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DESCRIPTION AND STATUS OF NASA-LeRC/DOE PHOTOVOLTAIC APPLICATIONS SYSTEMS EXPERIMENTS

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ABSTRACT

In its role of supporting the DOE Photovoltaic Program, the NASA-Lewis Research Center has designed, fabricated and installed 16 geographically dispersed photovoltaic systems. These systems are powering a refrigerator, highway warning sign, forest lookout towers, remote weather stations, a water chiller at a visitor center, and insect survey traps. Each of these systems is described in terms of load requirements, solar array and battery size, and instrumentation and controls. Operational experience is described and present status is given for each system. The P/V power systems have proven to be highly reliable with almost no problems with modules and very few problems overall.

INTRODUCTION

The Department of Energy (DOE) is pursuing a National Photovoltaic Program aimed at developing cost effective photovoltaic (P/V) power systems capable of providing a significant amount of the nation's energy requirements by the year 2000. This program has been divided into several projects, one of which is the Tests and Applications Project (T&A) which is being managed for the DOE by the NASA-Lewis Research Center (LeRC) in Cleveland, Ohio.

The Applications effort of the T&A Project is intended to introduce P/V power systems to a wide range of potential users with near-term applications to accelerate their entry into the commercial market. Applications which indicate near-term cost-effectiveness, technical feasibility, solar cell promotional value, and/or substantial use multiplication are considered for joint cost shared experiments. To date, seven different systems applications comprising a total of 16 systems were selected for implementation.

Photovoltaic systems applications approaching near-term cost-effectiveness are presently almost exclusively associated with remote applications where the users loads are presently powered by batteries, thermoelectric generators, or small engine-generators. LeRC studies indicated there were a substantial number of potential uses at remote applications within the Federal sector. These studies also indicated that within the Federal sector there was a general lack of awareness and understanding of the capabilities and availability of P/V systems. Thus the applications selected by LeRC were in the Federal sector and were almost exclusively low power systems operating in remote

areas. Because they are in remote locations, they are all stand-alone systems; i.e., there are no back-up power supplies.

Having selected a particular application, LeRC established a joint agreement with the participating agency and developed an implementation plan for the project. The implementation plan describes requirements and responsibilities for the design, fabrication, installation and operation of the P/V system. LeRC personnel worked closely with the user agencies during the design phase, particularly in the selection of loads and definition of load profiles since this is one of the most critical areas of P/V system design. LeRC also worked closely with the users to achieve P/V array structure designs that integrated well with the load structures and the environment.

All P/V modules for these systems were purchased from industry by JPL as part of a related DOE Project. The P/V modules were assembled into arrays and tested by LeRC.

P/V power system installation and checkout was accomplished by LeRC and using agency personnel. LeRC personnel instructed users in system operation and data recording. Following installation, checkout, and instruction, complete system operation is turned over to the using agency. P/V system problems or failures are reported to the LeRC who then provide corrective action or advise the user on the proper course of action.

LeRC personnel schedule at least one site visit per year to conduct a detailed inspection of the modules, array structure, wiring, instrumentation, and controls.

All of the systems are instrumented with simple panel meters which record system performance and display system status.

All of the systems reported herein are considered operational experiments. They provide the DOE P/V Project with system performance and P/V module endurance data. These data also give the user confidence in system design and operation, and form a basis for procuring additional systems. User personnel record the data and forward it to the LeRC for analysis. Data recording varies widely depending on seasonal accessibility and the normal maintenance requirements of each system.

System Design

There are five areas of primary concern in the design of a P/V power system; loads and load profiles, array size (peak power) and battery type and

capacity, array structure, system voltage regulation, and instrumentation and controls.

The design of a P/V system depends almost entirely on two factors: an accurate definition of load power requirements and duty cycles and the determination of the proper size P/V array and energy storage capacity. In addition, loads should be designed or modified to operate only when required and should use energy efficient devices. Conversion from P/V DC power to AC power should also be avoided.

The basic approach to determining P/V array size and battery capacity is to match the combination of P/V array output and energy storage capacity to the load requirements. For stand alone systems, this means that the P/V array must generate enough power to meet the total annual load requirements including battery charging inefficiencies, and that the batteries must be large enough to sustain system operation during periods of below average seasonal and diurnal insolation.

