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Fourth-Generation Photovoltaic Concentrator System Development

M. J. O'Neill and A. J. McDanal
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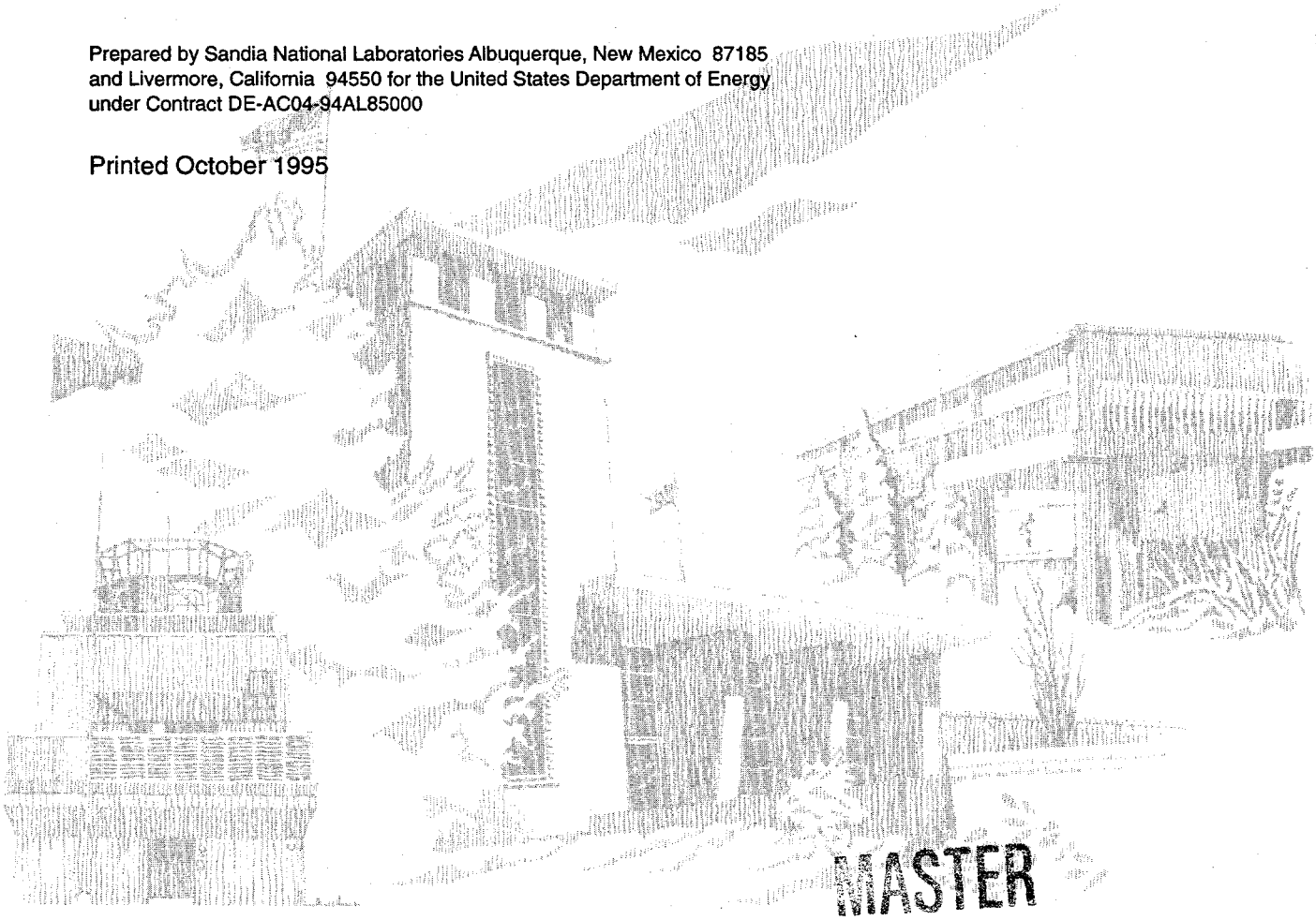

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Sandia Contract 40-8941A

ABSTRACT

In 1991, under a contract with Sandia for the Concentrator Initiative, the ENTECH team initiated the design and development of a fourth-generation concentrator module. In 1992, Sandia also contracted with ENTECH to develop a new control and drive system for the ENTECH array. This report documents the design and development work performed under both contracts. Manufacturing processes for the new module were developed at the same time under a complementary PVMaT contract with the National Renewable Energy Laboratory. Two 100-kW power plants were deployed in 1995 in Texas using the newly developed fourth-generation concentrator technology, one at the CSW Solar Park near Ft. Davis and one at TUE Energy Park in Dallas. Technology developed under the Sandia contracts has made a successful transition from the laboratory to the production line to the field.

ACKNOWLEDGEMENTS

Numerous people from several organizations have contributed to the work reported herein. Several of these team members are identified in Section 2.2. The authors especially thank the technical staff at Sandia, including Alex Maish, Dave King, Tom Hund, et al., for their contributions to the design, development, and thorough testing of the new concentrator technology described herein. We also especially thank Ken Goodman and Tommy Hicks of Prime Manufacturing, who developed a new sun-tracking controller for our fourth-generation array; Arnie Kapitz and his team at Consumers, Inc., who developed the new all-galvanized sun-tracking structures; our utility customers (including TU Electric, Central & South West Services, the PVUSA-Davis team, et al.) who are evaluating our fourth-generation hardware; and the entire technical staff at ENTECH, Inc.

