I-2098

DOE/ET/20279-175

DESIGN AND FABRICATION OF PROTOTYPE SYSTEMS FOR PHOTOVOLTAIC RESIDENCES IN THE NORTHEAST

FINAL REPORT

November 1981

E.M. Mehalick

Advanced Energy Programs Department
Energy Systems Technology Division
General Electric
King of Prussia, PA 19406

Under Purchase Order No. BX-566 between
General Electric Co. and M.I.T. Lincoln Laboratory

Massachusetts Institute of Technology
Lincoln Laboratory
Lexington, Massachusetts 02173

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

Additional copies available from the National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia 22161.

Price: Paper Copy $11.00
Microfiche $ 3.00

DOE/ET/20279--175

DE82 009179

DOE/ET/20279-175

Distribution Category UC 63a-e

DESIGN AND FABRICATION OF PROTOTYPE SYSTEMS FOR PHOTOVOLTAIC RESIDENCES IN THE NORTHEAST

FINAL REPORT

DOE/ET/20279--175

DE82 009179

November 1981

E.M. Mehalick

Advanced Energy Programs Department
Energy Systems Technology Division
General Electric
King of Prussia, PA 19406

Under Purchase Order No. BX-566 between
General Electric Co. and M.I.T. Lincoln Laboratory

Massachusetts Institute of Technology
Lincoln Laboratory
Lexington, Massachusetts 02173

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

ABSTRACT

A photovoltaic (PV) system has been designed and integrated into a residential home suitable for the Northeast region of the country. This report describes the house design and the PV system design which incorporates a unique PV shingle module developed by General Electric Company. The system has been installed and is currently being tested by MIT/Lincoln Laboratory on a prototype structure at the Northeast Residential Experiment Station in Concord, Massachusetts.

The PV system is grid-connected and is designed to meet both space conditioning requirements through a heat pump and all conventional electrical load requirements for an all-electric residence. The PV system consists of two major subsystems, the solar array and the power conversion subsystem. A 6.7-kW-peak power rating (100 mW/cm^2, 25°C Cell temperature) photovoltaic array has been designed for the house. The 73.3 m^2 of exposed solar array module area uses 375 direct-mounted shingle modules in a 25 series by 15 parallel network. The PV generated power is supplied to an Abacus 6-kW-output-rated dual-bridge inverter, which is controlled to track the solar-array maximum-power operating point. The inverter feeds the 240-VAC output power directly to the house loads or back to the utility when excess is generated. The DC power is isolated from the utility by a transformer. The system operation is automatic and the output is synchronized with the utility. The system automatically shuts down with loss of utility. The overall system is connected in parallel with the utility service to supply the residential load.

The installation of the modules was completed as planned by a local contractor without any problems. No module damage occurred during installation or in shipping and the measured array output was slightly above predictions. The installation was considered a complete success.

ACKNOWLEDGEMENTS

The residential photovoltaic (PV) system design described in this report is a result of contributions of several individuals from different organizations. The basic system design evolved from several previous studies performed by the General Electric Company for Sandia National Laboratories. The team formed for this project was led by the Advanced Energy Programs Department (AEPD) of the General Electric Company. AEPD had responsibility for the PV system design, the module fabrication, and program management. Massdesign Architects and Planners, Inc., of Cambridge, Massachusetts designed the residence and prototype structure. Johnson and Stover, Inc., of Middleborough, Massachusetts developed the electrical system design drawings and specifications. The electrical system was installed by Interstate Electrical Services of Burlington, Massachusetts.

Mr. E. Mehalick of General Electric served as the Program Manager. The GE team included: Mr. N. Shepard who designed the PV shingle module; Mr. G. O'Brien who led the overall system design; Mr. J. Parker who calculated the system performance; and Mr. C. Romig and Mr. R. Collingwood who were responsible for system installation and checkout. In addition, the GE module manufacturing team was led by Mr. J. Wright.

Mr. G. Tully was the principal contributor from Massdesign and Mr. J. Johnson was the individual contributor from Johnson and Stover.

The following MIT Lincoln Laboratory personnel also provided a smooth program interface and program support: Mr. M. Russell, Mr. B. Nichols, Mr. R. Cadieux and Dr. S. Forman.

The program could not have been a success without each individual contribution.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont.)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont.)

LIST OF TABLES

SECTION 1
RESIDENCE DESIGN

A residence was developed by Massdesign to incorporate conventional energy conservation and passive solar features to reduce thermal loads. The house is designed for modular construction, to provide a more widespread application for eventual large-scale PV system implementation. Figure 1-1 shows a photograph of a model of the house. The house is a single-story structure with a gross area of 156.9 m^2 (1,688 ft^2) and a fully heated basement which can be finished for additional living space. The house can be sited to allow two fully exposed levels on the back. The plan includes three bedrooms, two baths, a kitchen/dining room, and a living room with a greenhouse with a separate two-car garage.

1.1 HOUSE DRAWINGS

The floor plan of the house is shown in Figure 1-2. The floor plan is worked out carefully to provide flexibility in placing furniture in a relatively small house

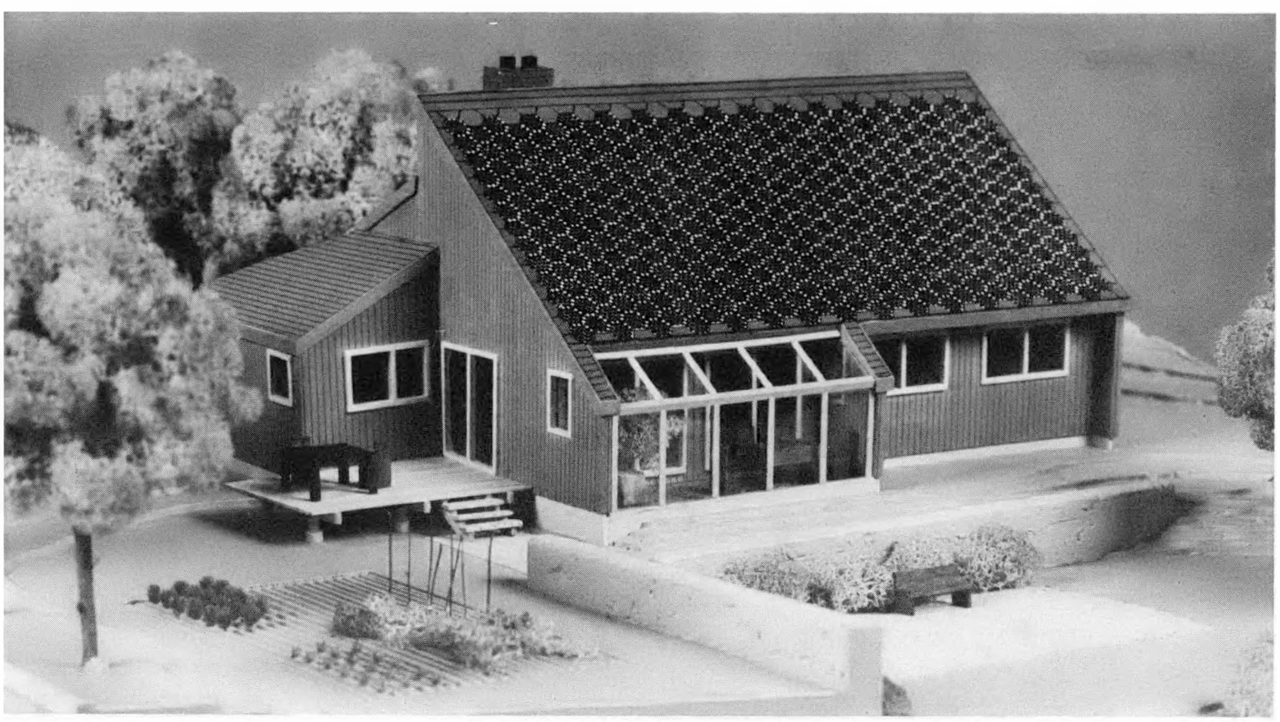


Figure 1-1. PV Residence Model

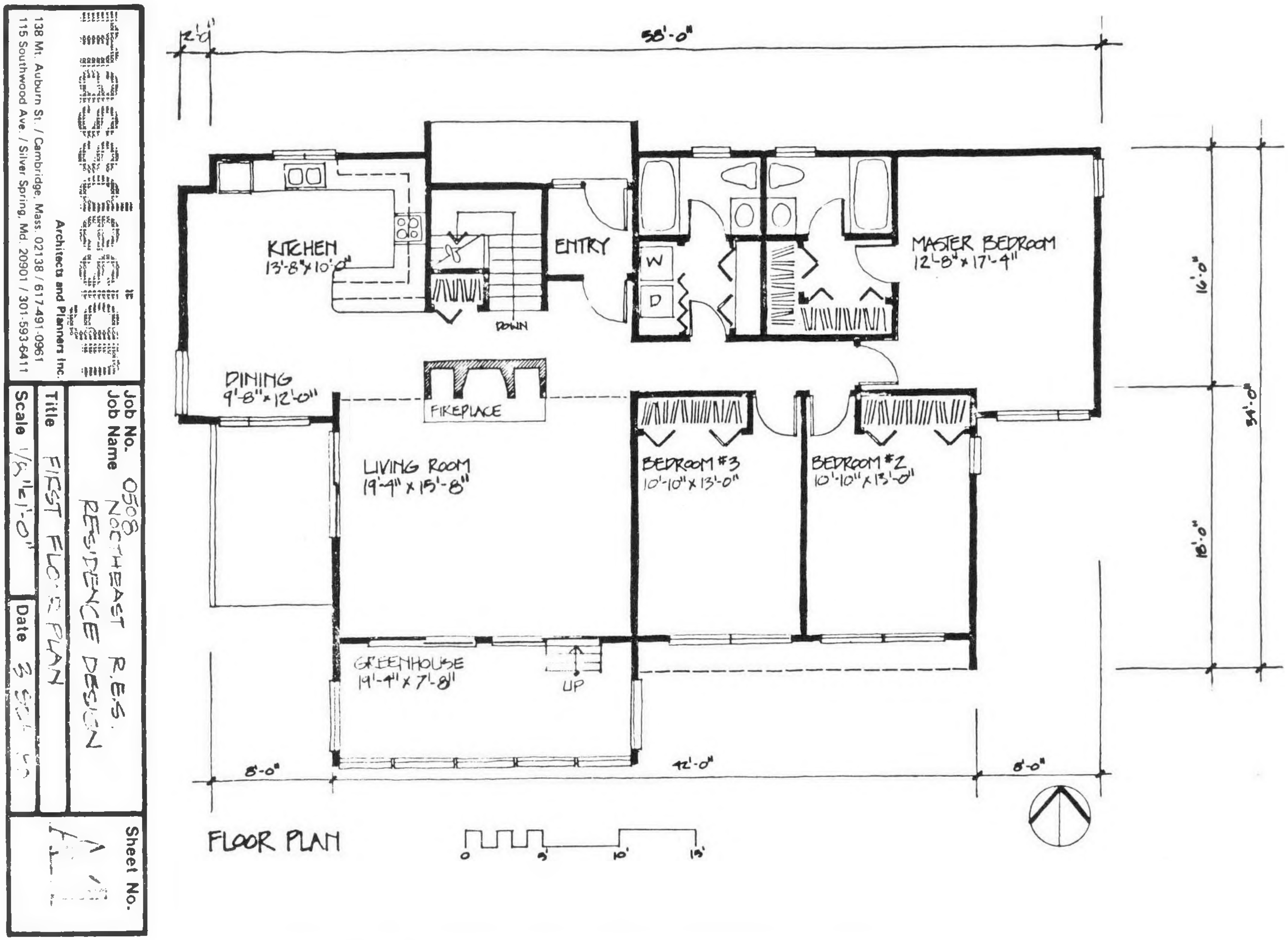


Figure 1-2. Floor Plan for the First Floor of the House

The master bedroom suite has a private bath and dressing room. In the living area, a small fireplace or wood stove vents to a chimney penetrating the north side of the roof to avoid shadowing the array. Its location at the center of the plan serves to focus activity around the warmth of the hearth.

The large PV roof corresponds to a cathedral ceiling inside, which covers the living room and the two smaller bedrooms. Each bedroom and the living room, have ventilating windows facing north. These windows have proved to be highly beneficial in the summer when used on other Massdesign houses, since the prevailing southerly winds induce air flow on warm evenings. South-facing clerestories do not function this way in the Boston area, because they face the cooling breezes.

The free-standing garage can be located to lead visitors toward the entrance, regardless of which side of the house faces the street. Also, the design can be adjusted to suit a modest slope in any direction, as opposed to a design which deliberately steps down to the south, thereby requiring a rare southsloping lot. The ability to use the design on nearly any lot is essential if the house is to be built on an easily accessible site in the Northeast, where lots with adequate unshaded solar gain are becoming more difficult to find.

Figure 1-3 shows the basement level floor plan which includes the equipment area.

The four elevations of the building are shown in Figure 1-4. The south elevation shows a continuous rectangular roof area facing south at an 8/12 pitch, totally unshaded to accommodate the photovoltaic array. The roof is 13.0 m (42.6 ft) in length and 6.8 m (22.4 ft) in slant height for a total available roof area of 88.6 m^2 (953 ft^2). The 8/12 pitch represents a compromise between the desire for snow to avalanche off the collector (which leans toward 10/12 and 12/12 pitches) and the desire for low tilt angles (which leans toward a 6/12 pitch) to maximize yearly energy gain. Because of the slippery glass surface of the array, and the total lack of small obstructions to snow sliding, the 8/12 (34^{o}) pitch is satisfactory. 8/12 is one of a number of standard roof pitches used in the area and is available in most building systems.

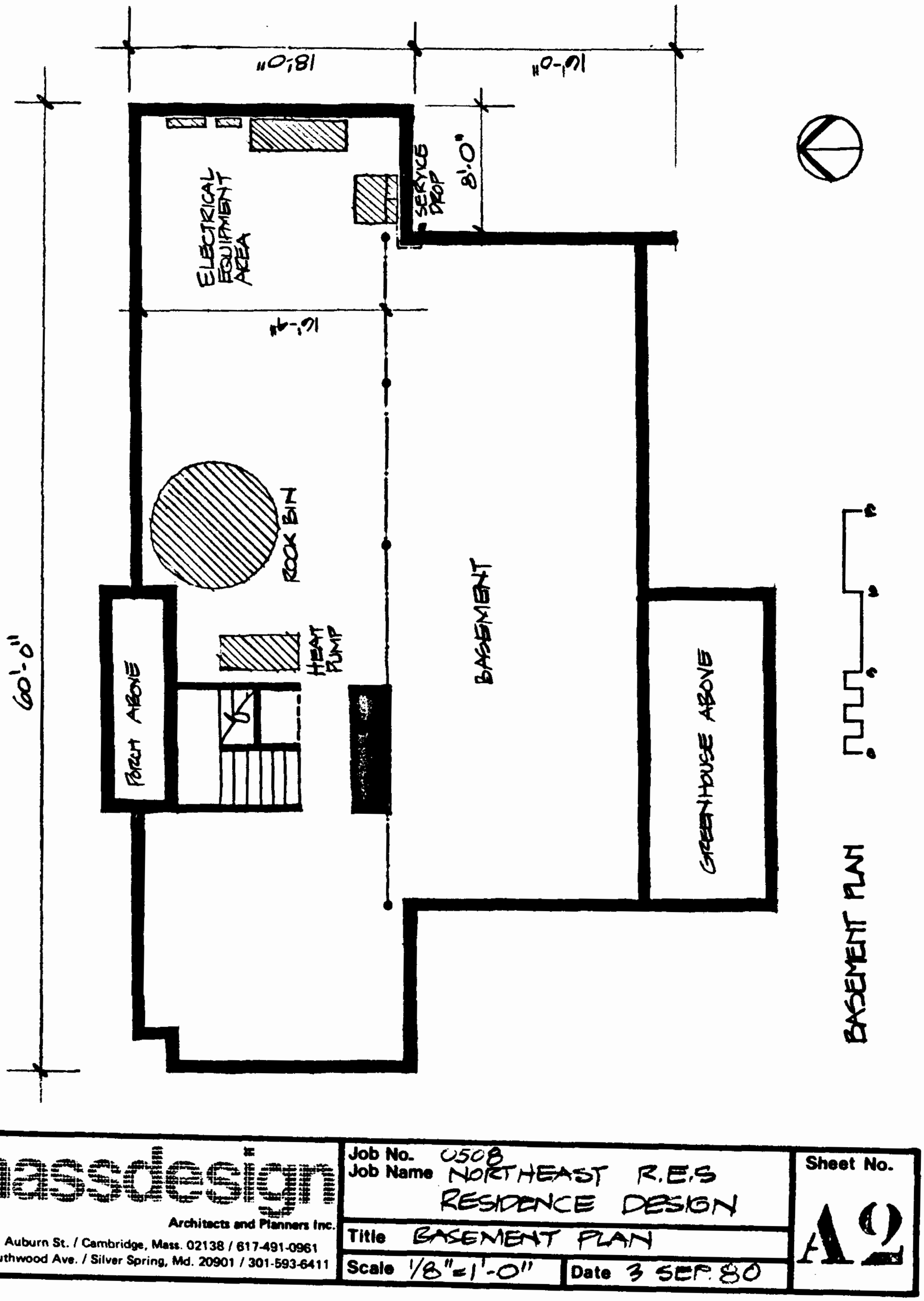


Figure 1-3. Basement Floor Plan

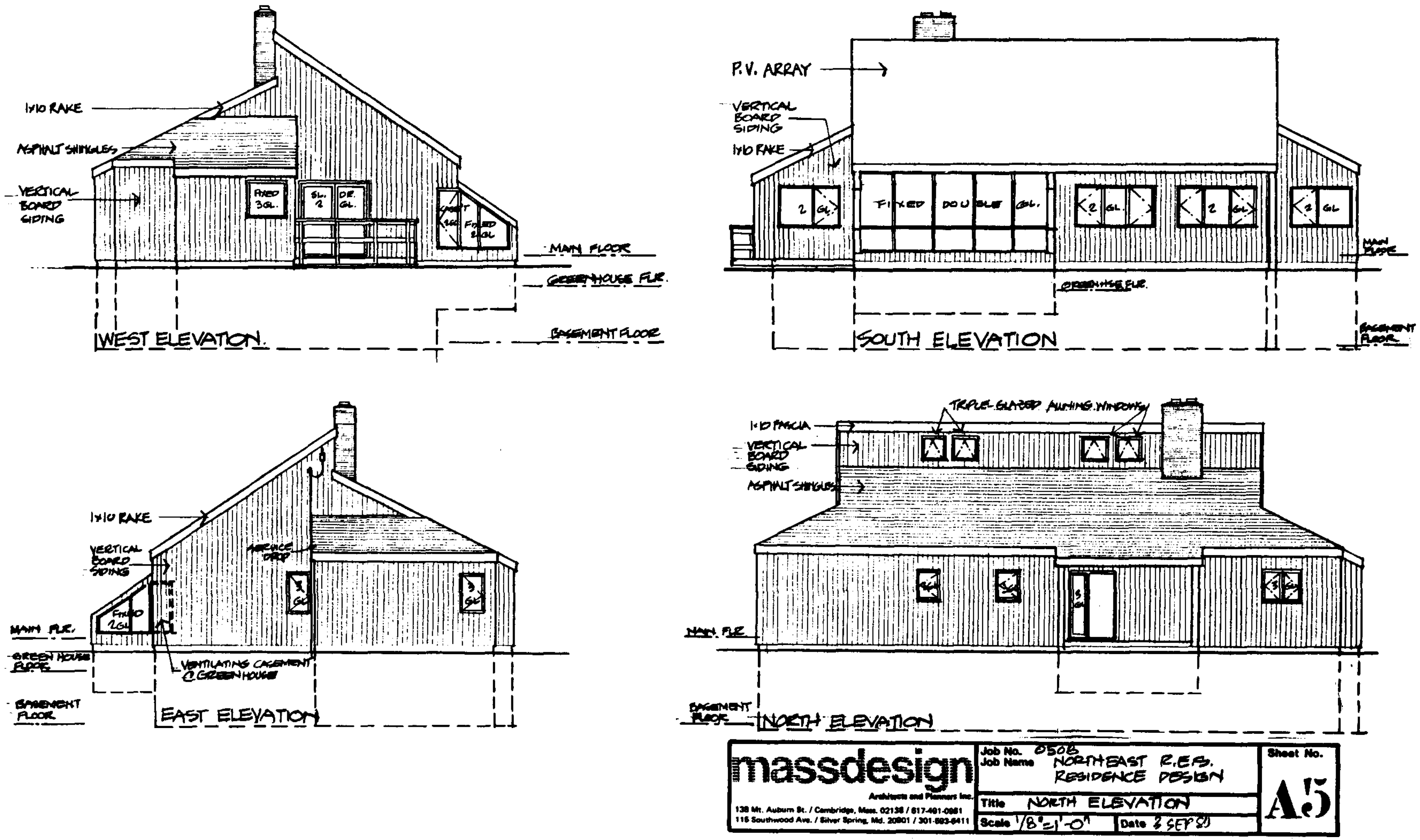


Fig. 1-4. Elevations of the Residence Design

1.1.1 ENERGY CONSERVATION FEATURES

To achieve the high levels of wall insulation required by current good practice and proposed codes, the building uses a layer of one inch foil-faced polyisocyanurate foam insulation on the inside of 2 x 4 stud construction with R-11 fiberglass, achieving an overall R-factor of 19. In the 10-inch joist construction at the cathedral ceiling, eight inches of fiberglass plus the one inch insulation board yields an R-factor of 30. A two-inch air space is left under the sheathing for moisture dispersion. R-38 insulation is used in the ceiling beneath an attic space. If tight wood sash are used, glazing is triple throughout; if inexpensive thermal-break sash are used, two sets of double-glazing is recommended. Both methods yield an overall window R-factor of between 3.0 and 3.4, with the triple glazing admitting more passive gain. No insulating curtains are assumed, since they are very expensive, require maintenance, and are often not used properly. The sun-space is fitted with double glazing, as is the wall between the sun-space and the house.

Basement walls are insulated with R-11 fiberglass batts in wood studs on the inside of the basement wall. The basement slab is insulated below with R-5 styrofoam (1 inch). An air-lock entry is included, since its addition involves only the cost of a door and partition. Figure 1-5 presents a section of the house with the insulated areas shown. Figure 1-6 presents a typical wall section.

1.1.2 Passive Solar Features

The design features a small sun-space off the living room. This very popular and attractive element, if coupled with adequate storage and if allowed to fall to relatively low temperatures at night, can provide some assistance in replacing the use of back-up heating. The sun-space cannot be justified economically as a heat source, but once it is present for other reasons, can be used as one.

As is becoming increasingly apparent throughout the housing industry, the provision of passive storage is expensive and runs counter to the general trend in the industry to reduce building mass. Since adequate storage is critical to the operation of the greenhouse, the problem is to provide storage at a minimum cost. For this design, a rock bin storage system is used.

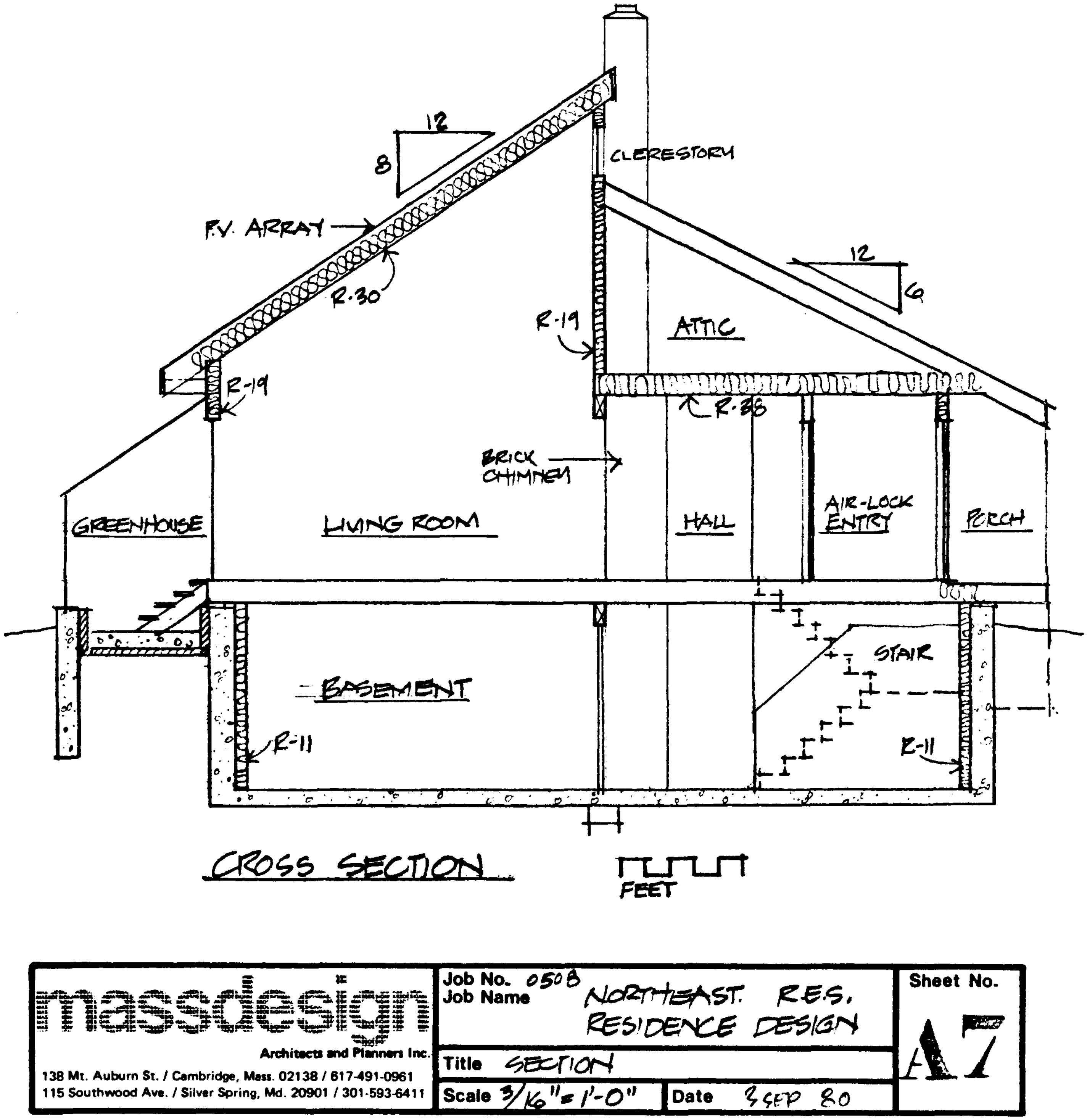


Figure 1-5. Section of House Design

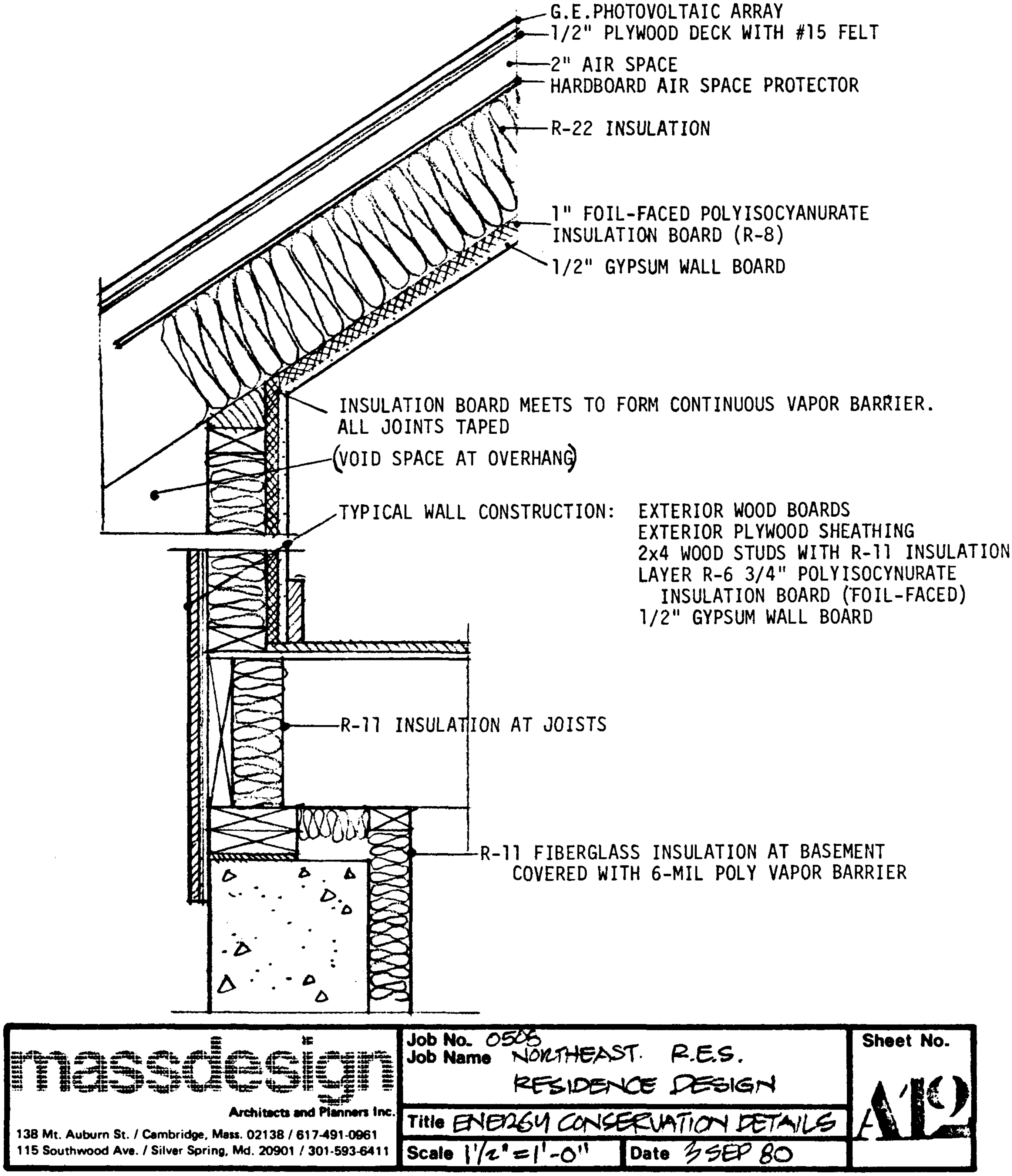


Figure 1-6. Typical Wall Section

In addition to the sun-space and associated storage, most of the major spaces in the house have direct solar gain, balanced to match the available storage within the normal construction of the space. The direct gain aperture, excluding that through the sun-space, is about 9.3 m^2 (100 ft^2).