LeRC has developed a computer program which determines average hourly P/V cell output by month for a particular location, and which determines P/V array size, tilt angle, and battery storage capacity. Inputs to the P/V cell output calculation are average monthly values of insolation, sky cover from the climatic atlas; precipitable water and atmospheric turbidity; and solar cell area, efficiency, and maximum power voltage. The P/V system simulation takes the output from the P/V cell calculation and matches it to an hourly load profile. The simulation program provides monthly system outputs over a 16 month period for specified numbers of series strings, battery capacities, and tilt angles. The simulation includes provisions for inputting P/V module degradation and random variation in insolation. The P/V array and battery are generally sized to limit battery maximum depth-of-discharge to 50%. Tilt angle is selected to optimize the array size and battery capacity. Selection of the optimum array size/battery capacity combination can be modified by system considerations (e.g., physical limitations for P/V array or batteries) or economic considerations.

Selecting the proper type battery is an important design function. Generally, automotive (SLI) type batteries are not well suited to use in P/V systems as they are not designed for deep discharge. Electric vehicle type batteries are better suited by virtue of deep discharge cycle capability and are fairly inexpensive. The so-called "Photovoltaic Batteries" being introduced by several manufacturers promise significant advantages, albeit at a higher price. These batteries have low self-discharge characteristics, high coulombic charge efficiency, large electrolyte capacity, deep discharge cycle life. Since present day P/V systems are almost always stand-alone systems, battery capacity must be adjusted to account for effective capacity as functions of state-of-charge at various temperatures, and the discharge rate.

The P/V array structure serves as a means for intergrating the relatively small, low power, low voltage, P/V module into a useable assembly. It serves as a mechanical support for the modules and also provides routing and attachment points for the wire harness which connects modules and collects power from the array. It should meet the

structural and aesthetic requirements of the installation without unnecessary cost burden. To meet these requirements the LeRC designed standard aluminum array frames. These frames were then used in either the LeRC free-standing support structure or were integrated into a structure compatible with the users overall system structure.

There are several approaches to system voltage regulation. For systems using a relatively small array and a relatively large battery, the need for a regulator may be eliminated by a judicious choice of P/V module relative to its number of series solar cells. For most systems, however, system voltage regulation is recommended.

A regulator can be simply a zener diode, or it can be a more sophisticated shunt or series type regulator which may or may not sense battery temperature and adjust maximum charge voltage accordingly. Another type of regulation being developed by the LeRC for the Papago Indian Village Power Project is array string switching. Here, series strings in the P/V array are switched on or off to regulate system voltage (1).

The systems described herein are operational experiments and are therefore instrumented. Each system contains ampere-hour meters to record P/V array output and load consumption, a system voltmeter, and an array ammeter. In addition, there are provisions in each system to measure the open circuit voltage and short circuit current of each series string in the P/V array. These are considered basic instrumentation. Some systems also contain a load ammeter and a run-time-meter. This instrumentation allows the user to monitor system status and provides data to the LeRC for system performance analysis.

The need for a control subsystem depends on the application. Occasionally a load need operate only during the day or only at night. The P/V array can then act as a sensor to turn loads on or off. Often it is desirable to include a low voltage load disconnect which would preclude damage to the batteries from extended deep discharge. In more complicated systems load management may be advisable as a way of offering maximum system utility while minimizing risk of damage to the batteries or the loss of critical loads (1).

Systems Descriptions and Status

Following are brief descriptions of the sixteen LeRC/DOE P/V systems and the status of each as of May 1, 1978.

P/V Powered Refrigerator, Isle Royale National Park, MI

A P/V power system was used to power a refrigerator at a remote trail maintenance camp at Isle Royale National Park, MI from June to Oct. 1976.

The P/V power system contained a 220 watt 12 VDC P/V array, 600 ampere-hours of automotive type batteries, and the basic instrumentation package, and powered a 12 VDC 4 cu. ft. recreational vehicle type refrigerator.

The P/V array consisted of 3 freestanding panels which were anchored in place with tent pegs. The refrigerator was mounted on a metal enclosure which housed six 100 ampere-hour batteries. A compact instrumentation assembly and simply shunt type system voltage regulator was mounted on top of the refrigerator. The instrumentation was read regu-

larly by the trail crew.