CONTENTS

Executive Summary

Significant improvements in manufacturability and energy cost were achieved by ENTECH , Inc. in the development of its fourth-generation photovoltaic (PV) concentrator module. Additionally, improvements were made in tracking system drive and controller design that benefit cost and reliability in both grid-connected and stand-alone installations. These accomplishments were demonstrated in two 100-kW utility-purchased systems installed in Texas. With a manufacturing volume of 10MW per year, ENTECH projects module manufacturing costs at $1.50 per watt, and system costs at $3 per watt, well below that of current flat plate photovoltaic systems. This work dramatically advances the commercial potential of photovoltaic concentrator technology for electrical power production.

Entech's fourth-generation module is the largest PV module produced from any manufacturer. It is 12 feet long and produces 430 Wp at 14% efficiency using 17% efficient cells. Manufacturing improvements are numerous. The receiver section was redesigned to halve the number of parts and eliminate curing wet adhesives. The line-focus Fresnel lens is pre-laminated by 3M, reducing costly and hazardous solvent bonding by ENTECH. 3M also developed a prismatic cell-cover optical tape with a contact adhesive to replace individually molded and applied silicone covers. Modified one-sun cells from four suppliers have been tested, demonstating efficiencies between 17% and 19%. An overheating problem in low winds with the third generation module was solved by developing a state-of-the-art aluminum heat sink extrusion with 15-cm long, 2-mm wide fins. Cell temperature under 21X concentration is now an acceptable 40 to 45°C above ambient, which is only 10 to 15°C above one-sun PV module cell operating temperatures.

To solve tracking control problems resulting from ac grid voltage spikes, ENTECH developed a battery-powered drive system with a PV charger. Two tracking control systems developed by Prime Industries and by Sandia National Laboratories have been tested with the tracker. In addition to improving the reliability of utility-scale systems, this has enabled ENTECH to offer a two-module 860Wp Sunline™ unit product for smaller applications.

1.0 INTRODUCTION & BACKGROUND

The ENTECH technical team has been developing, field testing, refining, and commercializing photovoltaic concentrator systems since 1978 (Refs. 1-7). These systems have been based on a patented arched Fresnel lens optical concentrator, which provides maximum optical efficiency coupled with exceptional real-world error tolerance (U.S. Patent No. 4,069,812). First-generation line-focus concentrator systems were deployed in the early 1980's, and provided the highest system performance levels of that era. Second-generation systems were deployed in the mid-1980's, and provided better performance at lower cost. Third-generation systems were deployed in the early 1990's. These systems were the first to use low-cost silicon cells made by one-sun module manufacturers.

One of the third-generation systems was deployed in early 1991 at the PVUSA test site in Davis, California. This array has been independently tested side-by-side with other leading photovoltaic technologies in array sizes of at least 20 kW. Figure 1 shows the long-term results of this independent testing. The various technologies fall into four performance groups: thin-film amorphous silicon arrays are lowest at about 3% efficiency; polycrystalline silicon arrays are next at about 8% efficiency; crystalline silicon is the highest of the one-sun arrays at about 10% efficiency; and the third-generation concentrator is the highest performer at about 11% efficiency.

In 1991, ENTECH won a Sandia contract (#40-8941A) under the Concentrator Initiative (CI) procurement. Under this CI contract, the ENTECH team initiated the design and development of a fourth-generation concentrator module. In 1992, Sandia also provided another contract (#87-5877) for the development of a new control and drive system for the ENTECH array. During the same period, ENTECH was also funded by NREL under the Photovoltaic Manufacturing Technology (PVMaT) procurement to develop the manufacturing processes for the new module. This report documents the design and development work performed under both Sandia contracts. The manufacturing processes for the new module were developed under the complementary PVMaT contract. Two 100-kW power plants were deployed in 1995, using the newly developed fourth-generation concentrator technology. One plant is at the CSW Solar Park near Ft. Davis, Texas. The other plant is at TUE Energy Park in Dallas, Texas. Thus, the two largest utility companies in Texas are presently evaluating the new technology.

The following sections discuss the development of the new module and array, and the impact of the advances made under the two contracts (#40-8941A and #87-5877).