The normal warm air system of the house is specified for "constant run" operation. This maximizes the distribution of passive gain throughout the house, and prevents local overheating by destratifying all spaces through high return grilles. Alternatively, special measures can be taken to destratify the spaces.

1.1.3 Thermal Subsystem

The space heating, cooling and domestic hot water requirements are provided by electrical energy. A block diagram and a list of components comprising the thermal subsystem is shown in Figure 1-7. All of the equipment is located in the basement as indicated in the floor plan of Figure 1-3. The system consists of a 2-ton GE Weathertron heat pump for heating and cooling with an electric resistive heating coil as back-up. The performance characteristics of this unit are shown in Section 1.2. A standard 40-gallon hot water heater is included in the design.

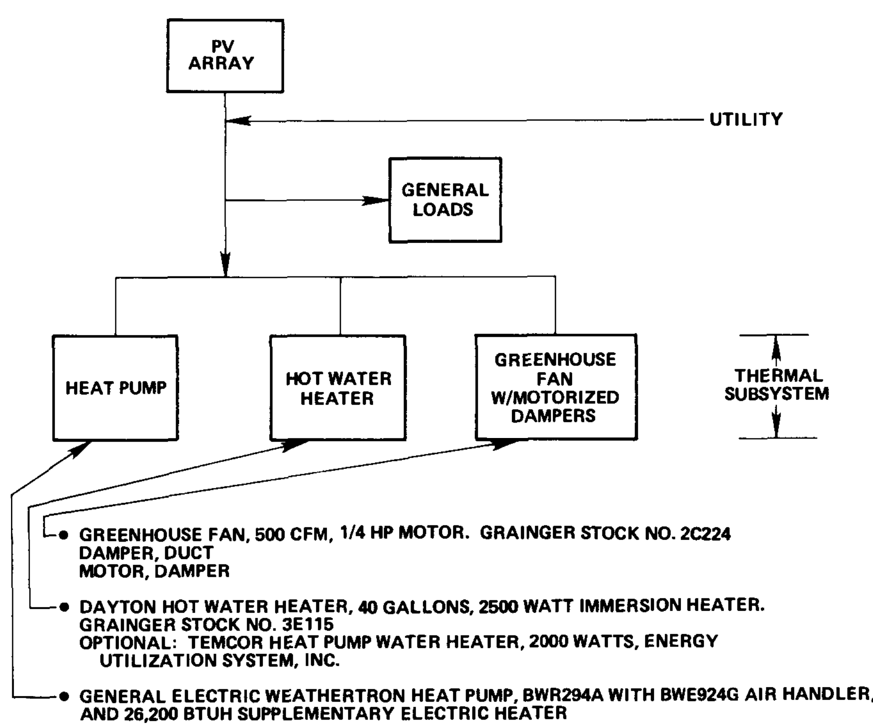


Figure 1-7. Thermal Subsystem Block Diagram

The special features of the heating system, however, utilize the passive heat gained by the greenhouse. The passive heating system is designed very much like an active air system, except that it utilizes a building component for the collection function, namely the greenhouse. Storage is provided by the rock bin. Control of the greenhouse is by a high and low limit thermostat, set by the owner. On a cold sunny day, the greenhouse will rise in temperature as the sun rises in the sky, until the high limit thermostat starts the greenhouse supply fan. This fan delivers 500 cfm of air to the bottom of the greenhouse, drawn from the air passages which run through the rock bin as shown in Figure 1-8. Hot air is removed from a duct running along the top of the greenhouse and is ducted to the rock bin. The air runs through the rock bin and emerges at the greenhouse supply fan for another loop. This cycle continues until the greenhouse drops below the high limit setting, at which point the fan stops and motorized dampers close off both supply and return ducts.

In the heating cycle, air is withdrawn from the "warm" end of the bin, passed through the indoor section of a heat pump (which includes the delivery fan), and supplied to the spaces. Return air is drawn half from the high clerestory and half from near the floor, down into the "cool" end of the bin to complete the loop. If the house calls for heat during collection, air is free to pass directly from the duct leaving the greenhouse into the supply to the house, since both sets of dampers will be open and since the greenhouse return and the house supply both enter the rock bin at the same end. Similarly, the return air from the house will move directly into the greenhouse through the greenhouse supply fan rather than pass through the rock bin.

In the summer, the greenhouse is disconnected from the rock bin loop by shutting down the two motorized dampers permanently for the season. An air intake grille near the floor is opened, and an exhaust fan near the ceiling is operated by the same high limit thermostat which in winter operates the supply fan. Thus, outside air can control overheating in the greenhouse.

Certain operating modes are relatively unimportant, and will not be handled automatically by the system. If the house overheats during sunny periods, the system cannot supply cool air from the storage to the house as it does to the greenhouse.

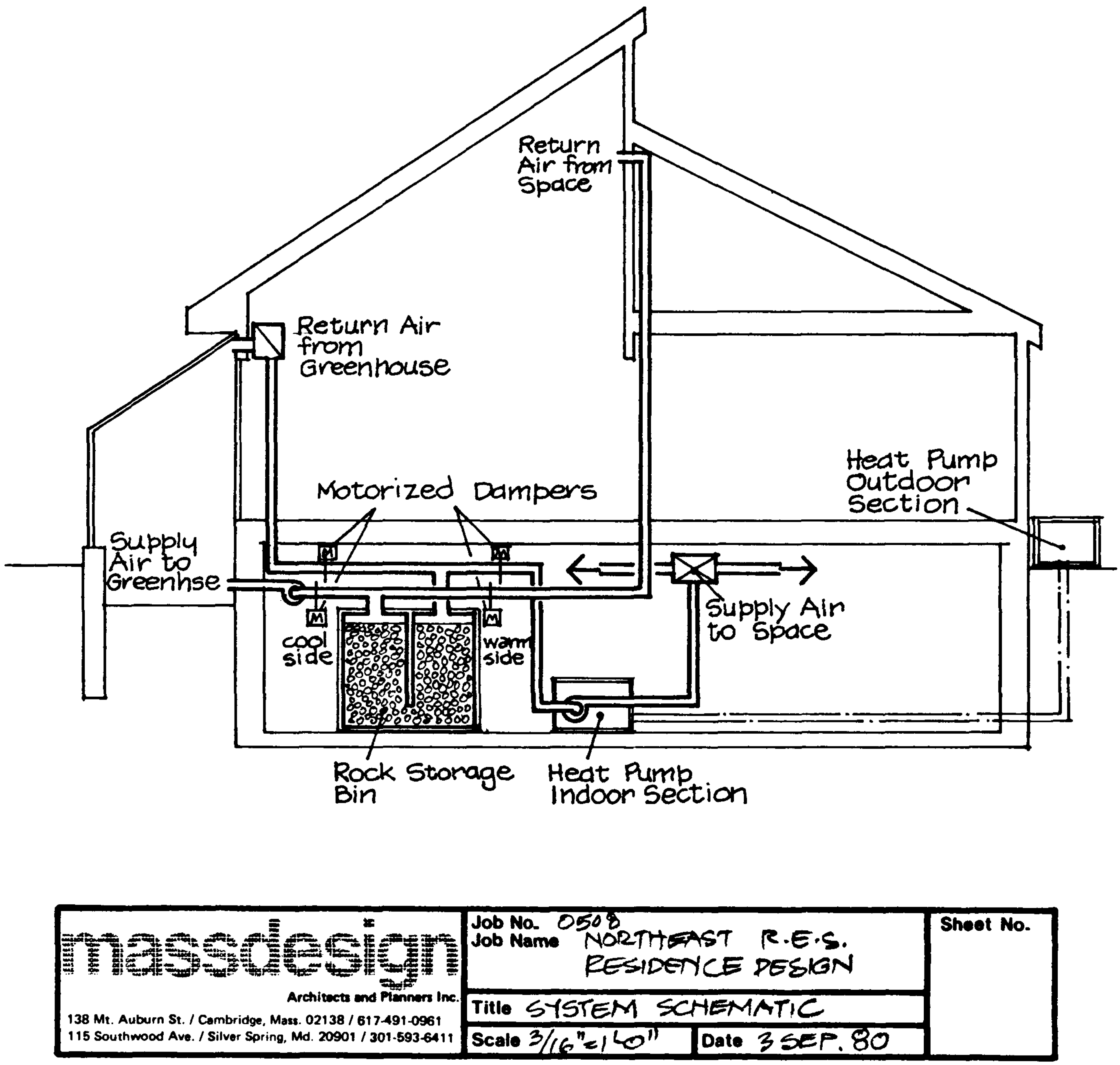


Figure 1-8. Passive Heating Circulation Loop

With the exception of the four motorized dampers, a small amount of extra duct-work, and the rock bin, the system is exactly like an ordinary force-air heating and cooling system. The greenhouse, while additional to the normal living space, is a very popular option, desired in any case.

Control of the house heating and cooling system is similar to normal heat pump control, except that the first stage operates the fan alone, while the second stage actuates the heat pump coil (in both heating and cooling modes). The final electric resistance coil auxiliary is operated by a separate manual switch, under the control of a separate thermostat set at 7.2°C (45°F). Figure 1-9 summarizes all of the thermal system operating modes.

1.2 HOUSE ENERGY AUDIT

The collector array is sized to meet a minimum of 50% of the total electrical load requirements of the house. The house load requirements are based on the results of previous studies and a thermal model for the space conditioning thermal requirements.

1.2.1 HEATING AND COOLING LOADS

The building space loads are calculated on an hourly basis using Boston Typical Meteorological Year (TMY) data.

Initially, the space heating and cooling loads are calculated for a baseline house which does not include the greenhouse. The effect of the greenhouse is treated by adjusting the baseline loads to account for the increased solar gain during the heating season and the improved ventilation during the warmer months (Reference 1*.) This technique produced annual thermal requirements loads of 6150 kWh heating (a 37% reduction in the baseline loads) and 1650 kWh cooling. Table 1-1 summarizes the monthly thermal loads. These thermal space conditioning requirements are translated into electrical load requirements through a heat pump simulation model.

---

*See Section 4 for references.

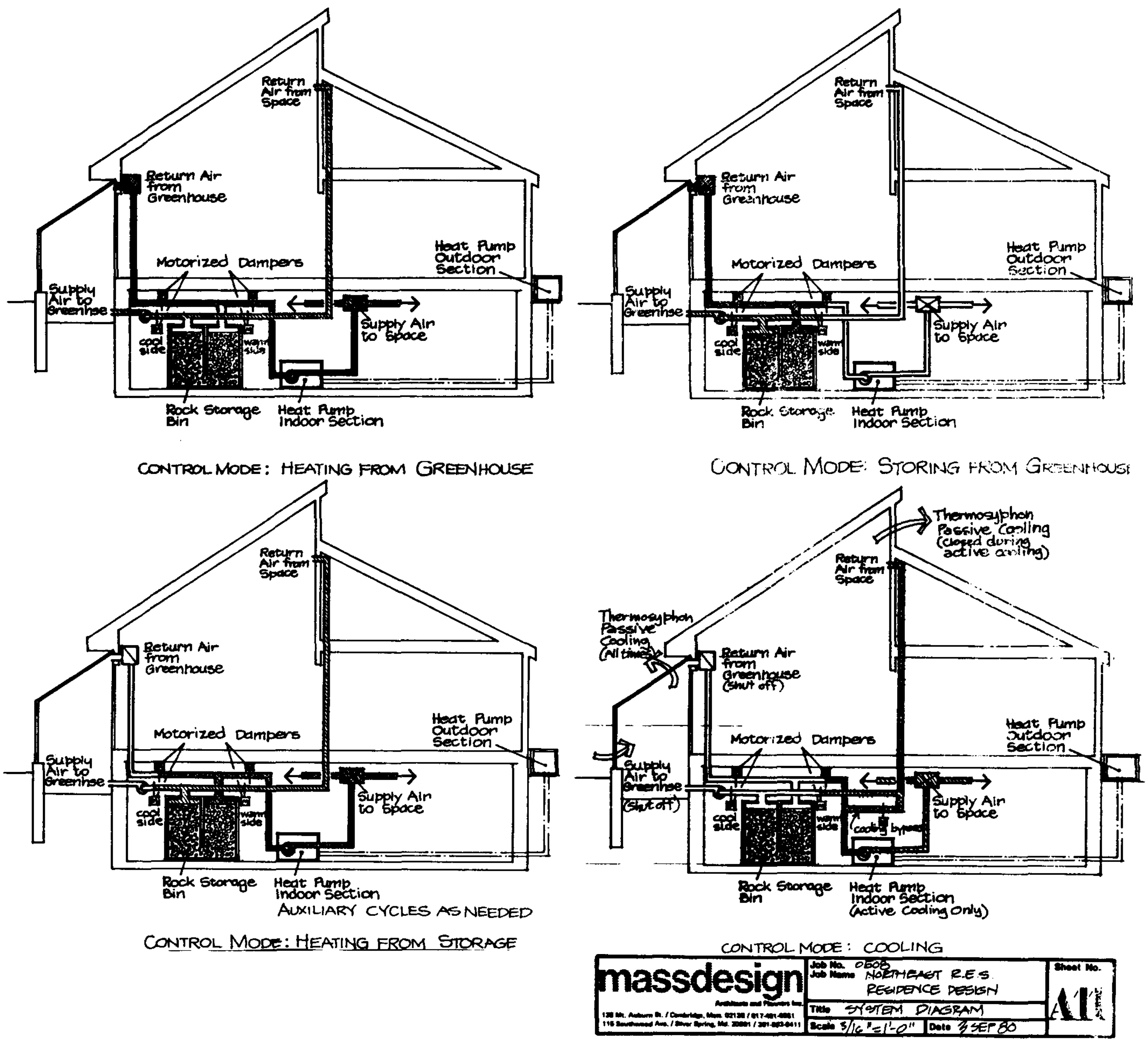


Fig. 1-9. Summary of Thermal System Operation Modes

Table 1-1. Single Family Monthly Load Profiles

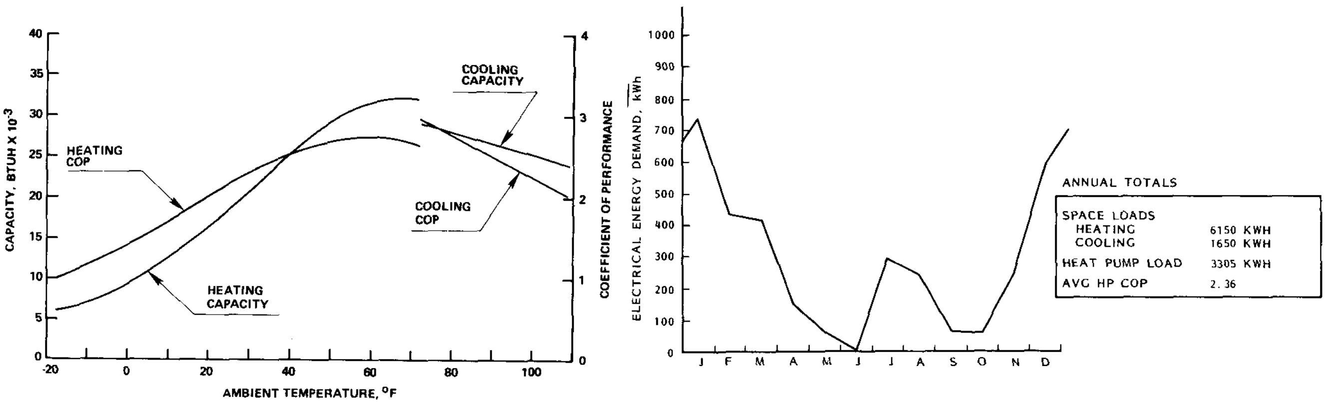
Site Location / Month	Boston (kWh)	
	Cooling	Heating
January	0	1537
February	0	986
March	0	969
April	0	386
May	0	181
June	0	20
July	796	0
August	668	0
September	185	0
October	0	155
November	0	605
December	0	1310
Total	1650	6150

A commercially available electrically driven heat pump is used to supply the space heating and cooling loads, and has been sized by conventional ASHRAE methods specifically for the photovoltaic residence design. The nominal rated capacity of the heat pump is 2 tons with an air flow of 800 cfm. The capacity and coefficient of performance are shown as a function of ambient temperature in Figure 1-10. These characteristics are modeled in the system performance computer program along with features associated with the defrost cycle.

The electrical loads for the heat pump operation to meet the thermal requirements are also summarized monthly in Figure 1-10.

1.2.2 DOMESTIC HOT WATER LOADS

The domestic hot water (dhw) load profile is defined based on the results of previous General Electric studies (References 2 and 3). The load profile was developed independent of region and then adjustment factors, reflecting the local



CHARACTERISTICS **ELECTRICAL REQUIREMENTS**

Figure 1-10. Heat Pump Characteristics and Space Conditioning Loads

ground temperature, are used to adjust the load levels. Figure 1-11 shows the hourly dhw load profile. The Boston area adjustment factor is 1.08. Thus, the daily dhw loads are 13.0 kWh/day or 4747 kWh annually.

1.2.3 DIVERSIFIED ELECTRIC LOAD

Average day electric demand profiles, also developed previously, are used for the analyses. These profiles are shown in Figure 1-11. The major components of the total load (cooking, drying, and baseload) are identified and quantified. The diversified load demand amounts to 19.2 kWh/day or 6988 kWh annually.

1.2.4 ESTIMATES OF SOLAR CONTRIBUTIONS

1.2.4.1 Array Sizing

Since the PV system output is proportional to the array size, and the size of the array impacts the system cost, the effect of array sizing is best evaluated in

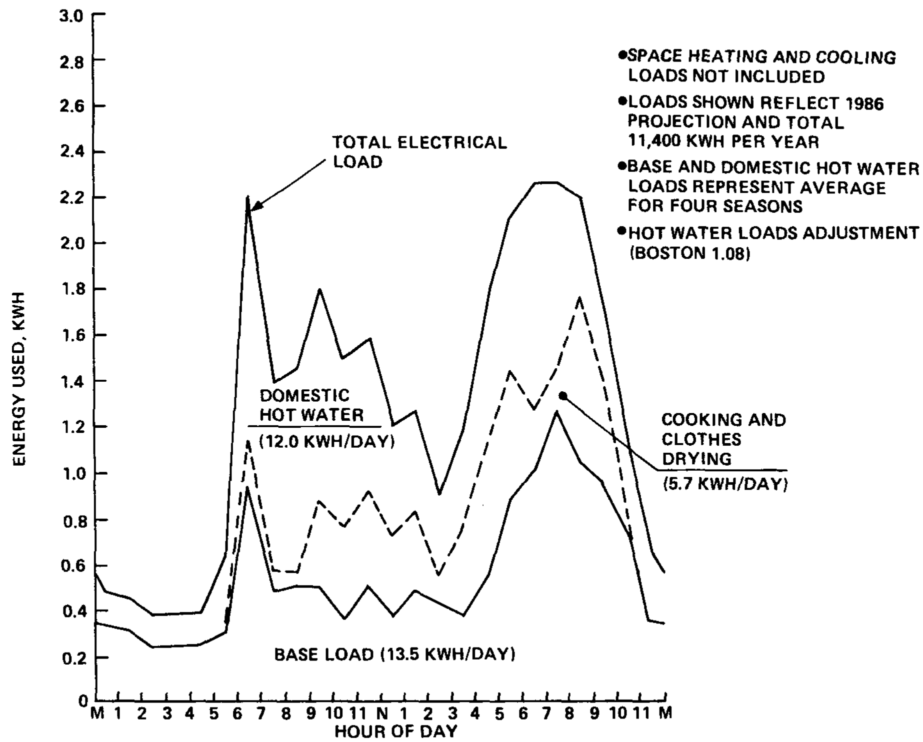


Figure 1-11. Average Daily Electrical Load Profiles

terms of economic factors, such as levelized annual cost-to-benefit ratio. Previous system studies have shown that systems with utility feedback having sell-back rates of 50% or more of the buy rate optimize at arrays covering the full roof. The requirements of the design, however, demand that the array be sized to provide an annual output energy between 50 and 100 % of the total estimated annual residential electrical load, but no larger than 74.4 m^2 (800 ft^2).

The array area was varied by maintaining 25 series modules along the roof slant height, yielding the same system operating voltage, and changing the number of parallel circuits. The resulting area variation is from 48 m^2 to 73.3 m^2 which is near the maximum allowable area. The results are shown in Figure 1-12 and indicate that a minimum of 14 parallel circuits are required to supply at least 50% of the total load. Following the results of the previous studies, a 25 series by 15 parallel exposed module area is selected as the design point.

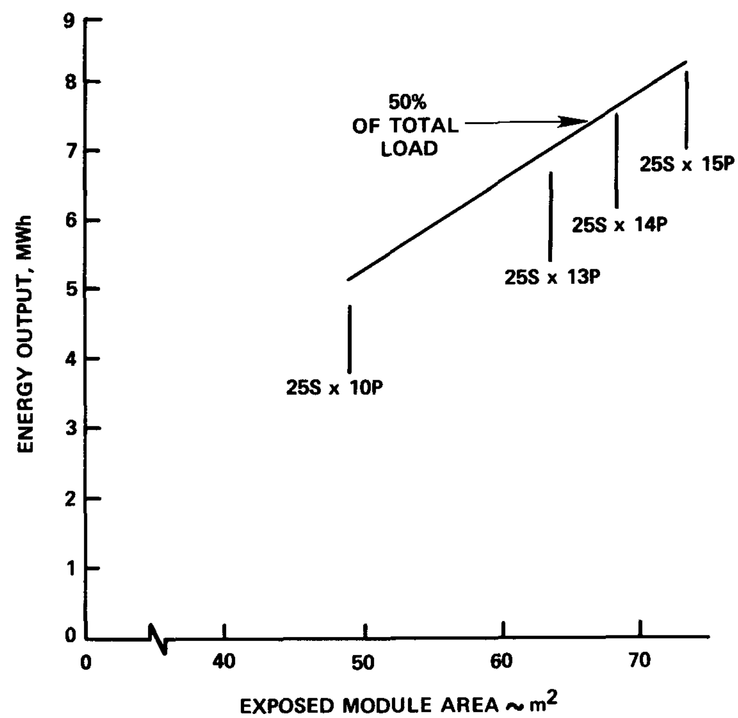


Figure 1-12. Effect of Collector Area on Net System Output

1.2.4.2 Array Tilt Sensitivity

The sensitivity of collector tilt or roof slope angle to net system output was investigated with the results as shown in Figure 1-13. For this analysis, the array consisted of 25 series collectors by 15 parallel circuits for a collector area of 73.3 m^2. The results indicate that the system output is maximized with a roof slope of approximately 34^o. This is consistent with trends established in earlier studies; i.e., the optimum tilt angle for PV arrays serving residential electric loads is about 10 degrees less than the latitude. The actual design slope was selected as 33.7^o, which conforms to the use of standard framing techniques (8-inch vertical, 12-inch horizontal). It is also evident that only small differences in net system output occur over the tilt angle range of 20 to 40^o.

1.2.4.3 Design Performance

The monthly performance of the nominal design PV system is shown in Figure 1-14 for Boston for the design array area of 73.3 m^2. The monthly load, total PV

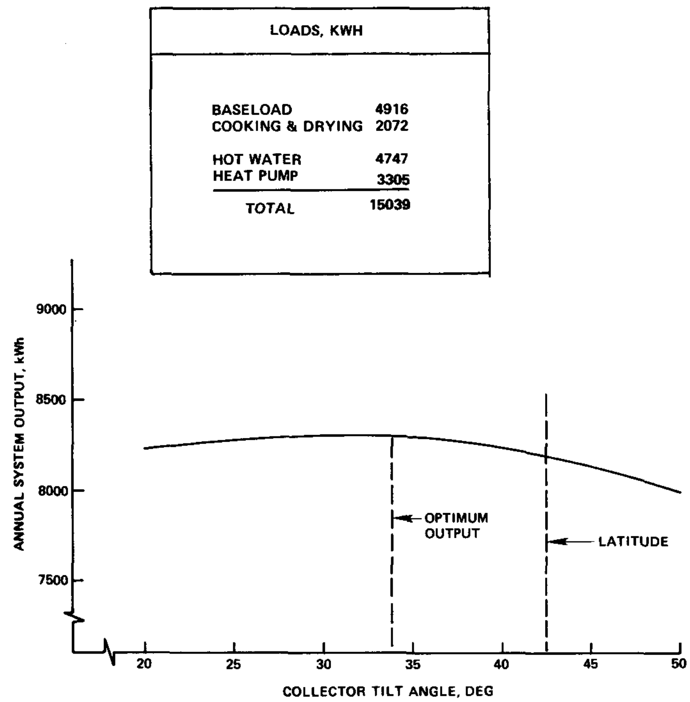


Figure 1-13. Array Tilt Angle Sensitivity

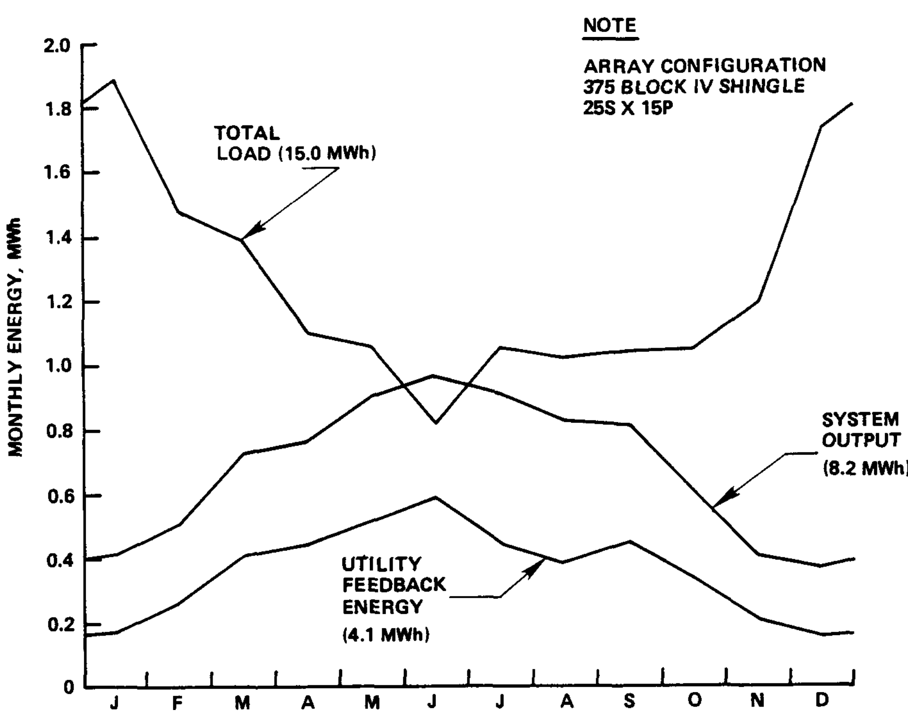


Figure 1-14. Monthly Performance for PV System for Boston Prototype Design

system output and energy feedback to the utility are shown. The system provides approximately 55% of the total electrical load. Table 1-2 summarizes the annual system performance. The solar array conversion efficiency is approximately 9.8% with less than 1% annual energy loss due to the series resistance losses in the shingle module bus strips, the termination bus bars, and the cabling between the bus bars and the inverter. The annual Power Conversion Subsystem efficiency amounts to approximately 85% with the efficiency model assumed, resulting in the overall annual system efficiency of 8.4%.

Table 1-2. Summary of System Performance for Boston

Parameter	Value
Total Exposed Module Area (m^2)	73.3
Annual DC Energy Input to Inverter (mWh)	9651
Annual AC Electrical Energy Output (mWh)	8216
Annual Insolation on Array Surface (kWh/m^2)	1341
Overall System Efficiency $\frac{\text{System Output}}{\text{Insolation X Array Area}}$	8.4%

SECTION 2
PROTOTYPE SYSTEM DESCRIPTION

To simulate the full-size residential system, a prototype system and structure has been designed and constructed. The structure supports a roof identical to the full-sized system, simulates the back surface temperature of the photovoltaic array, and provides interior space to house the balance of system equipment and load duplicating equipment. Figure 2-1 shows a photograph of the structure.

2.1 STRUCTURAL DESIGN

The design for the prototype structure had to meet the requirements of the program at a minimum building cost. The building is constructed on a platform of wood supported on the MIT foundation, supplemented by a center line of piers. The outer surfaces of the platform are weatherproofed with deck paint.

The platform is insulated beneath the building. The walls are adequately insulated (R-11), and are covered with stained plywood exterior finish for economy and acceptable appearance. Many residences use such construction, although the proposed residence described in Section 1:1 is more heavily insulated. The structure was built using components manufactured by Acorn Structures of Acton, Massachusetts. Figures 2-2 and 2-3 show the four elevations of the structure.

The platform is extended six feet beyond the building to the east and west to provide convenient entry and space for moving equipment. Standard doorways are provided on the east and west sides for easy access. The platform stops two feet beyond the roof to the south, in line with the edge of the curb, leaving adequate access for maintenance. Since the top of the platform is two feet from the access road, a step is provided at each end. While the building is temporary, it is attractive and residential in character.

Figure 2-3 also shows the interior floor plan for the structure, which has a total floor area of 62.5 m^2 (672 ft^2). The main entry is located on the west. Two windows are placed on the north wall to light the interior, supplemented by windows over the entry doors at each end.

Figure 2-1. Structure Photograph

Approximately two-thirds of the space has standing headroom, and it is entirely finished in painted gypsum board. The floor is covered with resilient tile.

Figure 2-4 shows a section of the prototype structure. The highest point of the structure is 5.3 m (17.3 ft) from the foundation. The lowest array point is 1.2 m (3.9 ft) from the foundation.

The building roof is identical to the residence roof, having a cathedral ceiling with R-30 insulation and a two-inch air space under the sheathing. Details of the roof at the eave overhang, at the rake and at the ridge are shown in Figure 2-5. Vent screens at the two ends of the roof section allow for an air flow beneath the roof array. Specifications of the building components for the roof are shown in the Figure.

Figure 2-6 shows additional details of the prototype structure, specifically showing the foundation details. Figure 2-7 shows the specifications and details for the windows, doors and skin.