The system operated satisfactorily throughout the four months. There were two minor problems, however, which did not effect its operation. The system was designed for and shipped with 600 ampere-hours of batteries. The complete battery complement was accidentally dropped while being transported from a boat to the camp site. One battery was observed to be ruined and only five batteries were therefore installed. During system removal in Oct. 1976 another battery was found to have been punctured and had lost all of its electrolyte. Thus the system operated with only 400 ampere-hours of storage. For the four month period of operation, the array, which was located in a small forest clearing and thus shadowing part of every day, generated 41% less power than had been predicted. The refrigerator, however, consumed 23.5% less power than had been predicted due to lower than anticipated ambient temperatures. The batteries were found to be deeply discharged (but not damaged) when the system was shut down.

The National Park Service of Isle Royale N.P. was extremely satisfied with the system and is presently planning a P/V power system for one of its three forest lookout towers and for its backcountry ranger stations.

P/V Powered Refrigerator, Sil Nakya, AZ

A P/V power system is being used to power a refrigerator in a remote indian village in Arizona. The system initially consisted of a 4 cu. ft. 12 VDC recreational vehicle refrigerator, a 220 watt 12 VDC P/V array, 600 ampere-hours of automotive type batteries, and basic instrumentation. It was configured identical to the Isle Royale system except that the P/V panels were mounted on uprights approximately 15 feet above the ground to be out of the way of livestock. The system is located in the community building in the Papago Indian village of Sil Nakya, AZ. The village, which is about 60 miles west of Tucson, has no other electricity. The refrigerator was intended primarily for storage of medication but is also used for food storage. This experimental application is a cooperative venture of LeRC; the Public Health Service, Indian Health Service, Office of Research and Development; and the Papago Tribal Council.

The system was installed in July of 1976 and is still in operation. Two significant problems have occurred since installation. Initially a defective refrigerator resulted in permanent damage to the original set of batteries. The refrigerator and batteries were replaced and satisfactory operation commenced Sept. 1976. During the winter 1976-1977, the refrigerator consumed considerably less energy than originally estimated. In response to villages request, two 20 watt 12 VDC fluorescent lights were also installed in the community building. The second problem occurred with the on-set of warm weather in May 1977. Proper temperatures could not be maintained within the refrigerator. System voltage readings indicated the batteries were not fully charged, but ampere-hour data indicated the P/V array was generating enough energy to meet the load requirements. An extensive investigation and analysis revealed that the load ampere-hour meter data was incomplete due to night time voltages that were lower than those required

for meter operation and that the warm weather refrigerator duty cycle was much higher than design assumptions. Recalculation of P/V array size based on a revised load profile (refrigerator duty cycle) indicated the need for a 50% longer array using the same battery capacity.

In Sept. 1977, the array was increased to 330 watts. The batteries were also replaced as two of the six batteries had developed shorted cells during previous periods of extended deep discharge. The instrumentation and system voltage regulator were modified to accomodate the larger array. The present instrumentation contains the basic instrumentation plus a load ammeter, a refrigerator runtime-meter, and thermistors to measure P/V module, ambient air, and refrigerator temperatures. A separate battery, charged from the P/V array but isolated from the refrigerator, was installed for the ampere-hour instrumentation. The system has operated satisfactory since these modifications.

For the period Sept. 76 through April 77, the array generated 81% of predicted power and the load consumed 48% of predicted power. For the period Sept. 77 through April 78, the array generated 78% of predicted power and the load consumed 48% of predicted power. For both periods, at least 10% of the shortfall in generated power was most likely due to dust on the array (2), the remainder being due to inherent uncertainties in predicting P/V output in remote areas. Also for both periods (which spanned the winter months) reduced refrigerator consumption was due to lack of data describing refrigerator duty cycle as a function of ambient temperature.

One P/V module has been replaced. It developed several fractured cells as the result of expanding encapsulent voids beneath the cells.

The system has served its primary function, i.e., storage of medications requiring refrigeration, and has at least on one occasion obviated the need for a lengthy hospital stay by a villager. In addition, it has provided the villagers, for the first time, an opportunity to keep perishable food on hand. The system has shown so much potential for providing electrical power at remote villages on the reservation that the LeRC Public Health Service, Indian Health Service, office of Research and Development and the Papago Tribal council are presently engaged in the construction of a P/V power system to supply the power requirements of a complete village (1).

