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CONSTRUCTION OF A PHOTOVOLTAIC POWER SYSTEM AT NATURAL BRIDGES NATIONAL MONUMENT

December 1980

MASTER

A. E. Benoit

Massachusetts Institute of Technology
Lincoln Laboratory
Lexington, Massachusetts 02173

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

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ABSTRACT

In 1979, MIT Lincoln Laboratory, in conjunction with the U.S. Departments of Energy and of the Interior, built a 100-kW-peak photovoltaic (PV) power system at Natural Bridges National Monument in Utah. At present, this system is the largest of its kind in the world. This report describes the construction phases of the program and gives a chronological history of the events and problems encountered when such a large and complex task is undertaken in a remote area with very limited fabrication facilities. This experiment will demonstrate the application of solar energy to the variety of loads found in a small and remote community. This solar energy system was designed to meet all electrical requirements when there is no utility grid, with only occasional back-up from an existing diesel generator.

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1.0 INTRODUCTION

Construction of a 100-kW-peak photovoltaic power system was completed at the Natural Bridges National Monument in southeastern Utah in June 1980. Sponsored jointly by the U.S. Department of Energy and the Department of the Interior, this system is the largest flat-plate photovoltaic (PV) array field in the world. The PV system meets the park's energy requirements and a diesel generator, previously the park's sole power source, has been relegated to a back-up mode. Taking DC power from the array and applying it to site loads as AC power, the system stores excess energy in a lead-calcium battery subsystem. The array field is made up of over a quarter-million cells supplied by three manufacturers and covers a 1-1/4-acre area.

Natural Bridges National Monument was chosen from over sixty possible site locations after a joint study by MIT Lincoln Laboratory and the National Park Service. Criteria sought were remoteness from an electrical utility grid, size and diversity of electrical loads, and accessibility to the public.

A team was then sent to the park to site the array field and the PV building which would house the power system's electronics equipment and battery subsystem. Sites were chosen for accessibility, both during construction and later for the visiting public, and for minimal impact on the natural beauty of the park.

F. J. Burton of Salt Lake City was selected by the National Park Service as the contractor for site preparation and construction of the PV building, while Ford, Bacon and Davis, Utah, was selected by MIT Lincoln Laboratory to design and install the overall system. Actual construction began in late June of 1979 with the felling of the first tree by the National Park Service contractor. Only trees which would obscure the array from total exposure to the sun were removed.

The aesthetics and remoteness of the park were major influences in all of the design and construction decisions described.

2.0 DIVISION OF RESPONSIBILITY

The National Park Service (NPS) provided all site development, including the preparation of the array field area, the construction of the PV building to house the battery subsystem and the power system's electronic components, the lightning protection subsystem, and the installation of the underground power and signal cables. The construction of access roads and trails and of an interpretive overlook of the photovoltaic array was also the responsibility of the NPS. During the construction period, the NPS supplied water, electrical services, parking and storage areas, and a great deal of moral support and enthusiasm.

The Department of Energy, through MIT Lincoln Laboratory, provided the solar arrays, the control and data subsystems, the battery subsystem and the power-conditioning system. Also provided by MIT Lincoln Laboratory were the underground power and signaling cables, the gas-detection subsystem, the 50-kVA, single-phase, 60-Hz inverter, the 40-kW battery charger, and a complete weather and data subsystem.

3.0 CONSTRUCTION OF THE ARRAY

3.1 Array Area Site Preparation

Figure 1 shows the area as it appeared before the NPS contractor began site preparation: cutting trees, grubbing, bucking and chipping. This work took approximately two weeks. In remote areas such as this, simple requirements often become complex. A nearby outside source of burrow to supply the same type of soil as that in the array area had to be found, and the material had to be hauled to the array area. The burrow was then spread, terraced and compacted to NPS specifications. In order to accomplish this 95% compaction, a great deal of water was necessary. Again, an outside source and more hauling were required and aesthetics and the remoteness of the site were major influences on the work. Proper drainage pipes and landscaping of the perimeter of the array area was also under way during this period. The careful execution of these tasks preserved the natural beauty of the surrounding landscape. By late July, 1979, the array area was roughly graded and taking shape, as is shown in Fig. 2.

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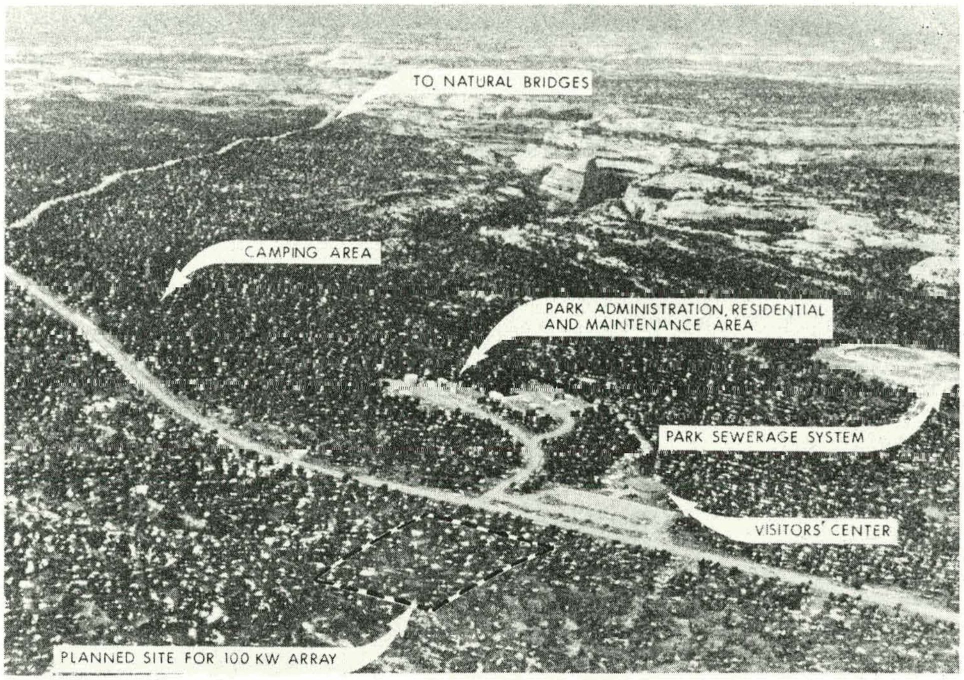

Fig. 1. Natural Bridges National Monument.

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Fig. 2. Rough grading of array field.

3.2 Lightning Protection Subsystem and Water Lines

The lightning protection subsystem and the water lines in the array area were installed during the rough grading.

Water lines, oriented from north to south, were centered in the array area to provide a permanent water supply for cleaning the modules at a minimum of cost and labor.

