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PHOTOVOLTAIC CONCENTRATOR MODULE TECHNOLOGY*

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ABSTRACT

We are continuing to see significant progress in the development of photovoltaic (PV) concentrator technology. New record cell and module efficiencies have been achieved, and improvements in cells, cell assemblies, and modules are increasing reliability and decreasing cost. The number of firms actively pursuing PV concentrator module technology has increased substantially in the last three years. Two new concentrator systems were installed last year, and more are likely to be installed in the near future. This paper describes the most significant developments of the last two years, including descriptions of advances in PV concentrator cell technology, module development and reliability activities, the new installations, a new Concentrator Initiative Program, and results of the latest costing study.

1. INTRODUCTION

Since the power from a solar cell is proportional to the intensity of the incident light, one approach to reducing the cost of photovoltaic-generated electricity is to use optical concentrators to increase the output of each solar cell. Thus, the basic idea of photovoltaic (PV) concentrator modules is to replace the amount of costly cell material required for a given power requirement with cheaper optics, housing materials, and fewer solar cells.

Most PV concentrator modules use plastic lenses to concentrate sunlight, either to a point or along a line. Point-focus lenses can achieve concentrations up to 400X, higher if secondary optics are used. Line-focus lenses are limited to concentrations of about 50X and below. Because of their arched construction, line-focus lenses generally are more efficient than point-focus designs. Other methods of concentration include reflective parabolic dishes and troughs. Although most concentrator designs require two-axis tracking, some line-focus modules have been designed for single-axis tracking. Because the optics usually can accommodate only a small portion of the diffuse light, concentrators are best suited for locations where the fraction of direct normal to horizontal insolation is high--for example, the southwestern United States.

The efficiency of solar cells decreases with increasing temperature by about 0.05%(relative)/°C. Because the cells are exposed to concentrated light, some means for removing excess heat must be employed. Most current PV concentrator designs use passive cooling, optimized for cell efficiency and cost. Resulting cell operating temperatures are about 40°C above ambient, about 20°C higher than flat-plate modules.

Concentrator cells are more efficient than one-sun cells because the semiconductor cell material is intrinsically more efficient under concentration. Also since fewer cells are required, one can afford additional processing costs to achieve better cells. This results in concentrator modules that are generally more efficient than flat-plate modules even after compensating for the efficiency losses of their optical system, their requirement to track the sun, and their higher cell operating temperatures.

We have seen significant progress in the development of PV concentrator technology in the last few years. New record cell and module efficiencies have been achieved, and improvements in cells, cell assemblies, and modules are increasing reliability and decreasing cost. The number of firms actively pursuing PV concentrator module development has increased substantially. Two new concentrator systems were installed in 1989, and we are likely to see more in the near future.

2. CONCENTRATOR CELL RESEARCH

A major achievement in concentrator cell research area was the attainment of 31% conversion efficiency for a mechanically stacked multijunction (MSMJ) concentrator cell at Sandia National Laboratories [1]. This MSMJ device used a gallium-arsenide cell fabricated by Varian Associates on top of a silicon cell fabricated by Stanford University. Sandia has since measured an even higher efficiency of 34.2% for a gallium-arsenide/gallium-antimonide MSMJ cell made by Boeing [2]. There have also been efficiency increases in a number of other concentrator cell areas over the past year, including 25% for a high-resistivity, front (and back) contact Si cell from Stanford, 28% for a single-junction gallium-arsenide cell, and 29% for a prism-covered, single-junction gallium-arsenide cell, both by Varian Associates. In addition, the following record efficiencies for monolithic multijunction cells have been measured at 1-sun levels at the Solar Energy Research Institute (SERI): 27.6% for AlGaAs/GaAs from Varian and 27.3% for GaInP/GaAs fabricated at SERI [3]. These 1-sun results suggest that higher efficiencies, probably in the range of 30 to 35%, for monolithic multijunction concentrator cells will be seen in the near future. The current efficiency status for various PV concentrator cell technologies is summarized in Table 1.