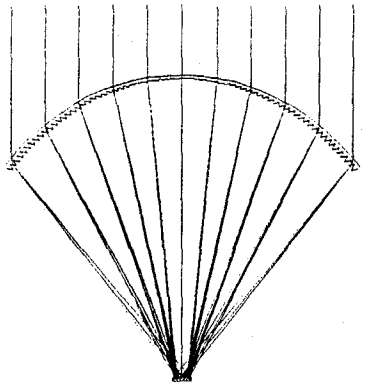
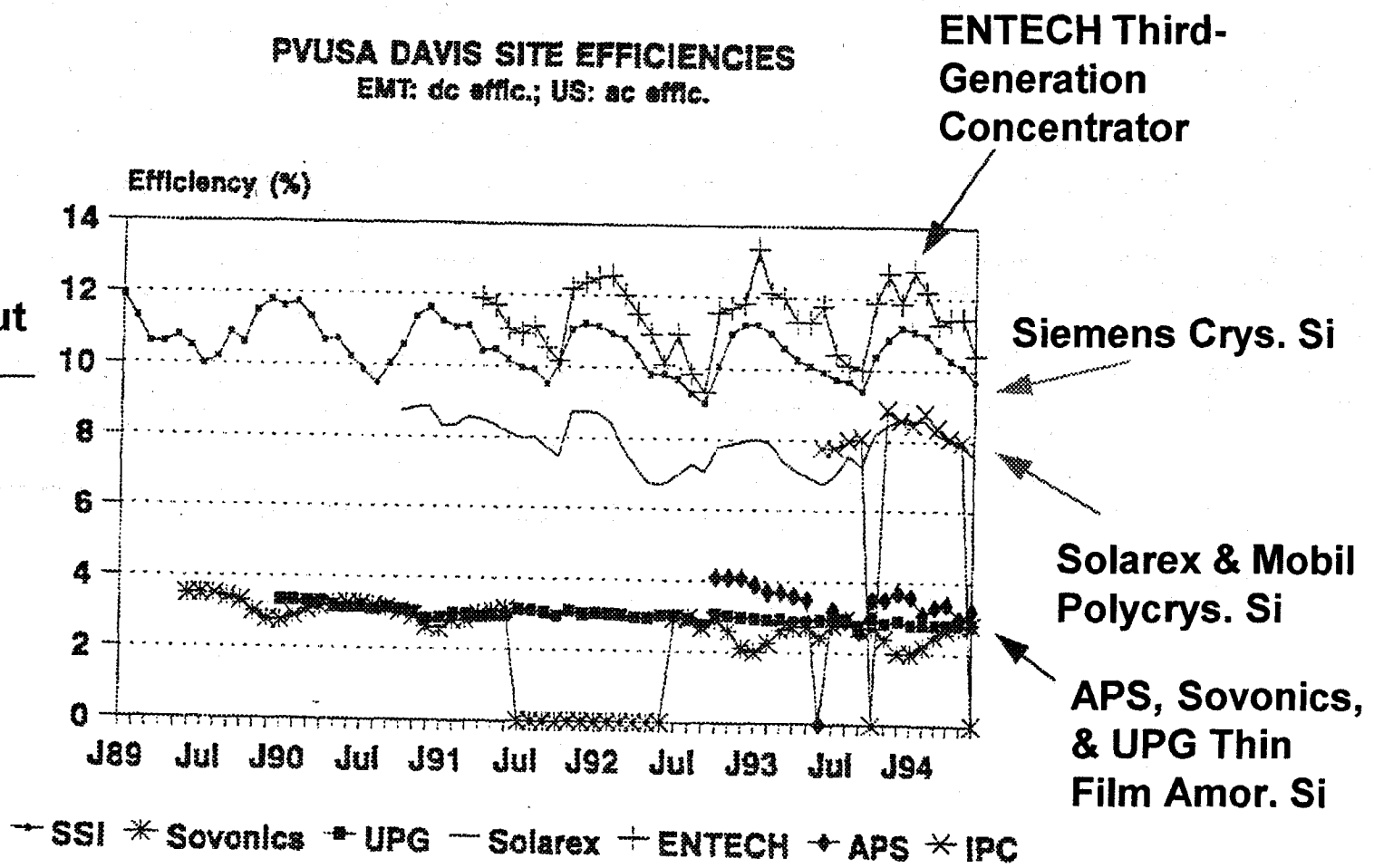


Fig. 1 - Long-Term Independent Test Results for Leading Photovoltaic Technologies

ENTECH, Inc.

Elec. Power Out

Solar Power In



2.0 MODULE DEVELOPMENT

2.1 Module Description

Figure 2 shows a cross-sectional schematic of the fourth-generation concentrator module. There are four key functional elements in the module. The Fresnel lens gathers and focusses the direct portion of the available solar irradiance into a focal line. The solar cell packages are arranged along the focal line produced by the lens to convert the sunlight to electrical power. The heat sink convectively dissipates waste heat from the solar cell packages to the surrounding atmosphere. The housing structure supports the lens and heat sink, and provides an environmental enclosure for the internal surfaces of the module. Module assembly is accomplished by snapping together six mating parts: the four sheet aluminum housing parts (two sidewalls and two endplates), the receiver assembly (one heat sink with cell packages attached), and the lens.

As further discussed in Section 2.2, the new fourth-generation module was designed by a team of organizations, including all of the suppliers of key parts. One of the first team design decisions for the fourth-generation module related to module size. To minimize parts count, the largest practical module size is preferred from both cost and reliability considerations. The lens aperture width limitation relates to the lens manufacturing process. Since 1978, Minnesota Mining & Manufacturing (3M) has produced the Fresnel lens for ENTECH, using the 3M-proprietary continuous Lensfilm process. In the early 1980's, the maximum prismatic pattern width for the Lensfilm process was 30 cm. By the late 1980's, this pattern width limitation was increased to 60 cm. By the early 1990's, the pattern width limitation was again increased to 100 cm. First-generation modules used four strips of Lensfilm to form a lens with a 91 cm wide aperture. Second- and third-generation modules used two strips of Lensfilm to form a lens with a 91 cm aperture. For these earlier-generation lenses, the use of multiple strips of Lensfilm to form a lens resulted in substantial yield losses during lamination of the 0.5 mm thick Lensfilm to 3.0 mm thick acrylic superstrate material. Thus, the decision was made to use a single strip of Lensfilm to form the fourth-generation lens. As further discussed in Section 2.3, this decision resulted in a new module aperture width of 85 cm, after arching the 100 cm wide Lensfilm material.