The lightning protection subsystem consists of a grid placed approximately two feet below the final grade. This grid is connected to several lightning rods in each of the 12 rows of the array and to the fence surrounding the array area. This offers an adequate protective umbrella for the photovoltaic system. All of the frames, subframes, modules and junction boxes are connected to this grid, thus providing a very substantial ground. (See Figs. 3 and 4.)

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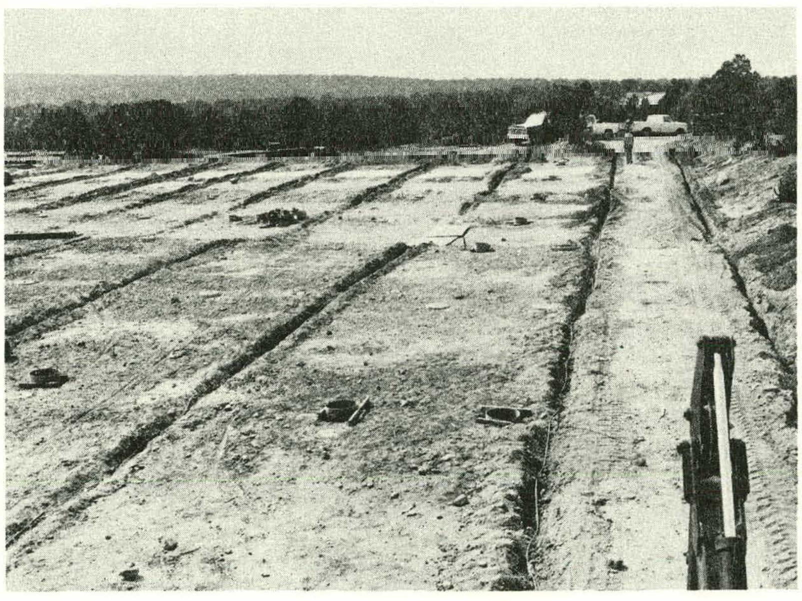

Fig. 3. Trenches with ground wires.

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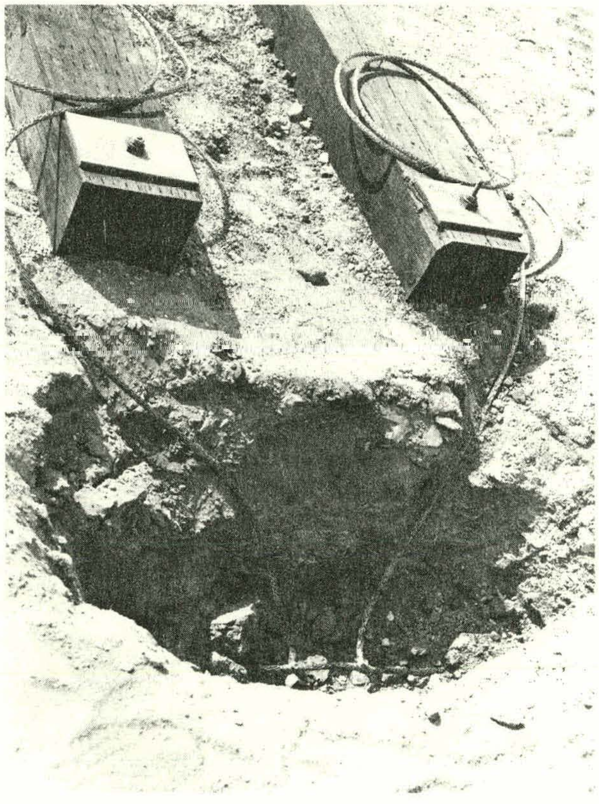

Fig. 4. Junctions to lightning grid.

3.3 Foundations

Surveying for the location of the piers to support each of the 48 2-kW array subfields began on 1 August 1979. Arranged in 12 rows approximately 200-feet long, this network of subfields required 288 piers, 18 inches in diameter and ranging in depth from 1 to 6 feet. The depth of each pier was determined by the depth of subsurface rock and by the dynamic and static loads each pier was required to support. As shown in Figure 5, two concrete piers were bridged by a 9-foot-long timber with an 8 by 10-inch cross section. This allowed a greater freedom from tolerances in location of the large 8 by 24-foot steel frames.

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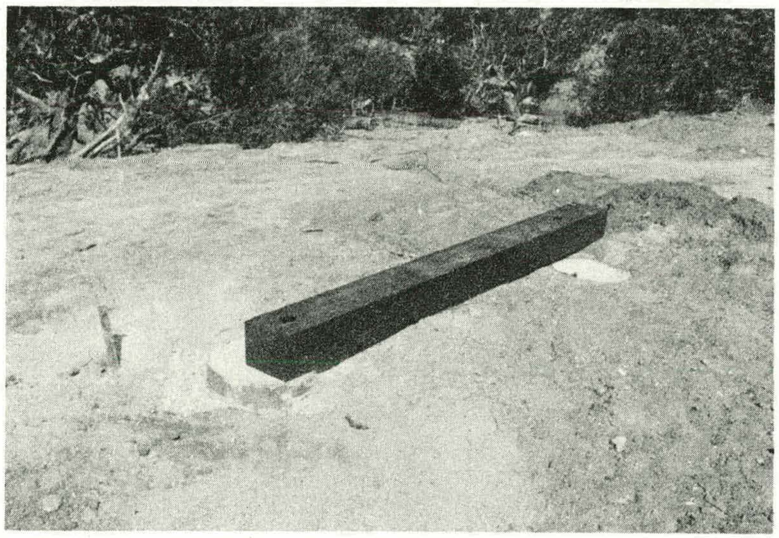

Fig. 5. Support timbers.

It should be mentioned here that the use of concrete in remote areas, in general, and at Natural Bridges National Monument, in particular, presents major logistical problems. Aggregate must be trucked from great distances, then the cement and water added at the site to obtain the proper slump. (The word "slump" refers to the consistency of the concrete at the time it is to be poured.) At NBNM, dry aggregate, rather than mixed batches of concrete, was hauled to the site for several reasons:

a. The elapsed time required to reach the site from an outside concrete batching point would have permitted the concrete to start curing in the truck.

b. Sharp curves and hills en route to the site could have caused dangerous shifting of the load.

c. Mixing the concrete at the site ensured that the proper quantities were used to obtain the correct strength of concrete.

A rock bolt in the center of each pier was used to fasten the timbers to the piers. The rock bolt holes were drilled using a template in order to achieve a greater degree of accuracy after the concrete piers had set up.