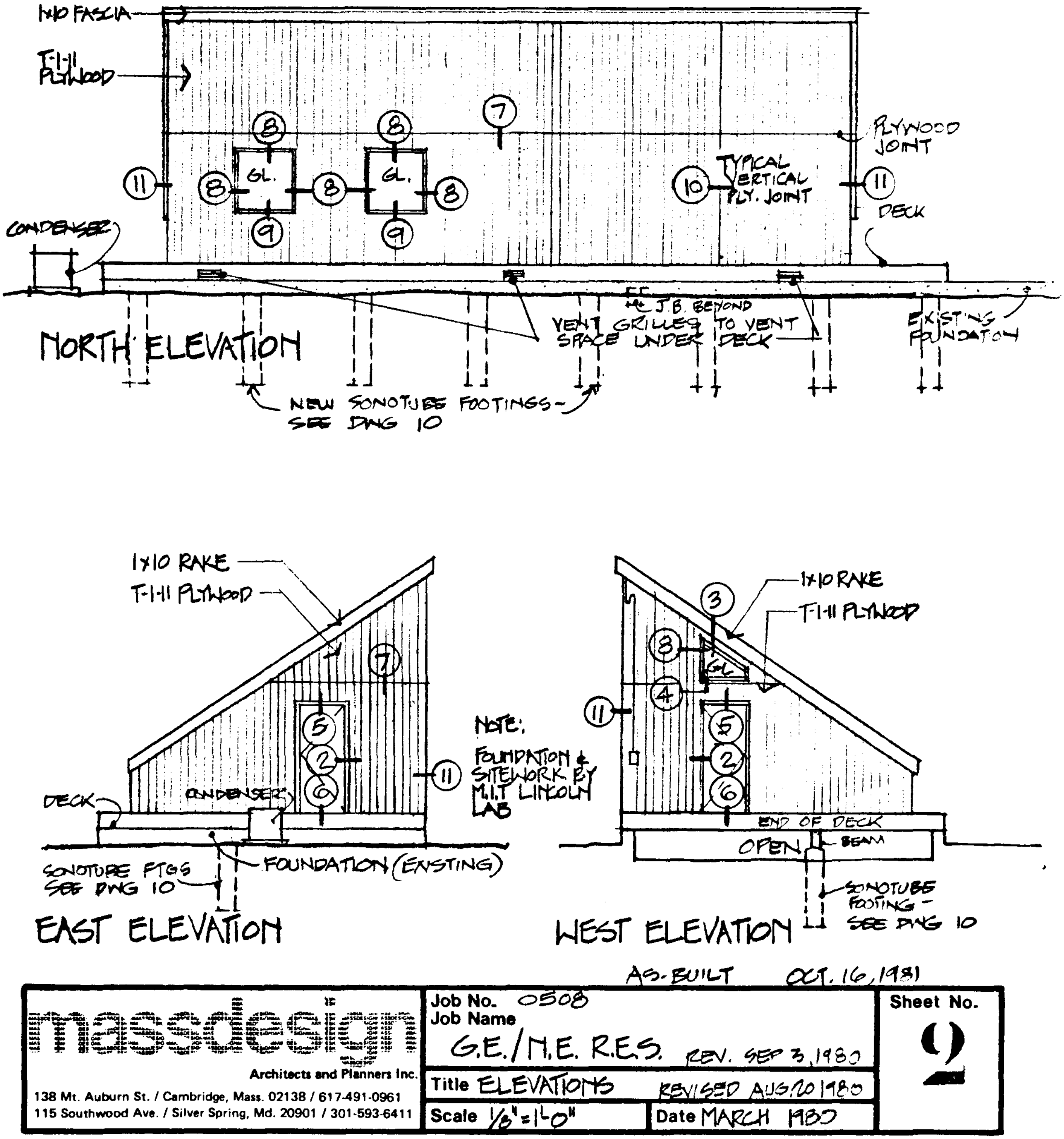


Figure 2-2. Elevations of the Prototype System Structure

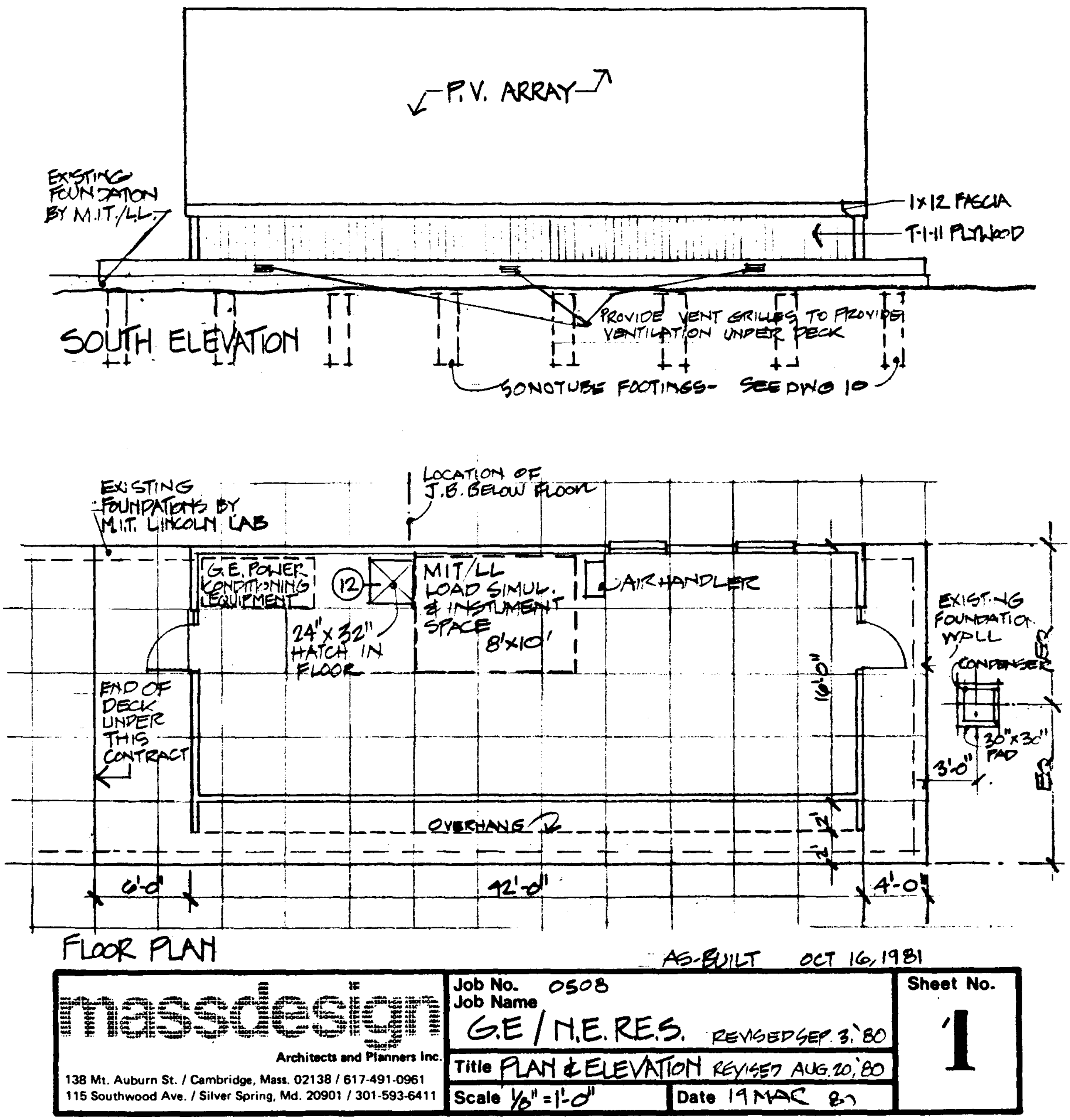


Figure 2-3. South Elevation and Floor Plan of the Prototype System Structure

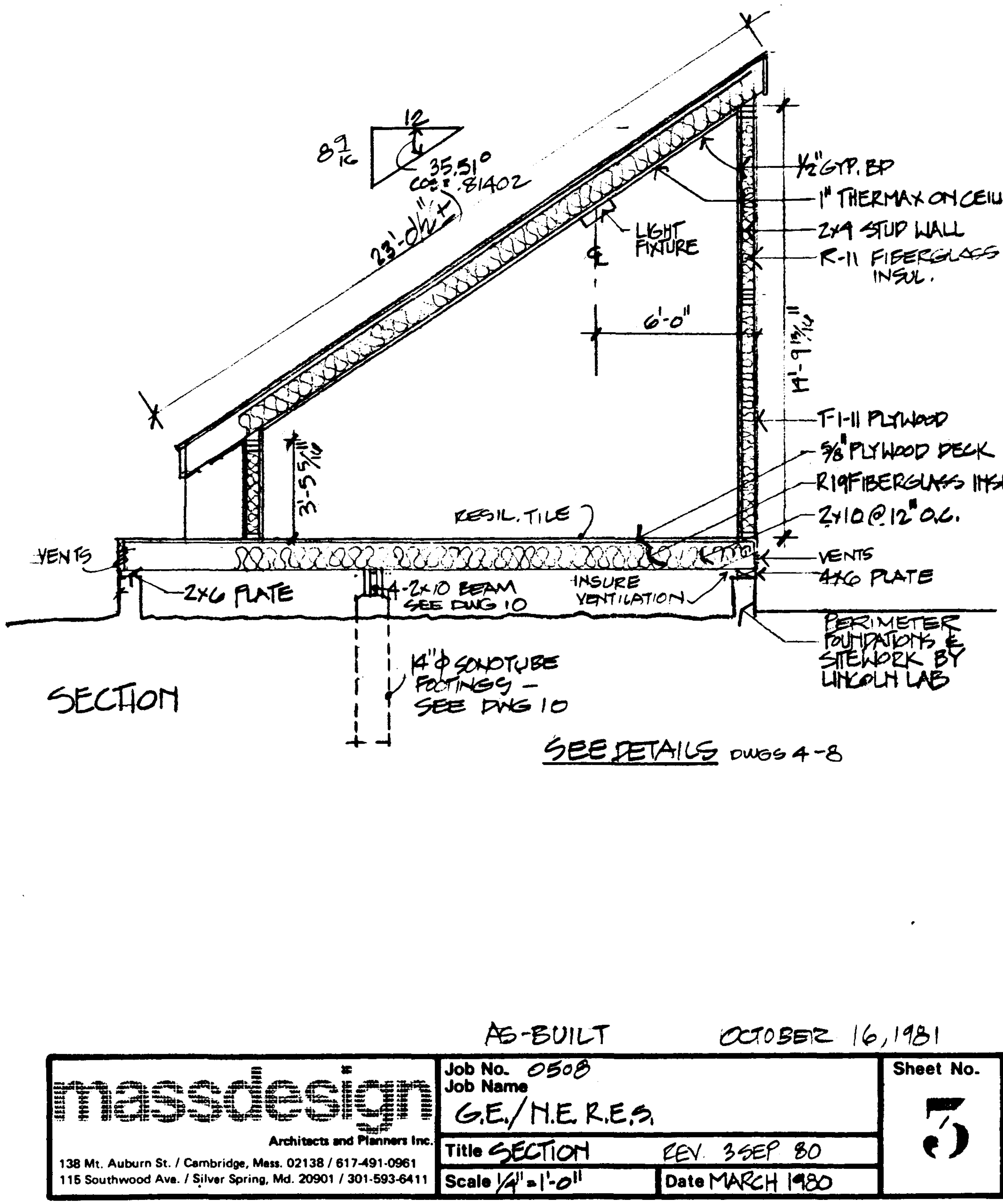


Figure 2-4. Section of the Prototype Structure

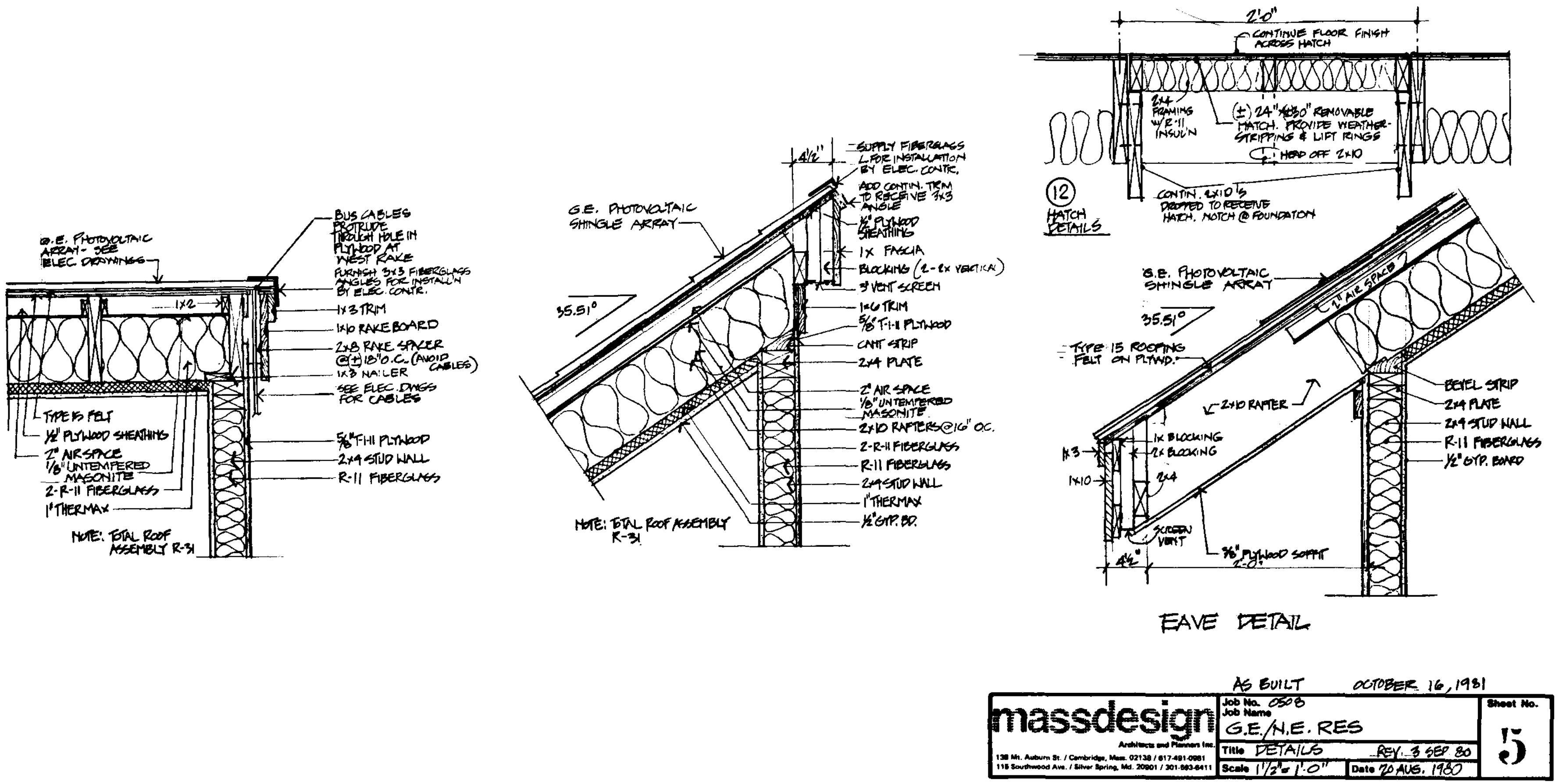


Fig. 2-5. Roof Installation Details for the Prototype Structure

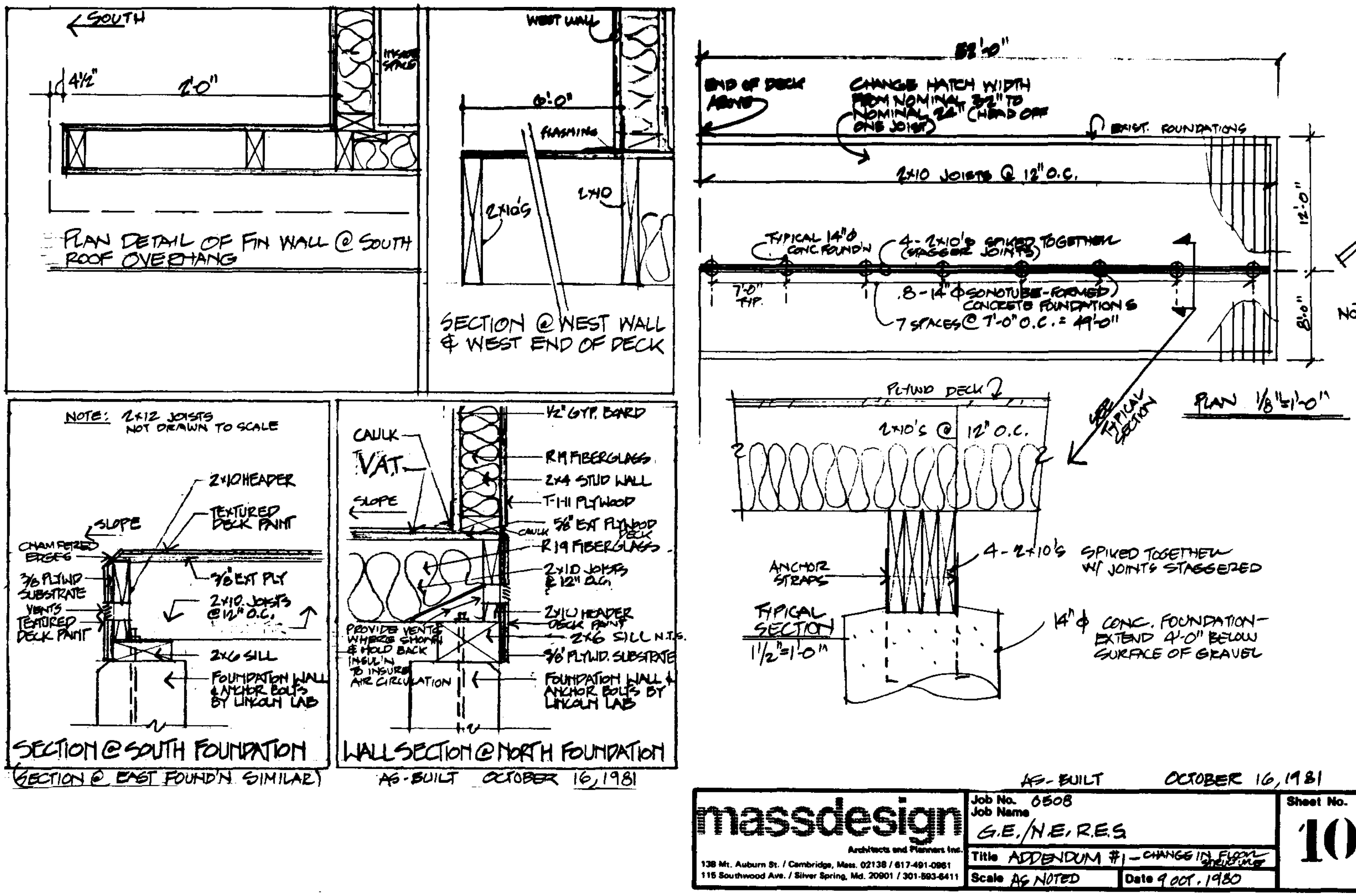
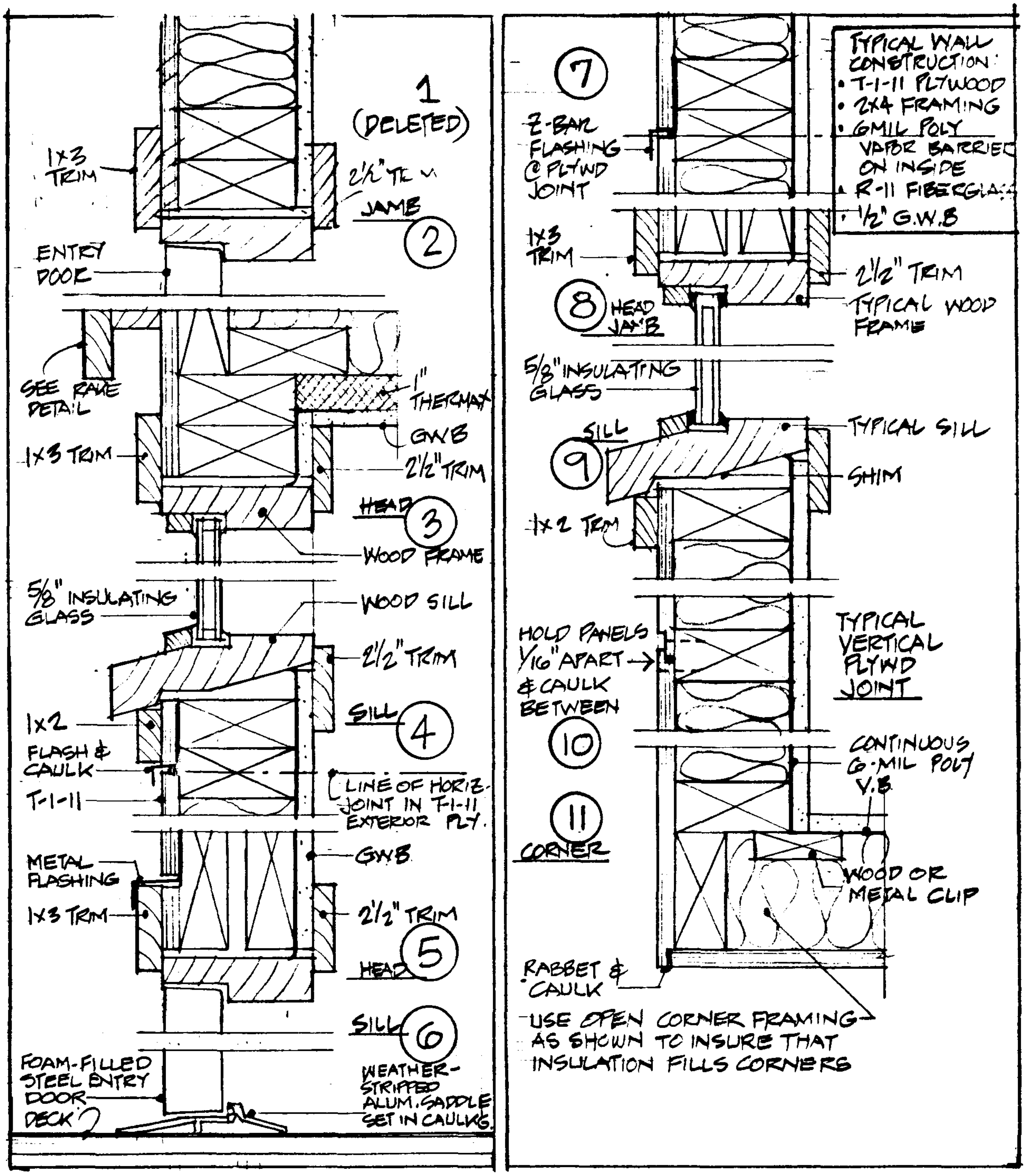


Fig. 2-6. Foundation Installation Details



AS-BUILT OCTOBER 16, 1981

massdesign Architects and Planners Inc.	Job No. 0508		Sheet No.
138 Mt. Auburn St. / Cambridge, Mass. 02138 / 617-491-0961	Job Name G.E./N.E. RES REV 3 SEP 80		8
115 Southwood Ave. / Silver Spring, Md. 20901 / 301-593-6411	Title WINDOW, DOOR & SKIN DETAILS		
	Scale 3"=1'-0"	Date 20 AUG. 80	

Figure 2-7. Window, Door and Skin Structure Details

The drawings also provide additional specification of the floor and wall materials.

A simple thermostatically controlled heating and cooling system was designed to maintain the temperature inside the prototype at levels similar to the proposed residence. The simplest and most practical heating and cooling system for the building is a unitized air handler with an electric resistance coil, and a coil connected to an outdoor condenser or heat pump. Since the heat pump option is only slightly more expensive than the standard A/C option, it was selected to economize on energy.

The indoor unit is a GE WE-918-G-100-E vertical air handler with an AY-96-X-1411 resistance heater coil. An AY-61-X-632 refrigeration line set connects the air handler to the BWB-918-A-100-A outdoor heat pump section, which is mounted on a concrete pad to the east of the building.

The air handler has an extension duct on the top which lifts the air above head height, discharging in three directions. This system provides thermal conditions for the cathedral ceiling and roof array similar to the full-size residence. It cannot cool the building if the simulated load is discharged into the space.

Lighting is supplied by four 8-foot, 2-tube fluorescent fixtures mounted to the sloped ceiling, to provide good light on the electrical equipment. Several windows provide natural light and vision inside for security checks, and help give the building a residential character. The electrical wiring for the lighting and heat pump operation is separate from the photovoltaic system. The lighting and heat pump wiring is shown in Figure 2-36 terminating at a separate house panel.

2.2 MECHANICAL DESIGN

The photovoltaic system has two primary subsystems: the array subsystem and the power conversion subsystem. The array subsystem consists of 375 PV modules wired in a 25-series x 15-parallel network. The power conversion subsystem consists of a single unit manufactured by Abacus Controls, Inc., of Sommerville, N.J.

2.2.1 MODULE PHYSICAL DETAILS

The module used in the array is the Block IVA shingle module, Figure 2-8, which has been designed, fabricated and qualification tested by GE under JPL Contract 955401. Representative modules have satisfactorily passed the JPL qualification testing program consisting of a thermal cycling exposure of 50 cycles between the extremes of -40 and 90°C, a seven-day humidity-temperature exposure, a wind resistance test per the requirements of UL997, a twisted mounting surface test, and a hail impact test using 0.75-inch diameter ice balls.

The module has a series string of 19-100 mm solar cells fabricated by SOLEC, International, Inc. of Hawthorne, California for a total cell area of 0.1480 m^2. The module glazing is SUNADEX tempered glass, 4.8 mm thick. The exposed module area is 0.1955 m^2 resulting in a module packing factor of 0.757. The weight of each module is 3.9 kg. The positive and negative leads from each module are UL-approved flat conductor cables (FCC) developed by AMP, Inc. These FCC leads consist of a polyester insulated copper foil strip (equivalent to AWG 12) which have varying lengths depending on whether the assembly is to be used as the positive or negative lead. The outer end of each FCC is terminated with a AMP patented, crimp-type connector which was developed, and has been UL-approved, for under carpet AC power distribution systems. The stripped end of each FCC is soldered to the appropriate cell interconnectors to form the terminations for the module.

The details of the module construction can be explained with the aid of Figure 2-9 which shows a sectional view of the laminated assembly at the transition between the exposed glass covered portion and the overlapped flexible substrate position.

2.2.1.1 <u>Coverplate</u>

The glass coverplate, which is the rigid exposed portion of the shingle module, is 4.8 mm thick ASG SUNADEX glass. This embossed low-iron soda lime glass is cut to the required hexagon shape and thermally tempered to achieve a mean modulus of rupture in bending of 138 MPa (20,000 psi). The solar cells are bonded to the embossed surface of the glass.

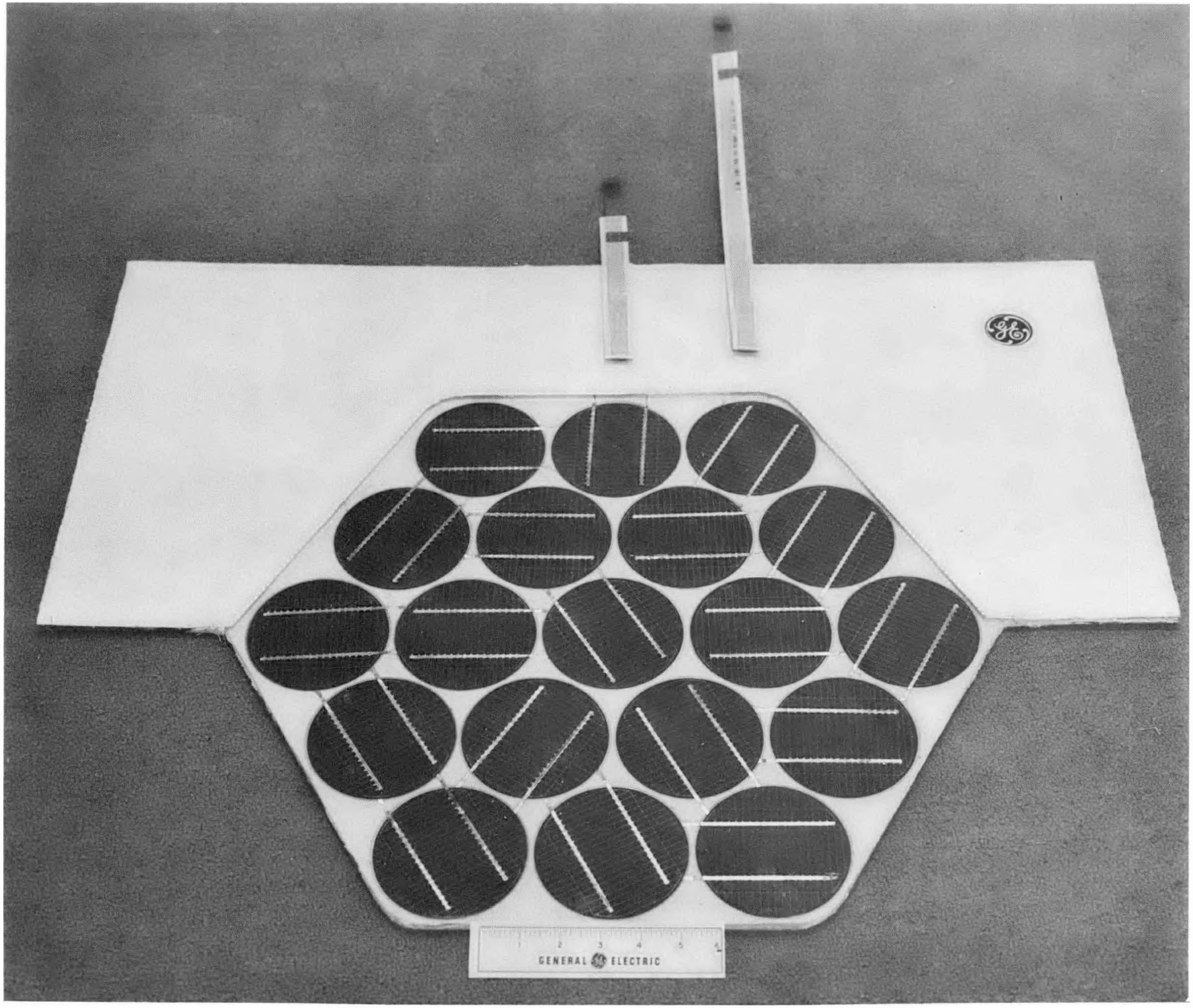


Figure 2-8. GE Block IVA PV Shingle Module

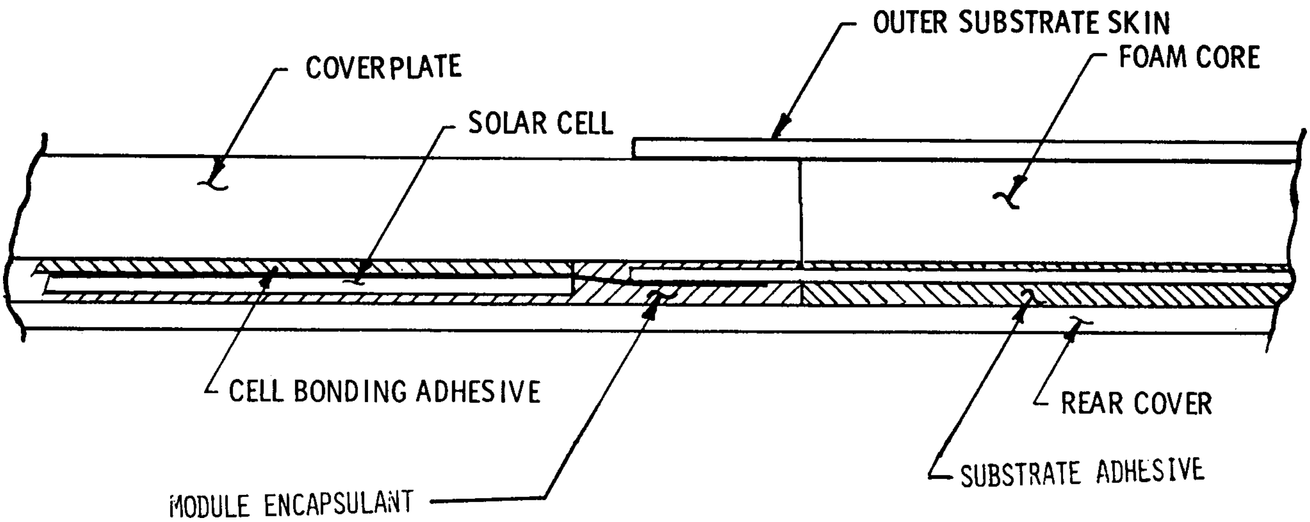


Figure 2-9. Shingle Module Construction Details

2.2.1.2 Cell Bonding Adhesive

A transparent bond between the cells and the glass coverplate is achieved by the use of an experimental silicone pottant developed by GE Silicone Products Department specifically for photovoltaic applications of this type. Designated by the number 534-044, this pottant requires no primers to achieve adequate adhesion to the glass and to the solar cell and can be cured at room temperature.