The other key module size dimension is module length. Since 1978, Consumers, Inc., has produced the marine-grade aluminum housings for ENTECH. To form the sidewalls of the module housing, Consumers uses large presses with maximum length limitations of 3.7 m. Thus, the decision was made to design the new housing at the

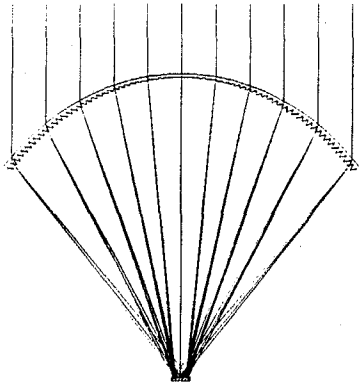
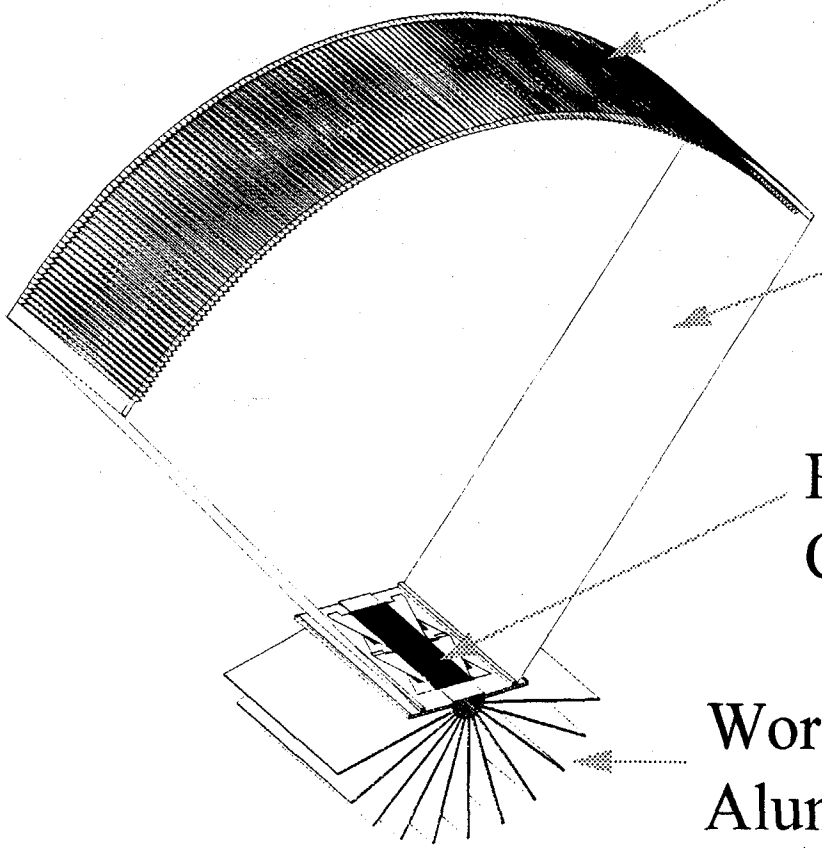


Fig. 2 - Fourth Generation Concentrator Module

ENTECH, Inc.



upper end of this equipment limitation. This decision resulted in a new module aperture length of 366 cm. The new module aperture area is 3.1 sq.m., which is the largest photovoltaic module area of any type yet produced.

As further discussed in Section 2.4, solar cells for the new module are being made by several leading one-sun module manufacturing firms. Presently, most of these firms start their cell production process with 100 mm square wafers trimmed from 125 mm diameter silicon wafers. As further discussed in Section 2.3, this wafer size is well matched with the new lens size if two rectangular concentrator cells (about 50 mm total width by about 100 mm total length) are cut from each square wafer. Using such cells, 37 cell packages will fit end-to-end along the heat sink in the focal line produced by the lens. These cell packages are electrically interconnected in series to provide a module voltage slightly higher than most one-sun modules, which typically use 36 cells in series. As further discussed in Sections 2.5 and 2.6, each cell package incorporates a prismatic cell cover to eliminate gridline obsuration losses and thereby boost cell performance. Each cell package also includes bypass diodes to protect the cell in case of shadowing.

As further discussed in Section 2.8, the cell packages are bonded to the heat sink using a proprietary new dry-film process. The dry film beneath the cell packages provides dielectric isolation between the cell circuit and the heat sink, as well as low thermal resistance between these parts. The entire cell circuit is also encapsulated with a second dielectric film above the cell packages. The assembly of interconnected cell packages, dielectric layers, and heat sink is often called a photovoltaic receiver. The new photovoltaic receiver assembly approach is the subject of a pending U.S. Patent.

The heat sink beneath the cell packages is needed to reject the waste heat resulting from the incomplete conversion of the focussed sunlight into electrical power. Under peak irradiance conditions, about 2 kW per receiver of waste heat must be dissipated to the surrounding atmosphere by convection. In the early 1980's, for second-generation modules, the convective heat sink was made by fabricating hundreds of fins and attaching these fins to the bottom of the cell mounting plate with an adhesive. A much more cost-effective method of mass-producing a large convective heat sink is by the aluminum extrusion process. Such an extruded heat sink was used on the third-generation concentrator module. However, the size of the third-generation heat sink was limited by available extrusion processes to a total fin area of about 1.7 sq.m. per meter of extruded heat sink length. In the early 1990's, this third-generation heat sink had the highest fin area/extruded length ratio yet achieved. For the fourth-generation heat sink, a new team member, Columbia Aluminum, was willing to attempt the

extrusion of a new heat sink with twice the total fin area of the third-generation heat sink. As further discussed in Section 2.7, Columbia was successful in producing the new heat sink, which provides a phenomenal 3.4 sq.m. of fin area per meter of extruded heat sink length.