3.4 Timbers

Special timbers requiring an 8-10 week lead time were shipped to the site from Washington state. These timbers were pressure treated with a preservative to produce a 30-year life expectancy and had been pre-cut and pre-drilled before shipment to the site. Upon arrival, it was noted that most were rather badly split. Again, the remoteness of the site was a determining factor in solving this problem. To replace the timbers would involve a lengthy delay and it was therefore decided to perform a field fix. As Figure 6 shows, compression plates were added to both ends of each timber to arrest the splitting and to produce the strength needed for the lag bolts holding the large steel frames in place.

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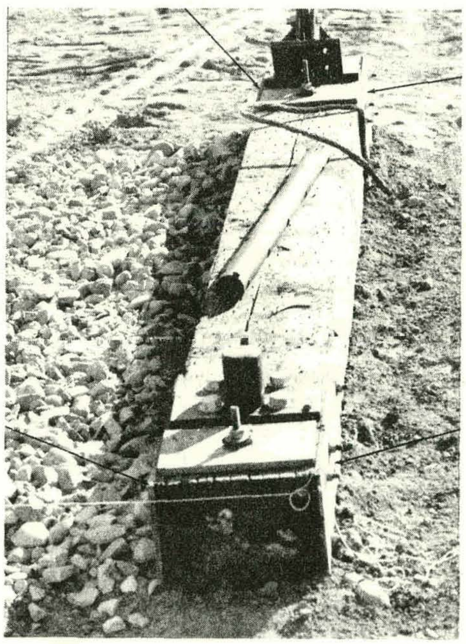

Fig. 6. Compression plates mounted to support timbers.

When the timbers were set at the proper alignment and elevations, the rock bolts were torqued down and grouted in place. Facing timbers were then bolted to the front edge of each row of timbers. The facing timbers serve a dual purpose: they provide a terracing effect, which allows the rows of array subfields to be closer together because of the progressive elevation difference between each row; they also serve as a protective shield over the PVC conduit. This conduit carries the wiring of each array subfield to the end of its respective row to join the underground cabling which terminates in the PV building. The facing timbers also retain the gravel and prevent soil erosion, as is shown in Fig. 7.

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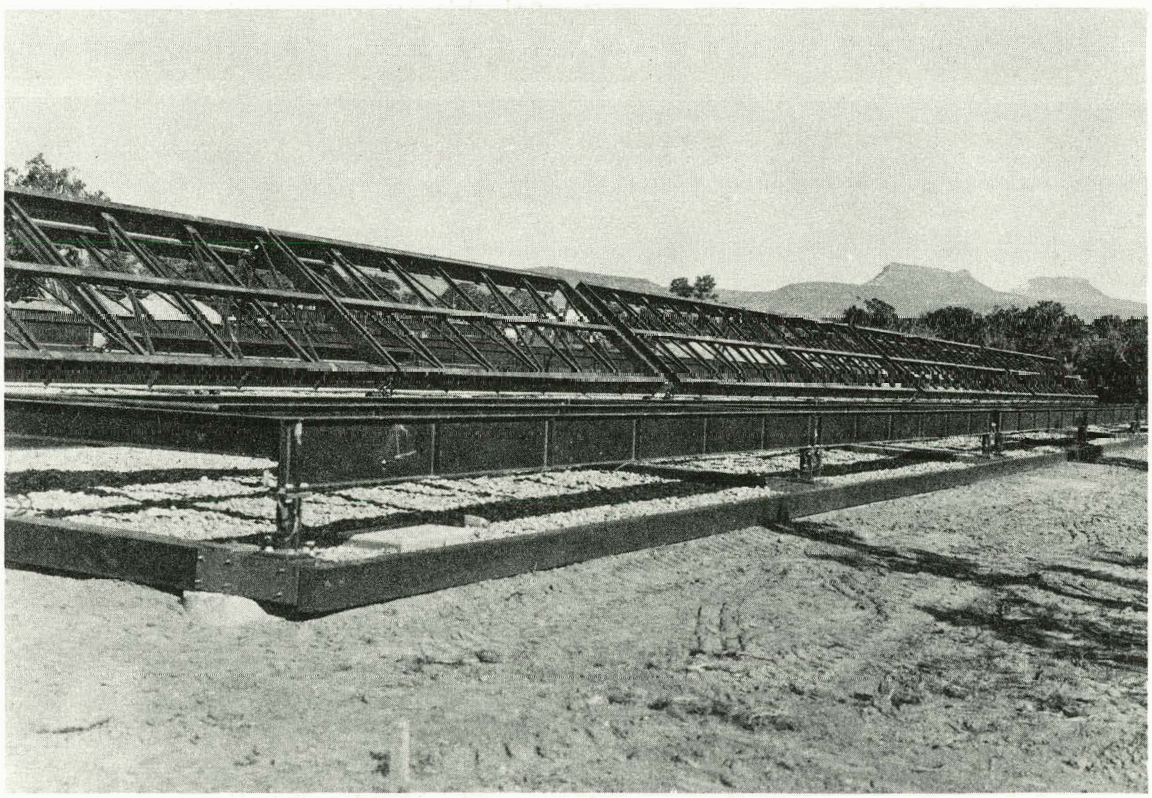

Fig. 7. Facing timbers on first row of array field.

3.5 Gravel

Approximately 600 cubic yards of crushed gravel of the appropriate size and color was spread over the entire array field to permit all-weather vehicular traffic and to hold the soil in place. This gravel covering also keeps down blowing dust and silt which could cover the modules thus reducing the power output of the array.

3.6 Transitional Agreements

To better meet scheduling commitments, it was decided that MIT Lincoln Laboratory's contractor would begin the second phase of the program before the NPS contractor's work was completed. With two contractors working in the same area at the same time, a great deal of cooperation was needed. A crew made up of personnel from both contractors was organized to perform the tasks directly related to the interface of the two contracts. The transition was efficiently accomplished and this seems to be a workable approach when good communication exists between all parties. Upon completion of nearly 90 percent of the NPS contractor's work, the site was accepted by the National Park Service representative and turned over to the contractor for MIT Lincoln Laboratory so that the second phase of the project, the installation of hardware, could commence.

3.7 Array Frames

The array field is comprised of ninety-six steel frames which measure 8 X 24 feet and weigh approximately 1500 pounds each. These frames each have twelve subframes mounted to them, making a total of 1152 subframe assemblies. Due to the size of the job and the limited facilities at the site, these components were assembled off-site. This permitted assembly in a parallel time period under more efficient working conditions and aided the contractors in meeting scheduling commitments. The large frames were assembled in a jig, then welded, painted, and shipped to the site for installation. At the site, the timbers were placed and the mounting brackets for the frames were aligned and made ready.

Access to the array field was from the northwest corner. The NPS contractor first completed work in the southern and eastern sections of the array field, so that the installation of the frames could begin in the southern section with minimal interference to the NPS contractor (Figure 8).

As each frame was set in place and aligned, cable harnesses were added, as well as all necessary junction boxes.