U.S. Forest Service Forest Lookout Towers

P/V systems are being used to provide complete power for two U.S. Forest Service Lookout Towers one each in the Lassen & Plumas National Forests in California (Fig. 1). The identical P/V systems contain a 294 12 VDC array, 3015 ampere-hours of lead-calcium photovoltaic system type batteries, and basic instrumentation plus load ammeters. The 12 VDC loads in each tower consist of a 3 cu. ft. refrigerator; a bilge pump to pump water from a storage tank to a kitchen sink, shower, and toilet; fluorescent and incandescent lights, a USFS radio, and at times operator provided 12 VDC television sets. Data is taken daily during fire season by the lookouts living in the towers.

Both systems were installed at the end of the fire season in Oct. 1976. The towers are vacated

for the winter and reoccupied in early summer. Data for the two lookouts for Sept. and Oct. 1977, shows average P/V array output as being 84 and 85% of predicted values and load consumption being 58 and 64% of predicted values. The only problem with these systems were wiring errors with the ampere-hour meters which voided data up to Sept. 1977. Otherwise the systems have operated satisfactorily and have been the object of considerable visitor interest besides being a absolute delight to the women living in them. The experience gained from these lookouts prompted the U.S. Forest Service to purchase a P/V system for a Forest Lookout on the Inyo National Forest, also in California.

Highway Dust Storm Warning Sign, AZ

A P/V power system is powering a changeable message highway sign on interstate route 10 between Tucson and Phoenix Arizona (Fig. 2). The power system contains a 116 watt 12 VDC P/V array, 200 ampere-hours of electric vehicle type batteries, a shunt type voltage regulator and a basic instrumentation package plus a load ammeter and a run-time-meter. The electrical loads in the sign are a transmitter/receiver which operates continuously and which is used to actuate a motor which rotates the multmessage sign face, flashing strobe lights, and a bank of fluorescent lights which illuminate the face of the sign. The sign is normally a passive interstate market, but when actuated warns motorists of hazardous conditions due to dust storms in the area. This is one of 50 such signs the Arizona Dept. of Transportation (ADOT) has in the Tucson, Phoenix, Gila Bend area. All others are powered by propane fueled thermoelectric generators.

This system was installed in April 1977 and has operated satisfactorily except for two load related problems. In June 1977, the sign mechanism jammed stalling the motor which discharged the batteries. In Dec. 77 and Jan. 78 the batteries were discharged as a result of the sign being activated 18 times for a total of 14.8 hours during periods of severe rainstorms. There were no design requirements for operation of the signs during these months and the batteries were discharged as the system was not designed for such winter loads.

From installation to May 1978, the P/V array has generated 95% of predicted power and the load consumed 92% of predicted power. For the 4 months of dust storm activity (June through Sept.), the sign was activated 25 times for a total of 47 hours as compared to predicted values of 48 times for a total of 144 hours.

The Arizona Dept. of Transportation has been satisfied with the operation of the system and is evaluating the economics of converting other signs to P/V power. In addition, as a result of publicity surrounding this system, several sign manufactures have become interested in P/V systems for their signs.

Remote Weather Stations

Six NOAA/NWS RAMOS (Remote Automatic Meteorological Observation Systems) have been equipped with P/V power systems (Fig. 3). The RAMOS were designed for unattended operation (with thermoelectric generators or utility power) and record a variety of meteorological data. The stations can be interrogated by GOES satellite, VHF radio, or

telephone. The six P/V powered RAMOS locations, dates of installation, 24 VDC P/V array power, and interrogation methods are: Stratford Shoals, Long Island, NY, March 1977, 111 watts, VHF radio; Clines Corners, NM, April 1977, 74 watts, GOES; Southpoint, HI, June 1977, 74 watts, telephone; Point Retreat (Admiralty Island) AK, July 1977, 148 watts, GOES; Halfway Rock, ME, Sept. 1977, 111 watts, VHF; and Dry Tortugas, FL, Oct. 1977, 74 watts, GOES. All systems except that at Point Retreat use the 60 ampere-hours of gelled electrolyte type batteries which were basic to the NOAA/RAMOS design. The system at Point Retreat uses an additional 1005 ampere-hours of lead-calcium photovoltaic batteries.

The P/V systems include shunt type voltage regulators and the basic instrumentation package. Additionally, P/V array current and system voltage is transmitted every time a station is interrogated. Data from those systems utilizing GOES can be received in real time at the LeRC. Interrogation data from other stations is mailed to LeRC.