Interesting results have been achieved in the area of fabricating PV concentrator cells. Both Applied Solar Energy Corporation (ASEC) and Spire Corporation have reported major advances in the development of gallium-arsenide cells on germanium and silicon substrates [3]. These results may lead to gallium-arsenide cells that are economically competitive with silicon concentrator cells. Also, the research programs at Stanford University and the University of New South Wales (UNSW) have made considerable advances in simplifying high-efficiency designs thereby reducing projected manufacturing costs. More emphasis is planned on the transfer of these research results to industry and on their technology development of high-efficiency concentrator cells under the Photovoltaic Concentrator Initiative (described in Section 6.)

3. PHOTOVOLTAIC CONCENTRATOR MODULE DESIGN

In addition to the dramatic progress in concentrator cell technology, many advances in PV concentrator module technology have occurred, including a new module efficiency record set by Sandia last year. In other areas, the prismatic cover design that ENTECH uses on low-concentration, line-focus modules has been modified for use in higher concentration, point-focus modules. Sandia's improvements in soldering technology now allow cells to be soldered directly to copper. New methods for electrically isolating the circuits while promoting good heat transfer have eliminated the need for finned heat dissipators. In addition, a number of projects are currently underway to reduce the cost of optical components.

3.1 20%-Efficient PV Concentrator Module

We established a new record PV module peak conversion efficiency of 20.3% using a silicon-based concentrator module (Figure 1) [4]. The module uses 12 silicon cells fabricated by the UNSW with prismatic covers developed with ENTECH and applied at Sandia. Cell efficiencies are about 24%. The total lens aperture area is 1875 cm^2, and the geometric concentration is 100X. The measured peak module

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TABLE 1

EFFICIENCY STATUS OF PV CONCENTRATOR CELLS

Manufacturer	Material	Cell Type	Mounted Cells Area (cm2)	Mounted Cells Conc.	Mounted Cells Eff. (%)	Experimental Cells Area (cm2)	Experimental Cells Conc.	Experimental Cells Eff. (%)
Stanford	FZ Si	High resistivity, back contact	0.64	100	27.2	0.15	140	28.2
	FZ Si	High resistivity, front contact	1.58	130	25.3			
UNSW	FZ Si	Low resistivity, prism covered*	1.58	125	25.2			
	FZ Si	Laser grooved	20.0	20	18.9			
AstroPower	CZ Si	Low resistivity, prism covered*	39.6	20	17.8			
Solarex	FZ Si	Low resistivity, prism covered*	1.58	150	21.5			
	CZ Si	Low resistivity, prism covered*	38.4	20	20.2			
	FX Si	Low resistivity, prism covered*	39.5	20	17.5			
SERA	FZ Si	High resistivity, back contact				0.065	65	23.9
SPIRE	FZ Si	Low resistivity, V-grooved				0.25	124	20.0
Varian	GaAs					0.126	403	28.1
	GaAs	Prism covered*				0.126	206	29.2
SPIRE	GaAs					0.317	200	28.7
Sandia/ Varian/ Stanford	GaAs/Si	Mechanically stacked, multijunction				0.317	500	31.0
Boeing	GaAs/GaSb	Mechanically stacked, multijunction				0.053	100	34.2

* Prismatic cover technology supplied by ENTECH

Figure 1. 20%-Efficient Photovoltaic Concentrator Module.

efficiencies range from 20.0% at a direct normal insolation (DNI) of 1000 W/m² to 20.3% at a DNI of 800 W/m² (Figure 2). (These peak efficiency measurements were taken at a cell temperature of 25°C.) Although the module employs independent cell positioning and active cooling to provide flexibility and accuracy in experimentation, these features would not be needed in a commercial module. An anti-reflective coating, which is not yet reliable or cost-effective for commercial modules, was applied to the lenses. However, other design features of the module, particularly the cells, cell mounts, and secondary optical elements, are considered readily adaptable to commercial production.