2.2.1.3 Outer Substrate Skin

The outer substrate skin is BF Goodrich FLEXSEAL wich is a 6 x 6 polyester scrim reinforced white HYPALON roofing membrane. HYPALON is a synthetic rubber with excellent weathering characteristics, low moisture vapor transmission rate, good oil and chemical resistance, and good abrasion and puncture resistance. The scrim reinforcement provides excellent tear resistance to prevent roofing nail tearout under wind loading conditions.

2.2.1.4 Foam Core

The foam core of the shingle substrate is 4.8 mm (0.188 inch) thick L-200 closed cell polyethylene foam manufactured by Rodgers Foam Corporation. This foam provides a low-cost, low-density filler material to maintain a nearly uniform shingle thickness. Material screening tests have indicated that this foam is the lowest cost material available with the required high temperature (95°C) survivability.

2.2.1.5 Rear Cover

The rear cover, which covers the entire rear surface of the shingle module, is cut from 1.5 mm thick "Pan-L-Board" manufactured by Mead Paperboard Products.

Pan-L-Board is a weather-proofed, fire-resistant, pressed paperboard panel which Mead claims has endured 17 years of outdoor weathering in Wisconsin. This rear cover provides a low cost barrier against the entry of water and moisture from the underside and also provides some degree of protection against penetration by sharp objects during handling.

2.2.1.6 Substrate Adhesive

The adhesive used to laminate the various layers of the substrate is M6338 Super White Silaprene manufactured by Uniroyal. This material is a blend of high solid elastomeric compounds which provides excellent bond strength to most surfaces without priming, heating or mixing.

2.2.1.7 Module Encapsulant

The space between the solar cells and the module rear cover is occupied by an encapsulant whose primary function is to prevent moisture from reaching the solar cells. A GE Silicone Construction Sealant, which is identified as Siliglaze SCS2402, has been selected for this application. This material, which is a one-component construction sealant, has excellent adhesion to glass and provides the white diffusely reflective medium in the interstitial spaces.

2.2.1.8 Flat Conductor Cable Assemblies

Two flat conductor cable (FCC) assemblies, which are manufactured by AMP, Inc., are provided in each module. Figure 2-10 shows the dimensions characteristics of the FCC. The stripped end of each FCC is soldered to the appropriate cell inter-

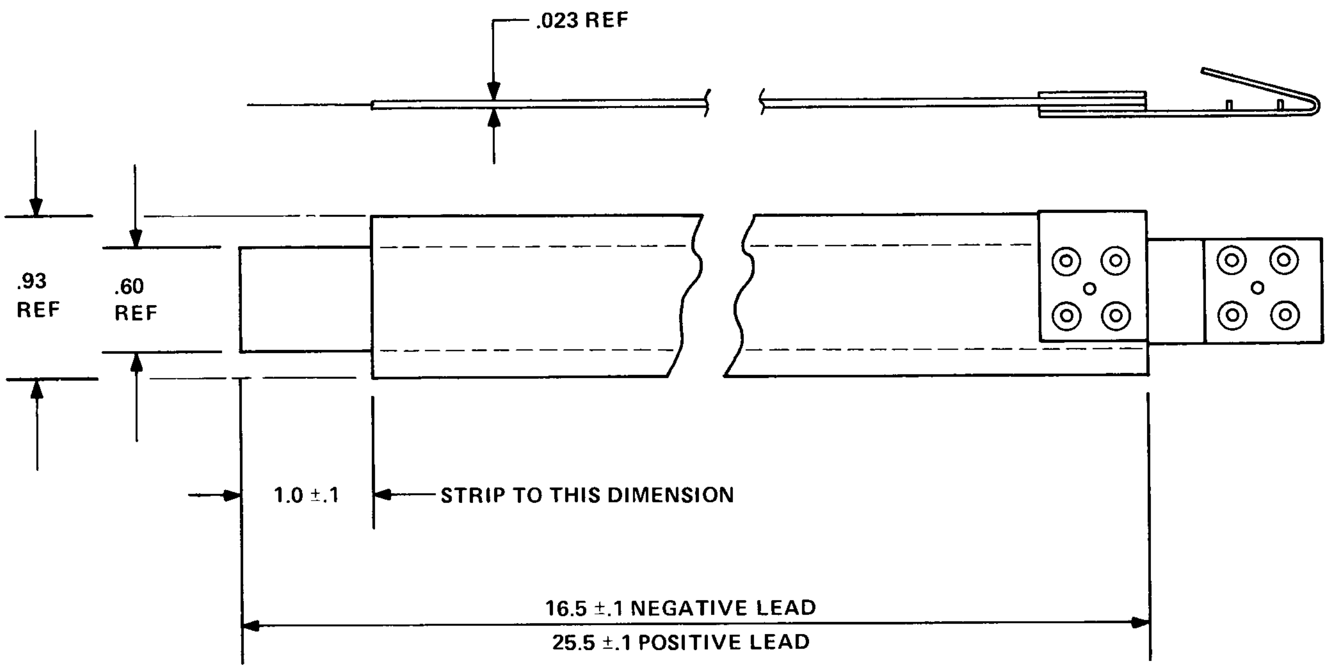


Figure 2-10. AMP, Inc. Flat Conductor Cable Assembly

connectors to form the terminations for the module. Strain relief of these solder joints is provided by bonding to FCC within the substrate lamination between the rear core and the foam core.

Figure 2-11 shows a plan view of the module. To complete the array installation, different types of "dummy" shingles are also used. The dummy shingles are constructed of a back layer of masonite with a bonded cover of hypalon. This provides a dummy shingle with the same thickness as the "active" modules for smooth transitions of the rakes and ridge of the roof. This type of dummy shingle was eventually replaced with a conventional asphalt shingle material built up to the required thickness.

2.2.2 MODULE MOUNTING DETAILS

The shingle module can be classified as a direct-mount system installation. It provides a weather-tight roof surface by virtue of its overlapping installation which is similar to a conventional asphalt shingle roof. Figure 2-12 shows a schematic of the overlapping technique on top of the roofing felt.

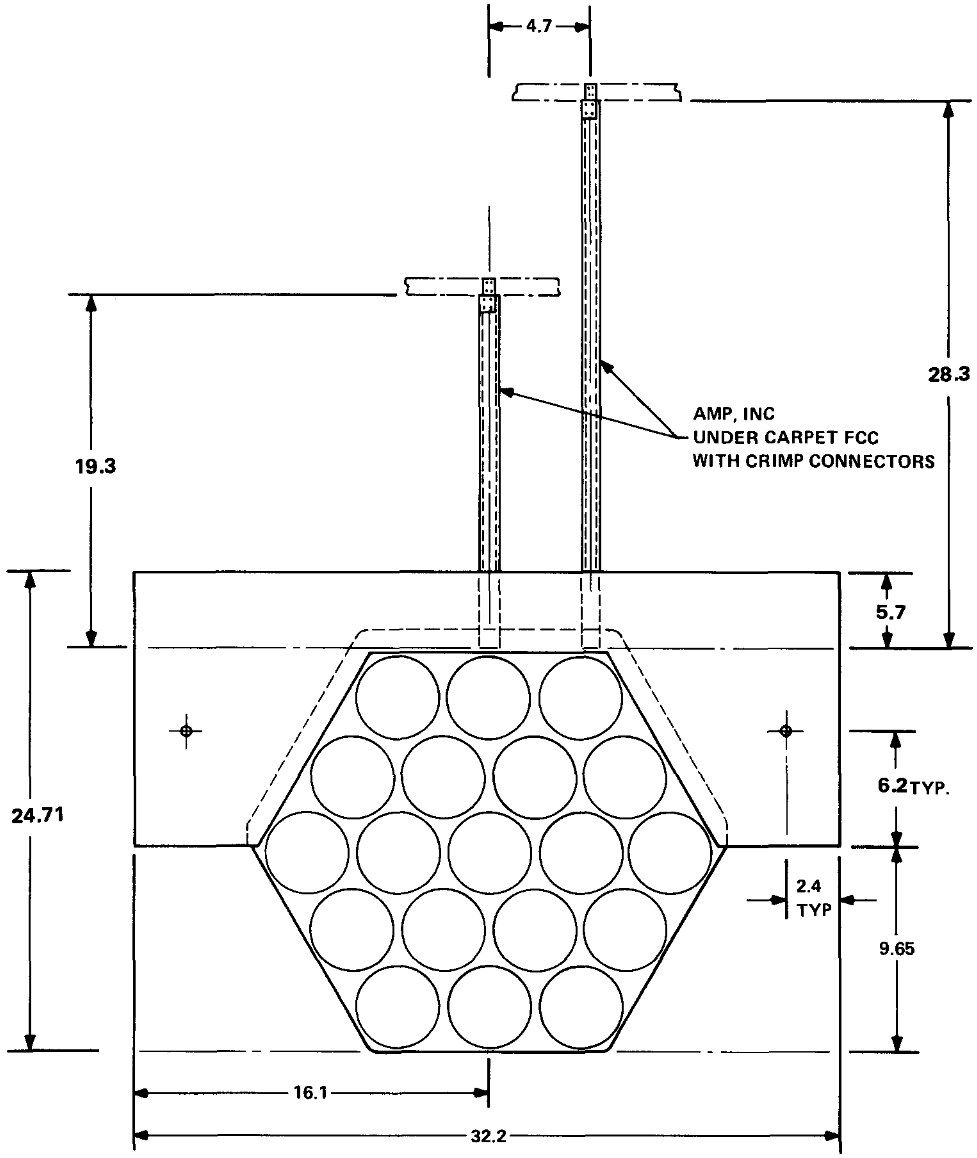


Figure 2-11 Dimensions of the Block IVA Shingle Module

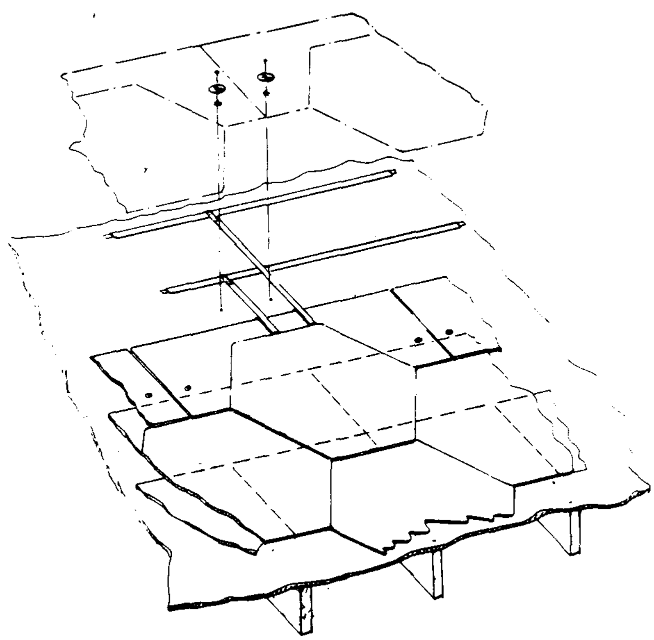


Figure 2-12. Typical Overlapping Module Installation Technique

The mechanical attachment of the module to the roof sheathing uses a special split washer under the roofing nailhead as shown in Figure 2-13. Two through holes, which are larger than the nailhead but smaller than the washer diameter, are provided in the module substrate at the locations indicated in Figure 2-11. The use of the large split washer under each nailhead permits the release of these attachments to the roof sheathing after the roof has been completely installed. A slender tool, which can be easily inserted between the shingle layers, can be engaged with the slot in the split washer and used to extract the washer, thereby releasing the tension load at the attachment point and permitting the shingle to be removed. Figure 2-14 shows the nail and washer mounting of two adjacent modules.

The weight of the installed photovoltaic roof array is approximately 20 kg/m^2 (4.1 lb/ft^2), which permits installation on conventional roofs without structural modifications.

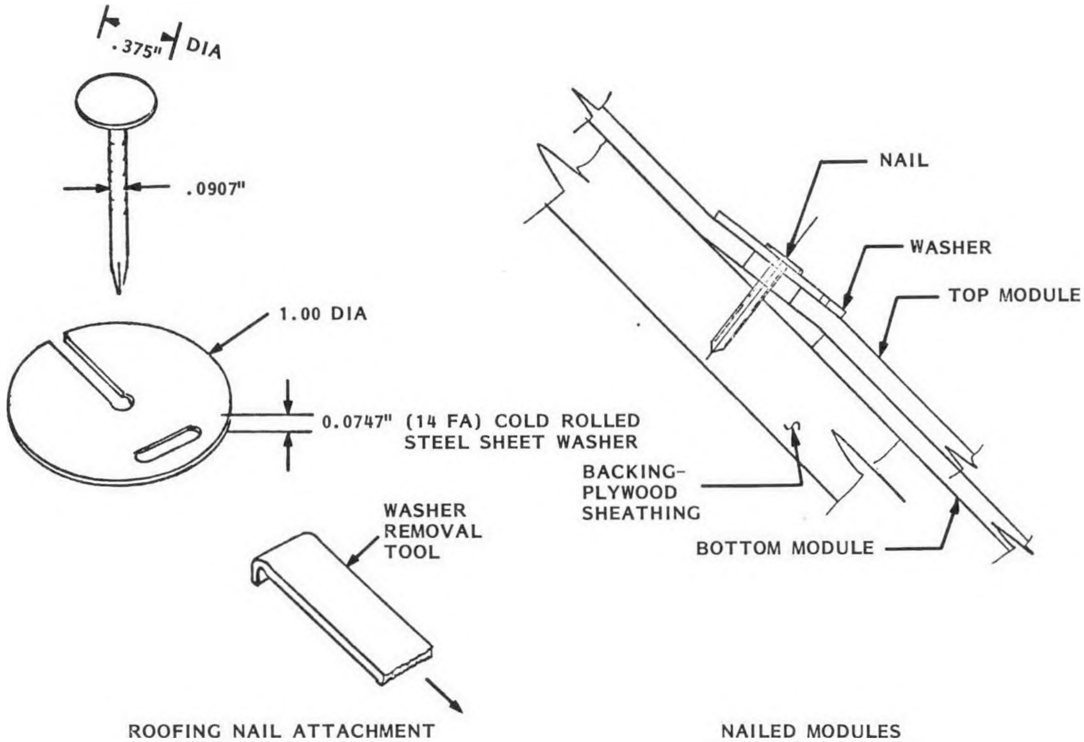


Figure 2-13. Roofing Nail Attachment of the Block IVA Shingle Module

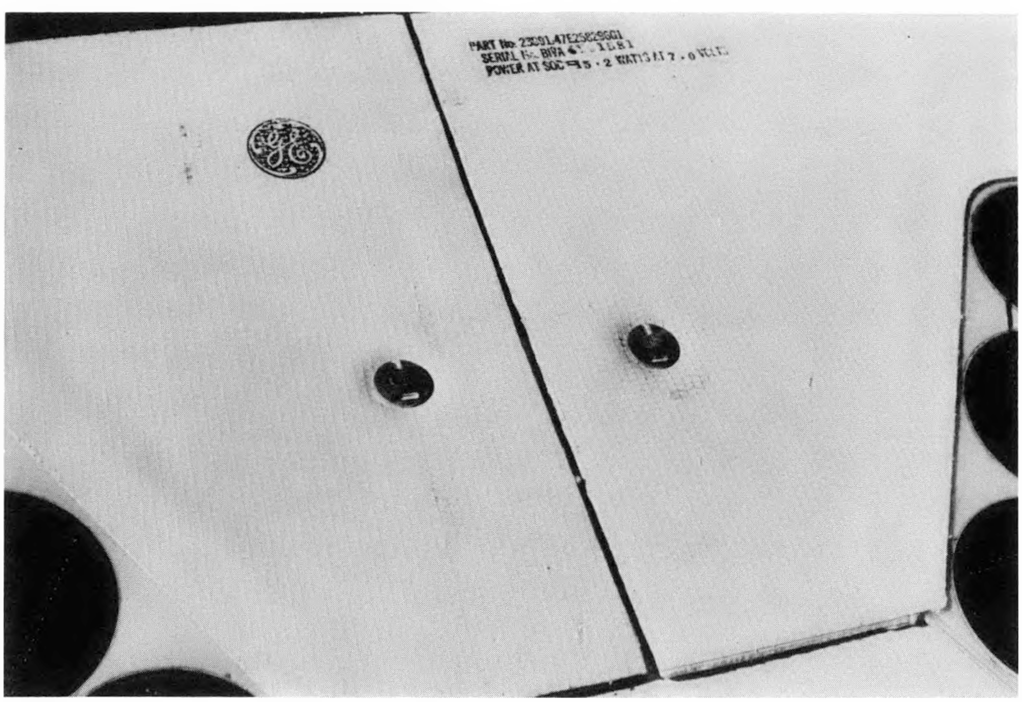


Figure 2-14. Mechanical Module Mounting

2.2.3 MODULE MOUNTING PROCEDURE

The installation starts with standard black roofing felt paper covering the plywood sheathing. Dimensional lines are marked on the felt to position horizontal FCC wire runs and the initial shingle course positions. The horizontal FCC runs are located based on established dimensions from the eave, Figure 2-15, and are attached to the felt by periodically taping. The positive and negative FCC runs, at the ridge and eave of the roof, respectively, are the system busbars and are routed to a selected location near the ridge. Ultimately, they transition to round conductors in an enclosed terminal block. The installation of shingle modules starts at the eave with the placement of two courses of dummy shingles which function to preserve the watertightness of the roof along this edge, as shown in Figure 2-16. The first course of active shingle modules is nailed in place. The negative FCC cables of these modules are attached to the first row of FCC cable which becomes the system negative busbar. The positive leads of the first row of PV shingles are attached to the second row of FCC cables (Figure 2-17). The FCC cables are folded as shown in the figure for replacement if required. The next row of modules can then be nailed in place and electrical connections made, Figure 2-18.

To proceed up the roof, ladders with horizontal planks provide a convenient work platform (Figure 2-19). The ladders are shown mounted from the ground, however, on an actual house installation they could be hooked and secured over the ridge. The platform is easily moved to adjust the working level up the roof (Figure 2-20).

Modules are installed to within a few feet of the roof peak. Dummy shingles are used to complete the weather seal at the ridge of the roof and also along the two edges. Note that moderate pressure from leaning against the modules is allowed.

The complete array installation procedure is summarized in Figure 2-21. A set of installation safety notes is included in Appendix A.

2.2.4 INVERTER PHYSICAL DETAILS

The power conversion subsystem consists of the basic inverter, a DC input filter, a controlled ferro-resonant transformer, maximum power tracker and amplitude control and sensing circuits. The complete subsystem is packaged into a single

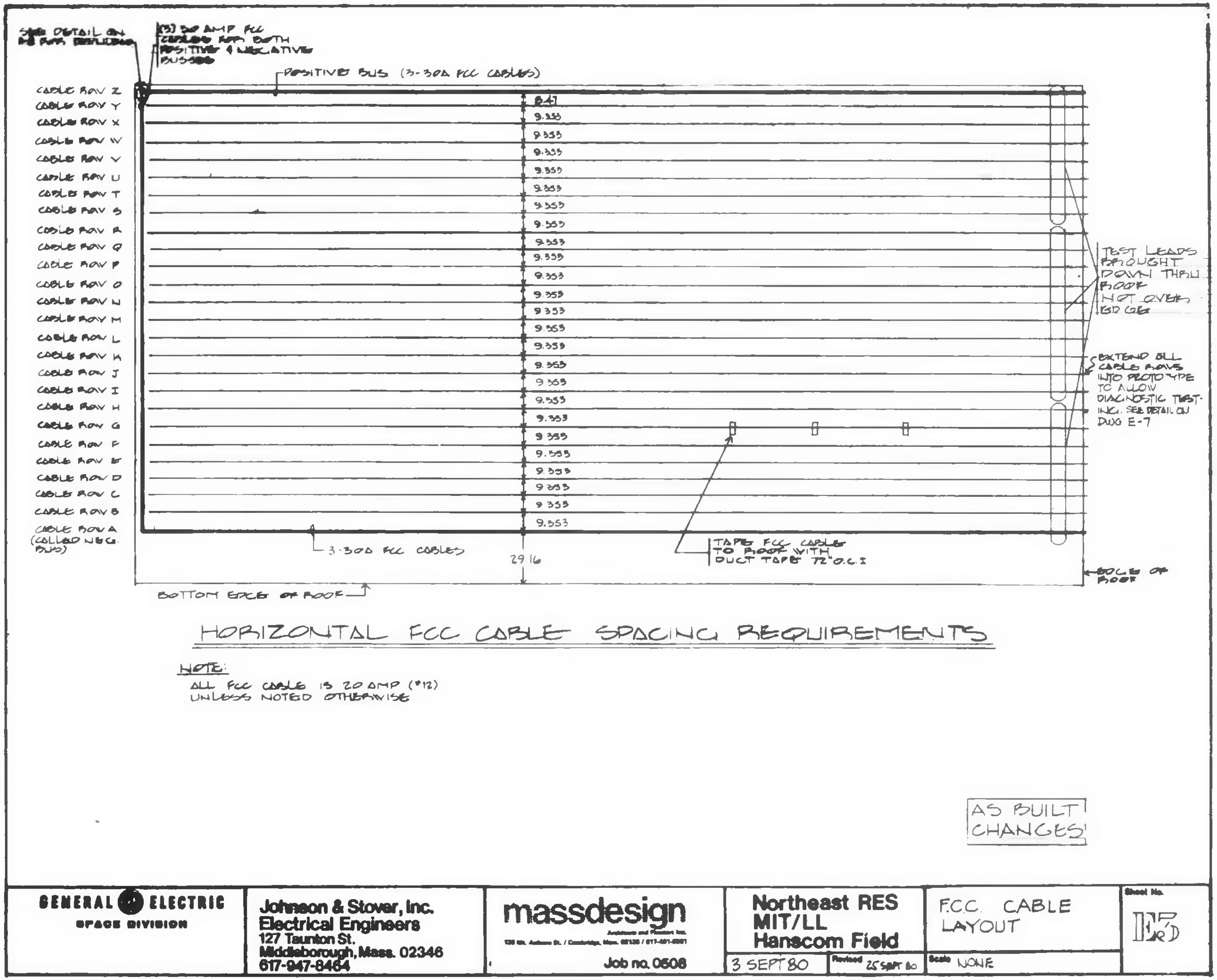


Fig. 2-15. FCC Layout on the Roof.

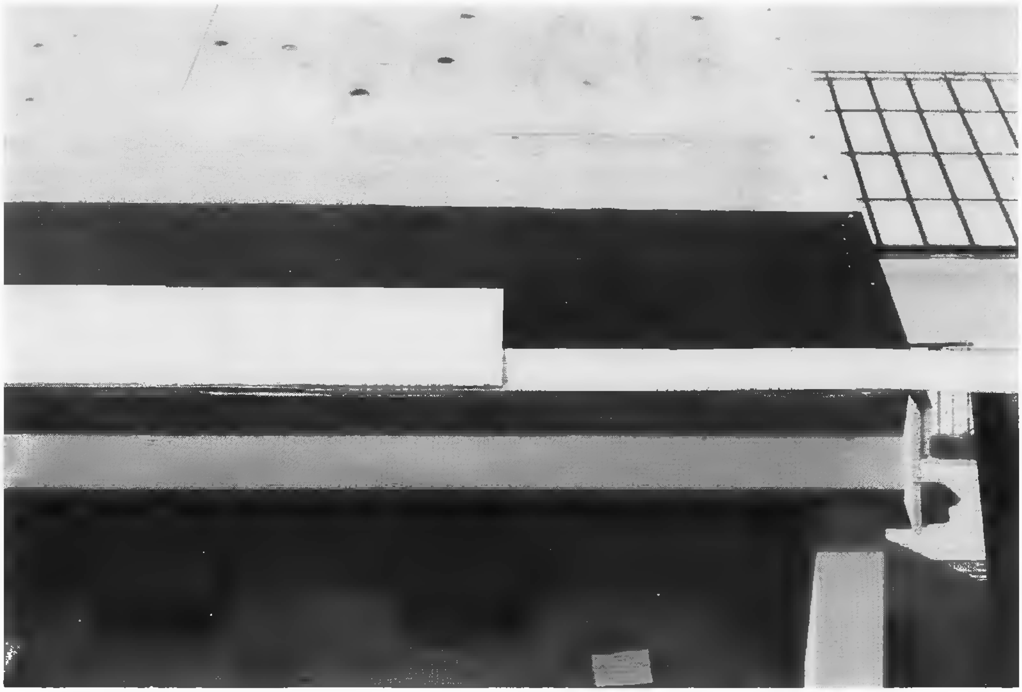


Figure 2-16. Two Rows of Dummy Shingles

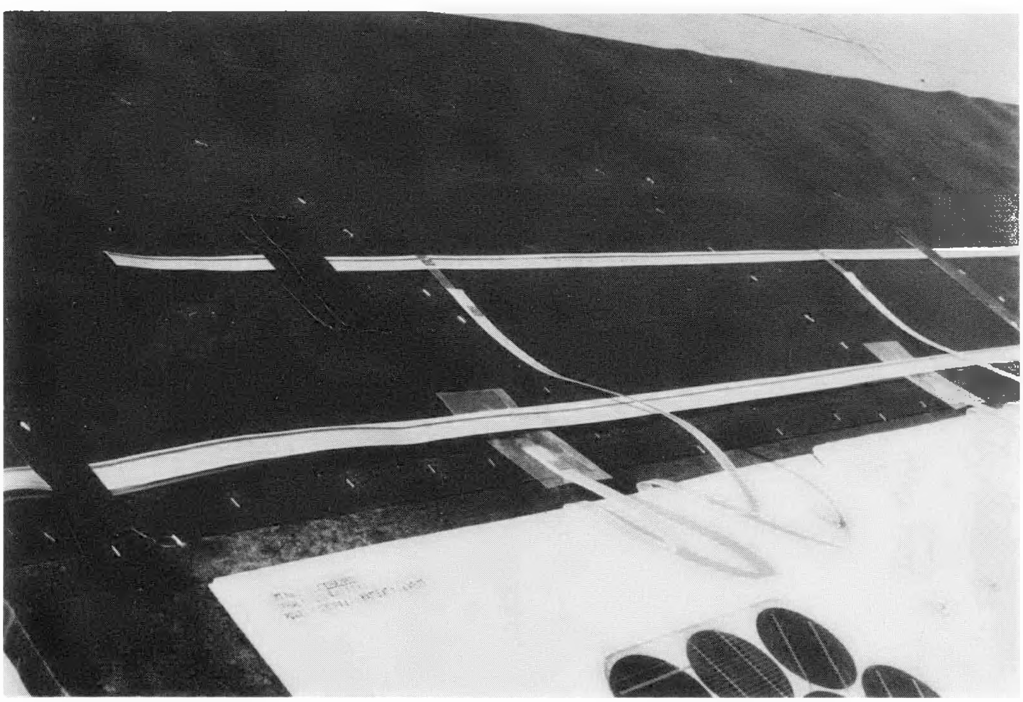


Figure 2-17. Electrical Connection of the Modules

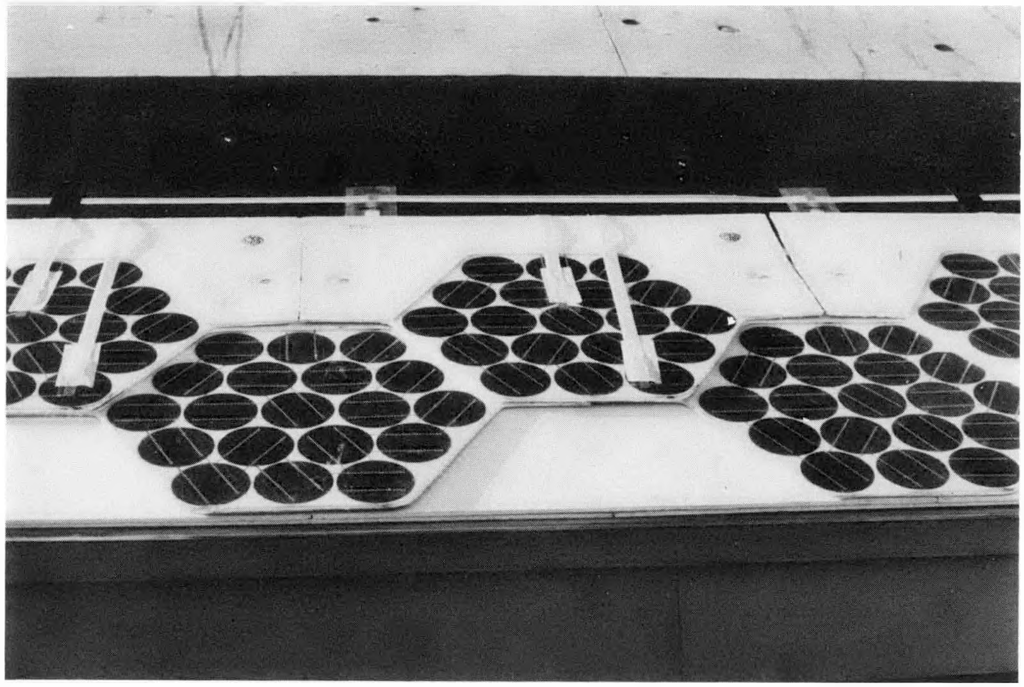


Figure 2-18. Two Rows of Installed Modules

Figure 2-19. Ladder/Platform Installation Technique

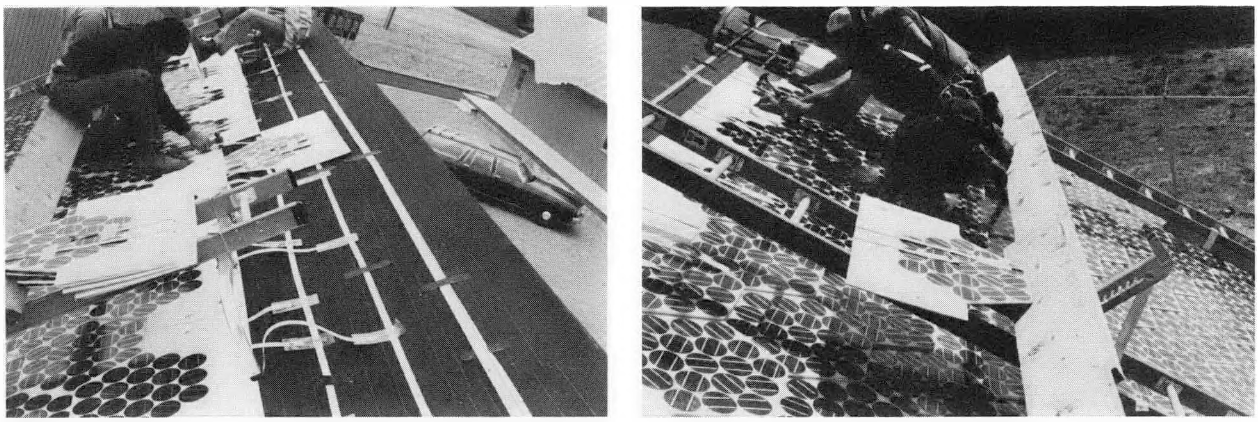


Figure 2-20. Module Installation Near the Roof Ridge

unit. The unit is floor mounted as shown in Figure 2-22. The unit dimensions are 1.6m high by 0.6m wide and 0.76m deep. Both front and back doors are provided on the unit for access to the circuitry. A thermostatically controlled fan is included in the unit to dissipate heat.