For the total heat sink length of 3.7 m, the new heat sink provides 12.4 sq.m. of total fin area per module. This fin area is 4 times the aperture area of the module. The ratio of heat transfer area to module aperture area is a key parameter in determining operating cell temperature, for either concentrator or one-sun modules. For a roof-mounted one-sun module, this ratio is about unity. For a frame-mounted, exposed-back one-sun module, this ratio is about 2. Thus, compared to a roof-mounted one-sun module, the fourth-generation concentrator has 4 times as much heat transfer area per unit aperture area. Compared to a frame-mounted one-sun module, the fourth-generation concentrator has 2 times as much heat transfer area per unit aperture area. With the new heat sink, the fourth-generation concentrator module has cell operating temperature levels much lower than for earlier generation concentrator modules. Indeed, side-by-side tests at both ENTECH and Sandia have confirmed that the cell operating temperature levels are similar for the new concentrator and for frame-mounted one-sun modules, as further discussed in Section 2.7.

As further discussed in Section 2.9, the electrical performance of the fourth-generation module is directly related to cell performance. The lens provides 90% net optical efficiency at 21X geometric concentration ratio. The encapsulating layer above the cell package circuit provides a transmittance of 94%. The cell package packing factor on the heat sink is 98%. The product of these three factors times the cell efficiency equals the module efficiency. The power output of the module equals module efficiency times aperture area times available direct normal irradiance. Under standard test conditions (STC) of 1,000 W/sq.m. irradiance and 25C cell temperature, the module output is about 430 W with 17% efficient cells, or about 480 W with 19% efficient cells. In terms of aperture area (3.1 sq.m.) and power output, the new module is clearly the largest and most powerful photovoltaic module of any type yet produced.

2.2 Team Development Approach

At the outset of the development program, a team of experts was assembled to simultaneously design the new module and its production processes. This team includes all key component suppliers, independent manufacturing experts, government lab technical personnel, as well as ENTECH's in-house technical staff. Key team members outside of ENTECH are identified in Table 1. 3M is the team member for optical components. Four of the leading silicon cell and one-sun module manufacturers from around the world are the team members for the concentrator cells and bypass diodes. The principal maker of solder-plated copper ribbon for the one-sun module industry is a team member. DuPont is the team member in the dielectric tape and film area. Consumers, Inc., continues to be the team member for module housings. Columbia is the heat sink team member. Two manufacturing technology firms, AIT and Klos, are also team members. Both National labs responsible for the Department of Energy's photovoltaic program are team members.

The team approach began at the brainstorming, conceptual design stage of the process and has continued through initial production and field deployment of the new module technology. Throughout, one key goal of the team approach has been to make maximum use of team members' existing production processes, rather than developing new in-house processes. A second key goal has been to incorporate continuous production processes instead of batch processes, wherever possible. Such continuous processes are obviously better equipped for high volume production at low cost than batch processes. A third key goal has been to minimize the number of parts and the number of process steps required to make a module. A fourth key goal has been to relax allowable tolerances in module assembly, installation, and operation. The results of this team approach are described in the following sections.

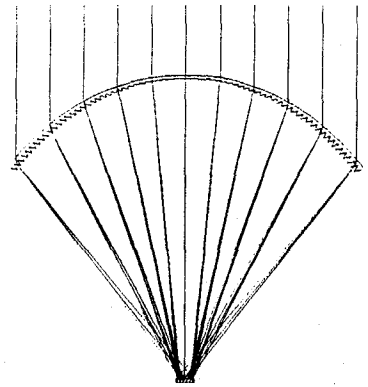


Table 1 - Fourth Generation Module Technical Team Members Outside of ENTECH

ENTECH, Inc.

- **Lenses and Prism Covers:**
  - » 3M - Paul Jaster
- **Cells and Diodes:**
  - » ASE - Wilfried Schmidt
  - » BP Solar - Tim Bruton
  - » Siemens - Richard King
  - » Solarex - John Wohlgemuth
- **Solder-Plated Cu Ribbon:**
  - » Brooks - John Sanders
- **Dielectric Tapes and Films:**
  - » DuPont - Stan Levy
- **Module Housings:**
  - » Consumers - Arnie Kapitz
- **Heat Sinks:**
  - » Columbia - Walt Brown
- **Process Automation:**
  - » AIT - Ed Chalupa
- **Process Development:**
  - » Klos - Rick Simpson
- **Technical Direction:**
  - » Sandia - Alex Maish
  - » NREL - Rick Mitchell

2.3 New Fresnel Lenses

Two new versions of ENTECH's patented arched Fresnel lens line-focus optical concentrator have been designed, tooled, and produced. Figure 3 shows the basic design approach used by ENTECH to define a new lens. The same design approach has been successfully used for the past two decades on all previous generations of the arched lens. The shape of the lens is dictated by the symmetrical refraction constraint used by ENTECH to maximize the lens optical efficiency and to minimize the effects of lens shape errors (U.S. Patent 4,069,812). This symmetrical refraction constraint dictates that each solar ray passes through the lens symmetrically in terms of its angles of incidence and emergence at the two lens/air interfaces. At any location in the lens, the angle of incidence of a ray relative to the smooth outer lens surface is equal to the angle of emergence of the ray relative to the prismatic inner lens surface. While this condition defines the basic lens shape, it does not define the scale nor the rim angle (equivalent to F Number) of the lens. The scale is selected to match the 3M Lensfilm process maximum prismatic pattern width. The rim angle is selected to maximize the concentration ratio in the presence of expected sun-pointing errors. For the fourth-generation module, both new versions of the lens provide the same focal length (73 cm), rim angle (40 degrees), and aperture width (85 cm). Both new lens versions are designed to focus sunlight onto a solar cell with an active width of 4.1 cm. Thus, the geometric concentration ratio for both versions is 21X (85 cm/4.1 cm). The only difference between the two new lens versions relates to sun-pointing error tolerance. One version, designated Solar Concentrating Lensfilm 1000 (SCL-1000) by 3M, is designed to accommodate up to $\pm$ 0.75 degree sun-pointing error levels, with only a 10% drop in optical performance. The other version, designated SCL-3000 by 3M, is designed to accommodate up to $\pm$ 1.0 degree sun-pointing error levels.