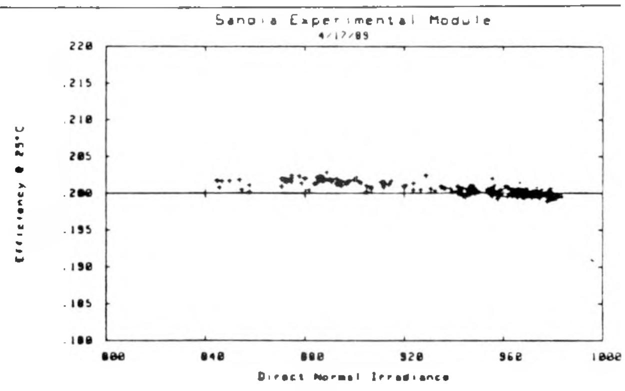

Figure 2. Efficiency vs. Direct Normal Insolation (DNI) of Sandia Experimental Module.

Increasing PV concentrator modules' efficiency is important for two reasons; first, large increases in efficiency are possible and second, an increase in module efficiency causes a proportional decrease in overall energy cost. The theoretical limit of silicon cell efficiency is in the range of 33 to 35% or approximately 50 percent over current levels [5,6]. Efficiencies above 25% for modules using silicon cells can be projected from existing measurements. Currently, small laboratory cells have efficiencies around 28.5% [6]. Optical efficiencies greater than 90% have been measured for line-focus lenses without anti-reflective (AR) coatings [7]. The efficiency of facetless uncoated lenses would equal the transmission of acrylic or 92%. With AR coatings, lens efficiencies are several percentage points greater. High-efficiency module technology is not necessarily complicated or expensive, although a sustained effort is required to develop the knowledge, processes, and tooling necessary to carry the technology through the prototype demonstration phase into commercial production.

3.2 Sandia Baseline Module 3 (SBM3)

To decrease the costs and increase the reliability of PV concentrator systems, the above advances must be incorporated into the design of manufacturable modules. To accelerate this process, Sandia designed, built, and is testing a new PV concentrator module, the Sandia Baseline Module 3 (SBM3) (Figure 3) [8]. The SBM3 combines advances in cells, cell assemblies, and electrical isolation techniques to produce a high-efficiency (nearly 20%) module that can be readily adapted for commercial production. The design is available to manufacturers interested in commercially developing the SBM3 or similar designs. Several developers are currently engaged in such activities.

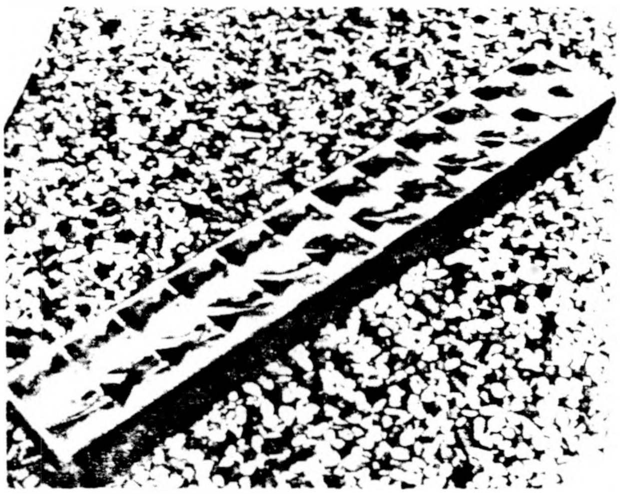

Figure 3. Sandia Baseline Module 3.

Figure 4 shows the basic components of the SBM3. It consists of 24 square lenses (17 cm on a side) and 24 square cells (1.25 cm on a side, active area), giving a geometric concentration of 185. The module features a new concept in cell assemblies (Figure 5) in which the cell is soldered directly to a copper heat spreader, eliminating the expensive ceramic wafer that has been used in previous designs [9]. The heat spreader also acts as the cell's bottom electrical contact. The top cell contact, also copper, supports the aluminum secondary reflector. (SBM3 cell assemblies were used in the module that set the 20% efficiency record described above.) The heat spreaders are attached to the housing with a thermally conductive adhesive. At an efficiency of 20%, the output would be 140 W at peak conditions.

