13
MODULE SERIAL NUMBER		4161	4160	4153	4157	4150	4154	4151	4162	4159	4172	4149	4167	4181
V_{OC}	28°C	19.0	19.0	19.2	19.0	18.8	19.0	18.9	18.7	18.7	19.0	18.8	19.0	19.2
	50°C	17.3	17.3	17.5	17.5	17.1	17.5	17.3	17.3	17.1	17.3	17.3	17.4	17.5
I_{SC}	28°C	2.66	2.65	2.71	2.63	2.72	2.7	2.7	2.65	2.65	2.75	2.64	2.6	2.75
	50°C	2.68	2.67	2.73	2.64	2.72	2.7	2.68	2.67	2.66	2.77	2.7	2.6	2.73
$I_{(14v)}$	28°C	2.418	2.428	2.528	2.378	2.45	2.495	2.39	2.383	2.411	2.487	2.385	2.35	2.348
	50°C	2.48	2.48	2.58	2.43	2.5	2.54	2.48	2.42	2.45	2.54	2.5	2.4	2.45
$P_{(14v)}$	28°C	38.20	38.36	39.94	37.57	38.71	39.42	37.76	37.65	38.09	39.3	37.68	37.18	37.1
	50°C	34.72	34.72	36.12	34.02	35.0	35.56	34.72	33.88	34.3	35.56	35.0	33.6	34.3
V_{MAX}	28°C	16.0	15.9	16.3	15.9	15.6	16.2	16.0	16.1	16.0	15.7	16.0	16.1	15.1
	50°C	14.2	14.3	14.5	14.4	14.3	14.4	14.4	14.5	14.2	14.4	14.3	14.5	13.1
I_{MAX}	28°C	2.44	2.45	2.53	2.4	2.47	2.47	2.4	2.37	2.4	2.5	2.4	2.39	2.53
	50°C	2.49	2.47	2.55	2.42	2.49	2.53	2.45	2.4	2.45	2.5	2.48	2.37	2.55
P_{MAX}	28°C	39.04	38.96	41.24	38.16	38.53	40.01	38.4	38.16	38.4	39.25	38.4	38.48	38.20
	50°C	35.36	35.32	36.98	34.85	35.61	36.43	35.28	34.80	34.79	36.0	35.46	34.37	33.41

APPENDIX D
ARRAY INSTALLATION COST BREAKDOWN

PROTOTYPE PHOTOVOLTAIC BALANCE-OF-SYSTEM COST REPORTING FORMS

MILES C. RUSSELL

MIT LINCOLN LABORATORY
LEXINGTON, MA

20 OCTOBER 1980

SW RES Update
12 December 1980

1.0 Introduction

2.0 Array Installation

2.1 Mounting Category Standoff (integral, direct, standoff, rack)

2.2 Array Dimensions 15.57 ft. x 4 ft. per row, 9 rows

2.3 Panel* Dimension 14 in. x 48 in.

2.4 Materials List - Array Installation

ITEM		DESCRIPTION		QUANTITY	COST
2.4.1	Frame (Batten, Sleepers, etc.)	Unistrut P/N P200-HS	18' x 10' 6' x 20'	300'	$470
2.4.2	Gasket	None			
2.4.3	Sealer	None			
2.4.4	Fasteners (bolts, screws, clips, etc.)	Unistrut-studs Nuts & washers		500 500 ea.	$250 $126
2.4.5	Flashing	N/A			
2.4.6	Special Hardware	Maintenance Ladder Ladder Mounts			
2.4.7	Other	2 x 6 Stringers & Standoff Blocks			
2.4.8	Displaced Roofing Materials	None			

*Panel - A collection of modules preassembled, wired together and designed to be field installed as a unit.

2.5 Labor Array Installation

	Task Description	Labor	Cost
2.5.1	Stringers & Blocks (painting, mounting & bolting)	16 man-hours	
2.5.2	Unistrut mounting	8 man-hours	
2.5.3	Module mounting and wiring	(Labor) 22 man-hours (Supervision) 6 man-hours	

(All labor hours are general construction laborer)

3.0 Array Wiring

3.1 Total number of modules wired 117. On-site 12 hours Cover on each J-box (modules) 234
In-house 40 hours

3.2 Array Electrical Configuration
Number of modules in series/parallel $\frac{\text{13 modules in series (1 row)}}{\text{9 rows in parallel}}$

3.3 Array nominal operating voltage and range 205V at 28°C (166V - 231V predicted in design)
160 - 240V range on inverter

3.4 Panel nominal voltage at max power observed 170 volts at $T^{cell} = 51^{o}C$
$T^{amb} = 23^{o}C$

3.4 Materials List - Array Wiring

ITEM		DESCRIPTION	QUANTITY	COST
3.4.1	Wire	a) Alpha Hook-up Wire 14 AWG	400'	$40.00 Total
		b) TW 14 AWG Building Wire	900'	9.00 Total
		c) TW 12 AWG Building Wire	50'	5.00 Total
		d) TW 10 AWG Building Wire	50'	5.00 Total
3.4.2	Junction Boxes	Row J-Boxes	9	7.00 Total
3.4.3	Quick Connectors	Amphenol 44 Series	130 set	200.00 Total
3.4.4	Diodes (External to module)	Motorola IN4725 or IN5003 or MR510 or IN540B	9	2.20 Each
3.4.5	Varistors	GE - P/N V320HE300	2	70.00 Total
3.4.6	Conduit	1/2" Diameter EMT thinwall conduit	41'	
		3/4" Diameter EMT thinwall conduit	40'	100.00 Total
		1" Diameter EMT thinwall conduit	30'	
3.4.7	Instrumentation	Maintenance and Safety Enclosures	1	350.00 Total
3.4.8	Other	Safety Lamps	2	50.00 Total

3.5 Labor - Array Wiring

Task Description		Labor	Cost
Safety and maintenance enclosure	In-house	44 hours	
	On-site	8 hours	
Safety Lamps		1 hour	
Conduit and J-Box		16 hours	

4.0 Power Conditioner Installation and Wiring

4.1 Power Conditioner Size and Weight
Dimensions: 24 in. width 48 in. height 24 in. depth weight: 175 lbs.

4.2 Power conditioner nominal peak rated capacity ___6___ kVA.

4.3 Isolation transformer required/included Yes ____ No __X__
If yes, transformer dimensions: ______ in width ______ in height ______ in depth
Weight: ________ lbs.

4.4 Materials List - Power Conditioner Installation and Wiring

ITEM		DESCRIPTION	QUANTITY	COST
4.4.1	Mounting Hardware	None		
4.4.2	Wire	TW, 12 AWG Building Wire	25'	2.50 Total
		TW, 6 AWG Building Wire	25'	2.50 Total
4.4.3	Conduit	Fix Conduit 1/2" Diameter	14'	25.00 Total
		1" Diameter	14'	
4.4.4	Junction Boxes	3" x 4" x 2"	1	7.00 Total
4.4.5	Other	None		