2.2.5 INVERTER INSTALLATION REQUIREMENTS

The Sunverter is a four wire unit, i.e., 2-wire DC input and 2-wire 240 VAC output. The unit is floor mounted as previously stated and should be located with sufficient open area around it to permit adequate heat dissipation. No additional specific mechanical installation requirements exist for the unit. The unit is mounted on casters for easy movement.

2.3 ELECTRICAL DESIGN

The electrical system is connected in parallel and synchronized with the utility. The system provides energy for both space conditioning and conventional household electrical load requirements. Power generated by the array in excess

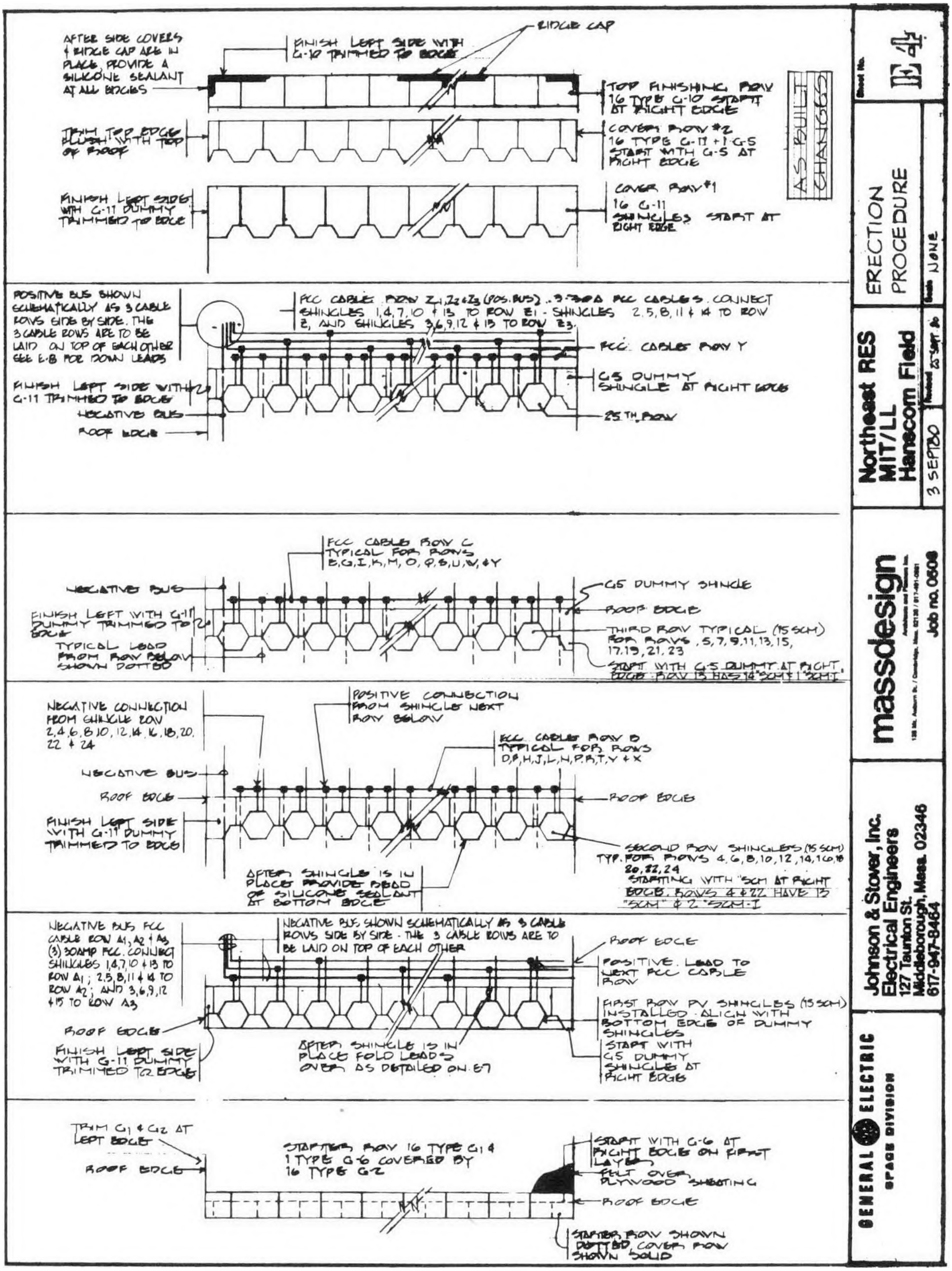


Fig. 2-21. PV Shingle Installation Procedure.

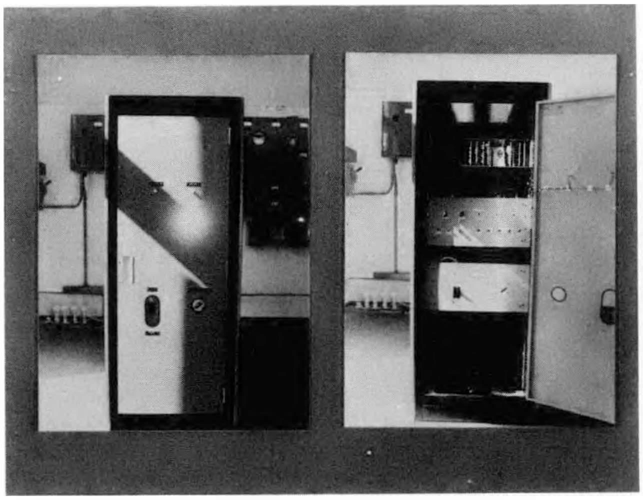


Figure 2-22. Abacus Power Conversion Unit

of residential loads is fed back into the utility grid. Residential loads in excess of the array power draw power from the utility grid. With this arrangement, all house demands are met, no electrical storage is required, and all net energy output of the photovoltaic system is used.

The system does not use blocking diodes due to the highly redundant series/parallel module network. However, due to this arrangement, the system is not designed to be short circuited for extended periods. Short circuit conditions are not anticipated in the normal residential installation.

Complete system installation specifications developed by Johnson & Stover are included in Appendix B.

2.3.1 MODULF ELECTRICAL CHARACTERISTICS

The GE Block IVA shingle module shown in Figure 2-8 consists of 19 series-connected 100-mm-diameter silicon solar cells. The module I-V characteristics are shown in Figure 2-23. The modules produce 15.W under typical operating conditions (100mW/cm^2 insolation, NOCT = 68^{o}C, and 20^{o}C ambient). The module has no internal diodes.

2.3.2 ARRAY ELECTRICAL CONFIGURATION

The solar array consists of 375 shingle modules connected electrically in a highly redundant series/paralled circuit arrangement with 25 modules in series and 15 parallel circuits. The module electrical circuit terminates in positive and negative busbars which are connected to cabling, run in conduit to the equipment room. The negative busbar is grounded. Figure 2-24 shows the overall array layout with each module assigned an identifying number. The electrical schematic of the series/parallel network is shown in Figure 2-25. With this highly redundant network no diodes are required in the array.

The electrical interconnection between modules is achieved with the UL-approved AMP FCC cables and crimp connectors discussed in Section 2.2.1. Connections are simply made with a crimping tool as shown in Figure 2-26. Insulating patches with adhesive are then placed over the connection to complete the installation.

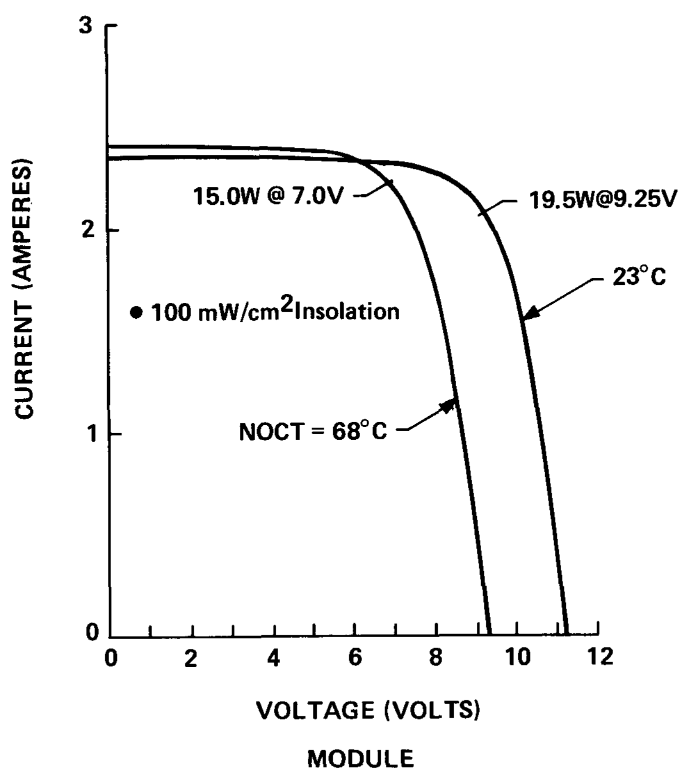
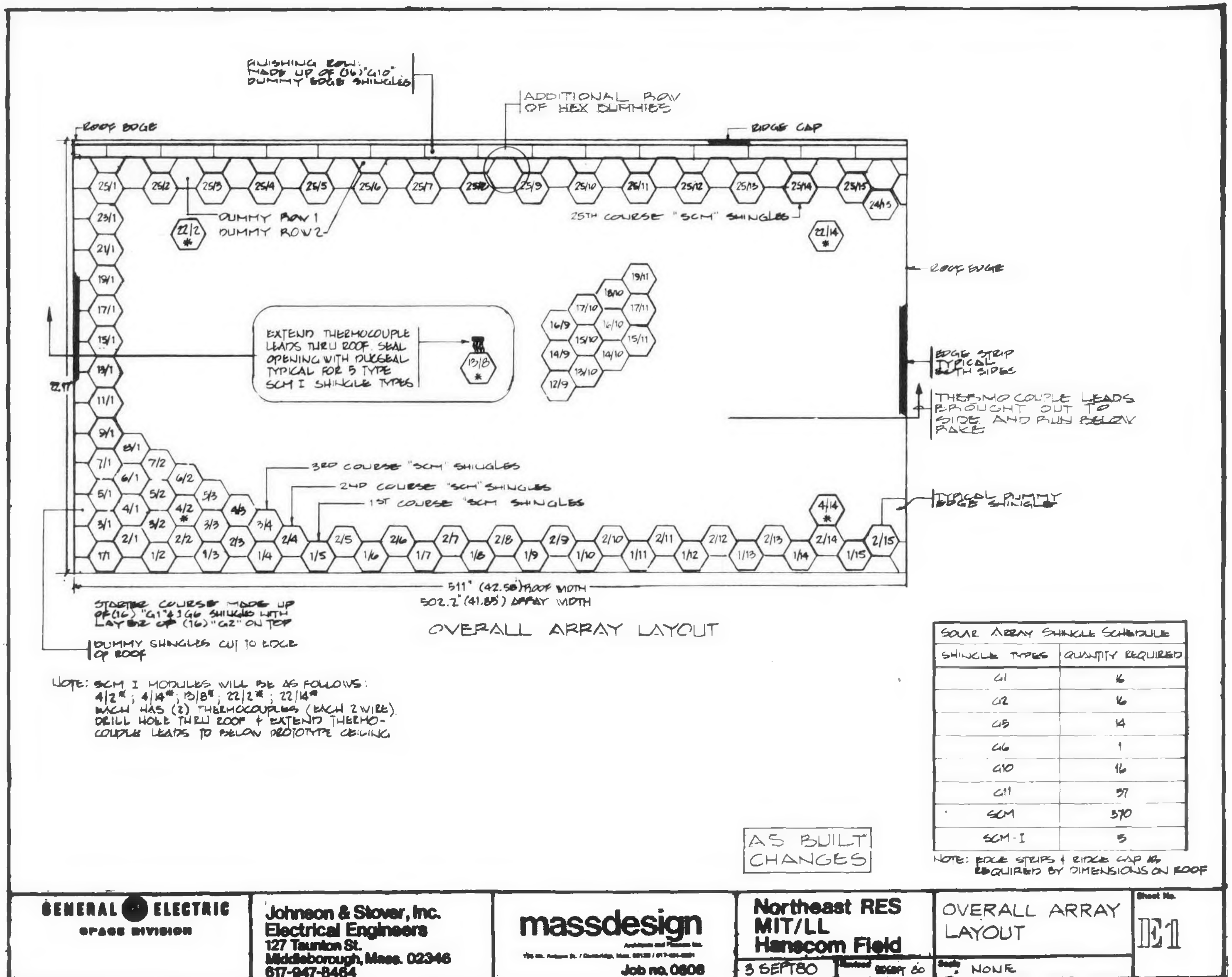


Figure 2-23. Module I-V Characteristics



SOLAR ARRAY SHINGLE SCHEDULE	
SHINGLE TYPES	QUANTITY REQUIRED
G1	16
G2	16
G5	14
G6	1
G10	16
G11	57
SCM	370
SCM-I	5

Fig. 2-24. Overall Solar Array Layout

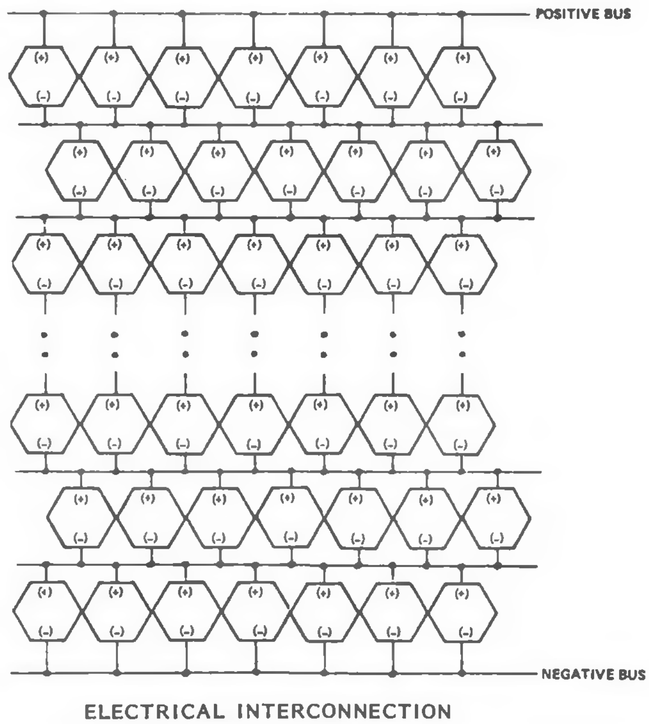


Figure 2-25. Solar Array Electrical Schematic

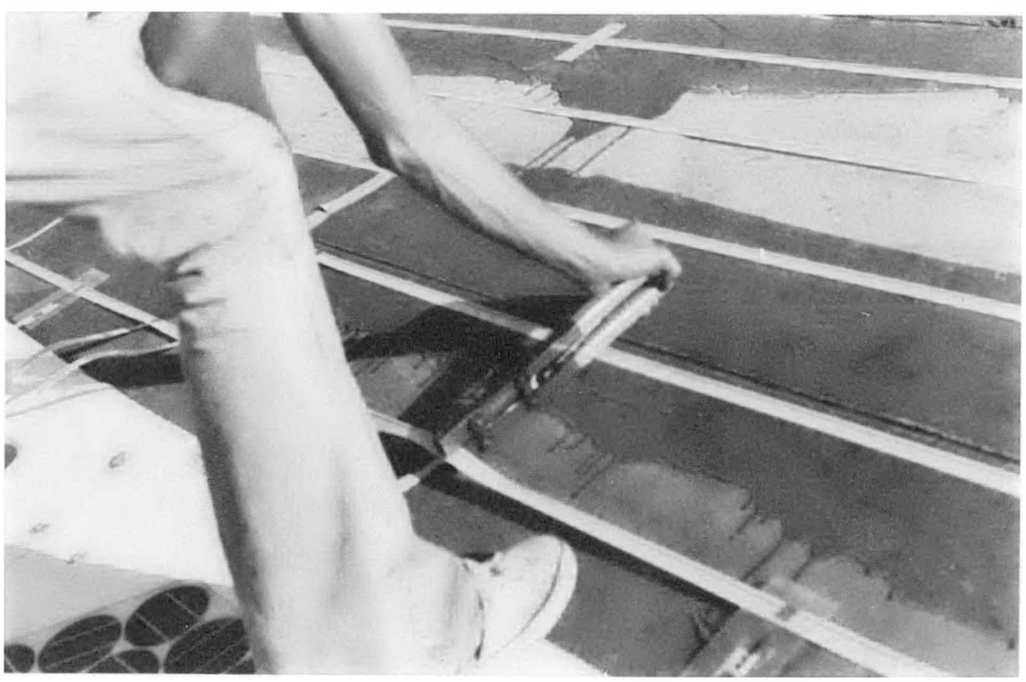


Figure 2-26. Use of the Crimp Tool for Module Interconnection

The modules are connected in series up the roof. Figure 2-27 shows this electrical interconnection. Note that the first row of FCC cable becomes the negative bus with only negative lead connections. Similarly, the last row connections are all positive connections forming the positive bus, Figure 2-28. Since the FCC is only available in #10 AWG or #12 AWG equivalent cable a triple layer of #10 is used for both buses and 1/3 of the modules in the first and last rows are connected to each layer to distribute the current in the cables.

Figure 2-29 shows typical interconnections for the whole array. The series circuits zig-zag up the roof.

The negative bus is run underneath the shingles along the rake to the ridge as shown in Figure 2-15. At the ridge, both the negative and positive FCC buses are fed through the rake (Figure 2-28) to a transition box. The transition box is supplied by AMP. The three negative and positive FCC buses are connected to a set

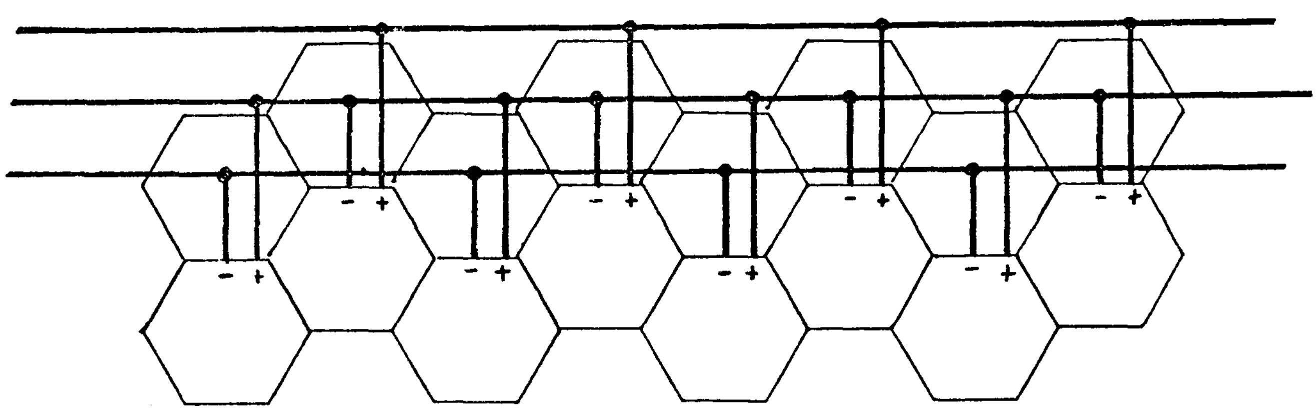


Figure 2-27. Electrical Interconnection Arrangement for the Single Module

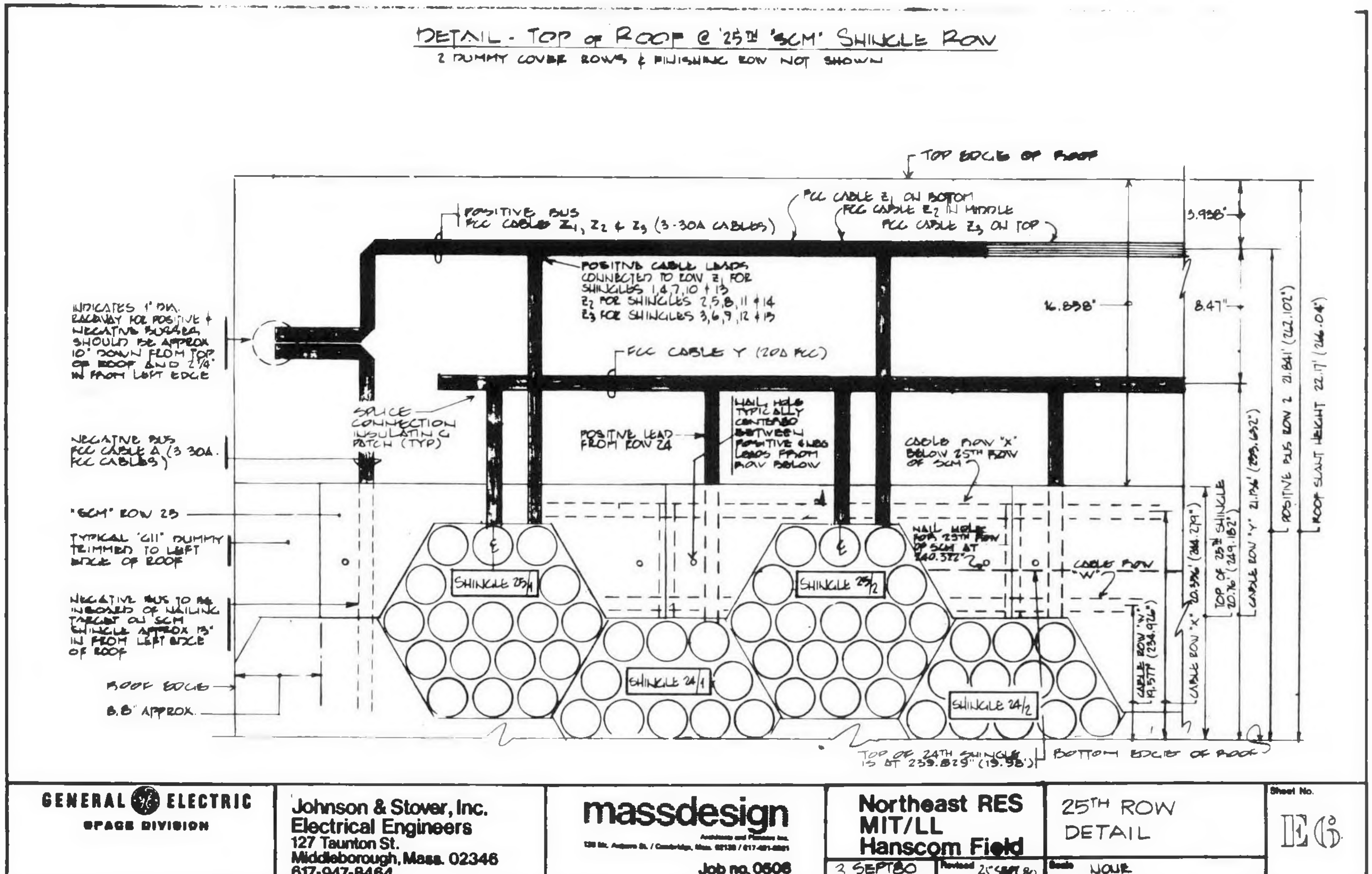


Fig. 2-28. Positive Bus Connections

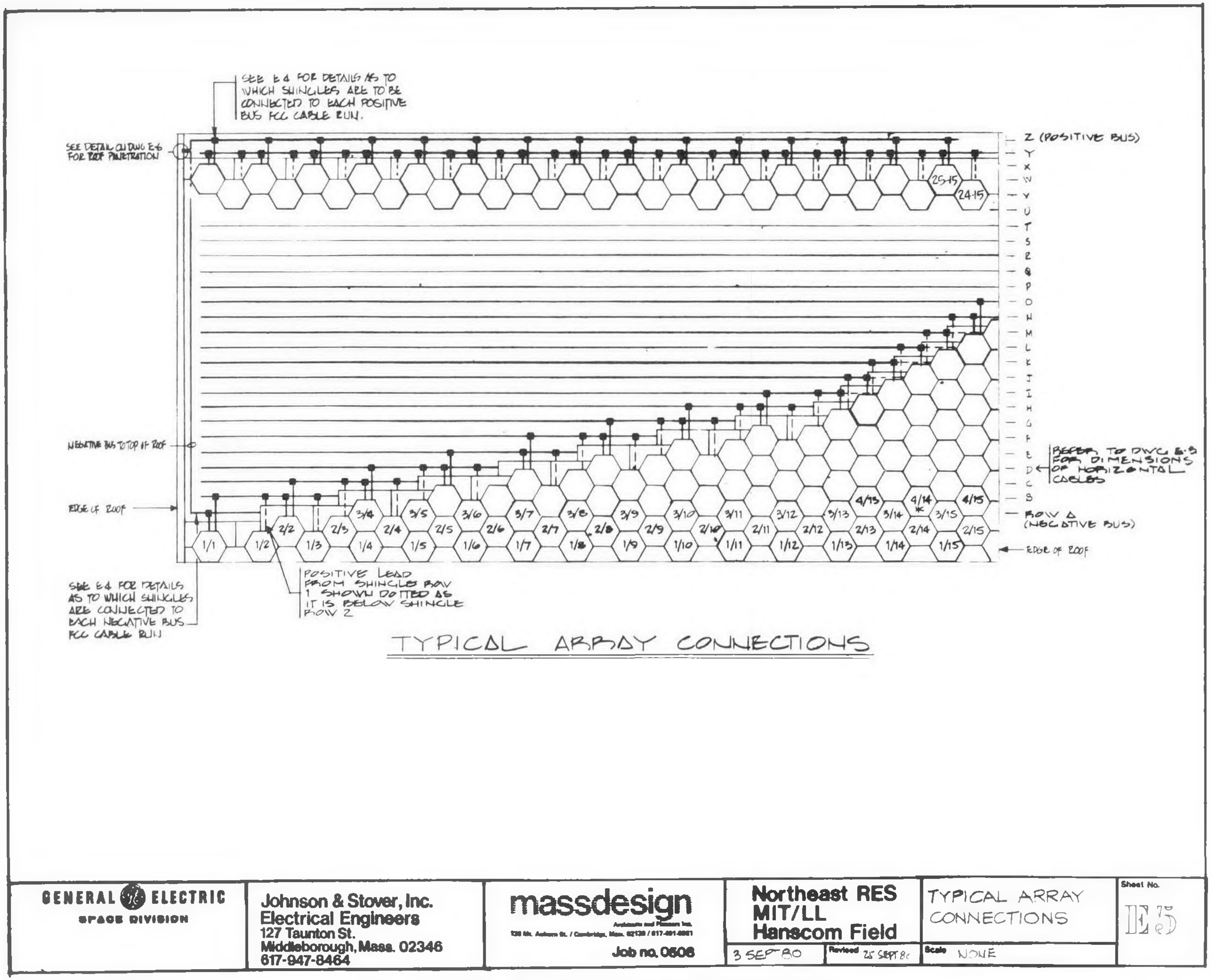


Fig. 2-29. Typical Array Connections

of copper plates which also have lug terminals for standard round AWG #6 cables. Thus, the transition of the FCC buses to round cable is achieved as shown in Figure 2-30. The buses are then fed to an external disconnect as shown in Figure 2-31. This service would be installed alongside of the conventional utility service to show the dual power sources.

2.3.3 SYSTEM ELECTRICAL DETAILS

A block diagram of the system components is shown in Figure 2-32. The major functional elements of the system, beside the array and the inverter are described briefly.

Transformer - The transformer provides both isolation of the AC and DC circuits and matching of the normal AC line voltage to the output DC voltage of the array.

DC Filter - This filter smooths the DC current flow which is subject to high harmonics as a result of the switching action of the thyristor valves.