The RAMOS P/V systems have generally operated satisfactorily, but have encountered several operational anomalies. Although installed first, the Stratford Shoals RAMOS is still not operational due to unforeseen problems with the NOAA designed VHF/telephone link to New York City. NOAA anticipates it will become operational in June 1978. And, although system at South Point was installed in June 1977, NOAA did not complete installation of the RAMOS until Jan. 1978. In June 1977, 3 modules of the Clines Corner P/V array were observed to have a total of 7 cells which suffered various size fracture patterns apparently from hail stones. Array output did not appear to be affected and these modules are still in place.

In Sept. 1977 the NWS at Juneau AK reported that 3 modules on the Point Retreat array had been damaged by vandals. These modules were replaced in Dec. 1977.

On Feb. 15, 1978, the NWS at Portland, ME reported that the complete RAMOS installation at Halfway Rock had been swept away by the severe winter storm which struck the East Coast on Feb. 7, 1978. The U.S. Coast Guard reported 40 foot seas at Halfway Rock which would have put the RAMOS 10 feet beneath wave crests. This RAMOS will not be replaced.

On April 4, 1978 LeRC and NWS personnel visited Stratford Shoals to determine why it could not be interrogated by portable VHF from shoreside at Port Jefferson, NY. They found that two of the three P/V array series strings were inoperative. A total of seven modules exhibited encapsulant delamination and cell contact corrosion and shorting and there was evidence of mechanical stress. Also, both of the NOAA supplied ambient air temperature and dewpoint air temperature sensors had been blown away as was one half of the VHF antenna and part of the wind vane. Heavy seas and/or ice damage may have caused these problems. Repairs are scheduled for the summer 1978. All of the P/V modules will be replaced and returned to LeRC and JPL for analysis.

Due to the remote locations of these systems and infrequent visits, little ampere-hour data is available. Data from the Clines Corners, NW system indicates that array has generated 88% of pre-

dicted power. Data from Point Retreat, AK indicates that array has generated approximately 86% of predicted power, there being some uncertainty as to the date the array was vandalized. Data from Dry Tortugas, FL indicates that array has generated 74% of predicted power. Data from other systems is unavailable for reasons discussed earlier.

With the exceptions noted above, the P/V systems have operated satisfactorily. Based on experience from these systems NOAA/NWS has independently equipped another RAMOS at Eldrod Rock, AK with a P/V power system. Additionally, the NWS is actively installing P/V power systems on many of its other remote meteorological stations.

USDA Insect Survey Traps

Four insect survey traps used by the Agricultural Research Service (ARS) of the U.S. Dept. of Agriculture in east central Texas are being powered by P/V systems. These traps are located in remote areas in fields and must otherwise be powered by utility power and very long extension cords, or with batteries which must be replaced weekly. All four P/V systems were installed in May 1977. Two of the systems use 163 watt 12 VDC arrays, 400 ampere-hours of electric vehicle type batteries to power 40 watt ultraviolet lamps. The other two systems use 23 watt 12 VDC arrays, 100 ampere-hours of electric vehicle type batteries to power a charged grid type trap. All systems use simple shunt voltage regulators and contain the basic instrumentation package plus load ammeters and run-time-meters. All traps operate only at night to survey night flying insects, with turn-on controlled by the P/V system.

Data is read regularly by ARS personnel when collecting insects from the traps. For the 1977 growing season (June through Sept.) the P/V power systems generated on the average 82% of predicted power and the loads consumed 79% of predicted power.

The systems have experienced three minor problems. One module failed open circuit shortly after installation and was replaced. One ampere-hour meter failed and was also replaced. Also, on one occasion, mud dauber wasps built a nest in one of the charged grid traps during the day which shorted the trap when it came on at night and which then discharged the batteries. Otherwise, all systems have operated satisfactorily.

The ARS has been satisfied with these systems and has relocated them in different areas for this season.

Water Cooler, Lone Pine, CA

A P/V power system is being used to power a water chiller for a drinking fountain at an Inter-agency Visitor Center at Lone Pine, CA which is located near the Mt. Whitney entrance portal and which is also on the route to Death Valley and major eastern Sierra recreational areas. The Center is a cooperative venture of 14 Federal State and local agencies, was opened in the spring of 1977, and is open 5 days a week year round.

The P/V power system consists of a 446 watt 120 VDC array, 100 ampere-hours of electric vehicle type batteries, a shunt type regulator, and the basic instrumentation plus load ammeter, run-time-meter and water meter. The load is a 120 VDC powered water chiller which is located in the Visitor Center building. The P/V power system was in-

stalled in Sept. 1977 and is designed and used as a display of the potential for P/V systems. The P/V array is designed to provide a shaded area from which to view Mt. Whitney (Fig. 4).