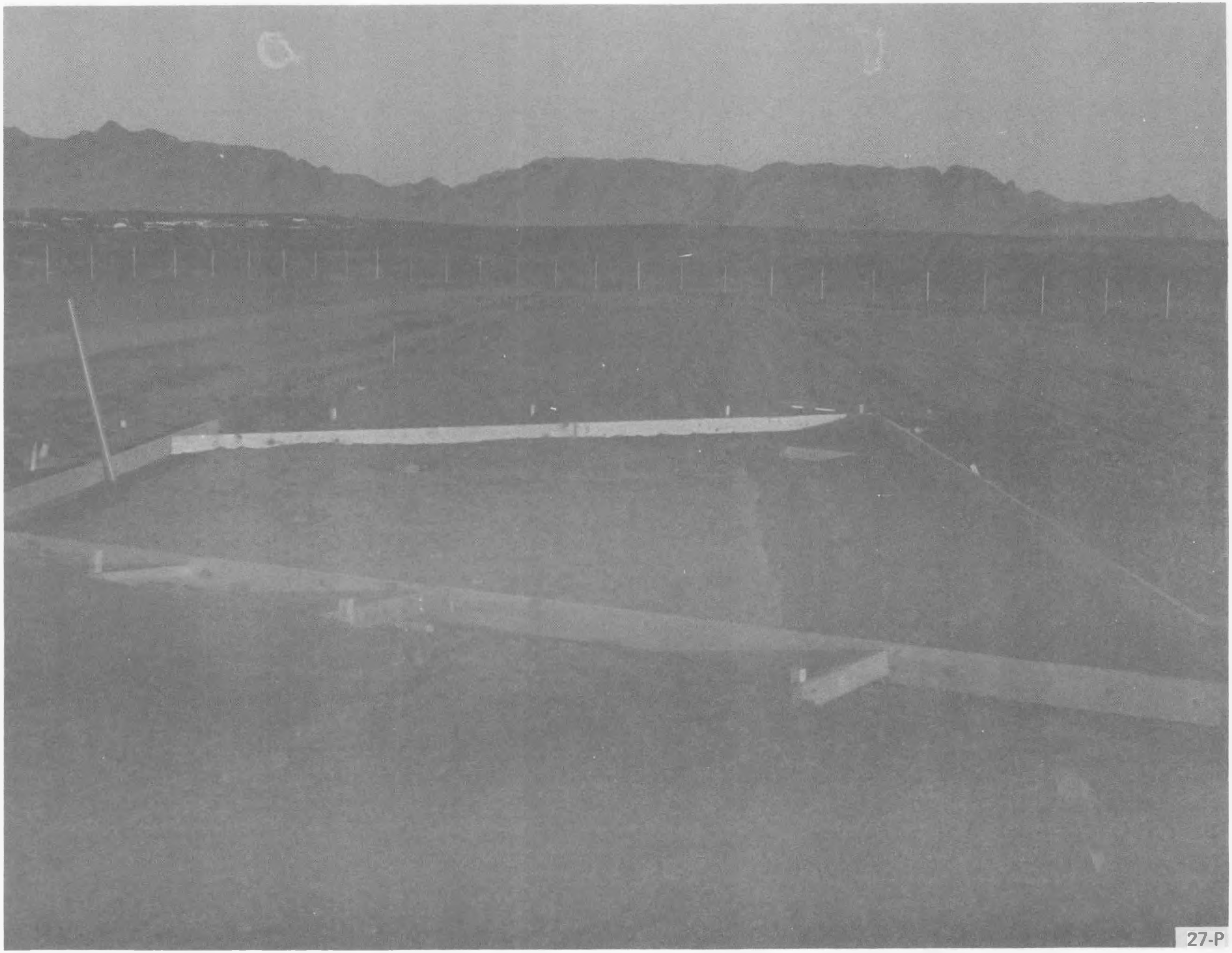
4.5 Labor - Power Conditioner Installation and Wiring

ITEM		DESCRIPTION	LABOR	COST
4.5.1	Mounting	DC to AC Inv	6 hours	
4.5.2	Wiring	Inv	3 hours	

APPENDIX E
CONSTRUCTION PHOTOGRAPHS

E-2


