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DESIGN AND CONSTRUCTION OF A ONE KILOWATT CONCENTRATOR PHOTOVOLTAIC SYSTEM

MASTER

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Design and Construction of a One Kilowatt Concentrator Photovoltaic System

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The construction details of a system which uses Fresnel lenses to concentrate sunlight on silicon solar cells are described. The cells are cooled either passively by convection or actively using a pumped fluid coolant. Construction and operation of the array have disclosed several unique problems; future modifications and improved future designs are being considered.

INTRODUCTION

The photovoltaic cell or solar cell is a device that converts sunlight directly into useful electrical energy with no moving parts. This feature makes these devices attractive for use in electrical power generation applications. The problem, however, is the high cost of solar cell systems. A flat plate array producing one peak kilowatt of power costs about $15,000 at present. The approach described in this report uses solar cells employing concentrated sunlight in order to reduce this high cost.

The purpose of this report is to describe design and construction details of a concentrated sunlight system using silicon solar cells and Fresnel lenses. Such details are not easily published in journal articles, so this report has been put together to document the construction details in hopes that it will facilitate transfer of information to private industry. The design and construction of the system is discussed in detail. An estimate of the cost of constructing the system, in moderate production quantities, is given. This cost estimate includes solar cells, Fresnel lenses, tracker with all associated electronics, support frame, and assembly costs. This estimate represents a cost decrease to about one fourth that of present flat-plate arrays. Further cost decreases are anticipated as higher efficiency solar cells are developed and production costs are reduced by mass production techniques.

GENERAL SYSTEM DESIGN CONSIDERATIONS

It was desired to construct a concentrator photovoltaic system and have it operational within a few months. The size of the system (electrical output) was required to be large enough to evaluate performance for systems up to 10 kW. A one kilowatt system was selected because it was felt that this size would not only meet the above requirement but could be made functional in a short time. Once the electrical size was selected it was necessary to decide on the concentration ratio, concentrator type, and solar cell configuration.

A concentration ratio of 50X was selected because previous studies[1] have shown that silicon cells can operate efficiently in the concentration ratio range of 50 to 100X. The Fresnel lens was chosen as the concentrator to broaden Sandia's experience with concentrators, since little information was available on refractive optics. Square Fresnel lenses with circular patterns were used to achieve a maximum packing factor for the array. Circular silicon solar cells were designed since this shape utilizes commercially available silicon substrate wafers. The cells are 5-cm in diameter and are fabricated at Sandia's Semiconductor Device Laboratory.

A 5-cm diameter silicon cell operating in sunlight concentrated by a factor of 50 will produce approximately 7.5 watts.[2] Therefore, 135 of these cells were required to generate the 1 kW design output. The final array, 135 cells and Fresnel lenses, was configured into 15 vertical columns by 9 horizontal rows. Figure 1 is a photograph of the completed system. In the following sections each subsystem is discussed.

Tracker

Some technique for both tracking the sun and providing structural support for the array was required. A 2-axis tracker was obtained from a search light mount; it is a typical yoke or saddle support unit (Fig. 2). This is ideal since the 9 x 15 array would mount directly to the yoke using two large gussets attached to the back side of the main frame (Fig. 4).

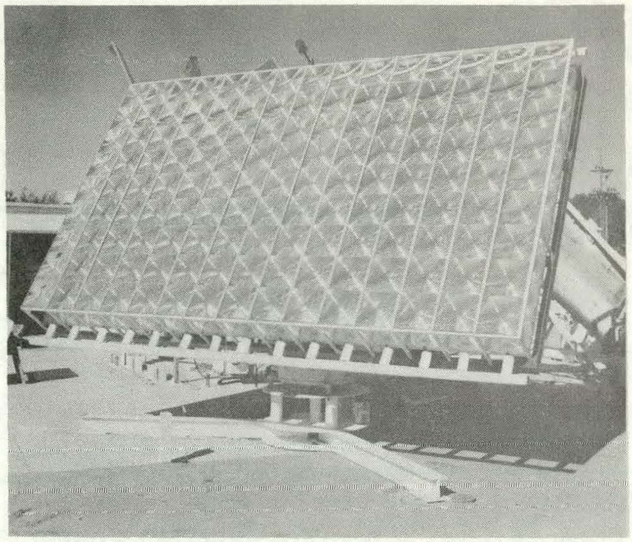


Fig. 1 Photograph of the completed 1 kW photovoltaic concentrator.