The subframe assemblies (Figure 9), which consist of a subframe and modules, were also assembled off-site, pre-wired and shipped to the site, to be installed on the large frames and connected to the harnesses. By prewiring and testing the subframe assemblies off-site, work was performed in a parallel time period and the necessity for on-site wiring was eliminated.

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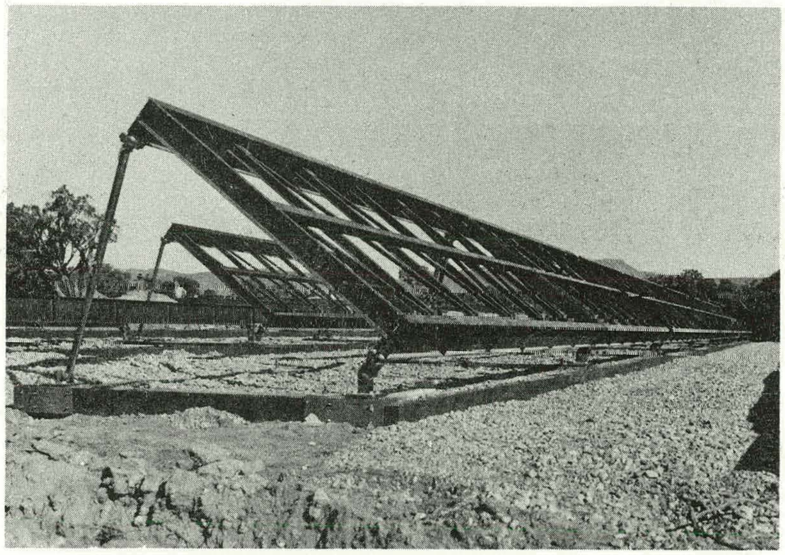

Fig. 8. Steel frames in place in southern section of array field.

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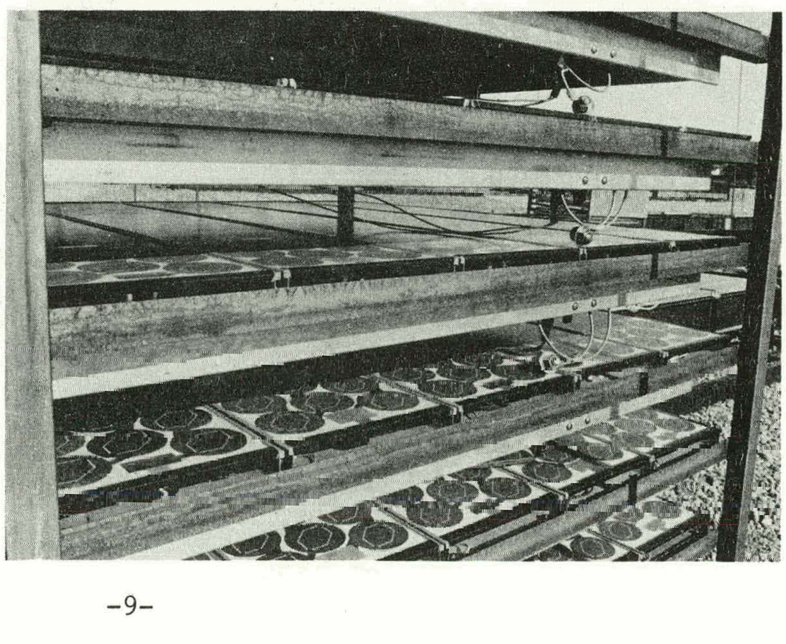

Fig. 9. Subframe assemblies in shipping containers.

3.8 Junction Boxes

The array junction boxes (one for each frame) were used to terminate the harnesses of each frame and to provide a test connector for the purpose of periodic maintenance and module degradation testing (Figure 10).

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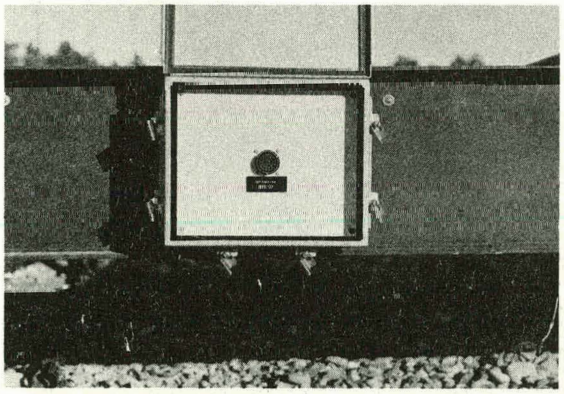

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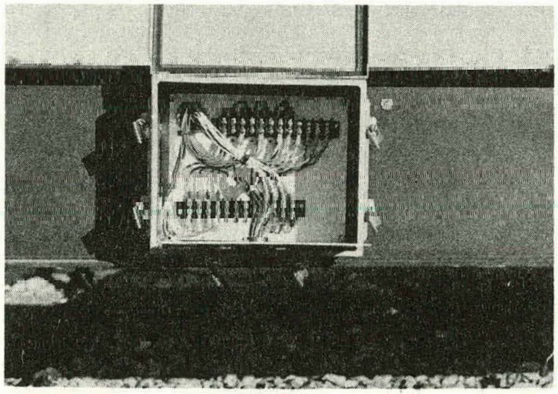

Fig. 10. Array junction box.

The array subfield junction boxes (one for each array subfield) connected two array-frame harnesses to provide slightly over 2-kW segments of power (Figure 11).

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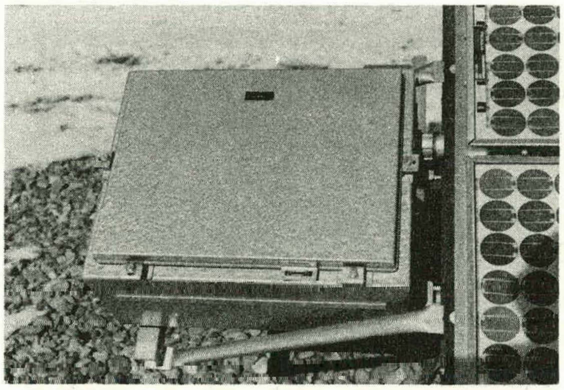

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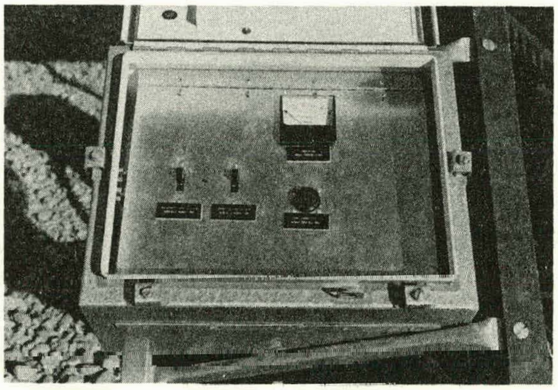

Fig. 11. Array subfield junction box.