28-P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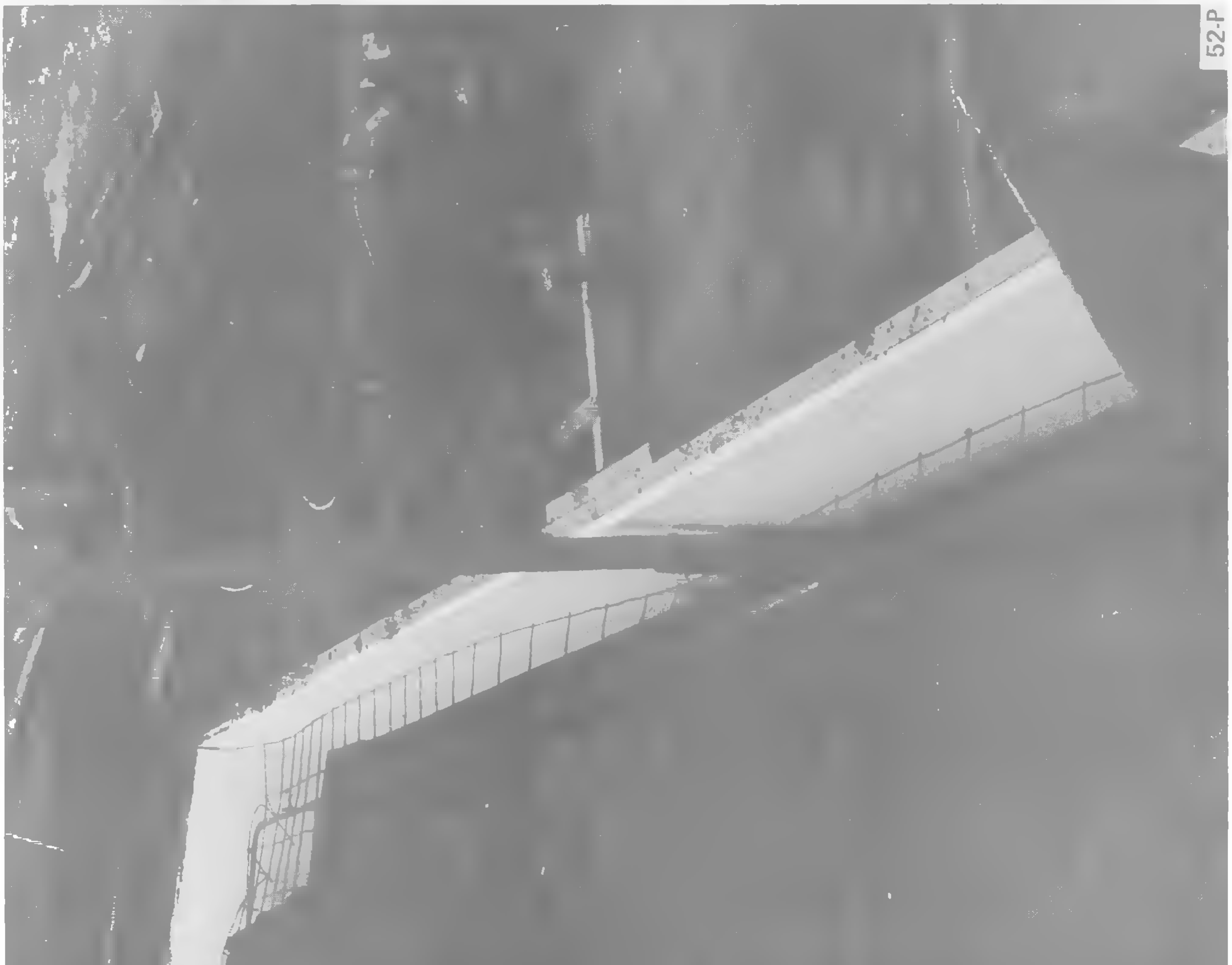
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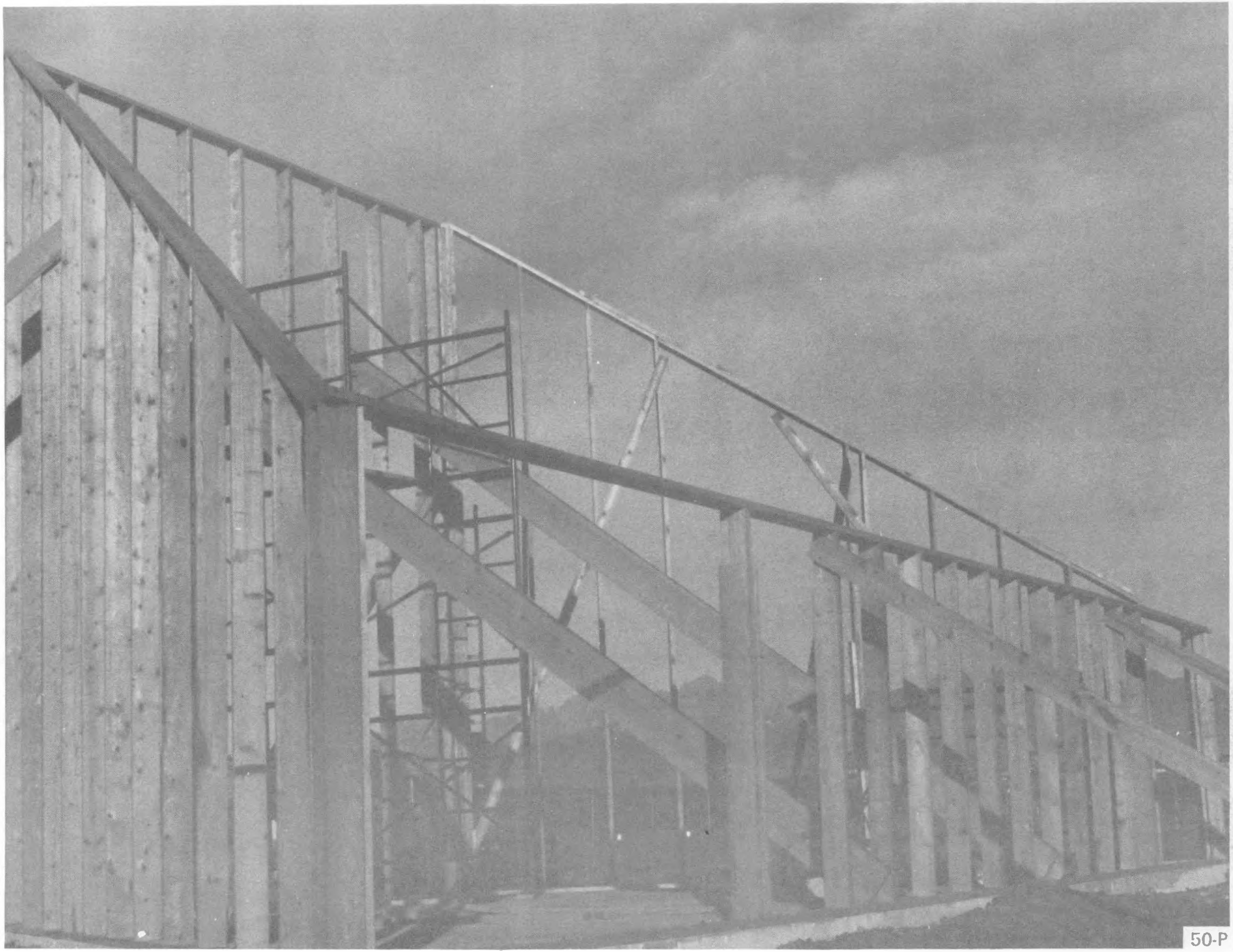
51-P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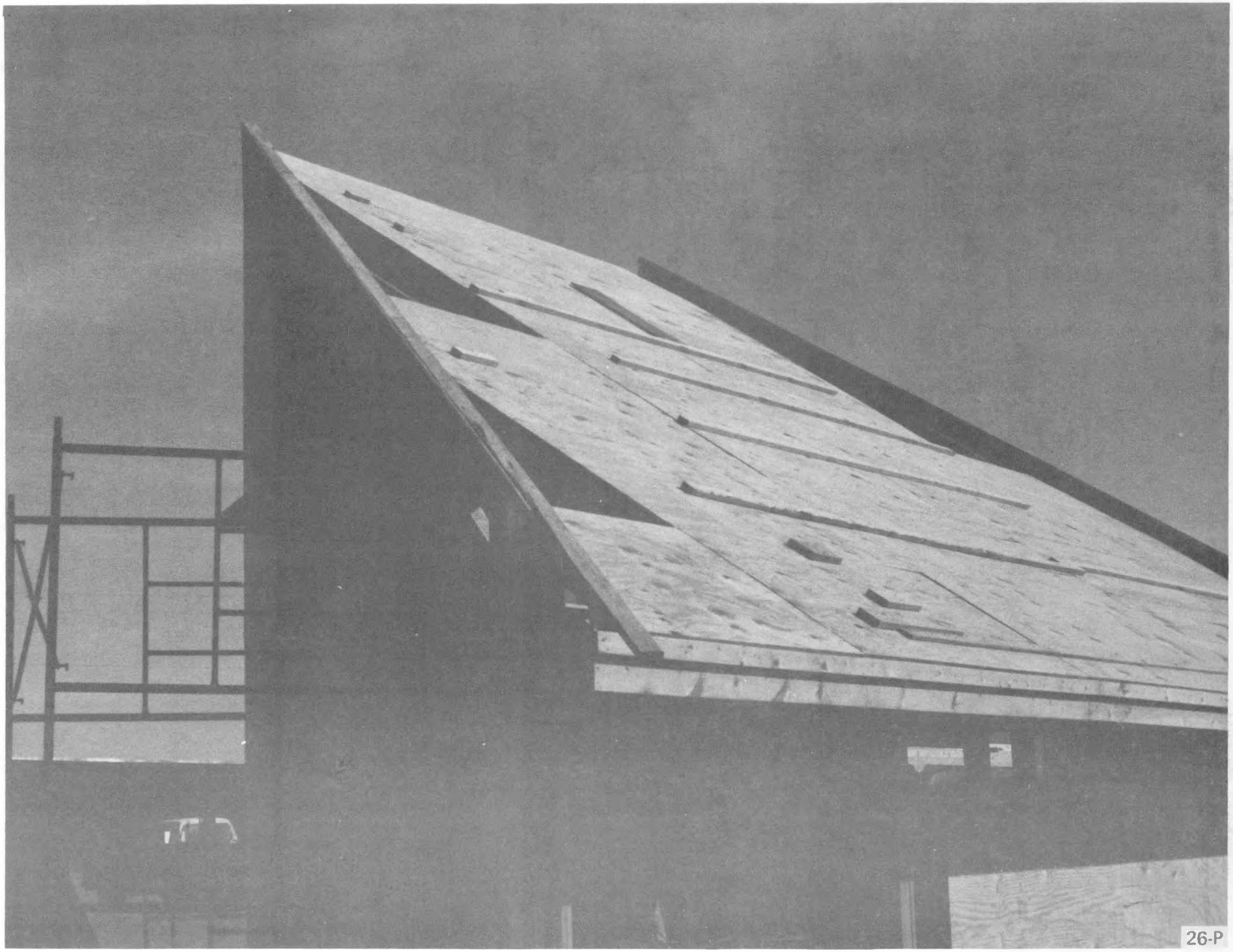
49-P