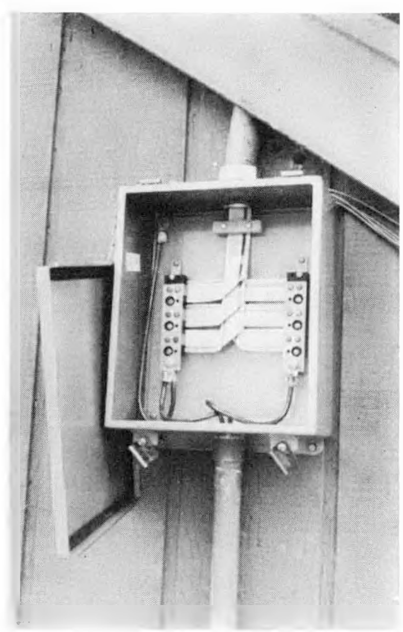


Figure 2-30. Transition Box Wiring

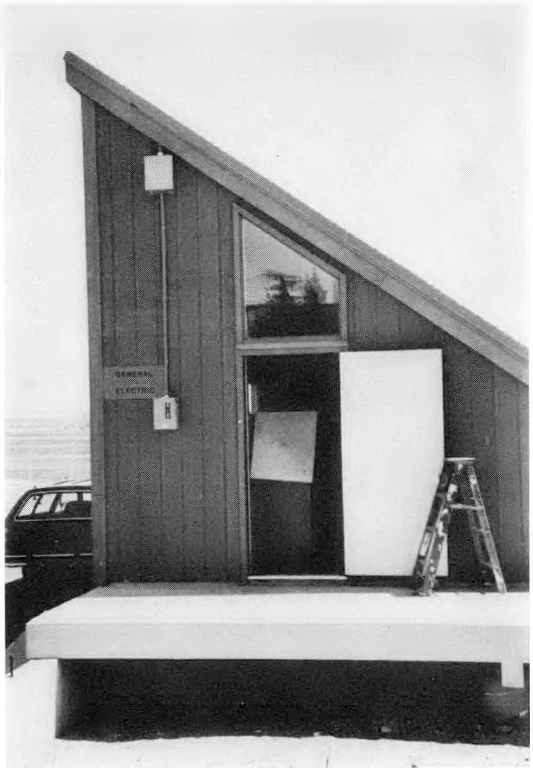


Figure 2-31. DC Power Drop Line

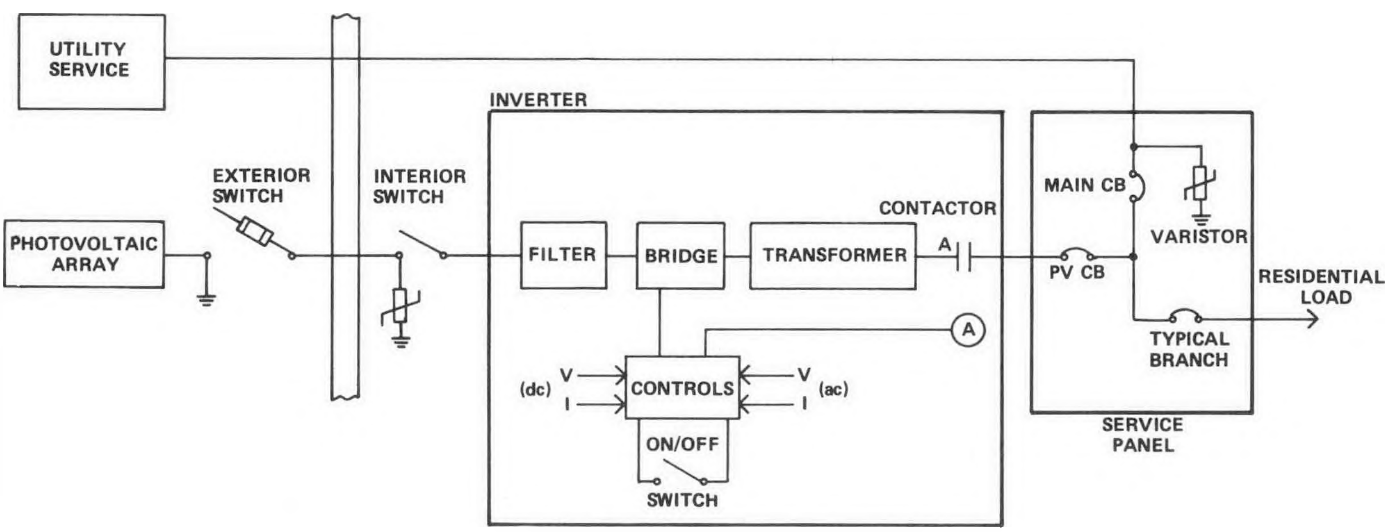


Figure 2-32. Residential Photovoltaic Block Line Diagram

Inverter Controls - These controls provide the timing signals for firing of the thyristor valves and, in turn, control the level and direction of power flow through the power conversion system.

Maximum Power Control - This control circuit modifies the inverter timing control circuit in a manner to operate the array at its dynamic maximum power point.

RFI Filter - This filter attenuates high frequency output harmonics to minimize radio and TV interference.

Input DC Contactor - This contactor closes only when the AC Line Contactor is closed.

Output AC Contactor - This contactor closes only when the array available output power is greater than the (PCS) no-load losses.

Exterior Array Fused Switch - This switch provides a visible exterior disconnect, and is fused only if required by a strict code interpretation, since array short circuit current is only slightly over full load current.

Varistors - Induced lightning transient protection for the inverter and household equipment is provided by the varistors on the DC and AC residence input lines.

Interior Disconnects - Isolation of the PCS for installation and service is provided by the interior DC switch and the circuit breaker in the service panel. The circuit breaker also protects the main service from short circuits in the inverter array system.

The system wiring details and specifications are summarized in Figure 2-33. An unfused disconnecting means is provided in the equipment room. This provides array isolation, in conjunction with the 60-amp breaker in the main panel should it be necessary to perform maintenance on the inverter equipment. Both positive and negative legs of the DC system are surge suppressed with varistors on the array side of the switch. This allows surge protection of the array even if the interior disconnect switch is open. Beyond the interior disconnect switch, the DC

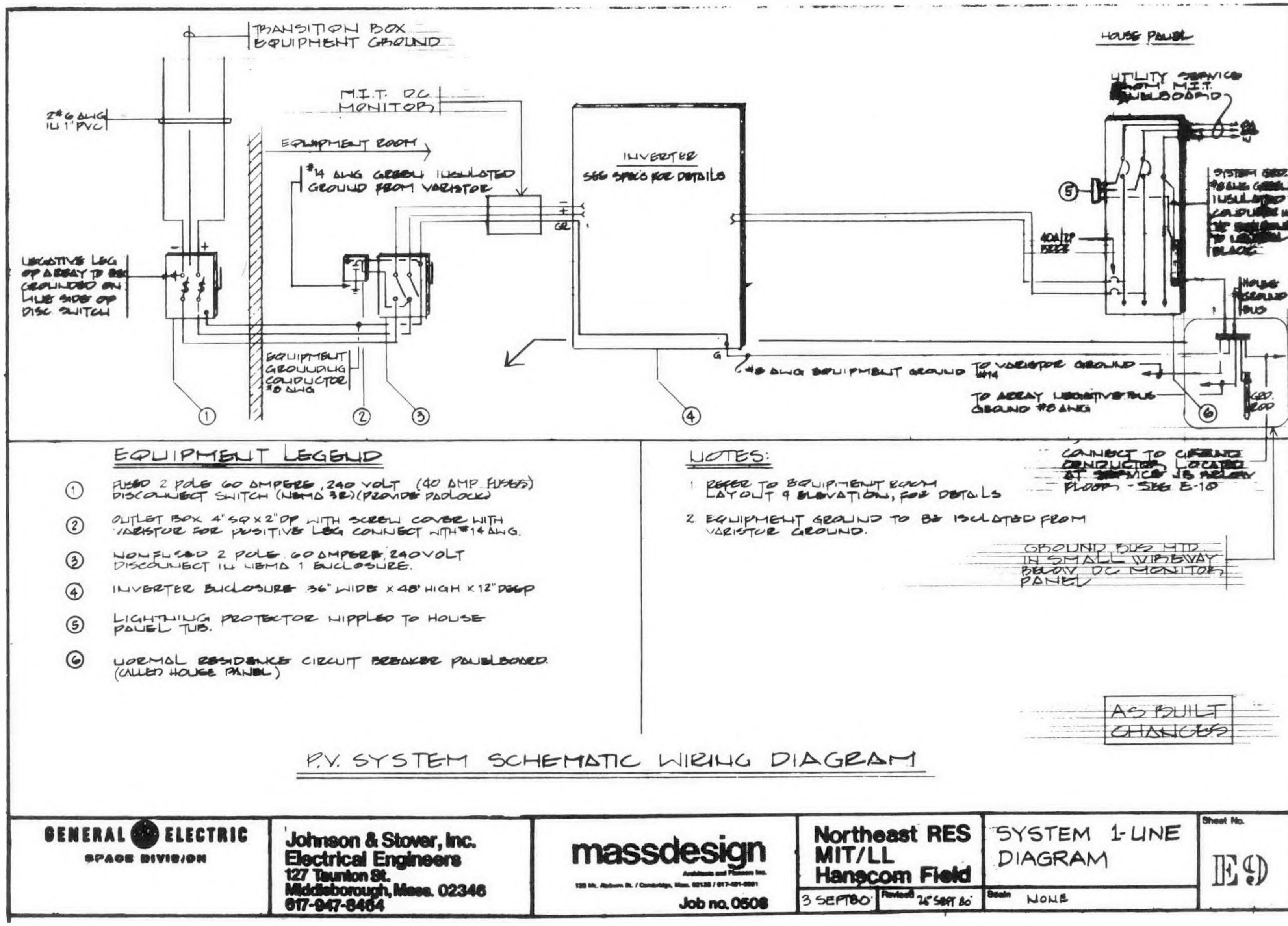


Fig. 2-33. System Wiring Schematic

power is carried through a raceway system to the inverter enclosure. The inverter's AC output connects to the service panelboard through a raceway. The service panelboard is provided with residential type lightning arrestors to provide inverter output circuit protection to induced voltage surges.

An exposed copper house ground bus is located directly below the service panelboard. This provides a visible and accessible means for terminating all grounding conductors. The equipment area contains all major equipment associated with the photovoltaic system with the exception of the solar array.

Service entry to the equipment area from the outside disconnect switch is via a thru-wall nipple. Typical equipment placement is shown in Figure 2-34. Wall installed equipment is mounted on a 3/4-inch plywood backboard. The inverter is floor mounted. Figure 2-34 also includes an equipment room elevation depicting interconnecting wiring with respect to the equipment placement plan. A tabulation of major equipment is listed in Table 2-1.

Table 2-1. Major Electrical Equipment List

- DC Power Transition Block
- Fused, 2-Pole 60-Ampere, 240 Volt Exterior Disconnect Switch
- Varistors, GE Type V275LA40B
- Nonfused 2-Pole, 60-Ampere, 240 Volts Interior Disconnect Switch
- Varistors, GE Type TLP175
- House Circuit Breaker Panelboard
- Utility Service Meter Socket

Figure 2-35 shows a photograph of the inside equipment. The photograph also shows the MIT/LL supplied instrumentation equipment and location. Only the floor mounted inverter and MIT/LL load duplication equipment are not shown in the photo. The basic lighting and power layout of the prototype structure independent of the PV system is shown in Figure 2-36.

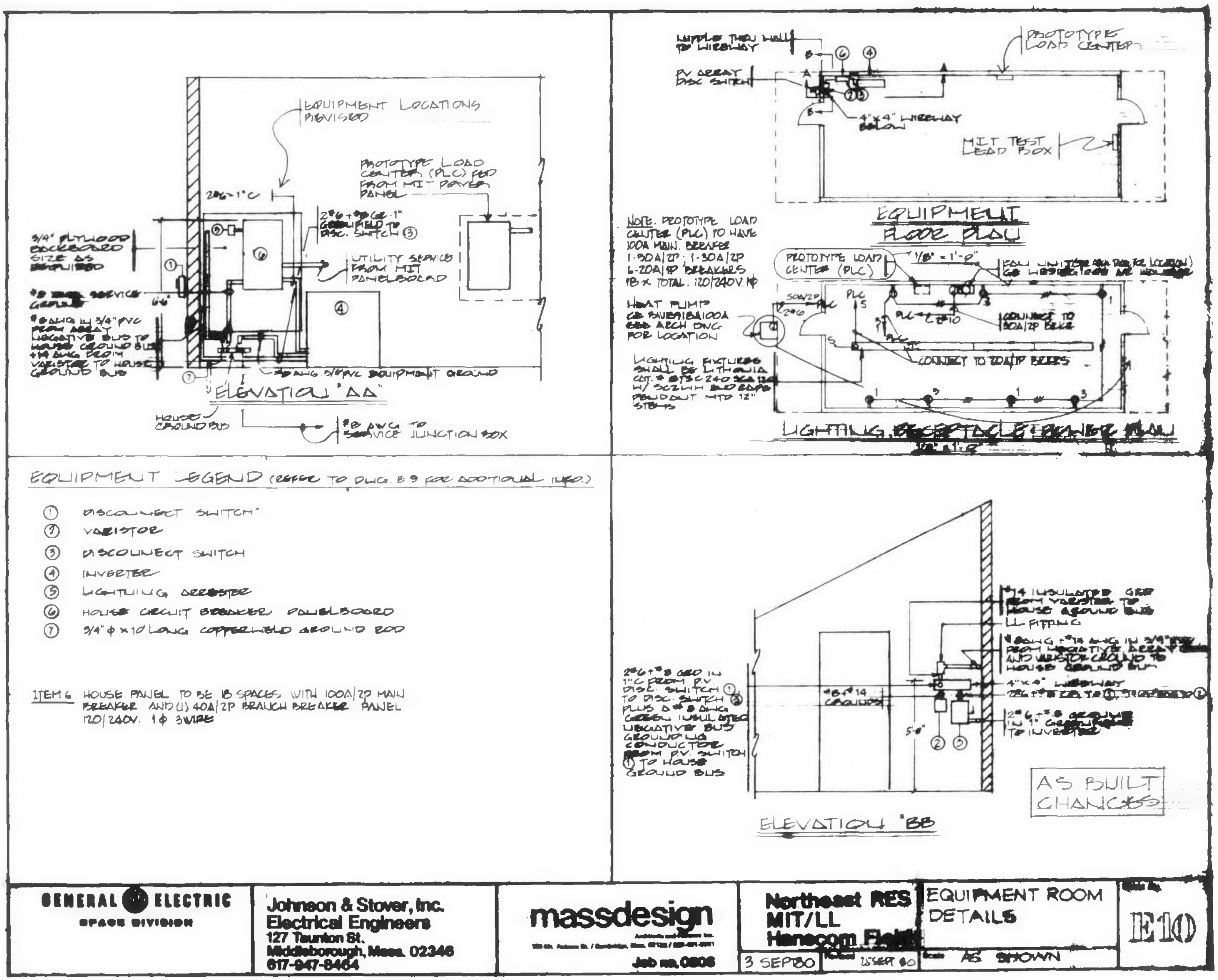


Fig. 2-34. Equipment Area Layout

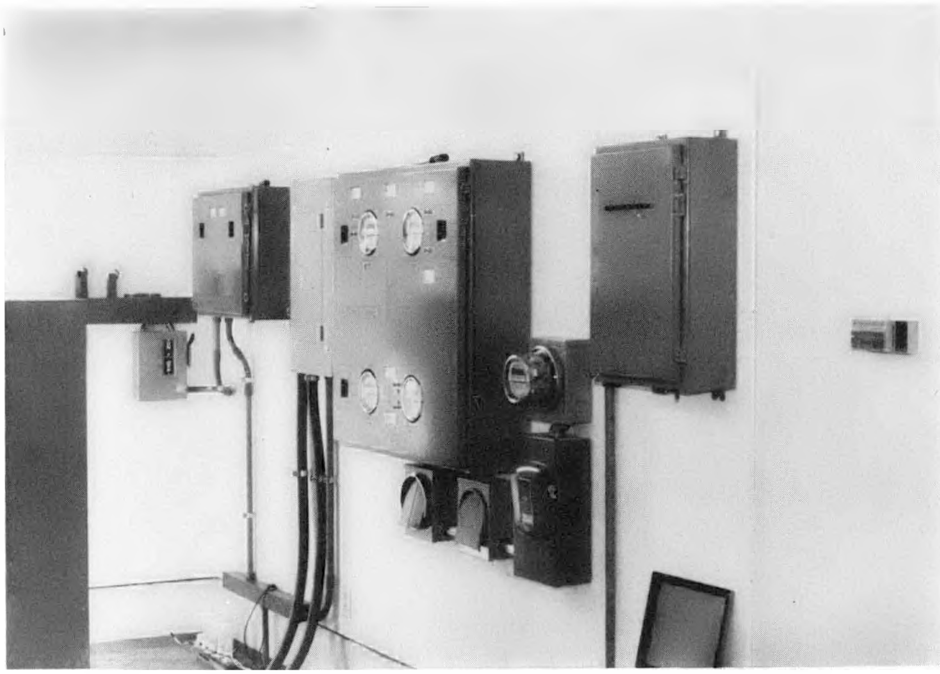


Figure 2-35. Equipment Installation

2.3.4 POWER CONVERSION SUBSYSTEM CHARACTERISTICS

The PCS specification (Appendix C) meets the electrical requirements of the system design. The Abacus inverter is a dual bridge unit using power transistors with digital sine wave synthesis to produce an output current with low total harmonic distortion at the utility line voltage. A functional block diagram for the inverter is shown in Figure 2-37. The digital pulse pattern is selected to eliminate low order harmonics, and a simple LC filter reduces the higher order harmonics, resulting in total harmonic distortion of only 5%. The output current is phase locked to the utility voltage, resulting in unity power factor. Adjustment of the inverter impedance presented to the array in the maximum power tracking mode is controlled by an output current amplitude sensing circuit.

The functional requirements for the Abacus inverter for this application are listed in Table 2-2.

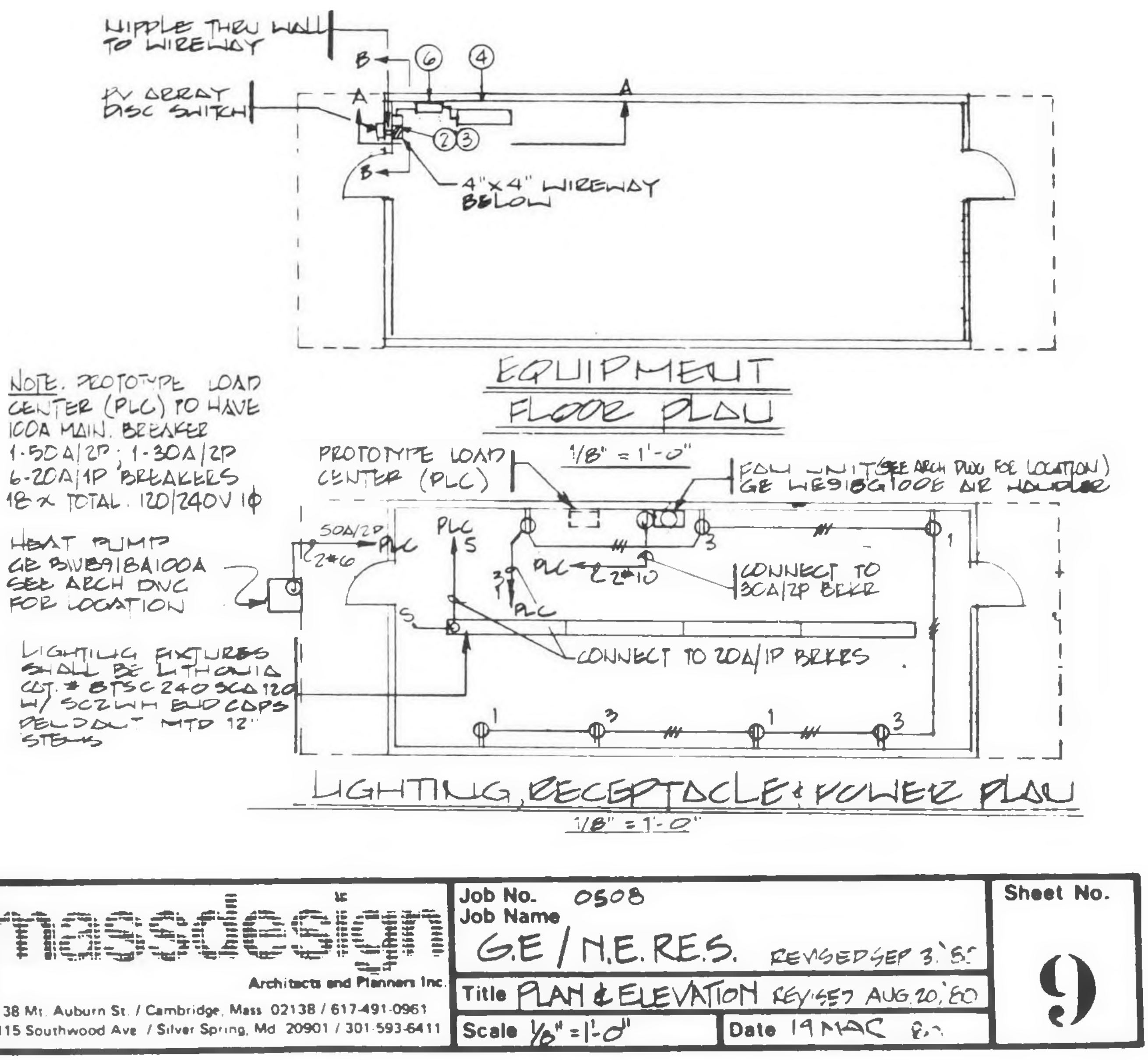


Figure 2-36. Prototype Lighting Power Plan

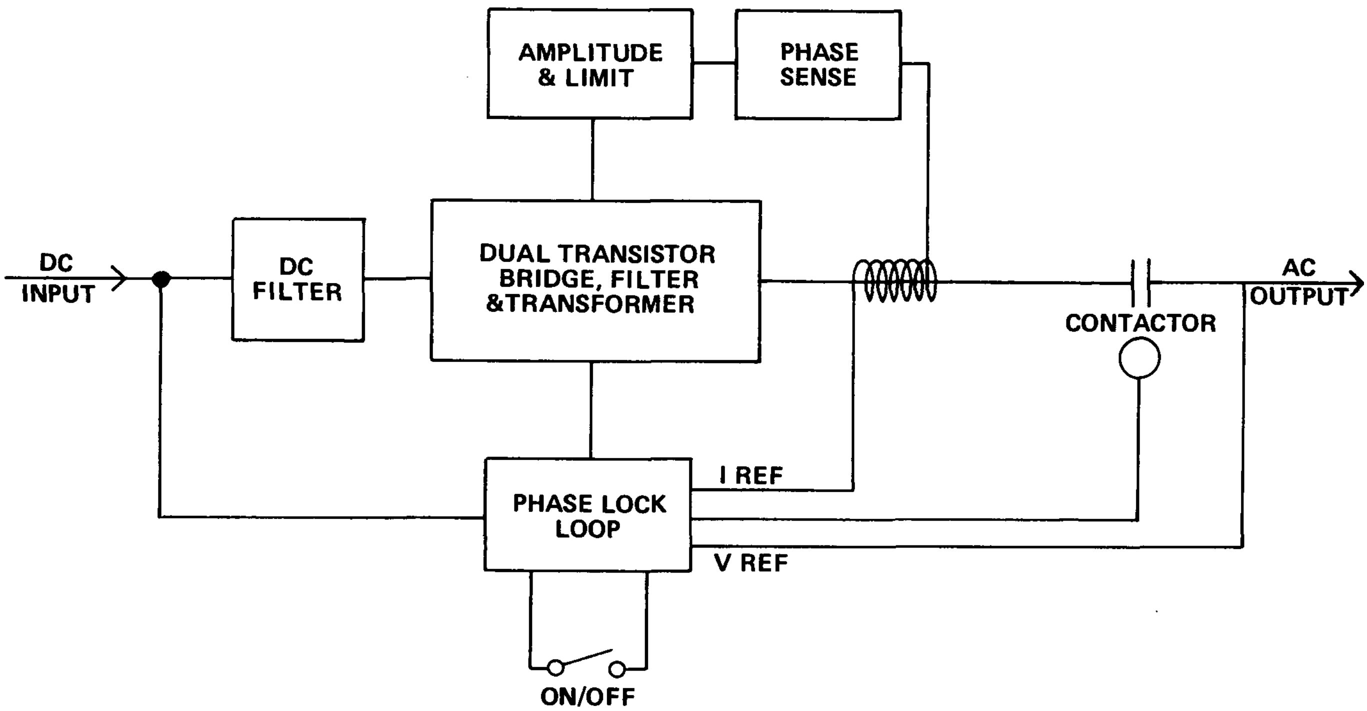


Figure 2-37. Inverter Functional Block Diagram

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

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

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

Table 2-2. Abacus Inverter Functional Performance

- Nominal Rating — 6 kW continuous operation; input 200 Vdc; Output 240 Vac, single phase, 60 Hz.
- Utility line voltage output control
- dc to ac transformer isolation
- Inverter operation enable/disable front panel switch control
- Automatic Operation enabled by switch and presence of utility voltage within limits of 240 Vac ± 10% on output. Automatic operation disabled by switch or ac voltage outside limits
- Start automatic operation when enabled and input power exceeds operational tare loss
- Operate automatically to adjust the input voltage over the range of 160 to 240 Vdc and produce the maximum power output ± 1%; operate at the range limit if the maximum power output requires adjustment beyond the range limit.
- Stop automatic operation when disabled or input does not exceed operation-at tare loss; automatic start shall be delayed 4 ± 1 minute following an automatic stop.
- Efficiency greater than 87% from 20% to full load
- Operational tare loss less than 250 watts
- Unity power factor
- Total harmonic distortion less than 5%
- Safety features
  - ac and dc "on" light
  - input and output fuses
  - manual reset on ac line loss
  - internal temperature controlled fan with automatic over temperature turnoff

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

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

Because of the high efficiency of the 763-4-200, cooling fans are connected through thermal switches which turn the fans on during high ambient temperature conditions. Cooling air exits at the top of the unit. Estimates of the inverter performance is shown in Figure 2-38.

2.3.4.1 Automatic Control Algorithm

The inverter's control circuits are continuously powered as long as the utility line is energized. When the DC solar array voltage reaches 180 volts, the following sequentially occurs: 1) a 5 volt signal is sent to the Phaselock Loop, 2) the Maximum Power Tracking (MPT) is energized at a predetermined set point, and 3) the AC line contactor is closed when the correct voltage and phase relationship are established. Under normal conditions, the MPT samples the AC output power through a sample-and-hold circuit. This insures the solar array is

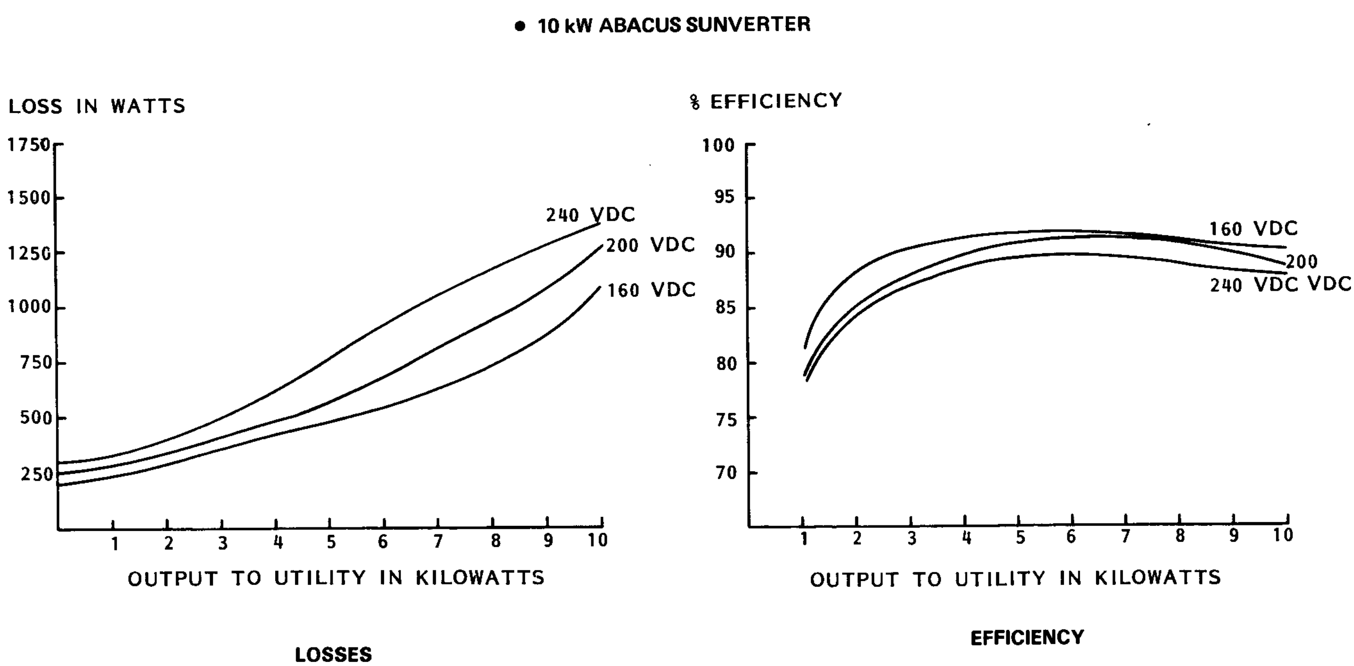


Figure 2-38. Summary of Inverter Performance

operated at the optimum loading for maximum AC output power. Should the solar array output voltage exceed 240 VDC, the operating point for the array is shifted to a lower voltage level to limit the DC voltage to 240 V. In a similar manner, if the AC output current were to exceed the rated value for the inverter (42 A to 240V), the operating point of the array would be shifted to a higher output voltage.

Should the DC array voltage fall below 160 V, the AC line contactor will open and stay open for 4 minutes (to minimize unnecessary breaking and making of the contactor contacts). The AC contactor will close automatically after 4 minutes, if the array voltage has returned to 180 V.

The following automatic disconnects are included features of the Abacus Sunverter: (1) For utility voltages greater than 264 VAC and less than 216 VAC, the inverter will disengage from the utility line; (2) also, for loss of utility power of phaselock, the inverter will be automatically disconnected from the utility line.

2.3.4.2 Power Conditioner Users Controls

The user controls for the unit includes a mode select switch, DC input power switch, an AC contactor switch and a reset switch. For this design,the mode select switch is set to the UTILITY position. Both the DC and AC switches must be on bus operation and the reset switch is used to restore the utility connection after being open.

Figure 2-39 shows the annual input voltage swing and operational power level for the inverter from the array as a function of the annual energy output. This data assumes Boston weather conditions.