The row-end junction boxes (which were installed at the west end of each row) connected each row of four array subfields to the underground cable feeding the PV building (Figure 12).

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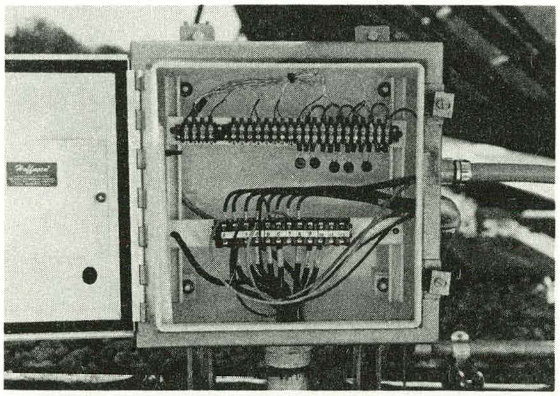

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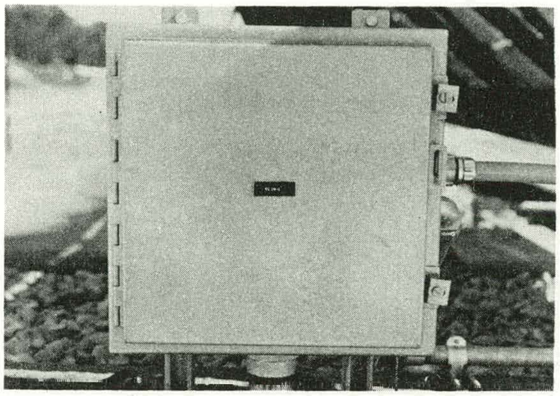

Fig. 12. Row-end junction box.

3.9 Safety Screens

Safety screens were installed on the back side of the arrays. These screens provide personnel with protection from the exposed terminals on each module. The safety screens also prevent rodents, birds, snakes, etc., from nesting or from damaging the insulation on the wires.

3.10 Safety Fencing

Another NPS contract was issued at this time to build a 6-foot fence around the entire array area. The fence is vinyl-clad wire screening, supported by metal posts, and is connected to the lightning grid. There is one vehicular entrance at the northwest corner of the fence. The post for the fence required that holes be drilled for the concrete supports. A careful watch was maintained to ensure that the power and signal cables were not damaged along the west side of the array. One utility wire was severed but was quickly repaired.

4.0 CONSTRUCTION OF THE PV BUILDING

In late August 1979, while construction of the array area continued, work was started on the PV building.

The PV building is located on the east side of the diesel generator building. It is divided into three rooms: one for the battery subsystem, another for the power-conditioning equipment, and the third to house the control and data subsystems and to provide some storage and work space. The PV building was designed and constructed by the NPS contractors under the direction of MIT Lincoln Laboratory.

4.1 Foundation

Concrete piers and grade beams with reinforcing steel provide the basic foundation of the PV building (Figure 13). The floor is made of reinforced concrete. In order to maintain stringent safety standards, an L-shaped, reinforced-concrete wall separates the battery room from the building proper, as shown in Figure 14. This was done because of dangerous hydrogen gases which are generated when batteries are equalized. The concrete wall will ensure personnel safety should excess hydrogen cause an explosion within the battery room. When the grade beams, floor slab, and concrete wall were completed, the sills were set and the framing of the building begun.

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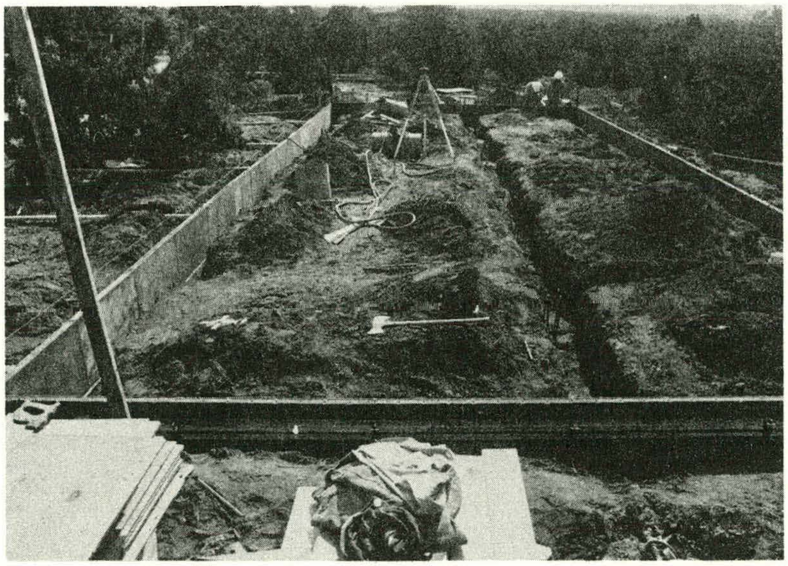
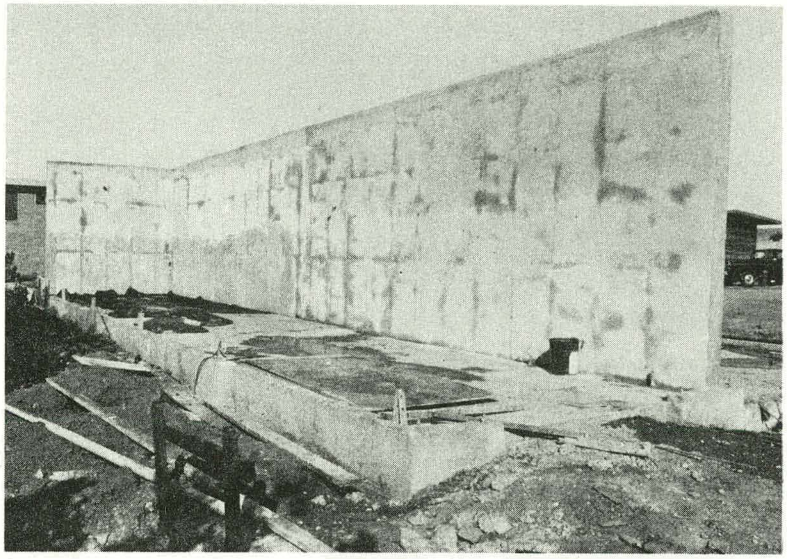


Fig. 13. Forms for grade beam on top of concrete piers for PV building.

Fig. 14. Concrete wall surrounding battery room.