47-P


48-P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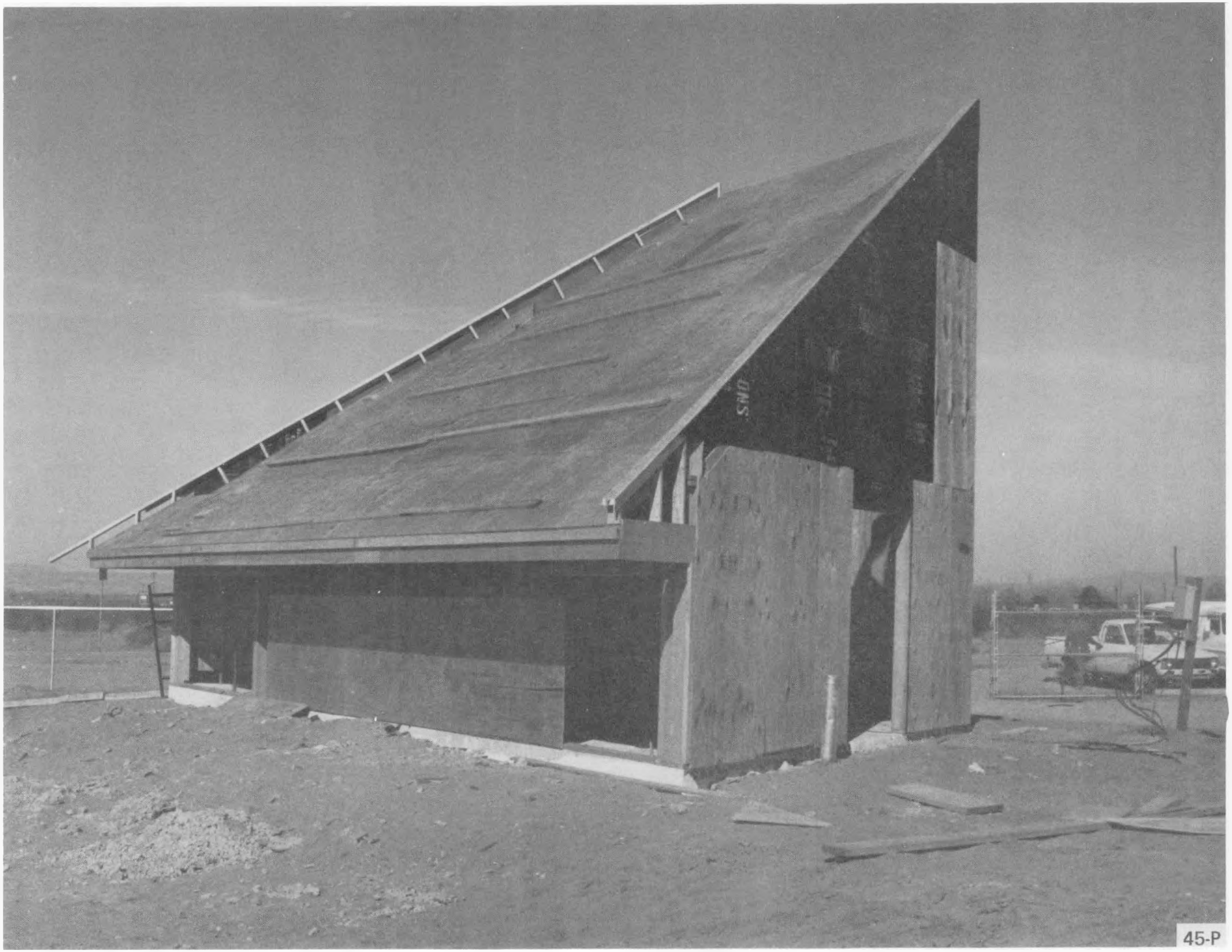
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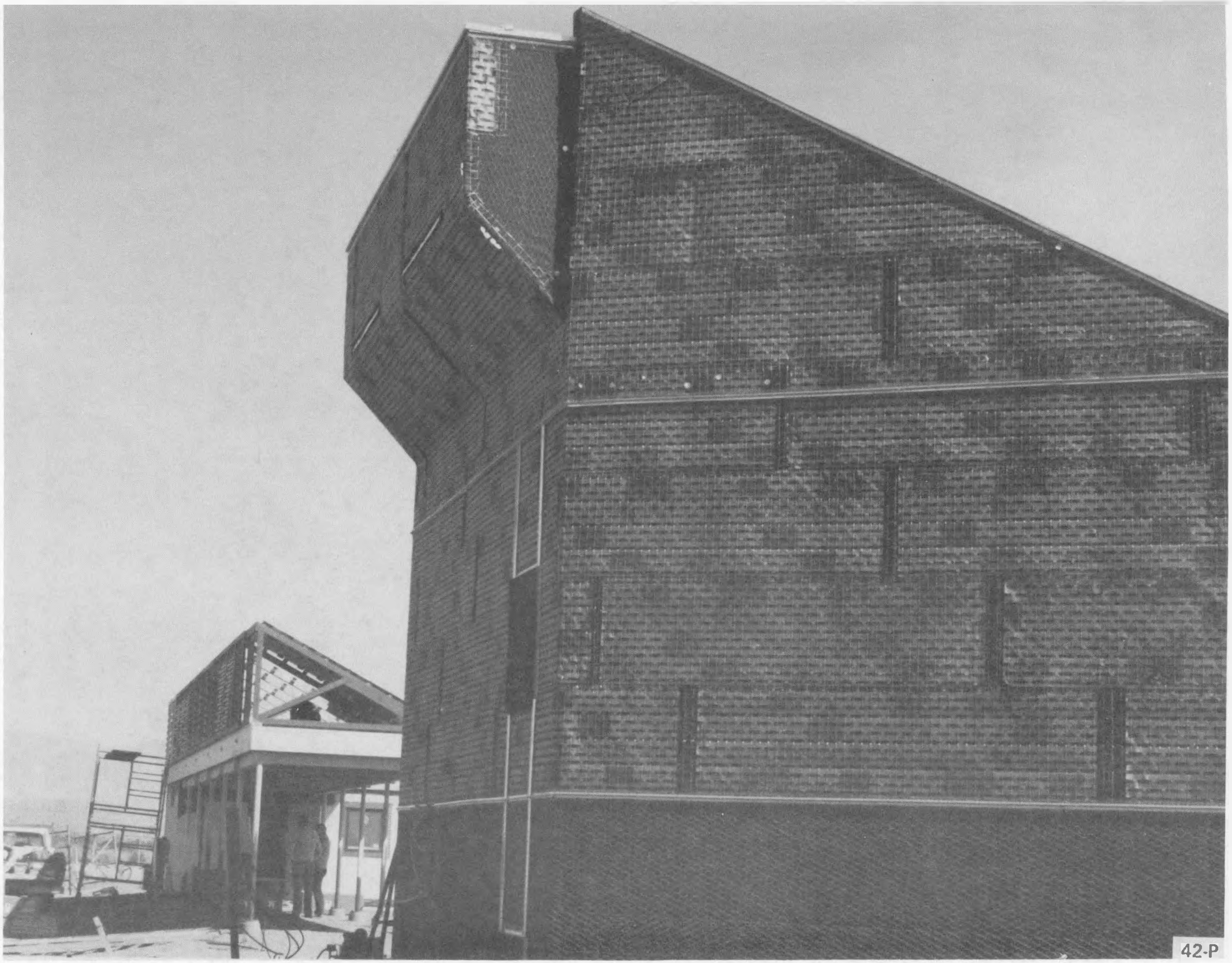
46-P