For more than a decade, ENTECH has successfully used the short-circuit current output of a scanning, 1 mm wide silicon cell to measure the photon flux profile across the focal plane of a Fresnel lens. Using this proven test, the focal plane irradiance profiles were scanned for both new lenses, with results shown in Figure 4. The net optical efficiency of the lens can be obtained by integrating under each of the two curves of Figure 4. For a 4.1 cm wide cell, this integration provides a net optical efficiency of 90% $\pm$ 1% for both new lenses.

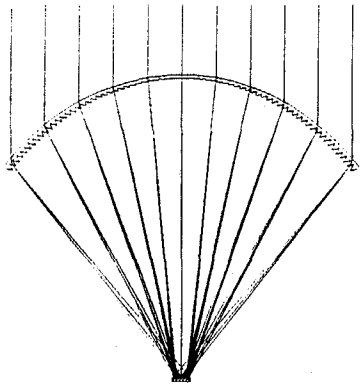
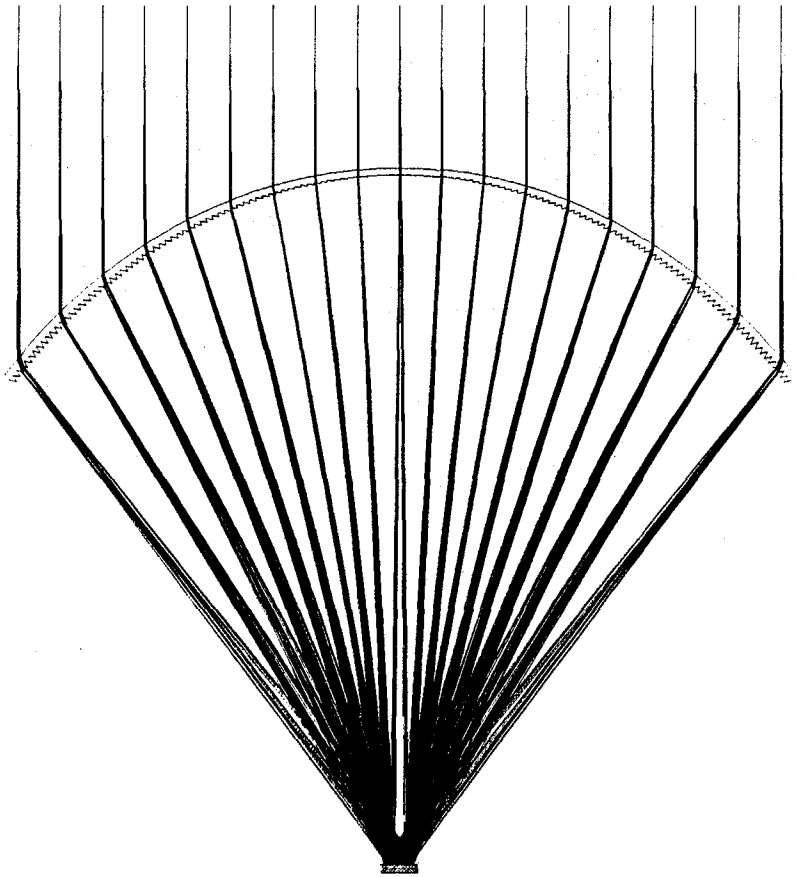


Fig. 3 - Performance-Based Lens Design

ENTECH, Inc.

- Red Edge Design
- Finite Solar Disk
- Dispersion
- Design Pointing Error
- Proper Cell Size
- Ray Trace Analysis
- Empirical Verification
- 90+% Efficiency