4.2 Building Design

The building design incorporates several passive solar energy techniques, including triple-glazed windows, full-insulated outer shell, proper placement of windows, and special thermal shutters. As an added safety feature, the southern wall of the battery room was built as a large blow-out panel. The interior walls of the room housing the power-conditioning equipment, which includes the inverter and the battery charger, are covered with an acoustical tile. The equipment and storage area is covered with a vinyl siding. The battery room has a standard painted gypsum board covering but the concrete wall which faces the southern windows is painted black for thermal gain.

For the most part, the construction of the PV building went smoothly. Plumbers, electricians and general contractors working in the same area interfaced well. The plumber had to lay water lines for the eye wash stations and the shower before the floor slab could be poured. The electrician also had similar tasks to do prior to the pouring of the floor, consequently, some delays were encountered. The electrician placed a lightning grid around the building and implanted ground plates throughout the equipment and inverter rooms for equipment connections. Careful coordination between so many subcontractors was essential. Locations of electrical outlets and conduit pipes had to be noted to avoid future problems when equipment was installed.

Exterior walls were sheathed with 4 x 8-foot sheets of plywood; interior walls were covered with gypsum board. The exterior walls were then covered with cedar siding, in keeping with other park buildings. Fans, coolers, windows, and doors were then added, and all building floors were covered with a vinyl asbestos tile.

The walls in the battery room were then painted and a 5-foot-high wainscot of protective acid-resistant coating was added, as shown in Figure 15.

With the addition of lights and heat, the PV building was ready for the installation of equipment.

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Fig. 15. Battery room.

4.3 Equipment Installation

The batteries, inverters and battery charger, after being tested at MIT Lincoln Laboratory, were shipped to the site. Again, because of remoteness and lack of facilities at the site, a moving company with its own equipment was contracted to place the batteries in the building. An all-terrain fork-lift truck was used to unload the batteries from the three moving vans. This battery subsystem has the storage capacity of 600 kWh of power.

The inverters and battery charger were placed in the inverter room and the MIT Lincoln Laboratory contractor began installation of the remaining power-conditioning junction boxes. The power and signal wires from the array area were terminated and all interconnections were made. Wires between the PV building and the diesel generator building were connected through the site transfer switch, enabling the site to be run by the solar array or the back-up diesel generator. Meters were added to measure the power consumption of the PV building as well as of the complete site.

4.4 Wires and Cables

The power and signal cables which connect the array area and the PV building were checked again for continuity and ground shorts. Some faulty signal wires were found but sufficient spares had been provided so that no delays resulted. The large No. 6 power cables were tested and found to be in good order. Testing revealed several ground currents on some of the subfields which were traced to shorted cells within the modules. New modules were installed.

4.5 Battery Bank Disconnect Switches

Two large, fused, battery-bank disconnect junction boxes were installed. One disconnect switch is located electrically at the mid-point of the battery subsystem to allow shutdown of one-half of the battery subsystem for maintenance and service (see Fig. 16). The second battery-bank disconnect junction box isolates the battery and subsystem from the inverter room and the power-conditioning subsystem (see Fig. 17). Both junction boxes are located on the exterior wall of the PV building for accessibility and safety.

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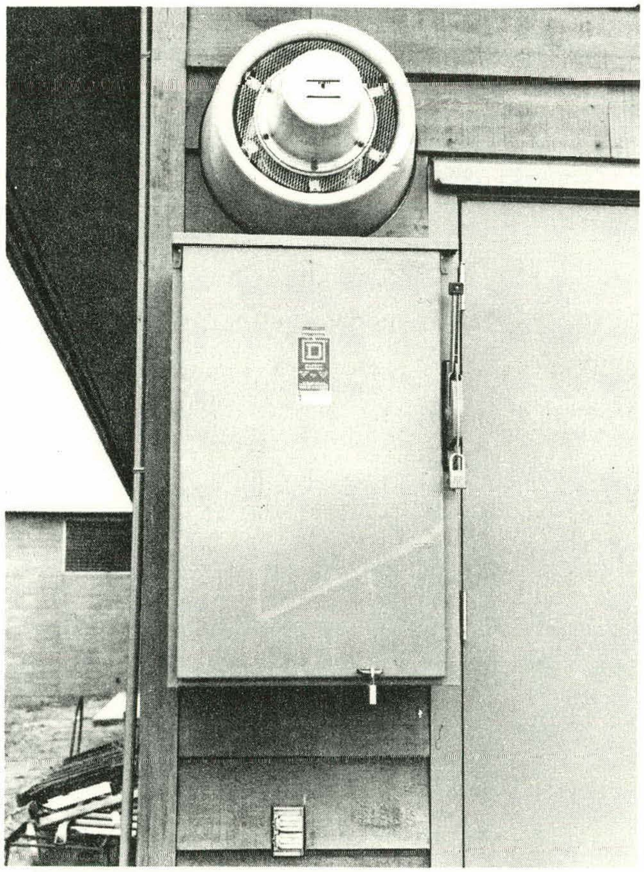

Fig. 16. Intermediate battery-bank disconnect switch.

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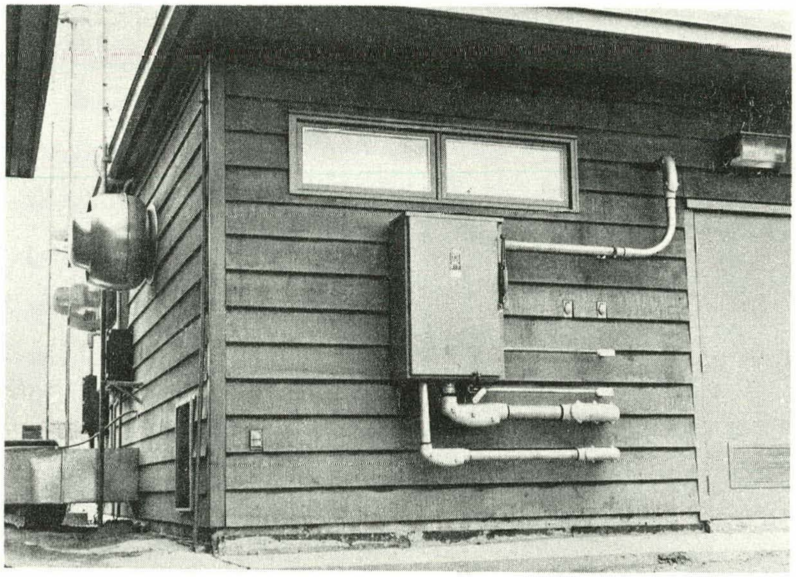

Fig. 17. Main battery-bank disconnect switch.

Connections from the battery subsystem to the power-conditioning subsystem were accomplished using 300 MCM cable in 2- and 3-inch conduit. The 300 MCM cable was used because of derating when placed in metal conduit. All conduit pipes have explosion-proof fittings located at the entrance of the conduit into the battery room. The hydrogen-sensor alarm system was installed and made operational.