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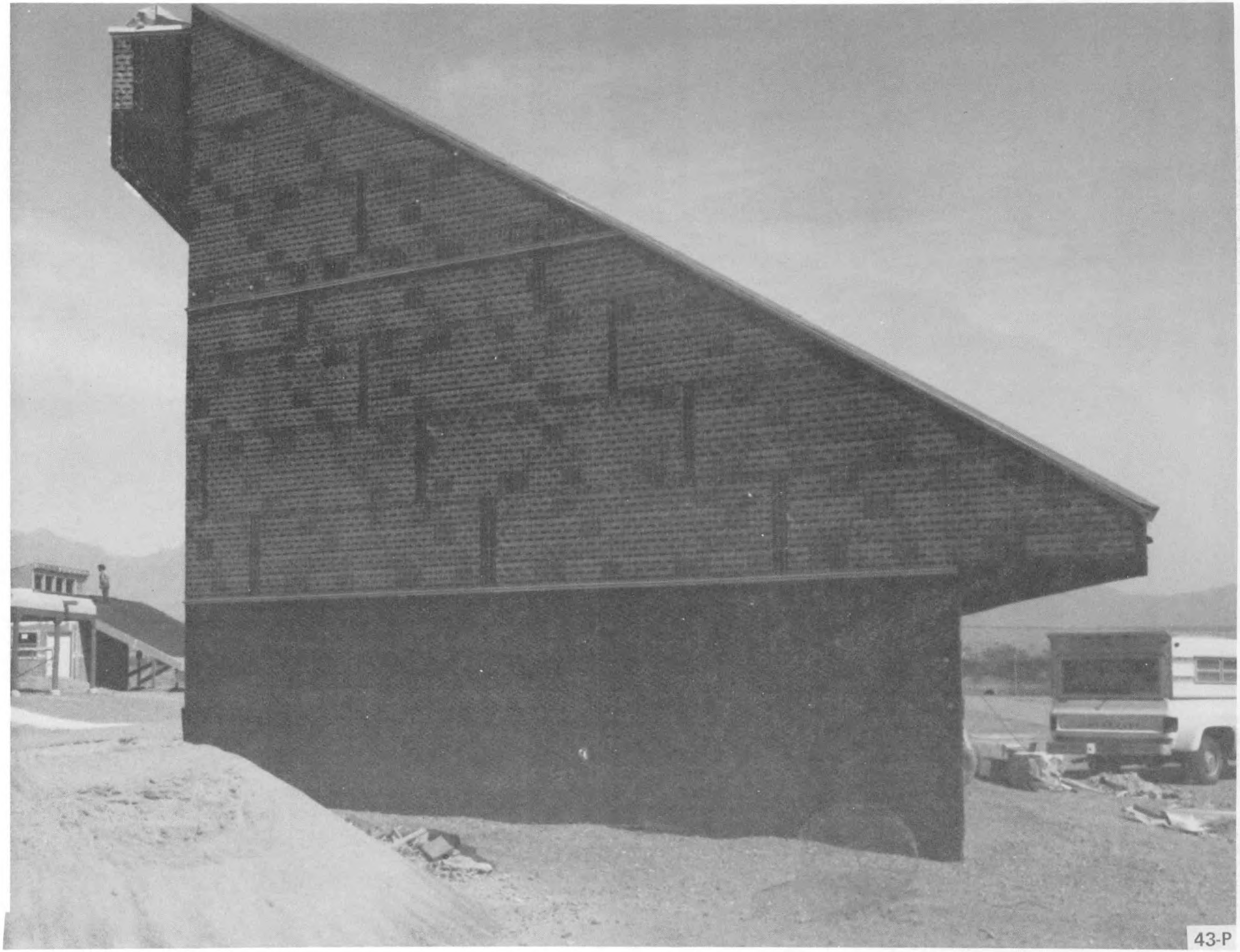
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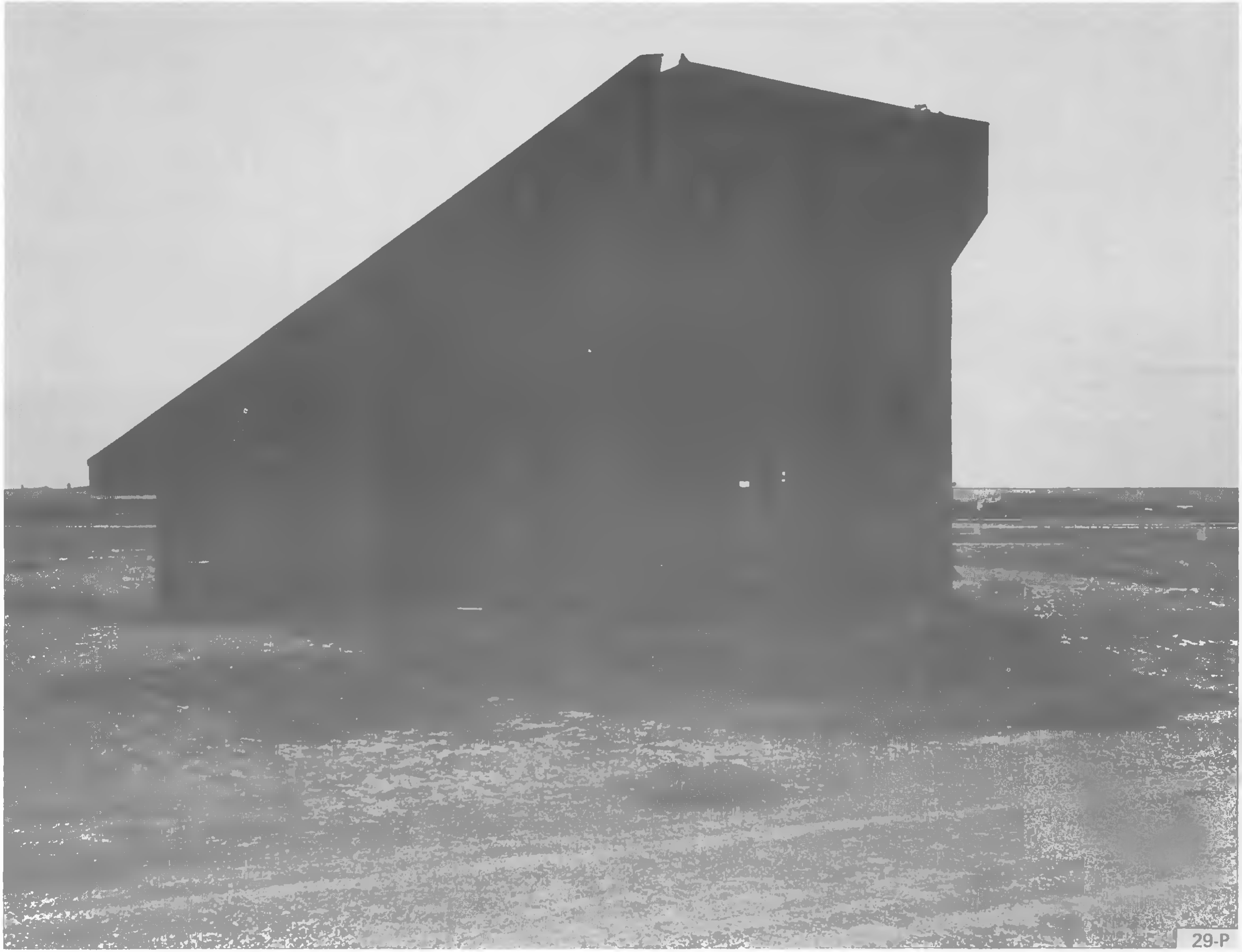