2.3.4.3 Alternate Automatic Control Option

Due to operational problems in start-up, shut-down and during maximum power tracking, Abacus Controls developed an alternate algorithm for the unit control. It consists of a pilot cell that performs the double duty functions of insolation measuring during times when the sunverter is off and as the reference to the maximum power tracker when the sunverter is on. With the pilot cell, the

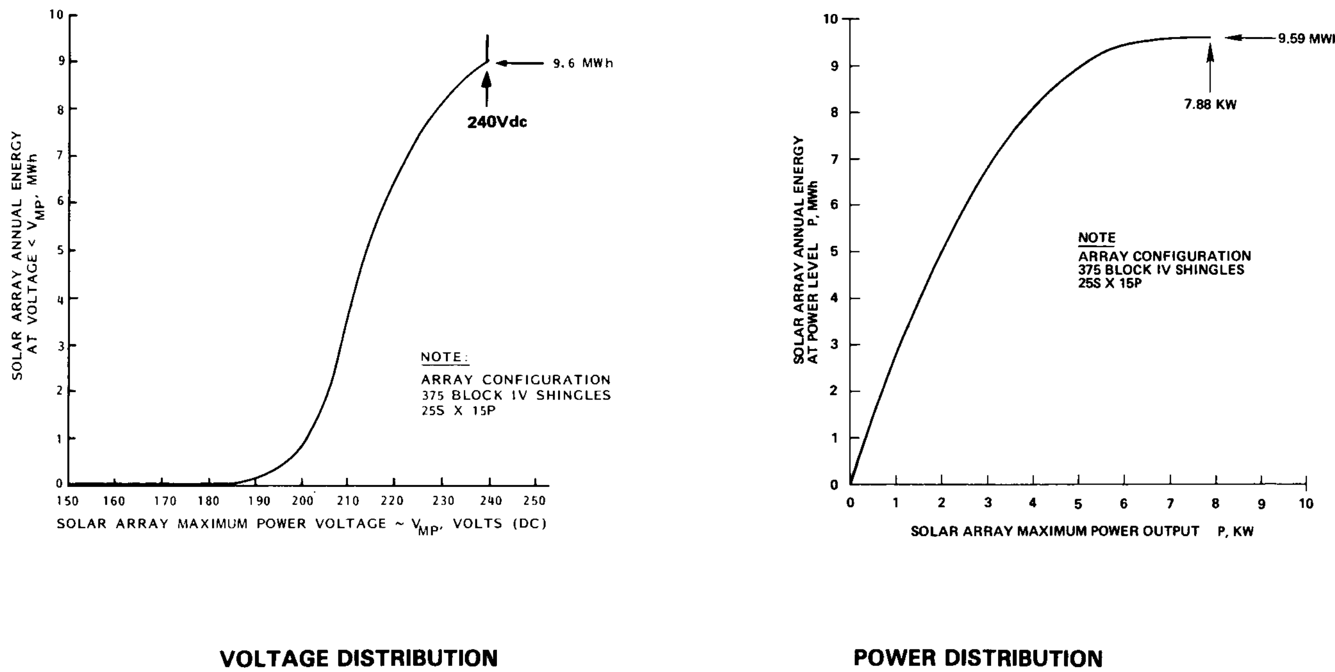


Figure 2-39. Estimated Annual Inverter Input Characteristics

complement of integrated circuits to accomplish both insolation sensing and max power tracking is four. Without the pilot cell, twenty-four integrated circuits and four power transistors on heat sinks are required to perform the two functions.

The max power tracker and insolation sensor provide a means of turning an Abacus Controls Sunverter on when there is sufficient power from the array on the roof. This is accomplished by shorting a pilot cell and measuring the short circuit current.

After the Sunverter turns on, the pilot cell is used to establish the open circuit voltage of a typical cell on the roof. This, in conjunction with a small negative voltage, provides the maximum power point signal to the Logic and Control Card in the Sunverter.

This option was incorporated into the GE Prototype in November, 1981.

SECTION 3
PROTOTYPE FABRICATION HISTORY

3.1 MODULES

3.1.1 MANUFACTURE

The PV shingle modules were fabricated by GE manufacturing personnel in a pilot production facility in Valley Forge, PA. This facility, Figure 3-1, which occupies $251 m^2$ ($2700 ft^2$) of floor area, was established to produce Block IVA shingle modules for use on the Northeast and Southwest Residential Experiment Station installations, on the JPL pre-production follow-on contract and future sales.

The Block IVA shingle module assembly procedure is outlined on the process flow diagram given in Figure 3-2. This sequence consists of ten distinct processing steps which are described below:

1. Cell-to-Glass Bonding. Nineteen solar cells which are selected from the same current rating group are positioned, active-side up, on the bonding fixture. GE 534-044 is sprayed on as a uniformly thick coating over the active area of each cell and a clean glass coverplate is positioned by the fixture and placed in contact with the bonding pottant. The glass coverplate/solar cell assembly is allowed to cure at room temperature for at least eight (8) hours. A module serial number is assigned and written on pressure-sensitive tape which is placed on the front of the glass coverplate.

2. "P" Contact Soldering. The interconnector strips (2 per cell) are soldered to the rear side of the adjacent cell at three (3) places per strip as determined by the location of the solderable pads on the rear contact. The glass coverplate/solar cell assembly is inspected in accordance with the in-process acceptance/rejection criteria. Rework is performed based on the findings of this inspection and the accepted parts are placed in inventory to await the next processing step.

3. Rework-Cell Replacement. Defective solar cells shall be removed from the glass coverplate and replaced with cells from a current rating group which is at least as high as the original cells. Reworked glass coverplate/cell assemblies are reinspected.

4. Outer Skin Bonding. An outer substrate skin is placed in the final assembly fixture and coated with a layer of Silaprene adhesive. The glass coverplate/solar cell assembly is then placed in the fixture to make the overlapped bond between the skin and the coverplate.

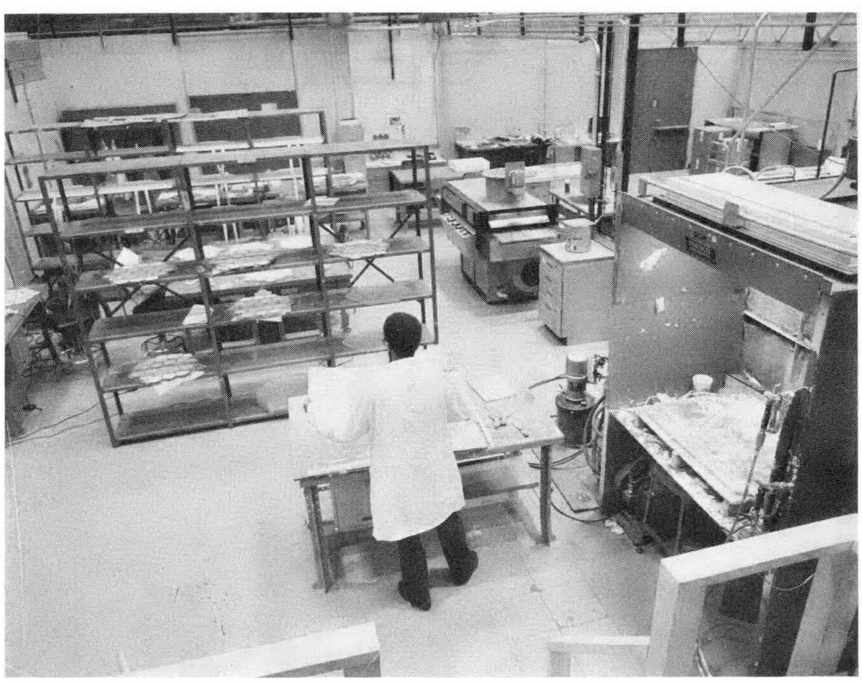


Figure 3-1. Block IV Shingle Module Manufacturing Facility

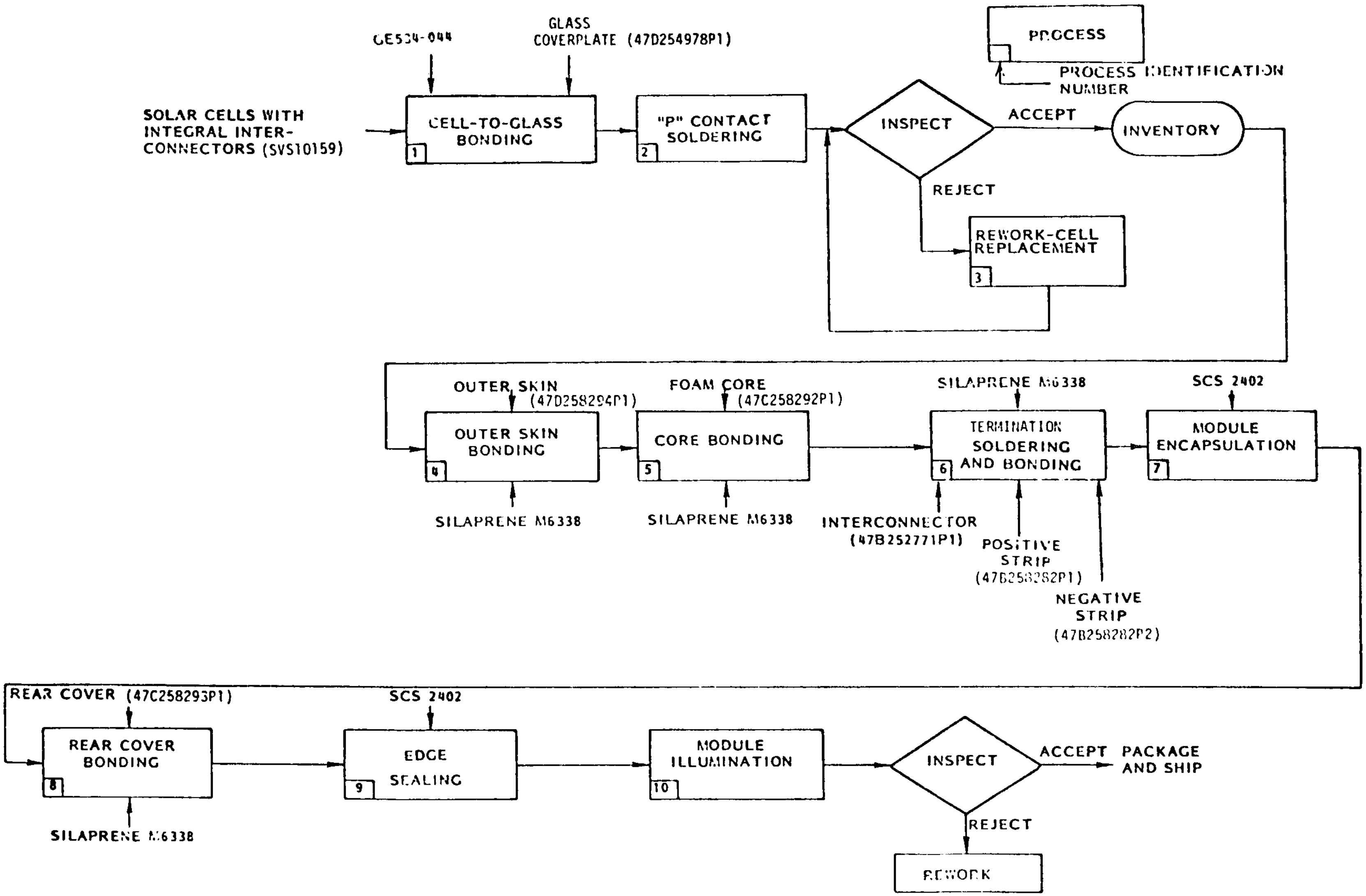


Figure 3-2. Block IV Shingle Solar Cell Module Process Flow Diagram

5. Core Bonding. The substrate core is immediately placed in the final assembly fixture and rolled to achieve a bond between the skin and the top surface of the foam core. Silaprene adhesive is applied and spread over the rear surface of the core.

6. Termination Strip Soldering and Bonding. The two termination strip assemblies are positioned in the fixture on the top of the Silaprene-coated rear surface of the foam core. The termination strips are soldered to the cell circuit positive and negative terminals using two additional interconnector strips to make the connection at the positive end. The rear surfaces of the termination strips are coated with Silaprene.

7. Module Encapsulation. The rear surface of the glass coverplate/solar cell assembly is coated with GE 2402 construction sealant. The material is spread to cover the entire area with a uniform thickness to just cover the back of each solar cell.

8. Rear Cover Bonding. The back of the foam core is covered with a layer of Silaprene and the rear cover is positioned in the lamination fixture and weighted over its entire area. After two hours at room temperature, the bonded module is removed from the final assembly fixture and placed on a bench for at least 3 days of final curing.

9. Edge Sealing. The glass edges are sealed all around with GE 2402 and the outer substrate skin is marked with the serial number. This completes the module assembly.

10. Module Illumination. The I-V characteristic for each module is measured on the LAPSS at the Optional Test Conditions (OTC). After conversion to the Standard Operating Conditions (SOC) the module output power at the Nominal Operating Voltage (V_{no}) is recorded in the serial number log and stamped on the module at the appropriate location on the outer substrate skin.

3.1.2 SHIPPING

The modules are shipped in wooden boxes approximately 1.2m square and 1m high. The box holds 45 modules packed with styrofoam fillers. The 375 modules were shipped in 9 boxes from Valley Forge to the site. Each box has a weight of 225kg and must be loaded and unloaded by a fork lift. The boxes are stored at the site as shown in Figure 3-3. No protective cover from the weather is required.

No modules were damaged in the complete shipment process. The modules were shipped with an I-V trace for each module.

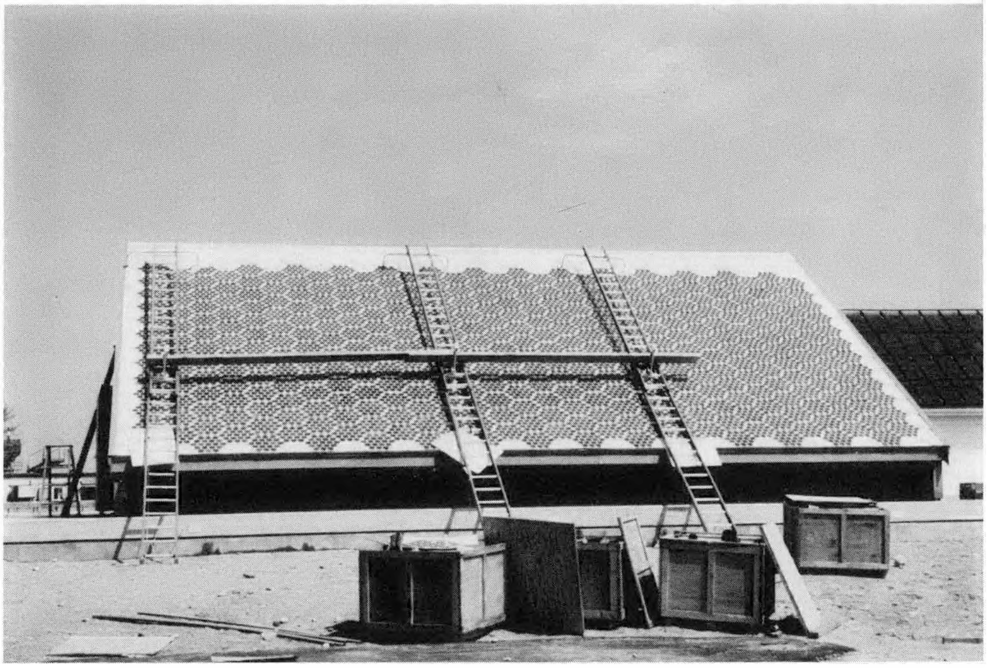


Figure 3-3. Shipping Boxes at the Installation Site

3.1.3 MODULE INSTALLATION

The shingle installation and wiring were divided into several separate specific tasks. Tables 3-1 and 3-2 provide a breakdown of the labor hours required for each of these tasks. In Table 3-1, the actual shingle placement and nailing takes less than half the total labor time. Installation of the sealer and roof angles are tasks which are planned to be eliminated in future installations. These labor savings reduce the module installation to 32 hours. The wiring labor hours total another 37 hours.

Table 3-1. Array Installation Labor

Task	Description	Labor
1	Set Up Staging and Moving Staging	8 Hours
2	Shingle Placement and Nailing	22 Hours
* 3	Install Sealer	17 Hours
* 4	Install Roof Angles	8 Hours
5	Disassemble Staging	2 Hours
	TOTAL	57 Hours

Table 3-2. Array Wiring Labor

Task	Description	Labor
1	Install Bus Wiring (30 Busses)	9 Hours
2	Crimp Modules to Bus and Apply Insulating Patch (750 Crimps and Patches)	22 Hours
3	Mounting and Wiring Transition Junction Box and External Disconnect	6 Hours
	TOTAL	37 Hours

During the installation of the photovoltaic shingle system, several points became apparent which should be considered in planning for future installations to save labor hours. The first and most important of these in terms of reducing the installation cost is to educate the installing contractors in the photovoltaic shingle system prior to their placing bids. This may be best accomplished by giving the contractors an opportunity for "hands-on" contact with the shingle modules as well as a presentation via photographs or slides of the installation sequence. During this presentation, the durability and ease of installation of the shingle modules should be stressed. This education should be key in reducing the contractor's contingency in his bid.

The following points relative to the installation would be helpful to note:

1. What equipment and materials the contractor will be expected to supply should be clarified.

2. Average installation time for placing, nailing and crimping the Block IV shingles was 5 man min. per shingle

3. The nailing and crimping procedure should be reviewed in detail using actual hardware

The second area which should be considered in future shingle projects would be some means to accommodate scaffolding for the initial installation as well as future inspection and replacement. In the installations, scaffolding has been the most time consuming and least productive step. Future installations should consider integrating a support rail at the top and bottom of the roof into the building design. This rail could support a rolling ladder which could be removed and stored until needed for service.

In lieu of an integrated support system, the Northeast array was installed using fiberglass extension ladders supported on the ground at the bottom of the roof and on blocking at the top of the roof. Intermediate supports at mid-span were padded with styrofoam sheets. Ladder jacks supported scaffold planks spanning between the ladders. The installers used the planks to hold their position on the roof and work across the rows; however, most of their weight was supported by kneeling on the shingles. This is a good example of demonstrating the shingle durability. Other interesting points with regard to durability include an instance during the Northeast installation when an installer accidentally dropped a hammer from the top of the roof. It skidded down the shingle faces to the ground without damaging the coverglass.

A third aspect to be considered in future installations is assisting the contractor in proper planning and sequencing of the installation. In the Northeast the installation was not accomplished in an orderly sequence and much time was wasted in switching from one task to another.

A minor area which still needs correction is the method of attaching the flat conductor buses to the roof. The current plan calls for the use of a duct tape every six feet along the row. When the bus cables are installed first, as they should be, they will be exposed to weather for a time before being covered with shingles. This weathering, along with the fine aggregate which the manufacturer places on the roofing felt to keep it from sticking together in the roll, causes poor adhesion in the duct tape. With a slight wind condition the bus cables blow off the roof. It was necessary to staple the tape to the roof deck to hold the buses in place. In attaching the bus cables to the roof it is necessary to consider the spacing of the positive and negative shingle leads since the bus cable must be lifted slightly to make the crimp connection.

An additional area of note is in the proper spacing of the first row of shingles. In order to have the completed array centered on the roof the middle shingle of the first row should be placed one quarter of the shingle width off the center line. This is necessary due to staggered row to row spacing of the shingle modules.

Also to ensure proper coverage of the roof, the roof dimensions should be verified prior to starting the installation. This will avoid a situation which occurred where the roof was one foot longer than designed, requiring an extra row of dummy shingles.

A final area for consideration in future shingle systems which require installation of the flat conductor cable test leads would be the installation of a wireway running parallel to the roof rafters, flush with the roof deck and near the edge of the roof. This would provide a space for the test lead beneath the shingles and would not create the lump which now occurs. Using asphalt shingles as dummies and the wireway to carry the test leads and main bus cables, the fiberglass angle trim along the roof rake could be eliminated.

3.2 POWER CONVERSION SUBSYSTEM

3.2.1 MANUFACTURE/PROCUREMENT

The power conversion subsystem was purchased as a complete unit according to the specification listed in Appendix C from Abacus Controls, Inc. of Sommerville, N.J.

3.2.2 SHIPPING

The unit was shipped from N.J. to the site by the vendor. The unit was tested and accepted by GE personnel at the manufacturing plant in N.J. prior to shipment. The unit was not damaged during shipment.

3.2.3 INSTALLATION

The actual installation of the unit was minimal since it is floor mounted and requires only 4 wire connections plus a ground. The tasks for completing the remainder of the system installation are listed in Table 3-3 along with the labor hour estimates. These estimates were provided by Interstate Electrical Services, the system installer. Note that running wiring in conduit is a major labor contributor.

3.3. SYSTEM

3.3.1 FINAL CHECKOUT PROCEDURE

A final checkout procedure was developed to verify system operation. The procedure is strictly related to the experimental nature of the installation, although many steps are applicable on a mature installation. The procedure also covers the requirements of the System Acceptance Plan developed by MIT/LL. The system was accepted on May 22, 1981.

Table 3-3. Power Conditioner Installation and Wiring Labor

Task	Description	Labor
1 Mounting All Equipment	Panels, Switches, etc.	4 Hours
2 Wiring	Complete Inside Wiring	10 Hours
3 Conduit Installation		8 Hours
4 Utility Feed	Tapping into Existing House Feed	4 Hours
	Total	26 Hours

3.3.1.1. Installation Complete Status

The first step is to verify that all wiring and connections have been checked for proper installation and continuity. All circuit breakers and switches should be in the open/off position. The programmable load box should be in an off condition with the main AC disconnect closed. Utility power should be supplied to the prototype load center loads (lighting, outlets, space conditioning, etc.)

3.3.1.2 On/Off Sequence

The status of the utility line should be checked with an oscilliscope prior to the turn-on sequence. The existence of voltage spikes, high harmonic content or other undesirable attributes should be noted, both with and without other site PV systems operating and corrected if possible before turn-on. A preferred state for turn-on is to have all other site PV systems off at the time the system is first turned on, or at least systems on the same single phase utility transformer turned off. This condition will expedite the isolation of faults among systems, if any faults develop from utility line interactions. Recheck the line after turn-on to note any changes created by turn-on.

From the installation complete status, the turn-on sequence can be initiated. Refer to Figure 2-34 for the appropriate switches referenced in this sequence.

1. Close the circuit breaker in the AC Power Panel Box.

2. Close the AC contactor coil switch on the inverter. Set the inverter dials to the utility position and auto position.

3. Close the external DC disconnect after checking that ground connection is on. Close the internal DC disconnect.

4. Close the DC switch on the inverter. The indicator light on the inverter should come on if there is 80 VDC from the array.

   The "Over Voltage/Under Voltage" (OV/UV) light should come on at 80 VDC 160. If the DC voltage 190 V, the inverter should turn on over a 15 second period, and the phase lock light will go on (an audible hum will be produced).

5. Normal system ON/OFF control can be exercised by the circuit breaker in the AC Power Panel, leaving all other switches in the operational position. The system will not turn on with the throw of this circuit breaker unless the DC voltage is less than 240 and greater than 190 V.

3.3.1.3 Module Test

Each module was flash tested prior to shipping. Upon arrival at the site, MIT/LL flash tested several modules which verified the data already supplied.

3.3.1.4 Array IV Trace

An array IV trace should be taken at the positive and negative array leads. MIT/LL supplied the electronic load and x-y plotter and conducted the test. Figure 3-4 shows an actual IV trace of the array taken during checkout. The array output slightly exceeded initial predictions. Under peak power rating conditions (100 mW/cm^2 insolation with 25^oC cell temperature) the array maximum power output is 6.7 kW. Under Normal Operating Conditions (NOC) the maximum array power output is 5.4 kW assuming an NOCT of 68^oC.

3.3.1.5 Power Conversion Subsystem

Subsystem checkout included the following items:

1. Automatic sunrise startup and sunset shutdown.
2. 8-hour normal operation at greater than 50% rating at some time during operation.
3. Maximum power point operation verification.
4. Utility interruption shutdown.

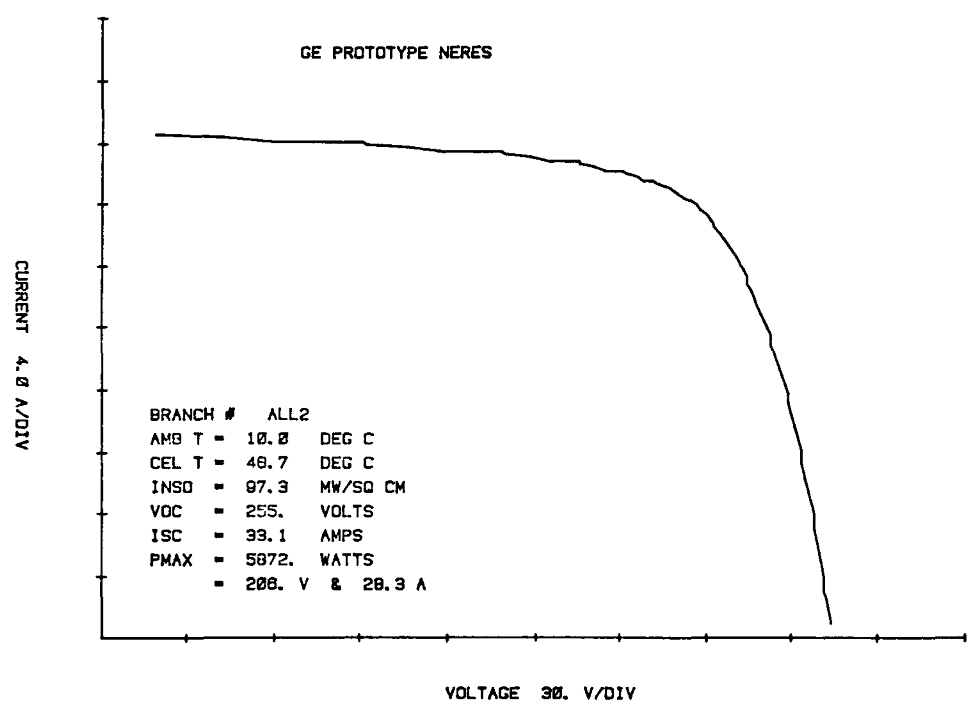


Figure 3-4. Actual Array IV Checkout Trace

Correct inverter operation was essentially achieved after a one-day period of troubleshooting, supplier telephone consultation and minor potentiometer adjustments. Several utility interrupts were simulated and successful operation shutdown and turn-on were accomplished.

Inverter automatic start-up proved troublesome as anticipated due to high open circuit voltage, prior to the level of insolation reaching a load carrying ability. When the cells in the array warmed up to about 30°C, and open circuit voltage had dropped to 265 VDC, the inverter started up easily in the automatic mode and tied to the utility line. Cycling was evident on both start-up and shutdown, but the unit did accomplish these requirements. Similarly, 8-hour system operation was also achieved.

Operation at maximum power appeared to be correct, but could not be exactly verified from the inverter controls only. It is necessary to do this verification when IV curve trace equipment and full sun are available. Maximum power point operations was verified in general by comparing the test operating point to the IV array trace shown in Figure 3-4. From start-up at open circuit, maximum power is achieved in a three- to four-minute period.

3.3.2 OPERATION AND MAINTENANCE PROCEDURES

3.3.2.1 Module Failure Detection/Location

The highly redundant series/parallel network of shingles precludes the observation of only a few defective modules. Several modules would have to be defective to detect problems with the IV trace. Since this is an experimental system, the FCC leads from each series row were run into the prototype structure and terminated in a panel box as shown in Figure 3-5. If questionable performance is suspected, the procedure listed in Table 3-4 would be followed.

A module identified as having little or no change in short circuit current on the row characteristics as it is shadowed is probably defective. The module should be removed and an IV flash test made to compare performance with the pre-installed performance data supplied with the module. This leads to an initial determination of whether the problem is in the module or with the FCC leads. All short circuit current tests should be limited to short durations.

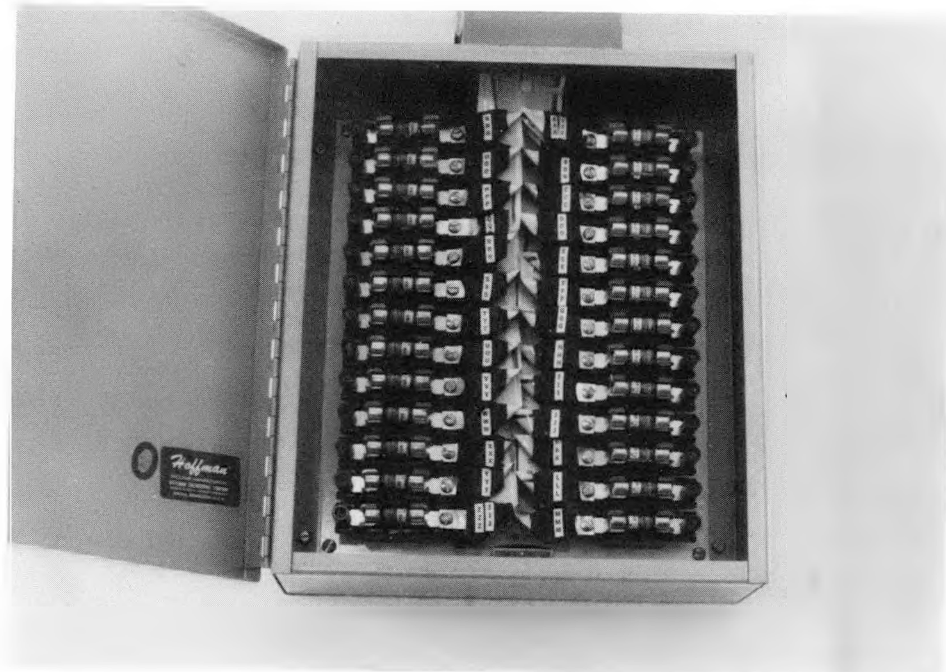


Figure 3-5. FCC Terminal Box for Diagnostic Procedures

Table 3-4. Diagnostic Procedure for Defective Modules

1. Under maximum power system operation, measure row-to-row voltage to isolate row(s) with significant mean row voltage deviations.
2. Check suspect row performance by measuring row short circuit current. A measured reduction in row short circuit current provides an identification of the number of suspect modules in that row.
3. Visually inspect modules in row for damaged cells.
4. Verify or locate single module in row by shading a single module at a time and repeating short circuit test looking for little or no change in current output.

3.3.2.2 Module Removal/Replacement

Access to the affected module can be achieved by using ladders, similar to the installation procedure. Table 3-5 lists the step-by-step procedure.

Removal of the defective module can be accomplished by first cutting out the bead of silicone construction sealant which holds the bottom edge of the module to the course below and three adjacent modules. A wedge is carefully forced beneath the glass coverplate of the modules on either side of the affected module in the course directly above. The split washer removal tool is inserted to remove the washers under each of the two nail heads. At this point the defective module can be lifted up so that the nailheads clear the thickness of the substrate and can be pulled out to the extent of the FCC length. The two FCC's are cut at the exit point from the module substrate to remove the module from the roof. A new module can be connected to the FCC ends remaining from the old module by using a splice crimp connector to make the butt joints. The new module can then be reinserted in the roof over the old nailheads. It is not necessary to reinsert the split washers since the replacement module should be adequately held by the surrounding modules once the caulking beads are applied.