It should be noted that when holes have to be cut for large conduit pipes through finished walls, particular care should be taken to avoid studding, especially load-carrying members. The PV building (Fig. 18) was complete and ready for the installation of equipment and testing.

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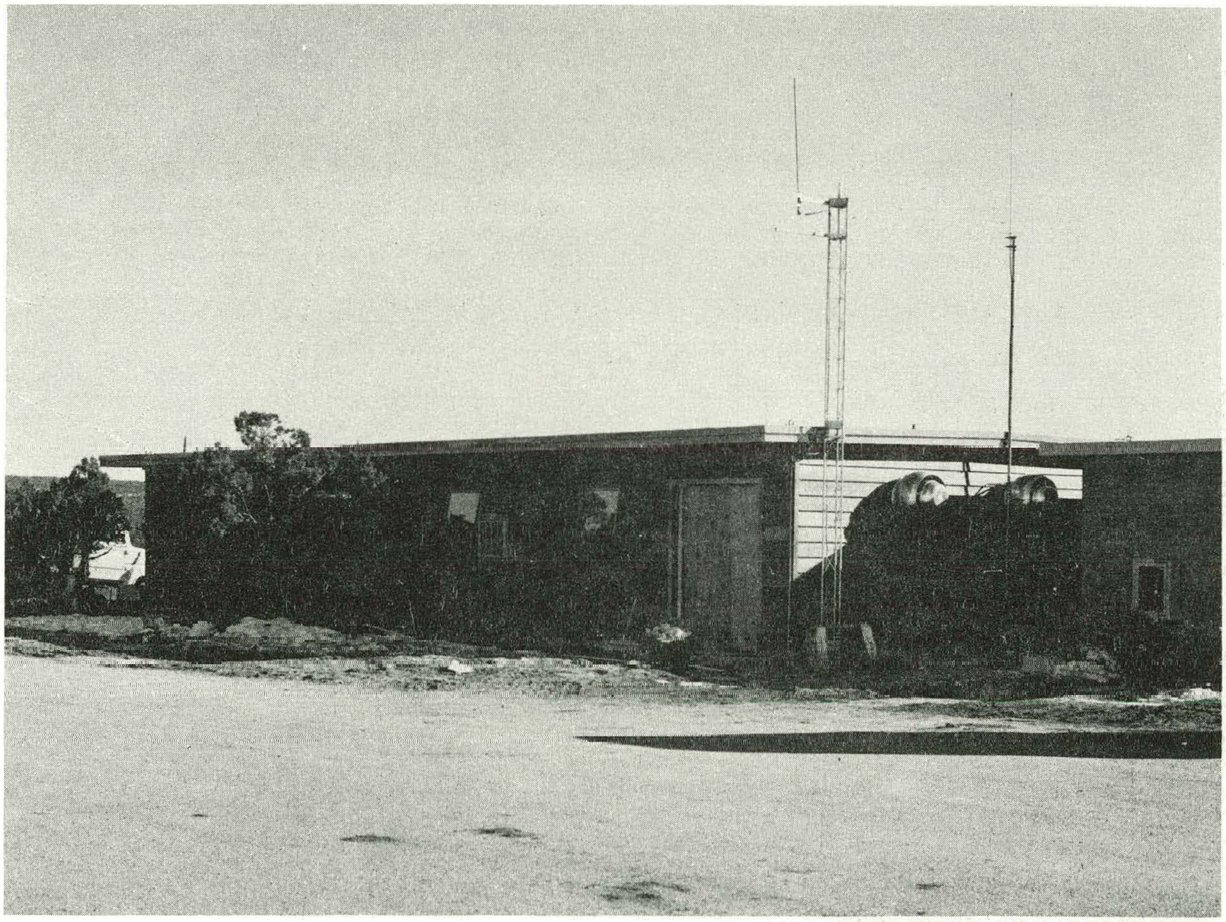

Fig. 18. PV building looking southeast.

4.6 Data Subsystem

Weather monitoring instruments and solar measuring devices were mounted on the roof of the PV building. These instruments and the electronic equipment shown in Fig. 19 comprise the data subsystem. Wind speed and direction, barometric pressure, precipitation, dew point temperature and ambient air temperature are monitored. Several pyranometers, a pyrheliometer, and a UV detector are used for measuring solar insolation (see Fig. 20). The pyrheliometer requires a very rigid mount to function properly. To accomplish this, holes were drilled in the top of the concrete wall which extends through the roof of the PV building. Long, threaded rods were grouted into these holes and the base of the pyrheliometer was securely fastened down. Data are displayed on the electronic instruments within the PV building and are also recorded on magnetic tape. These tapes are returned periodically to MIT Lincoln Laboratory for analyzing, thus providing the basis for an accurate evaluation of photovoltaics under field conditions.

Shown in the left foreground of Fig. 19 is the I-V load cabinet. This piece of equipment monitors the performance of the entire array field, recording data on magnetic tape for analysis. Every day, at approximately solar noon, a complete scan of the array field is made to observe the status of the photovoltaic system.

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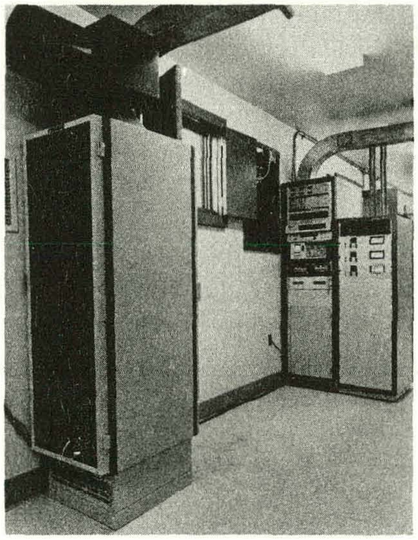

Fig. 19. Data subsystem electronic equipment.

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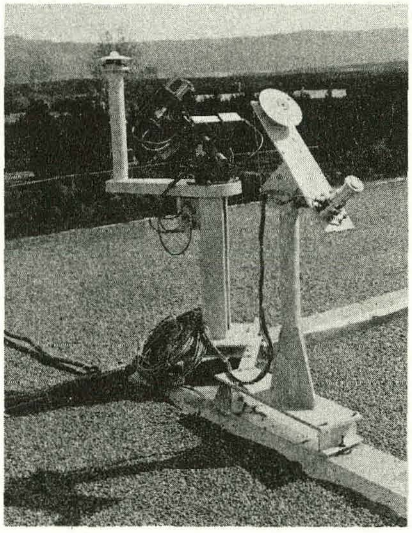

Fig. 20. Instrumentation for monitoring environmental conditions.