44-P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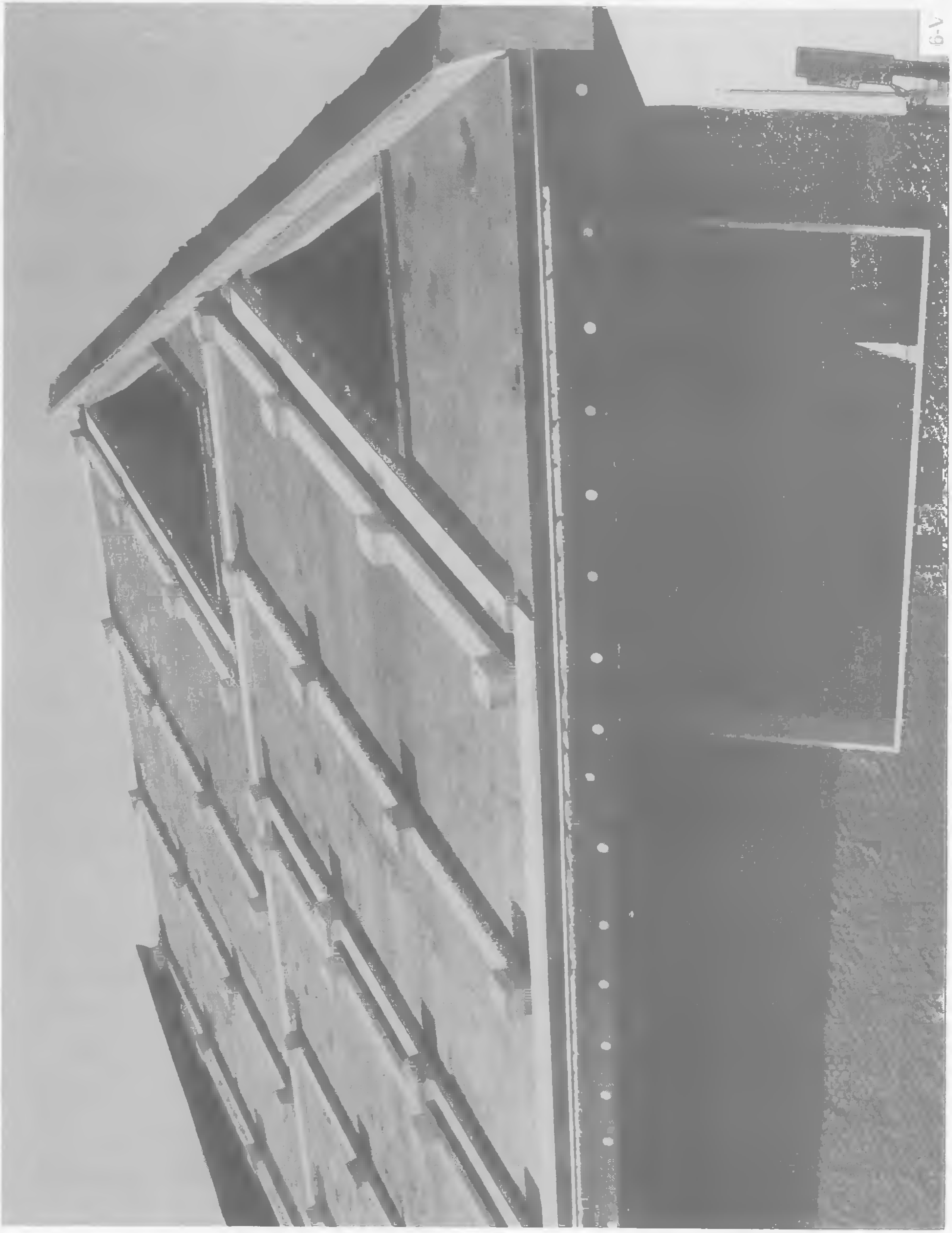
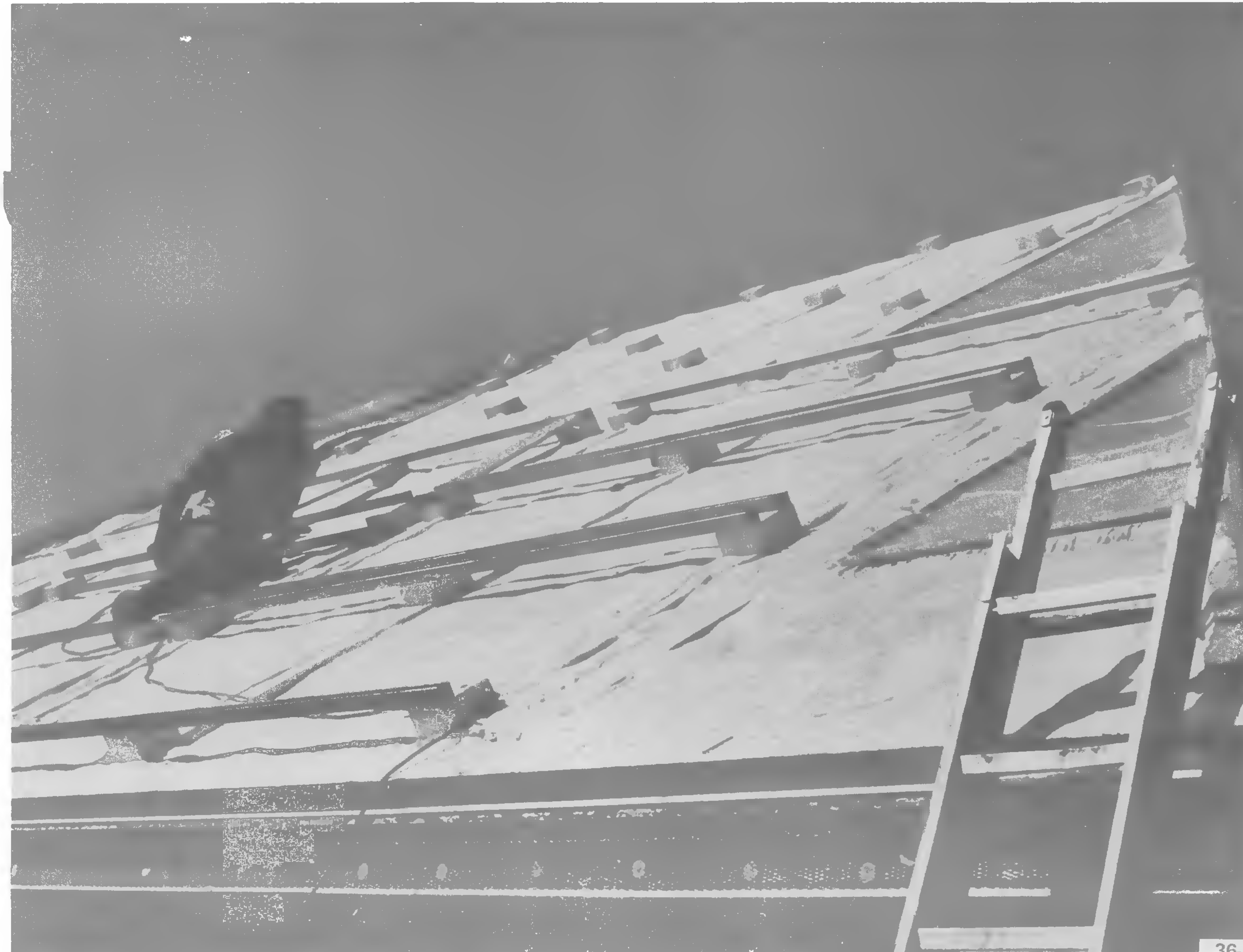
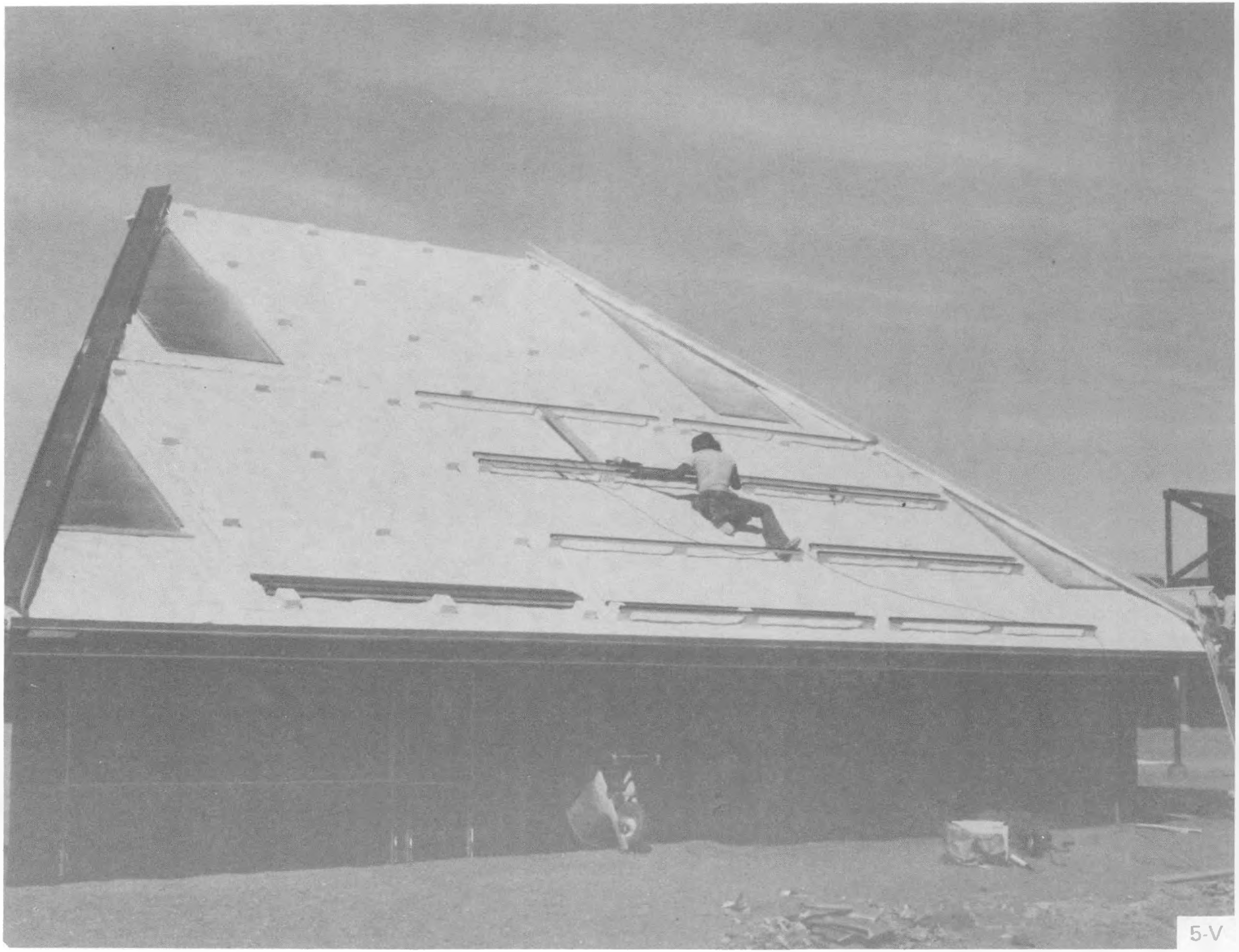