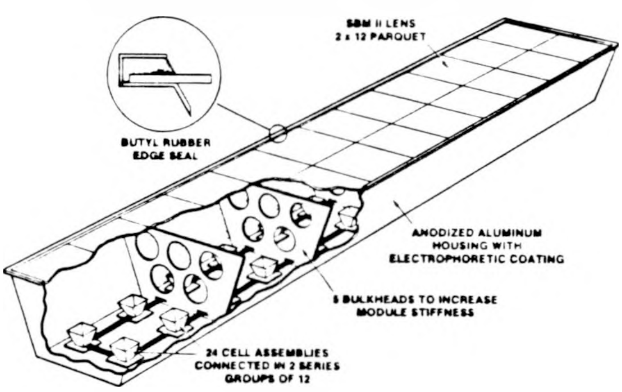

Figure 4. Artist's Conception of SBM3.

The housings employ an electrical isolation technique that has not been used before in PV modules. The 1-mm thick aluminum housing is first anodized and then electrophoretically (EP) coated with a high-temperature acrylic, leaving a thin (50 μm) electrically isolating layer capable of withstanding 3000 volts [10]. No additional electrical insulation between the electrically-live heat spreader and the housing is required, thereby enhancing heat transfer and, in combination with the copper heat spreader, eliminating the need for a separate heat dissipator.

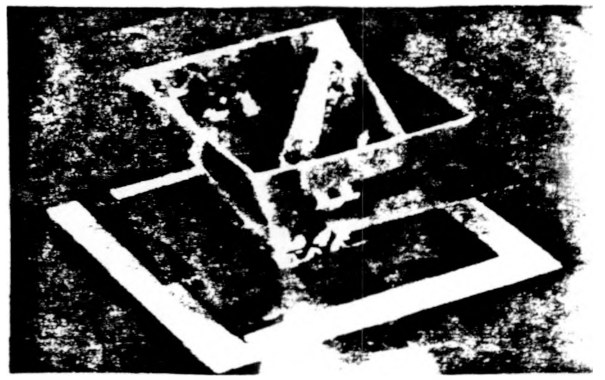

Figure 5. Cell Assembly for SBM3.

The optical system uses the point-focus Fresnel lens designed by General Electric and compression-molded by Fresnel Optics. The lens parquet is positioned in a channel in the housing and sealed with an ultraviolet-stabilized butyl rubber. A reflective secondary optical element is installed on each cell assembly to improve the uniformity of the flux distribution and to provide tolerance to tracking errors. The secondaries, which have a reflectivity of about 82%, are made of polished anodized aluminum and are attached to the upper cell interconnects with an adhesive.

The cells, designed and made at the UNSW, incorporate some of the recent advances in concentrator cell technology, such as light-trapping microgrooves, surface passivation, double-layer anti-reflection coating, and a thin low-resistivity base. ENTECH designed a prismatic cell cover, which refracts light that would otherwise hit the cell's top surface metallized electrical grid onto the cell's active area. This allowed us to increase the metallization coverage from 6%, which is optimum for cells without covers, to 15%. The cell's series-resistance losses are thereby reduced. The projected efficiency for the cells with prismatic covers was about 24%, we achieved as high as 25% on some cell assemblies [11].

During lens-cell testing last year we discovered a problem with the prismatic covers. Although indoor flash testing showed cell assembly efficiencies exceeding 25%, efficiencies were lower under a lens. Subsequent evaluation identified the problem to be that the prismatic covers were too thick. If the covers are too thick, their acceptance angles are too narrow to accommodate all the incident light. As the existing process used to mold the prismatic covers and glue them to the cells could not be modified to produce thinner covers, Sandia and ENTECH developed a process to mold the covers directly to the cells. This new process has great potential for automating the application of prismatic covers to cells, thereby decreasing the associated production costs.