Table 3-5. Module Replacement Procedure

- Cut sealant from defective module and adjacent modules
- Lift adjacent modules to expose nails on defective module
- Remove washer
- Lift module over roofing nails
- Extend FCC cable fold
- Cut FCC cable leads
- Position new module
- Interconnect FCC leads with splice connector and insulate
- Align module in place
- Apply sealant

3.3.2.3 Normal Operation

Normal system ON/OFF control can be accomplished by the circuit breaker in the AC power panel, leaving all other switches in the operation position. If utility loss occurs, the inverter reset switch must be depressed and then the AC contactor must be rethrown to the "on" position.

3.3.3 COST INFORMATION

Table 3-6 summarizes the system installation data. The numbers are normalized to a system peak power rating of 5350 W. The labor dollars assume a $15/hr rate. The array module installation labor can be reduced by eliminating the application of caulking and the roof angles, which saves 7¢/W_p of costs. These two items also are the two most significant contributions to the module installation material costs resulting in a 13¢/W_p savings if eliminated.

Table 3-6. Summary of System Costs

Description	Hours	Actual Costs $/$W_p$(1)
Array		
Modules	--	$30.27
Installation		
Labor (5)	57 hrs.	0.16(2)
Materials		0.16(3)
Wiring		
Labor	37 hrs.	0.10
Materials		0.16
Roofing Credit		(0.13)
Power Conditioning		
Inverter (4)		2.29
System Installation		
Wiring		
Labor	26 hrs.	0.07
Materials		0.08

NOTES

(1) Maximum power 5350 W at NOCT = 68°C
(2) Eliminating unneeded labor saves $0.07/$W_p$
(3) Eliminating unneeded materials saves $0.13/$W_p$
(4) Per peak array power, not inverter rating
(5) Assumes $15/hr average rate

The module and inverter costs are high since they both represent the first units produced.

Table 3-7, 3-8 and 3-9 presents the detailed material cost data for array installation, array wiring and system installation respectively.

Table 3-7. Array Installation Materials List

Item	Description	Quantity	Cost
* 1. Sealer	GE Silicone #1201	57 tubes	$370
2. Fasteners	Roofing Nails & Washers	Washers: 750 Nails: 10 lbs	$128 $ 10
* 3. Flashing	Fiberglass Roofing Angles	80 ft.	$349
TOTAL			$857
Displaced Roofing Materils	320 lb. Asphalt Shingles	790 ft^2	$711

*Planned to be omitted from future installations.

Table 3-8. Array Wiring Materials List

Item	Description	Quantity	Cost
1. Wire	a) #6 Cu. THHN (Transition Block to External Disconnect) b) #10 FCC (+ and - Busses) c) #12 FCC (24 runs @ 40')	24' 360' 960'	$ 4.00 $180.00 $480.00
2. Junction Boxes	FCC to AWG #6 Transition Box	1	$ 50.00
3. Quick Connectors	PVC Male Adapter and Lock Nut	2	$ 1.00
4. Conduit	1 PVC	10'	$ 2.00
5. Other	Clips-Screws, PVC Cement Insulating Patches Outside Disconnect Box Tape for Busses	Lot 750 1 ---	$ 2.00 $ 75.00 $ 51.00 $ 3.00
TOTAL			$848.00

Table 3-9. Power Conditioner Installation and System Wiring Materials List

Item	Description	Quantity	Cost
1. Mounting Hardware	Screws, bolts, nuts and washers	lot	$ 32.00
2. Wire	#14, #6, #8, #2	lot	$180.00
3. Conduit	1" PVC, 1" PVC Ells, sealtite 3/4" PVC, 3/4" PVC Ells	lot	$ 70.00
4. Junction	4" square with blank covers 4 x 4 wire way with plates	lot	$ 16.00
5. Miscellaneous Hardware	Connectors, couplings, tape, ground rod, clips, etc.	lot	$ 64.00
6. Miscellaneous Power Equipment	Inside Disconnect 40 AMP Breaker with Enclosure	1 1	$ 24.00 $ 32.00
7. Other	Varistor GE #V275 2A40B Lightening Arrestor	1 1	$ 6.00 $ 19.00
TOTAL			$443.00

SECTION 4

REFERENCES

1. Balcomb, J.D., et al, "Passive Solar Design Handbook, Volume 2", Los Alamos Scientific Laboratory, University of California, Department of Energy Report DOE/CS-0127/2, January, 1980.

2. "Final Report - Analysis and Design of Residential Load Centers", SAND 80-7017, General Electric Company, October 1981.

3. "The Design of a Photovoltaic System for a Southwest All-Electric Residence", SAND 79-7056, General Electric Company, February, 1980.

APPENDIX A

INSTALLATION SAFETY NOTES

FOR

PHOTOVOLTAIC SHINGLE MODULES

INSTALLATION SAFETY NOTES

FOR

PHOTOVOLTAIC SHINGLE MODULES

WARNING

EXERCISE CAUTION IN HANDLING AND INSTALLING PHOTOVOLTAIC SHINGLE MODULES. THESE MODULES ARE ELECTRICAL POWER SOURCES AT ALL TIMES WHEN EXPOSED TO ANY LIGHT LEVEL. HAZARDOUS ELECTRIC POTENTIALS EXIST AT THE EXPOSED TERMINALS OF INTERCONNECTED MODULES UNDER ANY LIGHT LEVEL CONDITIONS.

NORMAL FULL SUNLIGHT CAPACITY:

PHOTOVOLTAIC MODULE

OPEN CIRCUIT VOLTAGE	10 VOLTS DC
SHORT CIRCUIT CURRENT	2.5 AMPS DCS
MAXIMUM POWER RATING	7.2 V, 2.25 A.

ROOF ARRAY (25 SERIES COURSES OF 15 PARALLELED MODULES PER COURSE)

OPEN CIRCUIT VOLTAGE	235 VOLTS DC
SHORT CIRCUIT CURRENT	37.8 AMPS, DC
MAXIMUM POWER RATING	180 V, 34 A.

SEE PAGE A-2 FOR RECOMMENDED SAFETY PROCEDURES

SAFETY NOTES

Safety precautions must be enforced for all personnel that have access to the shingle modules and roof array. Each module generates electrical potentials similar to the levels available at the terminals of a standard 12-volt automobile battery. The series connection of modules up the slant height of the roof will generate electric potentials comparable to those of the normal residential utility 240-volt line service. The photovoltaic module electric potentials are always present under any light level. Safe handling and installation procedures must insure that no conductive path is provided across shingle module or roof installation terminals by any personnel or equipment. The procedures listed below should be followed during module installation:

SAFETY PROCEDURES

1. Installation should proceed only during dry weather on a completely dry roofing surface.

2. No metal ladders or scaffolding or other conductive equipment capable of spanning exposed terminals should be used.

3. The array negative ground terminal should not be connected until the electrical installation is complete.

4. The modules should be installed one course at a time from roof edge to roof edge, and not in any staggered pattern which provides exposure to series connected modules. Each termination must be suitably insulated as it is completed.

5. No electrically conductive material should be laid over the roofing surface.

6. The installation should be accomplished working from the felt roof surface as much as possible.

7. Grounded components, such as plumbing vent pipes, gutters, etc. should not be touched by personnel during the installation process. Ground potential and other conductive components should be covered with an electrical insulating cover during the installation process.

8. Care should be exercised not to make physical contact with module terminations across a series multiple of installed angles.

APPENDIX B

ELECTRICAL SYSTEM INSTALLATION SPECIFICATIONS

ELECTRICAL SPECIFICATIONS
FOR
GENERAL ELECTRIC COMPANY
REU #3

Northeast Residential
Experimental Station
MIT - Lincoln Lab
Hanscom Field

Prepared by

JOHNSON & STOVER, INC.

127 Taunton Street

Middleborough, Massachusetts 02346

September 8, 1980

Revised September 15, 1980

ELECTRICAL SPECIFICATIONS

FOR

GENERAL ELECTRIC COMPANY

REU #3

INDEX

RESIDENTIAL PROTOTYPE PHOTOVOLTAIC ELECTRICAL

INSTALLATION SPECIFICATIONS

PART 1: GENERAL REQUIREMENTS

1.1 GENERAL

A. This Specification includes all electrical work to install a roof-mounted photovoltaic (PV) system at Residential Experimental Unit #3 (REU #3) at the M.I.T. Lincoln Laboratory Northeast Residential Experimental Station at Hanscom Field, Bedford, Massachusetts.

B. Utility service will be provided by M.I.T. from their power panel to feed both the "House Service Panelboard" and the prototype load center "PLC".

C. The system consists of several types of shingles of the GE block IVA design which are to be interconnected by means of AMP Industries type FCC flat conductor cable. All shingles, FCC cables, and the necessary interconnectors, splice packs, and installation tools for use on FCC cable will be furnished to the contractor by General Electric Company. The inverter package will also be furnished to the contractor by General Electric Company

1.2 REFERENCES

A. Cooperate and coordinate all electrical work with other contractors on site.

B. The complete structure of the prototype will be constructed under another concurrent contract. The utility service will be provided to the M.I.T power panel as indicated on the drawings. The roof will be constructed and covered with roofing felt ready for shingle installation.

1.3 SCOPE OF WORK

A. Provide all labor, materials, equipment, and supervision necessary to complete the electrical work associated with a roof-mounted photovoltaic (PV) system, including all equipment identified. Interior electrical work including lighting fixtures, lamps, switches, receptacles, and connections to air conditioning equipment is also included.

1.4 WORK NOT INCLUDED

A. Utility service including the M.I.T.L.L. power panel will be provided by M.I.T.L.L.

B. Construction of prototype structure including roof underlayment and roofing felts.

1.5 QUALITY ASSURANCE

A. The work shall be executed in strict conformity with the latest edition of the National Electric Code and all local regulations that may apply. The installation of type FCC cable on a roof is not covered under Article 328 of the present National Electrical Code. The installation of the FCC cable shall be performed in strict accordance with manufacturer's recommendations and in accordance with the best practices of the trade. In case of conflict between contract documents and a governing code or ordinance, the more stringent standard shall apply.

B. Unless otherwise specified or indicated, materials and workmanship shall conform with the following standards and specifications (latest edition):

1. National Electric Code.

2. Occupational Safety and Health Act.

3. Standards of Underwriters Labs (UL).

4. National Fire Protection Association (NFPA).

5. National Electrical Safety Code.

6. Local Codes.

C. Carry out tests, secure permits, pay fees, and arrange for all inspection of regulatory agencies for work under this section.

1.6 SUBMISSION DATA

A. Submit six (6) copies of all equipment to be incorporated into the work for approval prior to ordering same.

1.7 PRODUCT DELIVERY, STORAGE, HANDLING

A. All equipment, upon receipt, shall be inspected for damage and shall then be stored and protected from damage until project completion.

1.8 OPERATING INSTRUCTIONS AND MAINTENANCE MANUALS

A. Provide operating instructions to designated persons with respect to operation functions and maintenance procedures for all equipment and systems installed.

B. At project completion provide two (2) copies of bound brochures including all shop drawings, maintenance manuals, and spare parts lists.

1.9 ELECTRICAL CHARACTERISTICS

A. The PV array will produce an output of approximately 180 volts DC, which will then be inverted to a nominal voltage of 120/240 volts, single phase. Capacity of the system is approximately 6 KW.

1.10 TEMPORARY LIGHT AND POWER

A. Provide temporary electricity from the utility service junction box as required to allow completion of the work. Remove any temporary wiring when no longer required.

1.11 RECORD DRAWINGS

A. Maintain two (2) copies of the documents on site and record any revisions on one set of the job progresses. At project completion, transfer all changes to the other set.

B. Maintain a log of any difficulties encountered during the installation and the steps taken to resolve same.

1.12 SAFETY PRECAUTIONS

A. The contractor shall be completely responsible for all safety precautions to be taken by installers of the array. Refer to Appendix A, PV Module and Installation Safety Notes.

PART 2: PRODUCTS

2.1 RACEWAYS AND FITTINGS

A. Conduit - General

1. No conduit shall be used smaller than 3/4" diameter. No conduit shall have more than four (4) 90° bends in any one run, and where necessary pull boxes shall be provided.

2. Rigid PVC conduit shall be Schedule 40 UL listed for 90°C. All fittings shall be solvent connected. Provide threaded fittings where connected to metallic boxes. PVC conduit shall be Carlon. PVC conduit shall be used for exterior work and for raceways enclosing ground conductors.

3. Thin wall conduit (EMT), zinc coated steel, conforming to industry standards shall be used for all interior raceway systems. Fittings for EMT shall be compression or set-screw type. EMT shall be equal to Pittsburgh Standard Conduit Company, Republic Steel Tube, or Youngstown Sheet and Tube Company.

4. Conduit Fittings

a. Insulated bushings shall be provided on all raceways larger than 3/4".

b. Access fittings shall be Type LL, LR, or LB as required, and shall be equal to Appleton, Crouse-Hinds, or RACO.

B. Outlet, Pull, and Junction Boxes

1. Each outlet box shall have sufficient volume to accommodate the quantity and size conductors entering the box in accordance with the requirements of the National Electric Code. Outlet boxes shall be pressed steel as manufactured by Steel City, RACO, or Appleton.

2. Pull boxes or junction boxes shall be constructed or code gauge sheet metal of a size not less than required by the National Electric Code, if no size is indicated on the drawings, and shall have hinged doors.

2.2 SUPPLEMENTARY STEEL, CHANNEL, AND SUPPORTS

A. Furnish and install all supplementary steel, channel, and supports necessary for the proper mounting and support of all equipment. Provide minimum of 3/4" thick plywood backboards for mounting of all equipment at the equipment area.

B. All supplementary steel, channel, and supports shall be UL approved, be galvanized steel, and be as manufactured by Steel City, Unistrut, Power Strut, or Kindorf.

2.3 CONDUCTORS

A. All conductors shall be stranded copper of the size indicated on the drawings. All conductors shall be Type THWN rated 90°C for dry locations and 75°C for wet locations.

B. Conductors for use on the DC system shall be color coded red for positive and black for negative. AC conductors shall be color coded black for Phase A, red for Phase B, white for Neutral and green for Ground. DC conductors shall also be identified as DC by label markers.

C. All conductor terminations shall be made up by standard lug connections on equipment having same. Terminations made up for attachment to positive or negative transition blocks at the roof and the DC input inductor or other devices not having standard lugs shall be bolted type compression lugs as manufactured by Burndy, Thomas & Betts, or Panduit of tinplated copper. Bolts shall be 1/4-20 silicon bronze.

D. All terminations, other than located within enclosures, shall be insulated.

E. Nonmetallic sheathed cable may be used for the lighting and receptacle outlets located within the prototype where installed concealed in walls and ceilings.

2.4 SAFETY SWITCHES

A. Safety switches shall be general duty 2-pole or 3-pole fused or non-fused in NEMA 1 or NEMA 3R enclosures as indicated on the drawings and shall be capable of being padlocked. Switches shall be equal to General Electric, Westinghouse, or Square D.

2.5 GROUNDING SYSTEM

A. There shall be four (4) isolated ground systems as follows:

1. Grounded Neutral: The house wiring system neutral of the prototype shall be grounded only at the house panel by means of a #8 AWG connection between the panel neutral bus and the panel ground bus. The panel neutral block shall be isolated from the panel enclosure. A #8 AWG green insulated ground conductor shall then interconnect the panel ground block to the house ground bus.

2. Equipment Ground: A #8 AWG green insulated ground shall be looped between all equipment and shall be connected to each piece of equipment by means of a ground lug on the equipment. This conductor shall terminate at the house ground bus.

3. Varistor Ground: The #14 AWG green insulated ground conductor from the Varistor shall be connected through a separate conduit system with the array negative ground. This ground shall terminate at the house ground bus below the house service panel.

4. Array Negative Bus Ground: Provide a #8 AWG green insulated ground conductor from the line side of negative bus terminal at the exterior mounted overcurrent device to the house ground bus below the service panel. Run in PVC raceway along with Varistor ground.

5. House Ground Bus: Provide a 12" long 1/8" x 1" copper ground bus on standoff insulators 12" above the floor below the AC panel. There shall be four (4) ground connections to the bus as follows: #8 AWG ground to house panel ground bus, #8 AWG ground to equipment ground system, #8 AWG ground at array negative bus, and #14 AWG ground for Varistor grounding. Provide a #8 AWG ground from the bus to the utility service ground located at the below-floor service junction box. In addition, provide a #8 AWG ground to a driven 3/4" x 10' long Copper Weld ground rod. This ground rod shall be located within the equipment area and shall extend 4" above the final floor location.

6. Varistor Surge Protection

   a. Furnish and install a Varistor for surge protection, which shall be mounted in a junction box sized as required on the drawings. The junction box shall be provided with an insulated mounting block and terminal bar isolated from the metal structure. A #14 AWG ground wire shall be tap-connected to the positive DC conductor which is to be protected by means of Burndy Servit type KS split bolt connector. This connector shall be insulated by taping. The load side #14 AWG ground from the Varistor shall be interconnected to the house ground bus located below the house panel.

   b. Varistor on the positive DC side of the invertor shall be General Electric catalog number V275 LA40B.

B. Furnish and install a General Electric Lightning Arrester nippled to the side of the house service panelboard. Unit shall be catalog number TLP 175 and shall be connected with black leads to line buses and white to ground.

2.6 PANELBOARDS

A. Two (2) panelboards, in accordance with the following, shall be provided. The House Service Panelboard is to be fed both from the AC output of the inverter and the M.I.T. power panel. The prototype load center "PLC" shall be fed only from the M.I.T. power panel and is to be used for the lighting, AC, and receptacle circuits within the prototype.

B. Panelboards shall be dead-front, safety type equipped with single or multi-pole circuit breakers, and shall be suitable for the voltage characteristics of the system; 120/240 volts, single phase, three wire.

C. Buses may be copper or aluminum. Both panelboards shall have a circuit directory card mounted in a frame with plastic cover installed on the inside of the door. Directory cards shall be properly filled in, using a typewriter, and indicating areas and devices served by each circuit. Panelboards shall be provided with a separate ground bus.

D. All circuit breakers shall be of quick-make, quick-break type on manual operation, trip free, and with inverse time characteristics. All multi-pole breakers shall have an overload element in each pole so designed that an overload in one pole automatically causes all poles to open.

E. Panelboard cabinets shall be made of code gauge steel, surface-mounted, and shall be ordered without knockouts. Wiring gutters shall not be less than 4" wide.

F. Panelboard trims shall be made of code gauge steel, surface type. Door shall be equipped with flush catch and lock.

G. Panelboards shall be General Electric type NLAB or approved equal. Breaker THQB bolt-on. SYM. INT. capacity 10,000 amps at 240 volts.

2.7 WIRING DEVICES

A. All wiring devices shall be for flush mounting and shall have an ivory finish. All coverplates shall be smooth ivory plastic.

B. 20 ampere receptacles NEMA Type 5-20R, Slater #330-IV, Leviton, or G.E.

C. 20 ampere switches shall be Slater #620-IV, Leviton, or G.E.

2.8 LIGHTING FIXTURES

A. Furnish, install, and connect a complete lighting system consisting of branch circuits, lighting fixtures, lamps, switches, devices, etc. Refer to the fixture schedule on the drawing.

B. Provide and install all special hangers and devices required. All fixtures shall be supported independently of the hung ceiling construction. Suspension method for fixtures shall be tube stems.

C. Furnish fixtures complete with standard or special mounting frames, lamps, ballasts, and other devices. All fluorescent fixtures shall be furnished with ETL/CBM approved high power factor quiet operating Class "P" ballasts and with warm white rapid start lamps. All fluorescent lamps shall be the "Watt-miser" type as manufactured by General Electric. Ballasts shall be energy saving type equal to advance Mark III.

2.9 PHOTOVOLTAIC EQUIPMENT

A. The photovoltaic equipment including all shingle modules as shown on the drawings and including the roofing nails and split washers will be provided by General Electric Company.

B. The inverter package which forms an integral part of the generating and conversion system will be provided by General Electric Company and shall be installed by the Electrical Contractor.

C. FCC Cable System: The FCC cable, splice connectors, insulating patches, and crimping tool will be as manufactured by AMP Industries and will be furnished by General Electric Company for installation by the Electrical Contractor.

D. Upon receipt of this equipment, each of the several parts shall be carefully examined to identify any possible shipping damages.

PART 3: EXECUTION

3.1 WORK COORDINATION AND JOB OPERATIONS

A. Be responsible for all equipment necessary for erection of the roof array including staging. Commencement of array erection signifies acceptance of the surface upon which the shingles are to be installed.

B. Coordinate all work prior to commencing with all existing conditions of the structure.

3.2 PLANS AND SPECIFICATIONS

A. The drawings showing layout of equipment, especially within the equipment area, show a suggested layout. Carefully check dimensions of all equipment and make any adjustments necessary to accommodate any variations.

B. Post the schematic diagram and equipment plan and elevation at a reduced scale under glass in the equipment area.

3.3 SYSTEM IDENTIFICATION

A. Provide screwed-on phenolic nameplates (black with white engraving) on all equipment. Differentiate between AC and DC equipment.

B. All raceways enclosing DC conductors shall be identified by appropriate labels.

3.4 WORKMANSHIP AND INSTALLATION METHODS

A. All work shall be installed in a first-class manner consistent with best current trade practices. All materials and equipment shall be securely installed plumb and/or level.

B. The inverter cabinet shall be mounted using Korfund vibration pods. All wiring connections to this cabinet shall be in flexible metal conduit.

C. All raceways shall be properly aligned, grouped, and supported at right angles to or parallel with the principal building members.

D. Any holes drilled through structure shall be neatly made and properly sealed after equipment installation.

E. All wiring in panelboards and enclosures shall be neatly formed and grouped.

F. Be responsible for all safety precautions and rubbish removal. Leave site in clean condition.

3.5 BRANCH CIRCUITS

A. Furnish, install, and connect all branch circuit wiring and outlets for a complete and operating system. The system shall consist of insulated wires connected to the panelboards and run in concealed rigid or EMT conduit or non-metallic sheathed cable as required to the final outlet and shall include all outlet boxes, supports, fittings, receptacles, plates, fuses, etc., as required.

B. The physical arrangement of branch circuit wiring shall correspond to the contract drawings. No combining of circuits will be allowed. When a common neutral is used for more than one circuit, the arrangement shall be such that a receptacle, fixture, or other device may be removed or disconnected without disconnecting the neutral for the other branch circuits.

C. All wiring in the panelboard and cabinets shall be neatly formed and grouped.

3.6 ARRAY ERECTION PROCEDURE

A. The roof will be approximately 8" wider than the array layout. The array, therefore, shall be oriented to start at the right side of the roof when facing the array from the front. The excess roof area at the left side shall be covered by dummy shingles as indicated on the erection procedure on drawing E-4. These dummy shingles shall then be cut flush with the left edge of the roof. The top row of G-11 dummy shingles when installed will extend above the peak of the roof and shall be cut flush with the peak of the roof.

B. It is recommended that the type FCC cable rows be secured to the roofing felts in their proper allignment prior to commencing erection of the shingles. Dimensions of FCC cable rows detailed on drawing E-3 are to cable center lines and are given exactly to the height each shingle row will advance up the roof. The connection of the shingle positive and negative leads allows some variation in the exact location of the cables. The cable row dimensions are identified so as to clear all nail holes.

C. The positive and negative leads of the shingles shall be connected to the horizontal FCC cable rows prior to nailing the shingles in place. Nailing of the shingles shall be done by means of the nails and split washers provided. The opening in the washer shall be oriented in a straight vertical position to allow future removal of the shingle with the shingle removal tool. After the shingles have been secured in place, a bead of clear silicone sealant shall be applied to the bottom edge of the Hex to prevent shingles lifting during wind conditions. The leads on the shingles are of sufficient length to allow removal of the shingle and reinstallation of a new shingle should it become necessary. After the shingle has been electrically connected and secured in place, the excess lead length shall be folded over on itself as indicated on Drawing E-7.

D. The positive and negative buses each consist of three (3) runs of FCC cable. The negative leads from the first row of "SCM" shingles and the positive leads of the top active row of "SCM" shingles shall be connected to the three runs of FCC cable by alternating between the three rows. Shingles 1, 4, 7, 10, and 13 are to be connected to one cable; 2, 5, 8, 11, and 14 to the second cable; and 3, 6, 9, 12, and 15 to the third cable.

E. The positive and negative buses shall be brought down through the roof approximately 10" down from the peak and 2¼" in from the edge. They shall pass between the rake and the exterior wall surface in a 1" diameter raceway sleeve from the roof to the top of the transition block enclosure. They shall then enter the top of the transition block enclosure and be terminated. Seal raceway openings in the transition block enclosure with Ducseal. Arrange enclosure to drain. All cables, including the positive and negative buses, extend over the right-hand side of the roof for diagnostic testing purposes. See details on drawings.

3.7 FCC CABLE INSTALLATION

A. The horizontal and vertical rows of FCC cables shall be secured to the roofing felt by means of duct tape approximately every 6'.

B. The positive and negative buses each consist of three (3) rows of FCC cable which shall be installed on top of each other. Tape the cables together periodically prior to securing to the roof.

C. Terminations and splicing shall be carried out in accordance with the manufacturer's recommended procedures. Special connector assemblies will be provided along with an installation crimping tool. The operation of the crimping tool is such that a positive connection is ensured prior to release of the tool jaws. Each splice or connection shall be insulated by means of a manufactured two-piece insulating patch.

D. The transition blocks will be provided by General Electric as part of the FCC cable package. Two transition blocks will be required and shall be mounted by the Electrical Contractor in an appropriately sized NEMA 3R hinge cover enclosure on the exterior of the prototype. The hinged cover enclosure shall be provided by the Electrical Contractor.

E. All horizontal runs of FCC cables shall be extended over the right-hand side of the roof between the exterior wall and the rake. They shall then run within the rake space to collection points as indicated on the drawings.

At the collection points they shall be extended into the prototype. A minimum of six feet of slack cable shall be left at the collection point.

Each cable shall be marked with the row designation indicated on the drawings. Openings through the exterior wall of the prototype shall be sealed with Ducseal.

The cable running between the rake boards and the exterior wall shall be tucked up into the space so as not to be visible from the exterior and so as not to be exposed to the weather.

The installing contractor shall quote a separate price for terminating these cables on stud type terminals within NEMA enclosures with #12 AWG leads connected to each cable and extended to a terminal board in NEMA enclosure to be located at the M.I.T. instrumentation area within the prototype.

3.8 ELECTRICAL SERVICES

A. The utility service will be provided by M.I.T. from the local utility company source and will terminate in a panelboard called the M.I.T. Power Panel.

B. The prototype load center "PLC" shall be provided by the Electrical Contractor and is to be used for termination of all branch circuit wiring associated with the prototype structure which includes receptacle outlets, lighting circuitry, and circuitry for heating and air conditioning. This panel is to be fed from the M.I.T. Power Panel through a suitable KW HR meter.

C. The House Service Panel shall be provided by the Electrical Contractor. It has no direct loads connected to it. It serves as the interface between the PV system and the M.I.T. Power Panel. It shall receive its 120/240 V, 1 Ø, 3 wire source of supply from the M.I.T. Power Panel. The inverter output shall be terminated at the panel through the circuit breaker indicated.

APPENDIX C
ABACUS CONTROLS SUNVERTER
SPECIFICATIONS

APPLICATION		REVISIONS			
NEXT ASSY	USED ON	LTR	DESCRIPTION	DATE	APPROVED

SUNVERTER SPECIFICATIONS

INPUT

1. Input is from a photovoltaic array with or without a battery.

2. Input DC voltage range is 200 to 300VDC.

2.1 Automatic startup at 220VDC.

2.2 Automatic turn-off at 200VDC.

2.3 Automatic turn-off at 300VDC.

3. Ripple current returned to utility: 2% rms of DC current.

OUTPUT

Nominal output is 240VAC 60Hz Single Phase.

4. Utility intertie

4.1 Two wire 240VAC (utility supplies neutral for 120V/120V).

4.2 Output current is phaselocked to utility voltage, resulting in unity power factor.

4.3 Output current is amplitude regulated with amplitude set by internal calibrated adjustment or signal from the max power track module.

4.4 Harmonic distortion of the current into the utility is 5% THD.

4.5 Automatic disconnect if utility voltage is less than 216VAC.

4.6 Automatic disconnect if utility voltage is greater than 264VAC.

4.7 Automatic disconnect if current exceeds rating.

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON FRACTIONS ± 1/64 DECIMALS ± .005 ANGLES ± 1/2°	CONTRACT NO.	abacus controls inc. 80 READINGTON ROAD SOMERVILLE, N.J. 08876
	DRAWN CR 10/16/79	
MATERIAL	CHECKED	SUNVERTER SPECIFICATIONS
	ENGINEER C. R. O'Sullivan	
FINISH	APPROVAL	SIZE A 54241 10552
		SCALE SHEET 1 OF 3

4.8 Automatic disconnect if phaselock is broken.

4.9 Automatic disconnect on loss of utility.

5. Stand Alone

5.1 Three wire 240VAC 60Hz Single Phase.

5.2 Voltage regulation ±2%.

5.3 Voltage is phaselocked to utility voltage if present; otherwise, 60Hz ±.25Hz.

5.4 Voltage harmonic distortion: 4% THD, 3% maximum any one frequency.

5.5 Automatic disconnect if inverter voltage is less than 216VAC.

5.6 Automatic disconnect if inverter voltage is greater than 264VAC.

5.7 Current limit protected and short circuit protected.

CONTROLS AND DISPLAYS

6. Front Panel

6.1 On-Off Switch

6.2 Mode Select

a. Stand alone (inverter to load)

b. Utility intertie (utility to load, inverter in parallel when available)

6.3 DC On Light

6.4 AC On Light

6.5 Contactor Open (red)

7. Inside Sunverter

7.1 Power level set adjustment (utility mode)

7.2 Contactor Reset

7.3 Contactor On-Off

7.4 Frequency Adjust

7.5 Voltage Adjust

GENERAL

8. Efficiency is 87% or greater from 20% load to full load.

9. Tare power is 250W maximum at 200VDC input.

10. Cooling is forced air as required (fans automatically turned on and off by thermal switch)

11. Size is 24"w x 30"d x 60"h.

12. Weight is 500 lbs. (10KVA)

13. Input/output isolation: 1500VAC hipot.

SAFETY FEATURES

(These are in addition to automatic turn-offs and disconnects cited above.)

14. DC On-Off Switch

15. Input fuses, both lines

16. Output fuses, both lines

17. Automatic turn-off for power transistor overtemperature.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1982 500-000/47