36-P


37-P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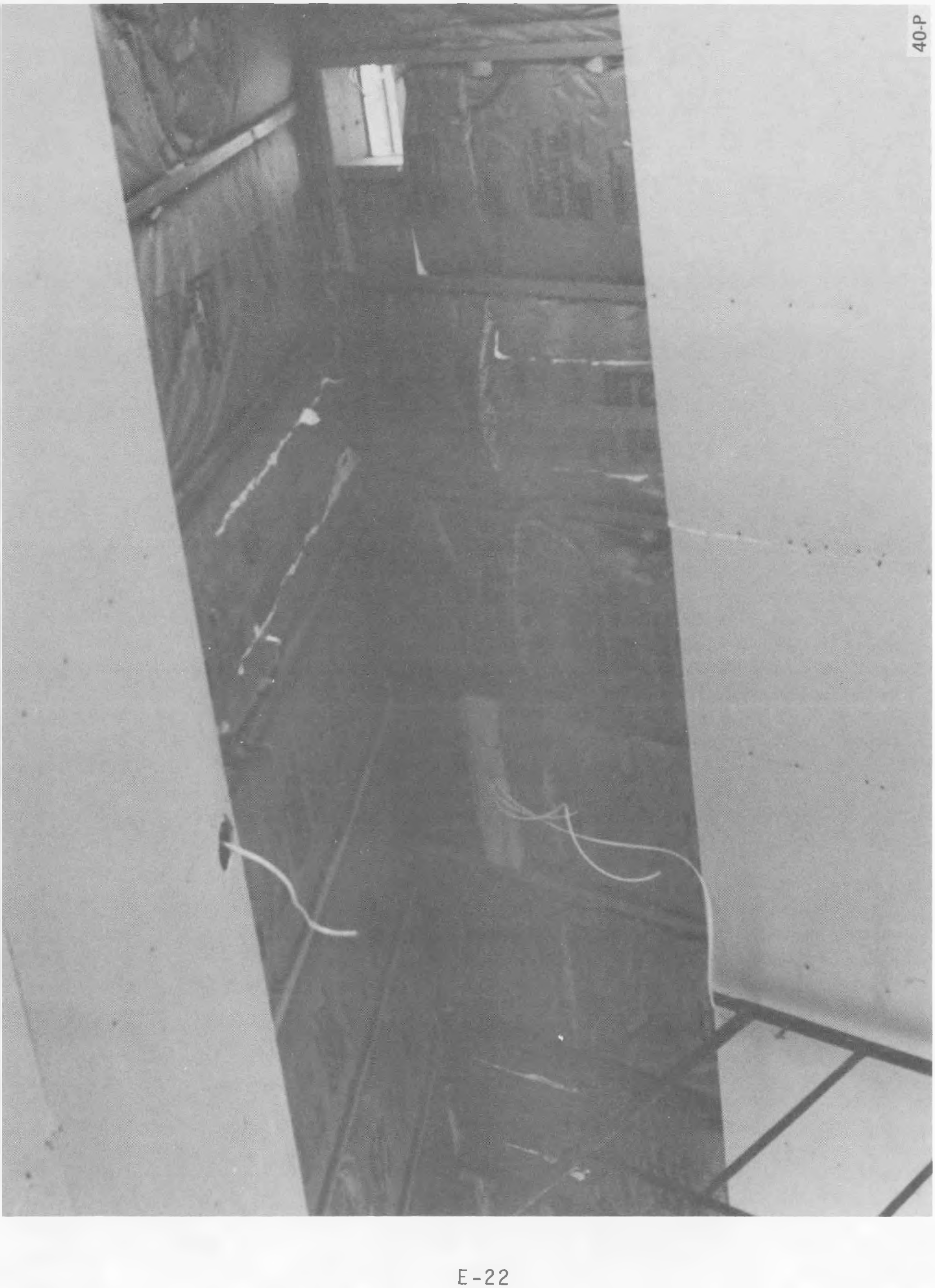
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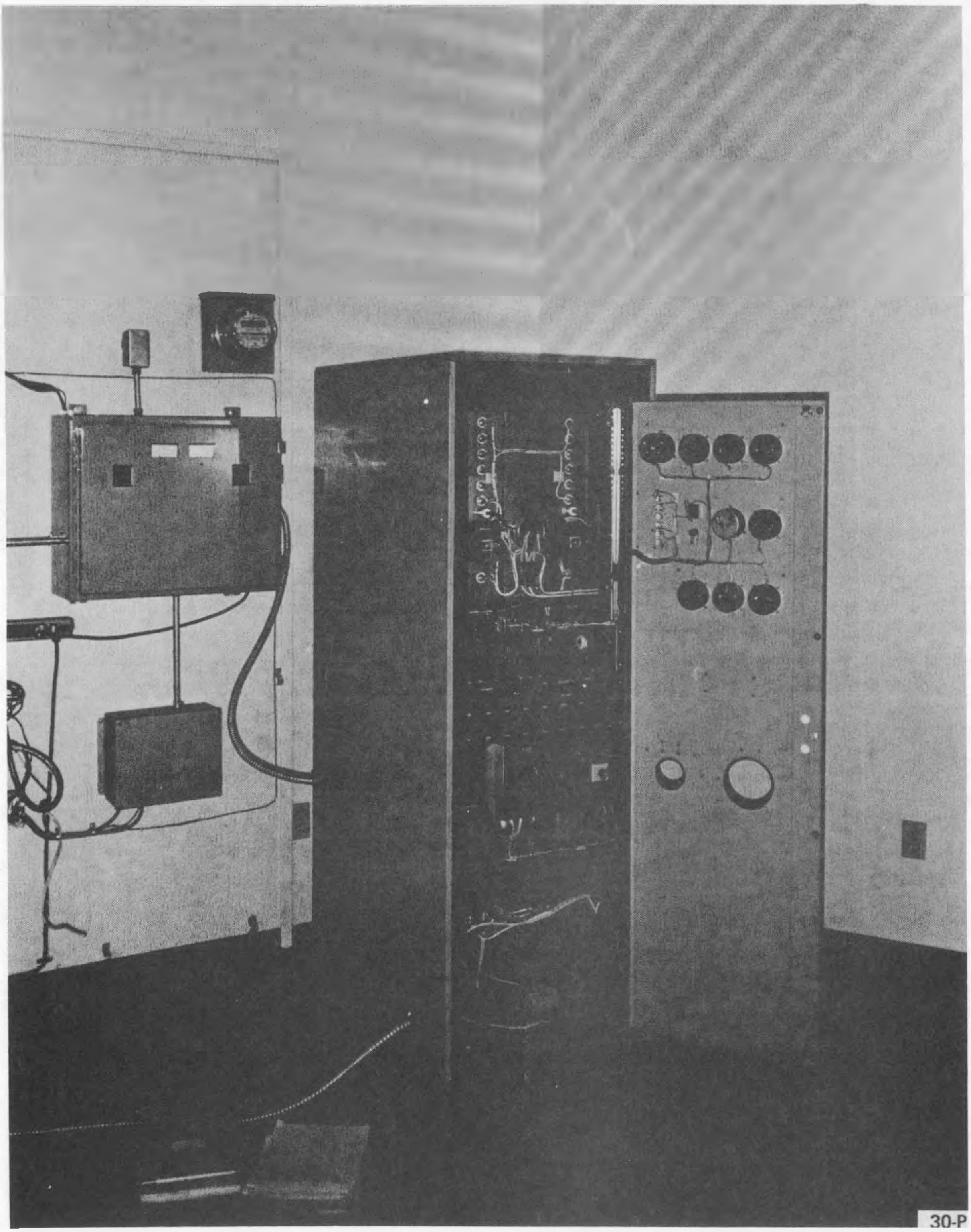
41-P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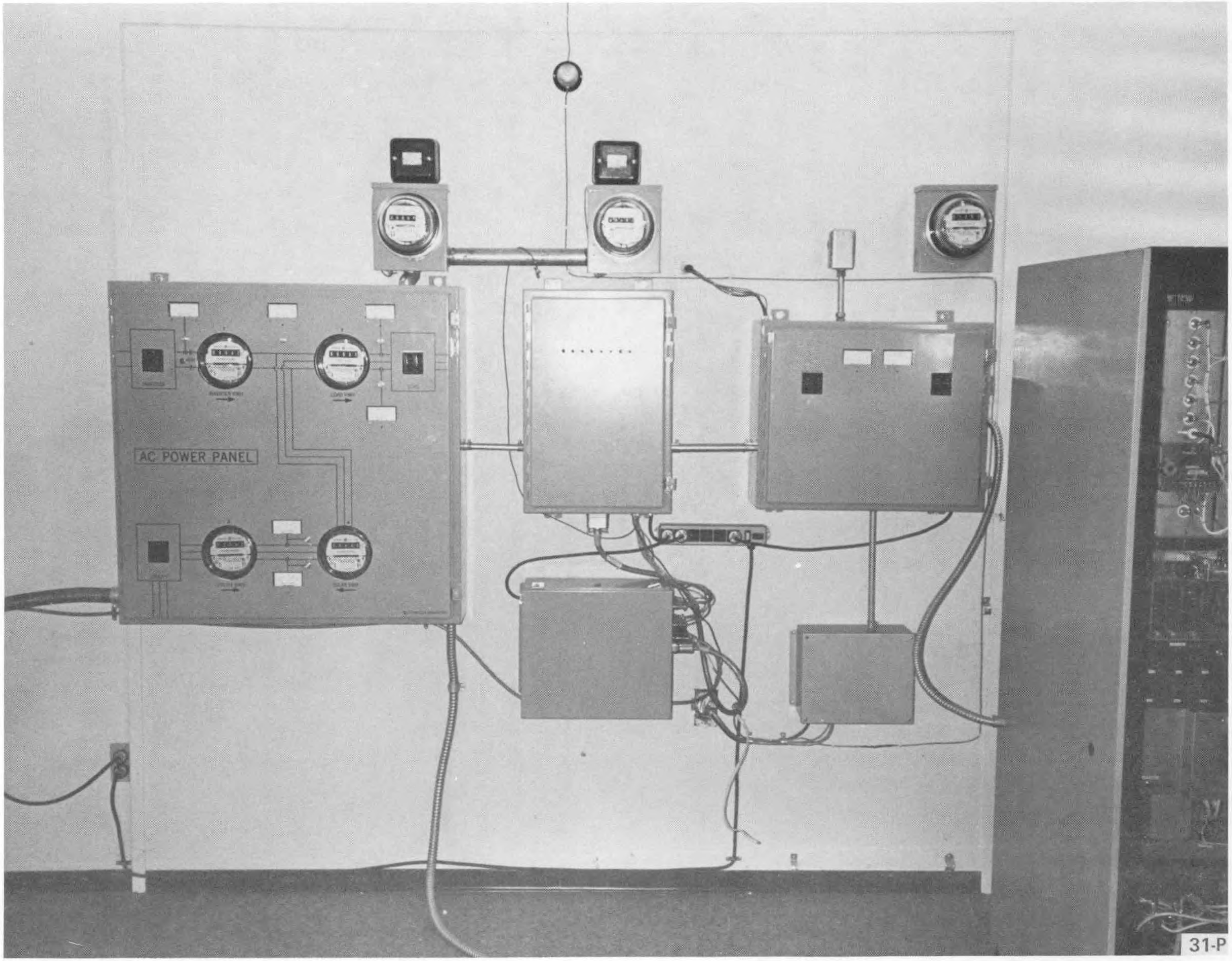
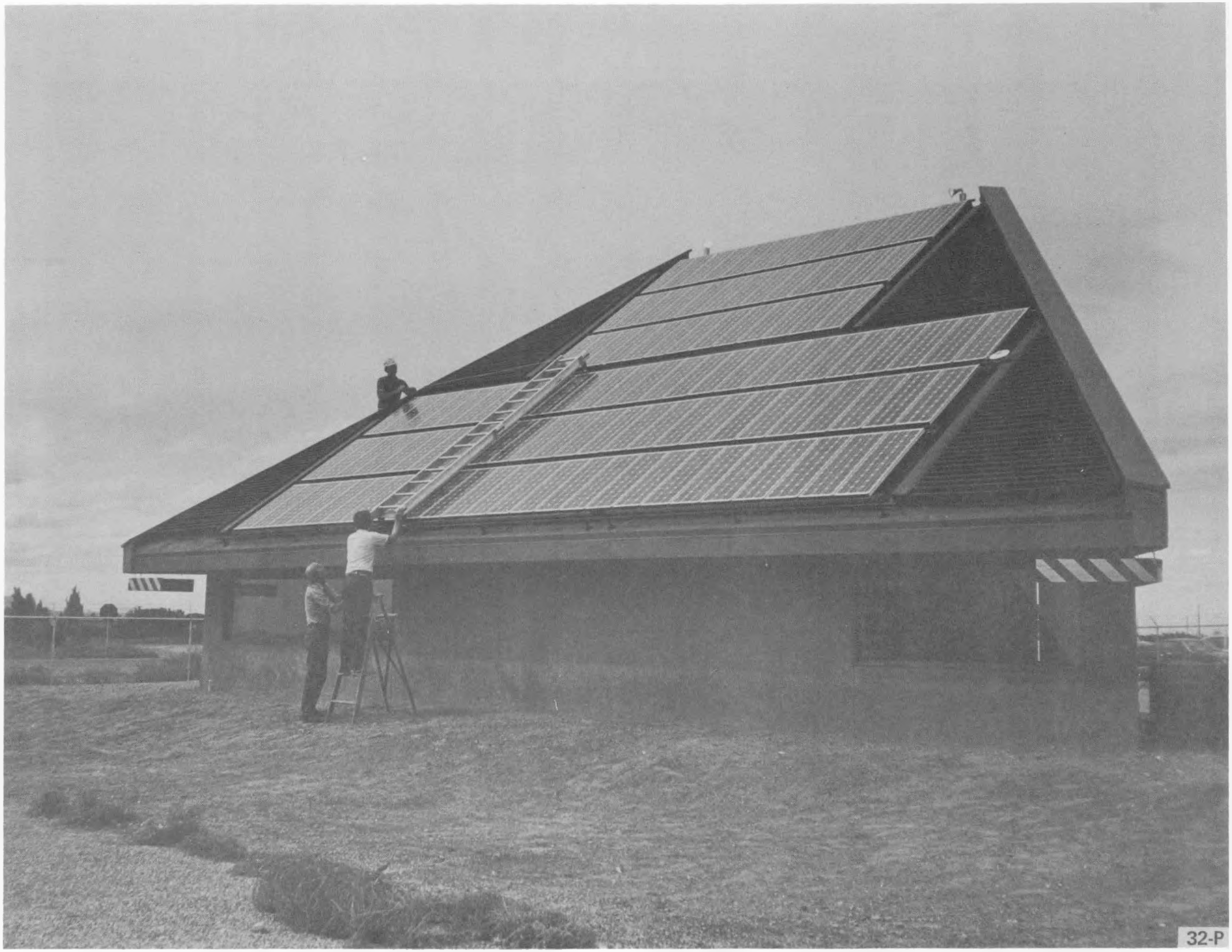