A four-cell "mini-module" using the SBM3 optics and cell assemblies has been tested outdoors. The results are given in Figures 6 and 7. The efficiency of this module was about 19% at 800 W m^{-2} and 25°C cell temperature. At ±0.5° off-track, the power output is 96% of on-track value, and at ±1° off-track, it is 90%. Complete SBM3 prototypes are currently being subjected to Sandia's qualification tests

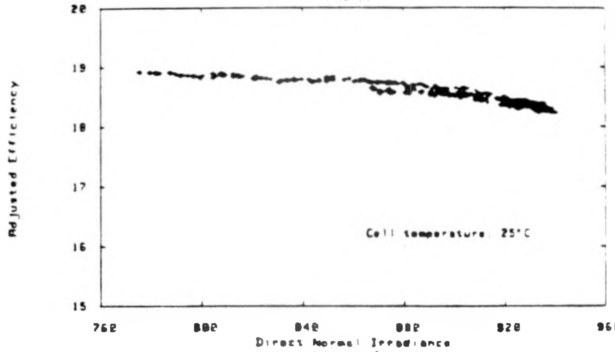

Figure 6. Efficiency vs. Direct Normal Insolation of SBM3 Mini-Module.

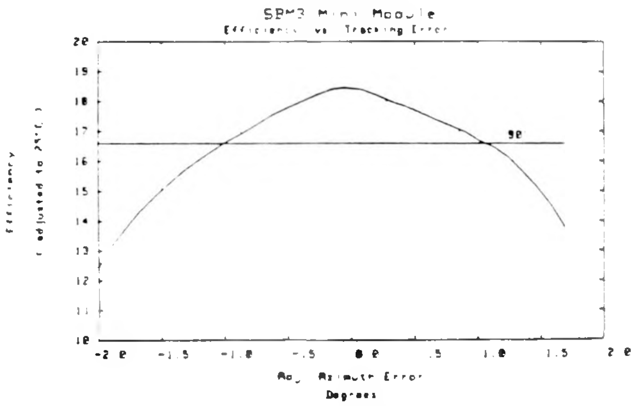

Figure 7. Off-Track Performance of SBM3 Mini-Module.

for concentrator modules [12]. The SBM3 cell assemblies have passed their qualification tests, surviving more than 1000 thermal cycles although the tests currently require only 250.

3.3 Other PV Concentrator Module Designs

Several firms are currently developing PV concentrator modules. Alpha Solarco has adapted the SBM3 design for use at an installation near Las Vegas, NV [13,14]. Solar Kinetics Inc. (SKI) is also developing a module based on the SBM3. Black & Veatch has designed and built a prototype of a point-focus module with a 5 x 6 Fresnel lens parquet and cells from the UNSW [15]. The Electric Power Research Institute (EPRI) has also designed a point-focus PV concentrator module using back-contact cells developed by Stanford University.

Designs using point-focus Fresnel lenses are not the only type of PV concentrator modules currently being pursued. Wattsun has designed and built prototypes of a "flat-plate concentrator" module that uses molded acrylic lenses 1.2-cm square and modified 1-sun cells [16,17]. ENTECH is continuing to develop modules that use linear Fresnel lenses and modified 1-sun cells with prismatic covers [18]. SEACorp is also working on a line-focus PV module. Science Applications International Corporation (SAIC) and Tactical Fabs Inc. (TFI) are developing a parabolic dish concentrator that uses an actively cooled PV receiver consisting of densely packed backcontact cells. Other firms developing PV concentrator modules include AESI, Midway Laboratories, and Sci-Tech International [19,20,21,22].

4. RELIABILITY ISSUES

The energy-cost goals given in the U.S. Department of Energy's (DOE) "Five-Year Plan for the National Photovoltaics Program" are based on PV modules that "will have a reliable output and an operational life expectancy of 30 years," [23]. Sandia maintains a program to ensure the reliability of PV concentrator modules. The program includes the development of qualification tests, extensive hardware testing and associated failure analyses, component reliability experiments, and surveys of fielded systems. In addition, we provide quality assurance/quality control (QA/QC) assistance to manufacturers of PV concentrator hardware. Reliability issues that are currently of concern include the applicability of wet insulation-resistance tests to concentrator modules, correlation of accelerated thermal cycling tests with life expectancy in the field, and the importance of quality assurance during manufacture.