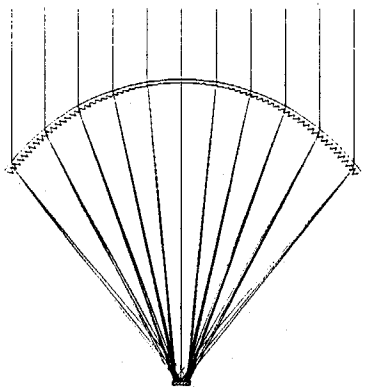
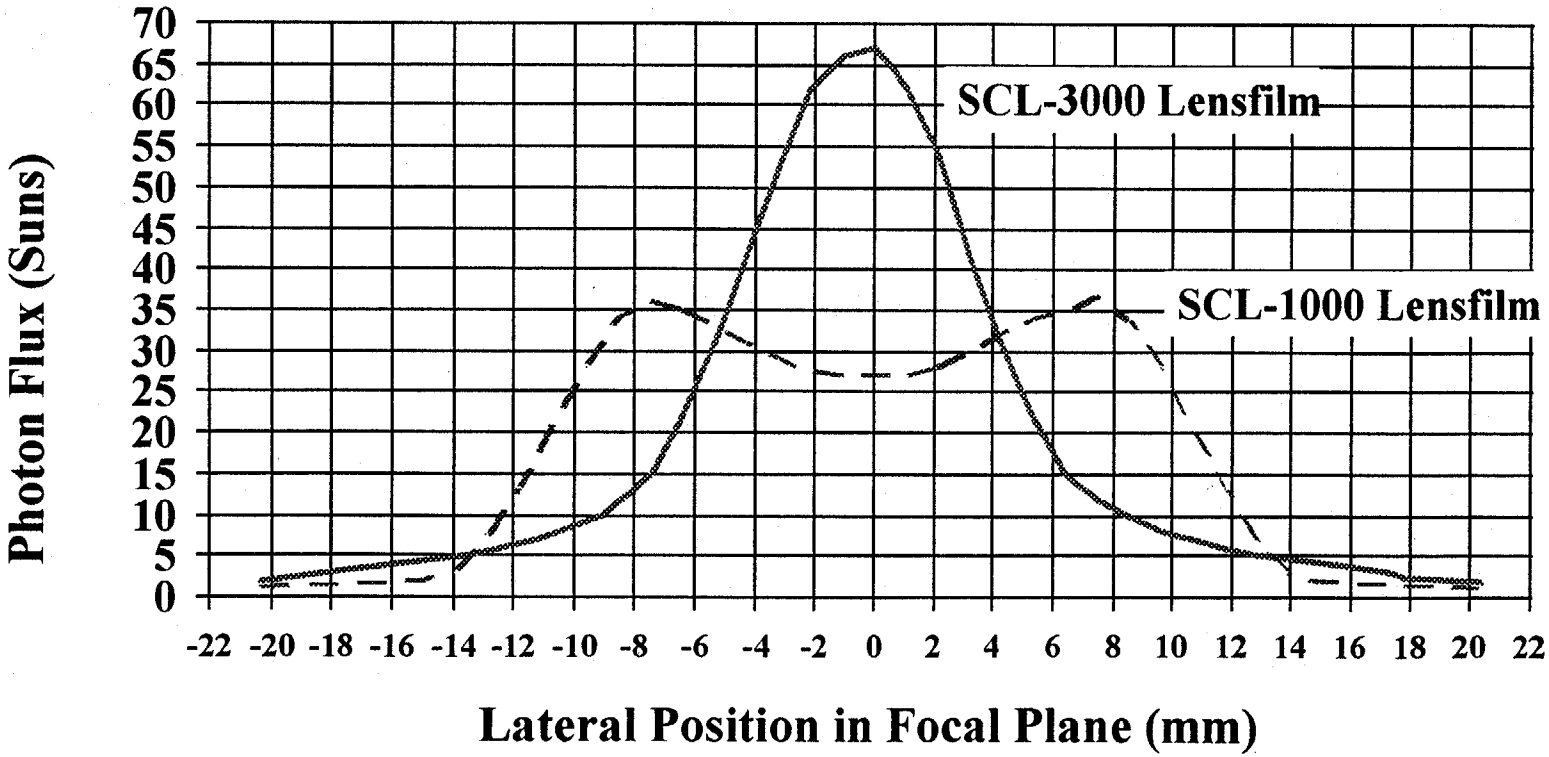


Fig. 4 - Measured Flux Profiles Over the Cell for Two Versions of the Lens

ENTECH, Inc.

• Cell Active Width: 41 mm (± 20.5 mm)



A second measurement of net optical efficiency was conducted by monitoring the short-circuit current output of a full-size cell with an active width of 4.1 cm. This test also provided a net optical efficiency measurement of 90% $\pm$ 1%. This same full-size cell test setup was also used to measure the sun-pointing error tolerance of both new lenses, with normalized results shown in Figure 5. Note that the mild-focus SCL-1000 lens loses less than 10% of its on-track performance up to $\pm$ 0.8 degree sun-pointing errors. Similarly, the sharp-focus SCL-3000 lens loses less than 10% of its on-track performance up to $\pm$ 1.0 degree sun-pointing errors.

Lens/cell combinations for the previous generation of modules were designed to accommodate only $\pm$ 0.25 degree sun-pointing errors. Thus, the fourth-generation module is designed to accommodate 3 or 4 times larger sun-pointing errors than earlier modules, depending on the new lens version selection. This increased sun-pointing error tolerance clearly provides a more robust module and array.

For prior generation lenses, ENTECH laminated the 0.5 mm Lensfilm to 3.0 mm thick acrylic superstrate material to form a single-piece lens. For the fourth-generation lenses, 3M provides pre-laminated, module-ready lenses. ENTECH no longer has to maintain a lamination facility and no longer has to absorb the yield losses associated with this batch process. Furthermore, ENTECH no longer must worry about the environmental, safety, and health (ES&H) concerns associated with solvent lamination. Finally, module-ready lens prices from 3M are very reasonable. In megawatt quantities, these lens prices are equivalent to about 30 cents per watt.