AC POWER PANEL
31-P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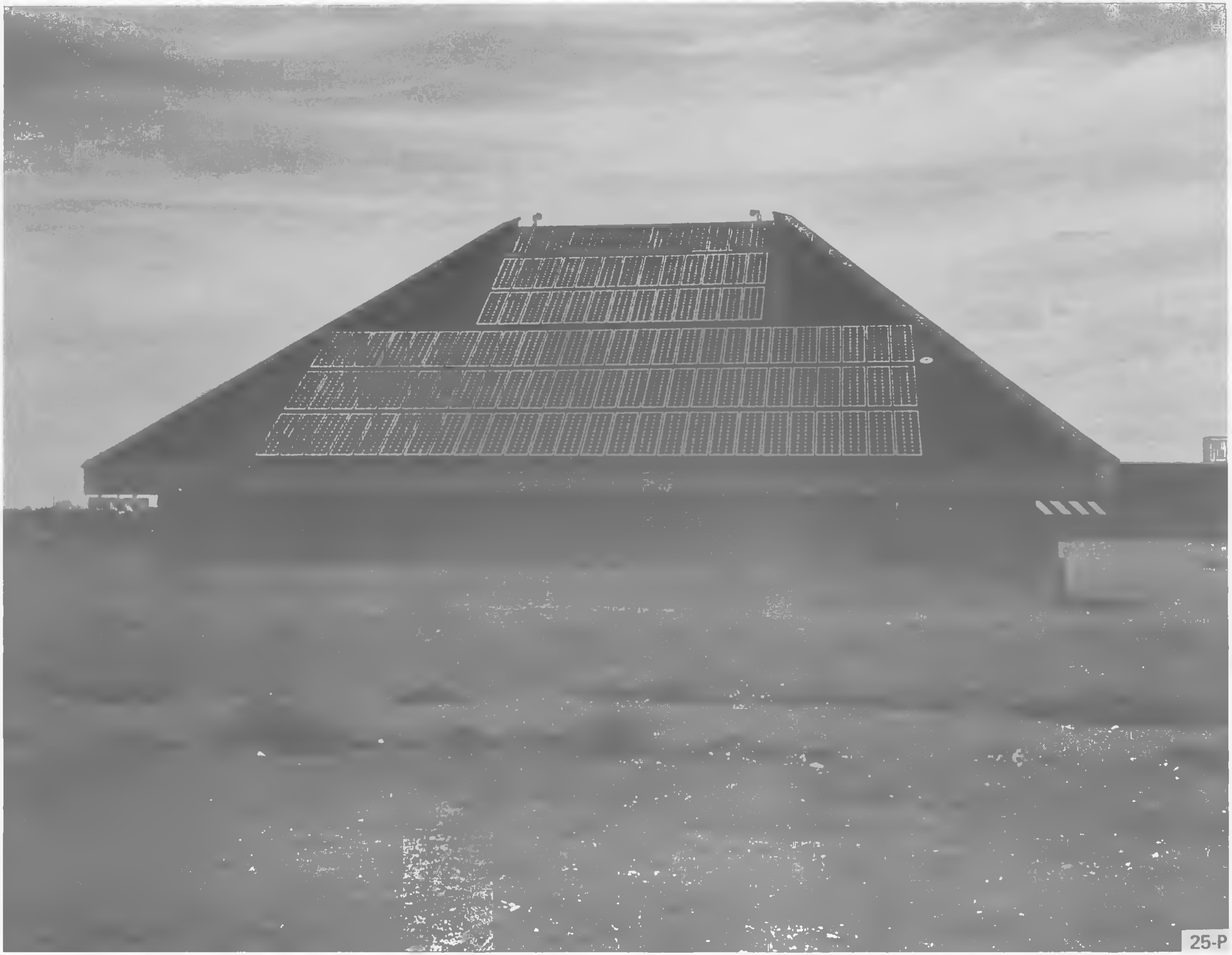
24-P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33-P


34-P


35-P