4.1 Qualification of PV Concentrator Modules

Sandia has developed and published qualification test specifications for PV concentrator modules [12]. These tests are designed to screen new designs and new production runs for susceptibility to known failure mechanisms. Since they experience a more severe environment than the rest of the module, cell assemblies and receiver sections are tested separately from complete modules. The tests include characterization of electrical performance, checks to assure safety and structural integrity of modules, and accelerated environmental aging (including ultraviolet light exposure).

The specifications are currently being revised to incorporate the latest information on failure mechanisms, and the relationships between accelerated tests and field reliability. The revisions are designed to help establish a 30-year field life for concentrator modules. The current specifications require survival of 250 thermal cycles for cell assemblies and receiver sections. The new tests will require a minimum of 500 thermal cycles, reflecting our increased understanding of the correlation between field life and accelerated testing [24].

Testing in the field and in environmental chambers has established that moisture intrusion, especially condensation, is an important reliability and personnel safety issue which must be addressed in the qualification of PV concentrator modules. A wet insulation-resistance test is being considered, which may allow only one polarity (the PV circuit or ground) to be exposed inside a module. This requirement could have a significant impact on future concentrator module designs.

A number of other less consequential changes, such as adjusting the allowable degradation levels, adjusting thermal cycling temperatures and frequencies, and specifying tests for optical components and bypass diodes, are also being considered.

4.2 Module and Component Testing

Sandia conducts qualification tests of both in-house module designs and those developed by the industry. Recent tests have included the SBM3, ENTECH's line-focus module, Alpha Solarco's point-focus module, and Wattsun's "flat-plate concentrator" module.

Other tests recently conducted include investigations of the pull-strength of the metallization on concentrator cells, high-voltage breakdown of electrophoretic coatings used in the SBM3, and module sealing systems. We routinely characterize lenses and secondary optical elements, conduct aging studies on materials, and measure module performance. The test results are provided to the manufacturers to assist in their development efforts.

4.3 Solder Fatigue Experiments

We recently conducted an experiment to compare the results from qualification thermal cycling tests with actual field life [24]. The first half of the experiment considered fatigue of solder joining top contacts to solar cells. By comparing the results from thermal cycling of two sets of cell assemblies, one aged through field use and the other kept in storage, we estimated that 30 years in the field is roughly equivalent to 800, -40 to +110°C thermal cycles applied at a rate of 30 cycles per day.

The second half of the experiment considered cracking of the solder bonding silicon chips to copper heat spreaders. The experiment consisted of identical soldered parts placed in thermal cycling chambers operating at frequencies of 1, 8, or 24 cycles per day. The temperature range was not exaggerated but two temperature ranges corresponding to winter and summer were alternated in each chamber. An additional set of parts was subjected to the qualification tests' thermal cycle. Degradation of the solder joint, as measured by ultrasonic imaging and expressed as a percentage of the original bonded area, was characterized as a function of two variables, number of cycles and cycling frequency.

The results from the second half of the experiment are shown in Figure 8. Although it is hard to see on the graph, the parts subjected to 1 cycle per day (which probably corresponds most closely to field