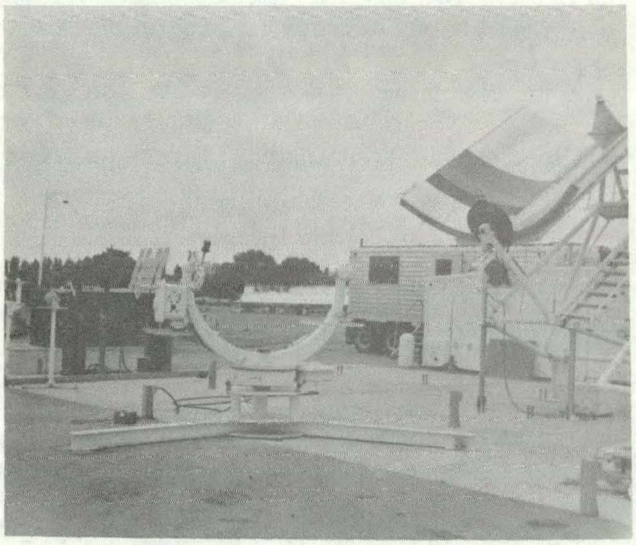


Fig. 2 Structural support showing yoke and I-beam base.

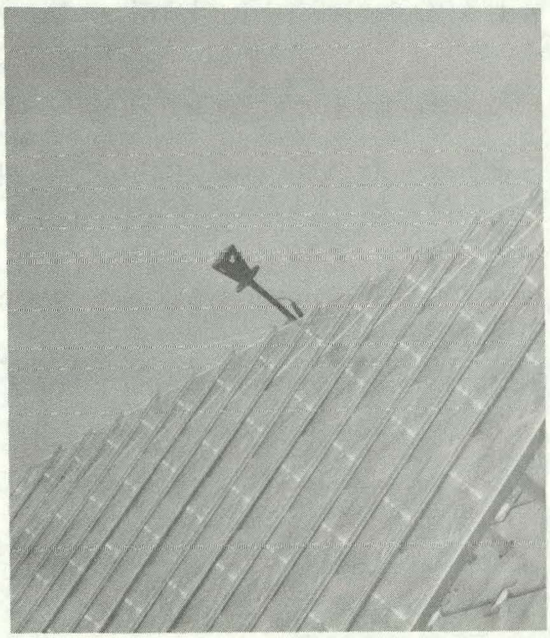


Fig. 3 Two-axis electronic tracker.

The only required modification to the tracker was the removal of several extra struts and uncoupling the unit from its mobile mount. Several drive gears were replaced to make the system functional, however, there still remains inherent backlash in the gear drive.

The electrical tracking capability for the array was designed by B. E. Hammons, 5132.[3] It incorporates a shadow-balance technique to provide equal electrical outputs from sensor cells which cause the system to remain aimed at the sun (Fig. 3). This is accomplished when the pair of north-south or east-west sensor cells sense an unbalance in output. This signal is fed to a differential amplifier which drives the axis-motor and moves the system back to a neutral setting, aligning the array perpendicular to the sun.

The tracker is mounted on a large Y-shape configuration constructed of 4-inch (10.16 cm) steel I-beams with a base diameter of 16 feet (49 m). The Y-structure is anchored directly to buried concrete pillars (Fig. 1).

Support Frame

Mechanical strength of a system this large must be considered. The back side of the array is quite simple in design, however, careful thought went into its structural characteristics. Basically, it is a large "X" laid sideways with two main gussets that fit within the tracking mechanism yoke. The gussets are 3/4-inch (1.905 cm) thick aluminum plate and run the full height of the array. Lateral support is accomplished by four smaller gussets which aid in supporting the large main yoke gussets. The 9 ft. x 15 ft. (2.7 m x 4.5 m) main "X" frame is constructed from 4 inch (10.16 cm) aluminum channels (Fig. 4). The frame was designed to withstand a 90 mph (145 km) wind load.

Fig. 4 Back side of the main support frame.