The system has operated satisfactorily except for a failure of a component in the voltage regulator which has been repaired.

Data is taken daily by the Visitor Center manager. Since installation the P/V array has generated 71% of predicted power. Array power generation has been affected by accumulations of dust and alkali deposits from nearby Owens Lake. Also the Sierra Nevada Mountains reduce the hours of possible sunlight in the afternoon.

The load power consumption has been 10% of that predicted. The load profile was based on the forecast number of visitors and an estimate of how much chilled water would be consumed. Chilled water consumption is expected to increase substantially during the summer months.

The P/V power system is a major attraction at this Visitor Center and, by way of an associated display, promises to give P/V systems wide visibility.

SUMMARY

A total of sixteen P/V power systems powering seven different types of loads have been designed, built and installed by the LERC since May 1976. All systems are currently operating satisfactorily except for one seasonal installation which was operated for only one summer, and for another system which was lost in a severe storm. The P/V systems have proven to be highly reliable. There have been almost no problems with modules and very few technical problems with the systems overall.

In general, the P/V arrays are generating about 18% less power than was predicted. This is considered to be within expected prediction accuracy considering the remote locations of these systems. Actual load power requirements have been found to vary, often considerably, from predicted values. This reinforces the fact that one of the most important and often most difficult to define factors in P/V system design is an accurate load profile.

Although the instrumentation installed with each system will provide the data required for system performance analysis, relying on user personnel for regular and frequent readings is not always practical. An automatic data system with long term recording capabilities and low power consumption used in conjunction with panel meters would be a preferred approach to data collection.

The information and experience gained from operating these systems and analyzing their performance has resulted in increased awareness and confidence in P/V systems by the user community and is bringing additional applications into the marketplace.

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P/V POWERED U.S. FOREST SERVICE LOOKOUT
PLUMAS NATIONAL FOREST, CA



Figure 1.

P/V POWERED HIGHWAY DUST STORM
WARNING SIGN
PHOENIX, AZ



Figure 2.

P/V RAMOS WEATHER STATION
STRATFORD SHOALS, NY

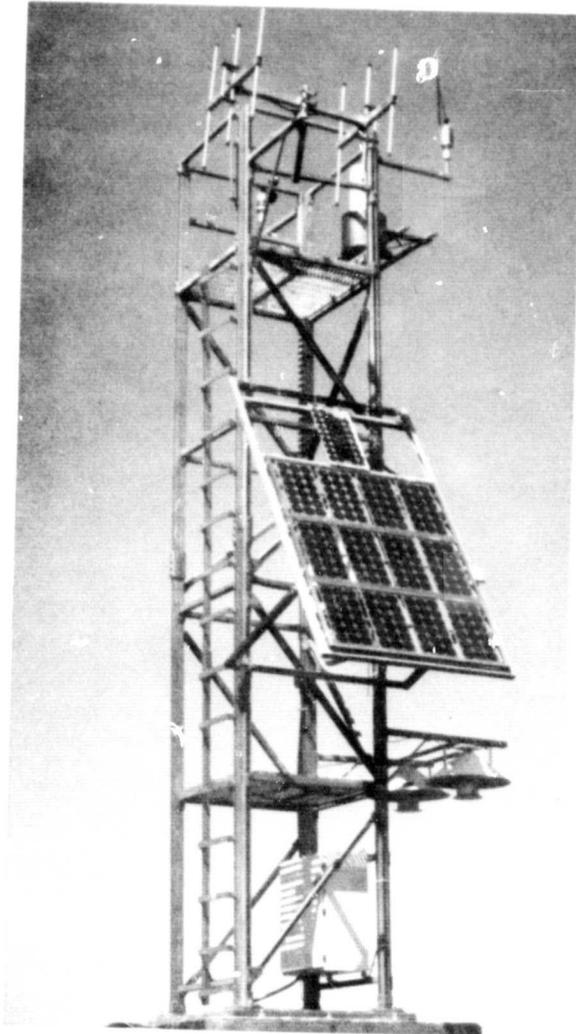


Figure 3.

P/V ARRAY FOR P/V POWERED WATER CHILLER
LONE PINE, CA



Figure 4.

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