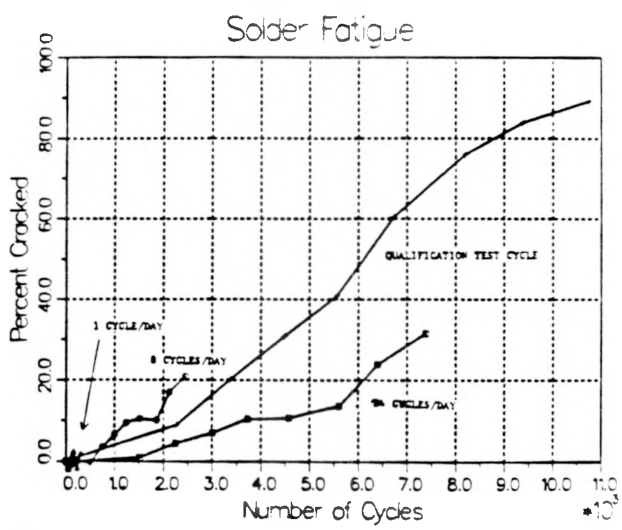

Figure 8. Solder Bond Failure Percentage vs. Number of Cycles

exposure) have the highest crack growth rate per cycle. We believe the solder has time to creep between cycles, causing greater strain. Twenty-four cycles per day appears to be the least severe. The qualification test cycle currently uses 36 exaggerated temperature cycles per day. Its severity falls between that of 8 and 24 cycles per day. While the results from this experiment provide guidance in selecting a cycling frequency and temperature range for qualification, it is likely that parts made with other sizes and types of solar cells will exhibit different degradation rates. Thus, it is necessary to individually evaluate each design, an expensive and time-consuming process.

4.4 Field Surveys

Surveys of the three fielded first-generation concentrator systems have been used to identify failure modes in order to improve future designs. SOLERAS, installed in 1981, has shown less than 1% per year field-power degradation with the vast majority of the modules showing no decrease in output. The degradation was mostly attributable to poor quality control during cell soldering. The vast majority of the modules show no decrease in output. At the ENTECH DFW Airport installation one module failed as a result of insulation being rubbed off a wire. After washing, the system is within 2% of the original output measured in 1982. The Sky Harbor Airport installation in Phoenix had about 3% per year module failures between 1982 and 1987 (when it was dismantled). These appeared to be caused by open circuits in the solder bonds (poor quality control during manufacture).

Results from the first five years of field operation have shown that concentrator modules can be a reliable technology. No degradation in cell output has been observed, and the vast majority of modules show no degradation in output. The power degradation that has occurred is due mostly to discrete module failures caused by open circuits in the solder bonds connecting the cell assemblies. In general, the failures observed in the first-generation hardware can be avoided with improved designs and better production quality control.

4.5 Quality Assurance/Quality Control

The results from the field surveys and qualification tests at Sandia emphasize the importance of quality control during manufacture. In support of the Photovoltaic Concentrator Initiative, Sandia is writing a generic QA/QC manual to provide guidelines for manufacturers of PV concentrator hardware [25]. While the specific purpose of the manual is to ensure that all participants in the Initiative incorporate a minimum level of QA/QC in their contract activities, it is applicable to the industry in general. The manual will specify actions necessary to assure quality in procurement of materials and components, production and testing of PV hardware, and the maintenance of traceable designs and data. In addition, Sandia provides other QA/QC assistance to concentrator module manufacturers, including technical support during module production, and failure analysis.

5. NEW SYSTEMS

Two new PV concentrator power systems have been constructed in the past year. One is a 300-kW, linear-Fresnel system installed by ENTECH at the new 3M Company facility in Austin, TX [18]. This system is a roof-mounted, passively cooled, two-axis tracking array with 720 modules that use modified 1-sun silicon cells made by Solarex. Preliminary measurements suggest that the peak dc field efficiency is about 15% (at a 25°C cell temperature) making this the highest rated efficiency PV power system ever installed. This project was funded by the DOE, 3M Company, City of Austin, ENTECH, and the state of Texas.

The other new PV concentrator system was installed near Las Vegas, NV by Alpha Solarco [14]. This system consists of a single pedestal array with a peak power output of about 10 kW. The module is based on the SBM3 design and uses cells soldered to copper heat spreaders and point-focus Fresnel lenses. It has refractive secondary optical elements. The silicon concentrator cells were made by ASEC. Current plans call for the construction and installation of several more arrays following checkout and initial operation of the first array. This project was funded entirely by Alpha Solarco.