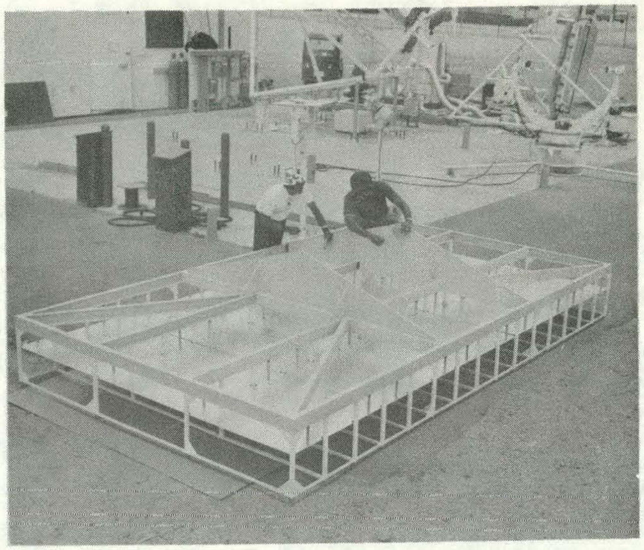


Fig. 5 Upper portion of array showing risers and aluminum "T" sections that support Fresnel lenses.

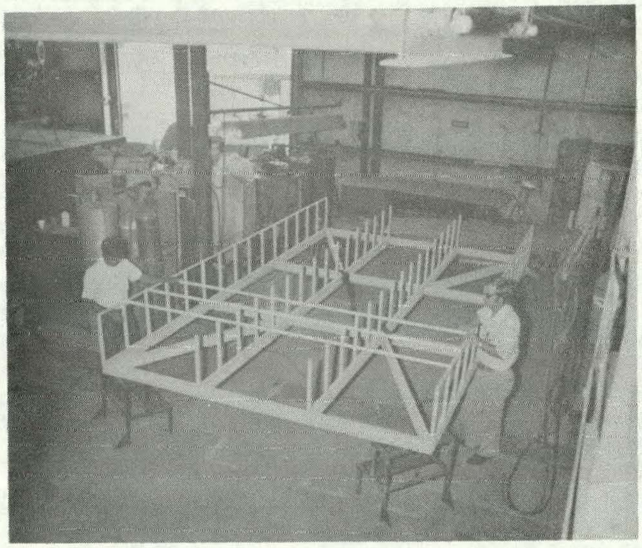
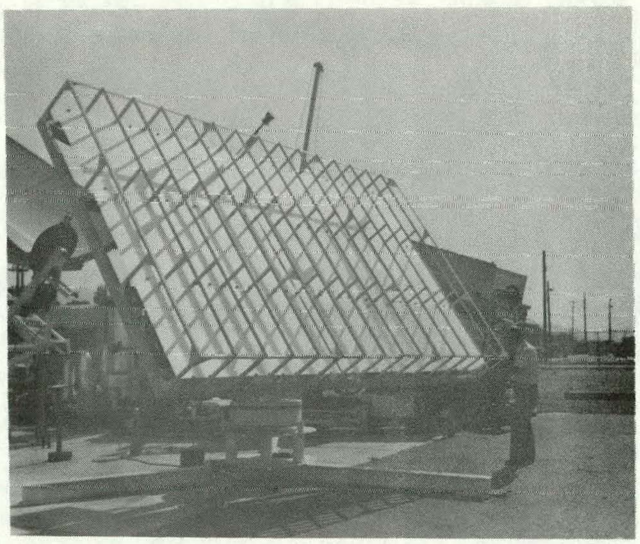


Fig. 6 The array without the Fresnel lenses or the liquid coolant manifold mounted. The large aluminum sheet is the heat sink for the passive coolant mode; the cells are bonded directly to this sink.



The upper portion of the array is constructed from one inch square aluminum tubing. It supports "T" sections of aluminum which in turn support the Fresnel lenses (Fig. 5). The Fresnel lenses are cushioned by 1/8 in. (0.317 cm) thick strips of neoprene which act as a seal to enclose the array and provide a "greenhouse" effect when the array is operated as a combined thermal-electrical system. Actual securing of the lens is accomplished with 9-ft. (2.7 m) long aluminum "L" brackets that are attached with small screws. This seals the lens and the neopren between the "L"-bracket and the "T"-section aluminum.