5.0 PRELIMINARY SITE TEST

While off-site testing was in progress on the control system, a preliminary test and turn-on experiment was conducted at Natural Bridges National Monument. A special switching box was assembled and brought to the site for this preliminary test. This test box was used as an interface between the array, the power-conditioning subsystem, and the battery subsystem.

A complete checkout of the battery subsystem, the battery chargers, and the inverter was conducted. The batteries were connected and the state-of-charge meter was hooked up. Also the hydrogen sensor system was brought on-line.

Fuses were installed in the ASJBs of 12 array subfields. The inverter was brought on-line to power the PV building, the residences, the utility building and the generator building. The large transformer, which supplies power to the Visitor's Center, created an inrush current which caused an adverse reaction to the inverter. A 2.2-ohms, 250-W series resistor was installed to rectify the problem, and all the site loads were placed on the inverter. The inverter used the batteries for its power source. The battery charges were then energized, using the diesel generator. The array provided power to the site and the diesel generator recharged the batteries. The air compressor and air-lift system was used to "bubble" the batteries and the batteries were then equalized. At this point the site was complete and ready for the installation of the control system.

6.0 FINAL TEST AND ACCEPTANCE

The control system arrived at the site after many weeks of off-site testing. It consists of four cabinets containing the array field switching modules and terminations, Fig. 21, two cabinets containing the microprocessor, and three cabinets housing the sensor conditioning system. In addition, there is a manual control panel, Figure 22.

CP267-5736A

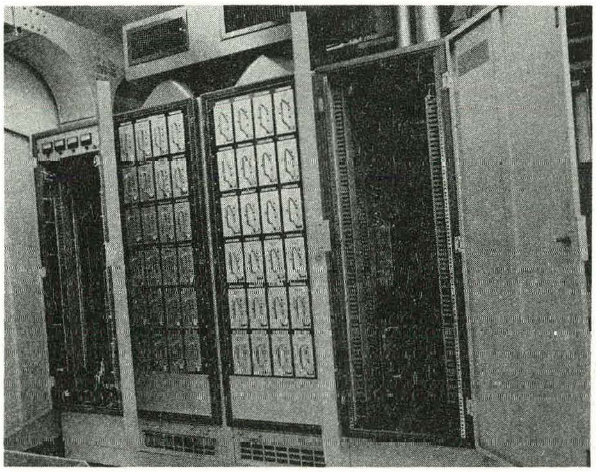

Fig. 21. Array field switching cabinets (AFSC).

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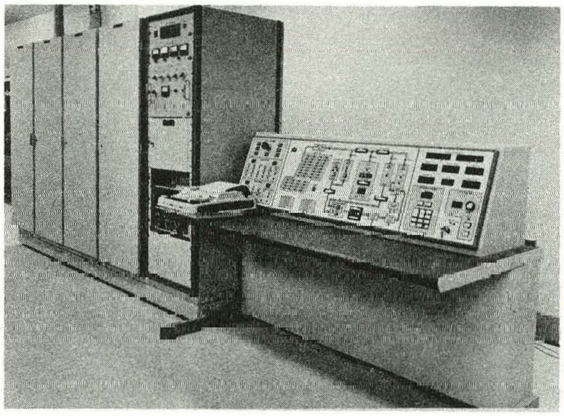

Fig. 22. Master control panel (MCP) and microprocessor cabinets.

All of this instrumentation was placed in the PV building's control room in pre-determined positions. This complex system with its delicate instrumentation was carefully wired into the battery subsystem, the power-conditioning subsystem and the array field. Final testing was conducted and acceptance of the entire system was brought to a close. Operation manuals and procedures were de-bugged and the NPS personnel responsible for the continuous operation of the world's largest photovoltaic system were instructed in its use.

The 100-kW-peak photovoltaic (PV) power system was officially dedicated on 7 June 1980.

7.0 CONCLUSION

Several conclusions can be drawn from the experiences gained at the Natural Bridges National Monument solar project. When a project of this magnitude is undertaken, involving two or more government agencies and several contractors and subcontractors cooperation between all is paramount to a successful completion.

Thorough preliminary studies and research must be carried out, for once a project as remote and as complex as this is started, it is extremely difficult in the field to incorporate changes in design or scope. All changes increase cost and should be kept to a minimum and field changes often have hidden costs not immediately apparent. On-the-spot decisions invariably affect other contractors, can be very subtle, and can dramatically increase costs. All of these factors lend emphasis to the importance of thorough preliminary efforts by all parties involved and to the very real necessity for good communications.

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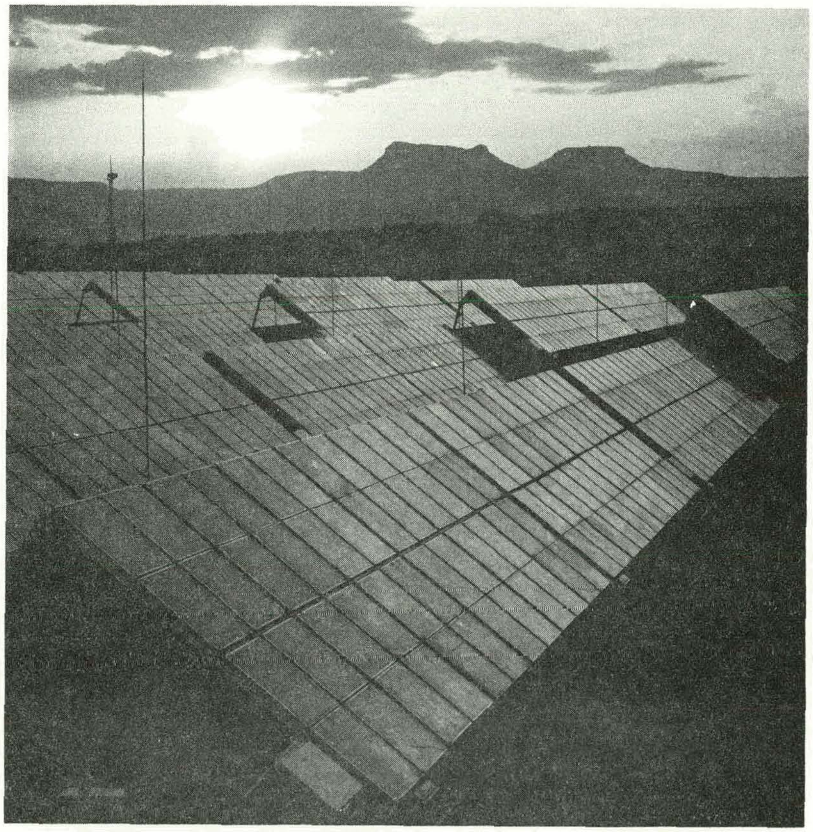

Fig. 23. Sunrise over the array.