6. PHOTOVOLTAIC CONCENTRATOR INITIATIVE

As a result of the recent substantial improvements in concentrator cell efficiencies and progress in low-cost module designs, the DOE has established the Photovoltaic Concentrator Initiative. The Initiative is designed to foster the development of PV concentrator systems and accelerate achieving the near-term, peak-power generation cost goal. The Initiative consists of two major efforts: development of PV concentrator technology and the transfer of high-efficiency concentrator cell technology demonstrated by DOE-sponsored research projects to the cell fabrication industry. These efforts will be achieved through competitively placed, multi-year contracts. Since Sandia has unique capabilities in both the cell and module development and testing areas, cooperative efforts using these resources are planned. All modules developed under this program will be tested to ensure they satisfy Sandia's qualification testing requirements.

Fifteen proposals were received from industry under the cell development portion of this initiative, and thirteen proposals were received under the collector development portion. Both sets of proposals covered a diverse set of approaches to the achievement of cost-effective cells and collectors. The proposals have been evaluated and contract negotiations with the selected developers are underway. We anticipate that this Initiative will result in proven technologies capable of competing in the peak-power generation market.

While the full Concentrator Initiative began in Fiscal Year (FY) 1990, preliminary efforts where undertaken in FY89 with the contracting of short-term interim module development projects. These projects are intended to attack critical design issues whose solution would permit the developer to better participate in the full initiative. Contracts, which are currently nearing completion, were placed with five companies representing the full range of technologies.

7. COST

The DOE's Five-Year Plan has established energy cost goals of \$0.12/kWh in the 1990s and \$0.06/kWh for the year 2000 (1986 dollars) [23]. These goals represent significant entry points for competition with utility peak- and base-power generation, respectively.

We periodically conduct costing studies to assess the PV concentrator industry's approach to meeting these goals. In the latest of these studies six module developers, Alpha Solarco, Black and Veatch, ENTECH, Sandia, SEA Corporation, and Wattsun, provided module costs for their designs. Using DOE guidelines for solar resource, economic, and balance-of-system factors, the 30-year levelized electrical energy costs for these systems were determined [26]. The results are summarized in Figure 9.

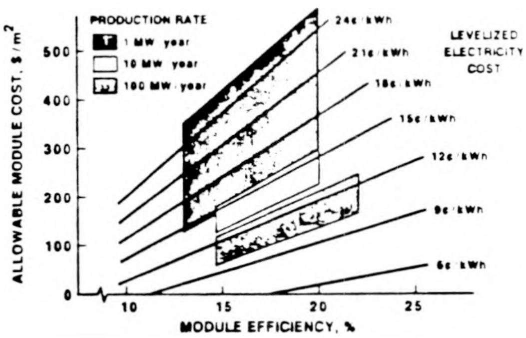

Figure 9. Projected Module Cost/Efficiency Envelopes.

The figure shows projected module-cost/efficiency envelopes for the six module designs at three different production rates, 1, 10, and 100 MW/year plotted over levelized electricity costs. Given sufficient production, these systems will be capable of meeting the DOE goals for entry into the peak-power generation market. The envelopes include the projected improvements in concentrator cell efficiency likely to occur during the production build-up period. These cost projections were further substantiated by information provided by developers responding to both the preliminary and full Concentrator Initiative proposal requests.

The data suggest that the goal for the year 2000 probably will not be met by merely learning curve improvements of these designs. However, innovative designs based on developmental concentrator cells, automated module manufacturing techniques, and reduced indirect costs associated with larger systems offer promise in achieving the longer term goal.

8. SUMMARY

Progress in PV concentrator module technology over the past two years has been substantial. Significant gains have been achieved in both concentrator cell and module development, including the establishment of new record efficiencies in both areas. New technology has been or is being transferred to industry, and cost studies indicate that several PV concentrator designs have the potential to compete effectively in the utility market given sufficient production rates. Significant attention has been given to the area of reliability, and results from field surveys of first-generation systems show that the basic technology is reliable. A new program initiative has been instituted to accelerate the development of a PV concentrator industry.

9. ACKNOWLEDGEMENTS

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