A counterweight was needed to balance the array since the main frame is not centered on the tracker. The counterweight is approximately 36 in. (91.4 cm) from the centerline of the yoke. It is a one cubic foot block of lead in a square steel box. This is a 700 lb. (315 kg) weight, which is the amount needed to balance the 1000 lb. (450 kg) array.

Cell Cooling

The capability for both actively and passively cooling the system exists. Aluminum tubes were bonded with metal filled epoxy to the back side of the heat sink plate. Tubes were run behind each row of solar cells and were connected at each end to manifolds. Water flow control is accomplished by individual valves on the lower manifold, therefore, any single tube or group of tubes can be isolated for cell cooling. Z. R. Ortiz, 5151, was responsible for fabricating the liquid cooling manifolds and assisted in installing these tubes. The passive mode for cooling the system is achieved by convection of thermal energy away from both sides of the large heat sink plate to which the cells are bonded (Fig. 6, Fig. 9). Finned heat sinks could also be attached behind each device, making the passive mode more efficient.

Cells

The technique used in the growing of single-crystal silicon material dictates that circular rods be grown, therefore, the

for the solar cell is circular. Five-centimeter diameter silicon wafers were used to fabricate the cells (Fig. 7). The 5-cm diameter cells each have an active area of 15.2 cm^2 and can be expected to produce approximately 0.5 volt and 0.300 amperes when operating at 100 mW/cm^2 incident solar radiation. When the sunlight is concentrated by a factor of 50X, the current would be expected to increase to about 15 amperes. With the 135 cells connected electrically in series, the array would then produce about 68 volts at 15 amps. Further discussion on the development of this cell is available elsewhere.[4]

The cells were attached to the heat sink using a room temperature curing (RTV) silicon adhesive. To ensure good thermal conductance the adhesive thickness had to be maintained at no more than a few thousandths of an inch. It was also necessary to provide electrical isolation of the cell from the heat sink with this RTV.

Lens Design

Square Fresnel lenses were used to achieve a maximum packing factor for the array. The lenses are unique in design in that the image projected is a circular pattern. This is necessary since the solar cells are circular. The corner portions of the lens have variable focal lengths while the center area focuses on a point.[5]

When the cell is located at the design distance from the lens, the entire 5-cm cell diameter is illuminated. More intense light resembling a four leaf clover pattern falls on the cell due to the lens corners. Figure 8 shows details of how this is optically accomplished. The cutting

Fig. 7 A 5-cm diameter solar cell fabricated at Sandia's Semiconductor Device Laboratory.

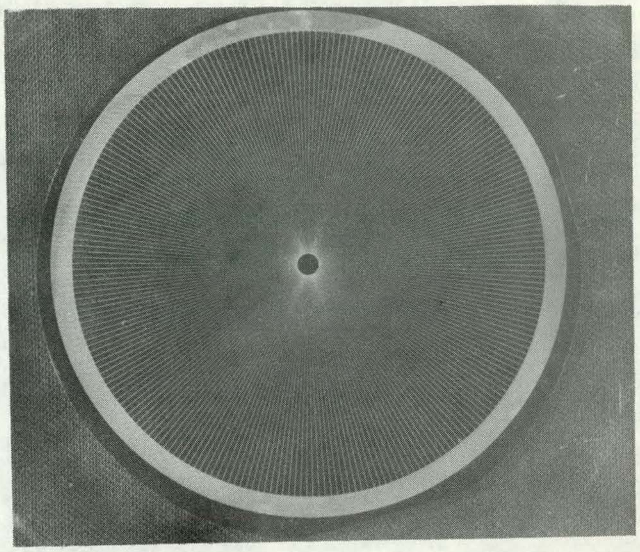


Fig. 8 Drawing showing the imaging details of square Fresnel lens design. The corner portion of the lens has variable focal lengths while the center area focuses on a common point.

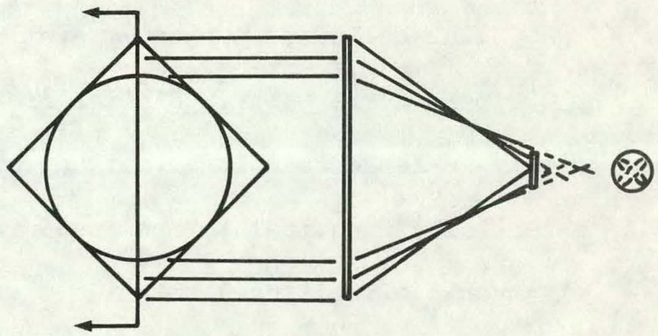
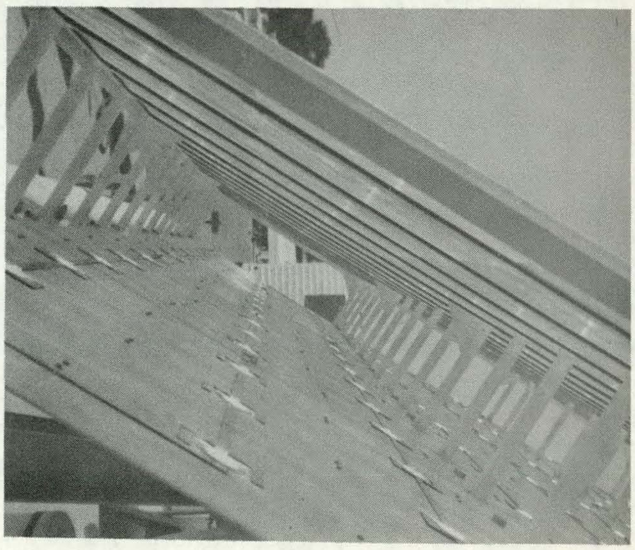


Fig. 9 A side view of the array showing the circular illumination pattern on actual cells.



and actual fabrication of the lenses were done by Fresnel Optics, Incorporated of Rochester, New York.

COST ESTIMATES

The generator is constructed from various components: the Fresnel lenses, the solar cell devices, the tracker, and the main support frame. Estimated costs of mass producing similar arrays are given below.

Solar Cells	$ 700
Fresnel lenses	800
Tracker/electronics	500
Support Structure	1000
Assembly	500
	$3500

Solar cells are presently available at a cost of between $2000 and $3000 per square meter. Similar Fresnel lenses can be purchased commercially in large quantities for approximately $6.00 each; these lenses are essentially identical to ones used in vugraph projectors. Once the electronic circuit used to guide the tracker is designed, the cost, in large quantities would be comparable to the cost of a transistor radio. The main support structure could conceivably be less than our estimate due in part to simplifying the design and also the variety of equatorial mounts currently available. A modification to a commercial mount could function quite well and in large production numbers be attractively inexpensive.

PRELIMINARY PERFORMANCE RESULTS

Design and construction of the array was completed in the required 9 month period. When tested in the passively cooled mode, the maximum power output was only 506 watts. The reason for this low power output was that approximately 20% of the cells had a very high series resistance. At the maximum operating power point, these cells became back biased and absorbed power rather than generated it.

The array is being fitted with new cells to eliminate the high contact resistances. Additional testing is planned; as yet the array has not been tested as a combined thermal-electrical system. It is expected that the design goal of 1 kW will be reached when the slightly higher efficiency cells become available.

A new cell holder incorporating a quick disconnect feature is being tested. Cells are bonded directly to the holder with a low temperature solder so that excellent thermal conductivity is achieved. This permits the cells to operate more efficiently than in the present configuration. The quick-disconnect cell holder provides for faster cell replacement.

To reduce the inherent backlash a new tracker is being designed and built. The drive will be identical to the present 2-axis system which utilizes two motors to align the array. The new tracker should be operational by late 1977.

CONCLUSIONS

The concentrator described has been designed and constructed. The ultimate power anticipated is approximately 1 kW peak electrical. Fresnel lenses are being used to concentrate sunlight. New silicon solar cells being developed will operate at the 50X concentration ratio with efficiencies of approximately 15%. Construction problems encountered have suggested future design modifications. The cost analysis comparing flat plate photovoltaic collectors to concentrator photovoltaic arrays indicates that the costs of concentrator systems produced in mass production quantities are quite attractive.

ACKNOWLEDGMENTS

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