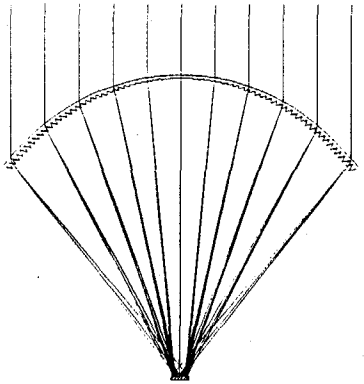
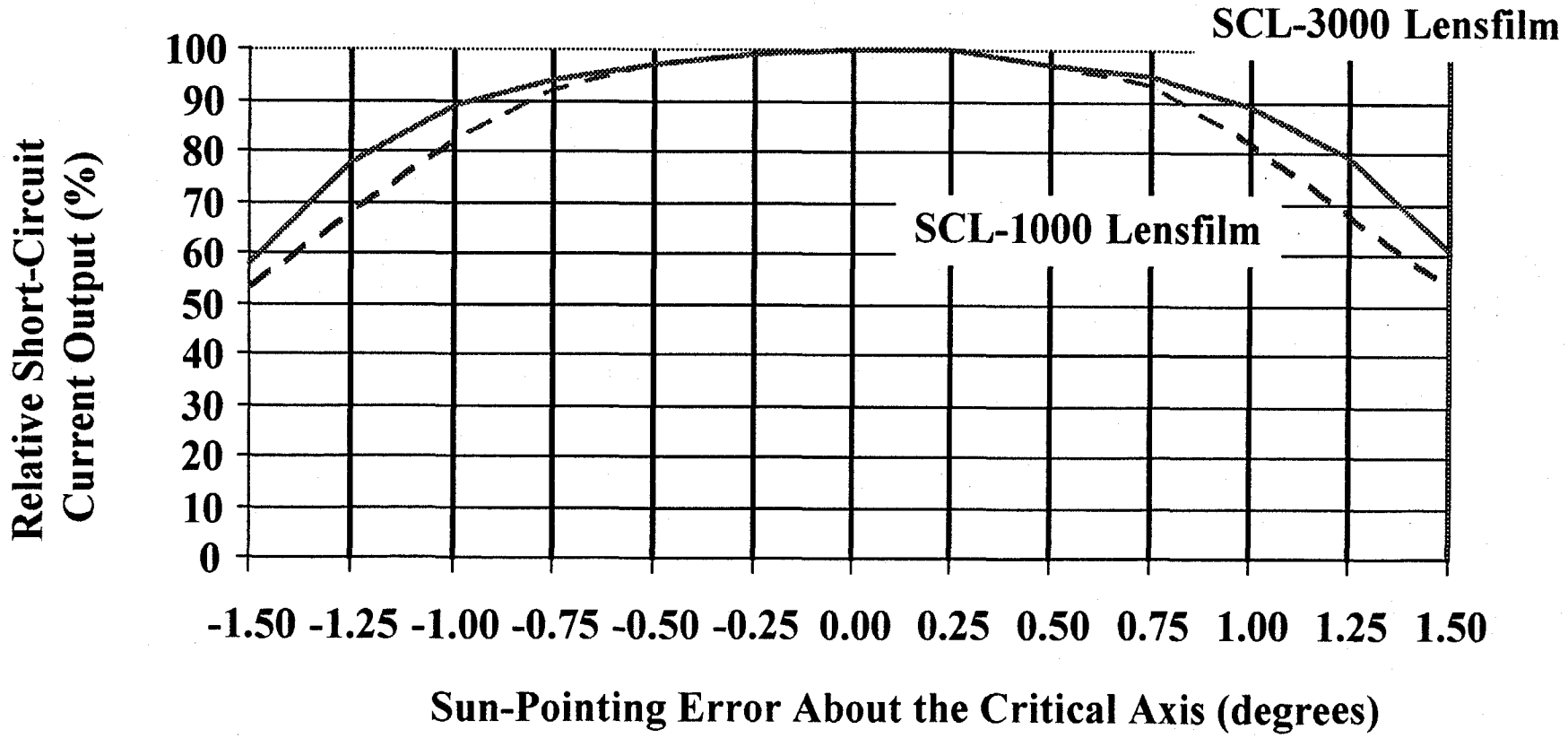


Fig. 5 - Measured Lens/Cell Sun-Pointing Error Tolerance for Two Versions of the Lens

ENTECH, Inc.

- 85 cm Lens Aperture Width
- 4.1 cm Active Cell Width



2.4 New Solar Cells

ENTECH's first- and second-generation modules used relatively expensive concentrator cells from Applied Solar Energy Corporation (ASEC). In the mid-1980's, ENTECH began to explore the use of one-sun type cells being made by one-sun module manufacturers, including ARCO Solar and Solarex. In the late 1980's and early 1990's, Solarex provided the cells for ENTECH's third-generation modules, including those for the 20 kW array at the PVUSA test site in Davis, California. In 1991, Sandia provided a separate Concentrator Initiative (CI) cell development contract to Solarex to develop the next generation of concentrator cell for ENTECH's fourth-generation module. During the early 1990's, ENTECH also began working with three other cell suppliers, ASE, BP Solar, and Siemens Solar. By 1993, all four cell suppliers were able to provide excellent cells for ENTECH's fourth-generation module.

All four cell suppliers start with squared wafers cut from round silicon wafers, as shown in Figure 6. Two of ENTECH's rectangular cells can be obtained from each squared wafer. Dual busbars are used on each cell to minimize gridline resistance losses. Parallel gridlines are used to be compatible with ENTECH's prismatic cell cover, which is further discussed in Section 2.6. Beyond these similarities, the four cell suppliers use significantly different manufacturing processes. Solarex uses diamond saws to groove the cell to form buried front contacts. BP Solar uses lasers to groove the cell to form buried front contacts. ASE uses a shadow mask evaporation process to form the front contacts. Siemens uses screen-printed front contacts. The four firms are also at different stages in the development cycle of the concentrator cells. ASE and BP Solar have both produced thousands of cells under commercial orders from ENTECH. Siemens has only produced sample quantities of cells for ENTECH, but has produced production quantities for another concentrator firm, SEACorp. Solarex has only produced sample quantities of cells for ENTECH, but has provided quotations for multi-megawatt cell quantities for utility-scale applications.

In a normal one-sun module, a 100 mm square wafer would provide about 1.5 W of power. If the one-sun cell manufacturer can produce the 100 mm square one-sun cell for $3 per watt, this equates to $4.5 per wafer. In ENTECH's module, this same wafer would provide about 28 W of power at an 18% cell efficiency. At $4.5 per wafer, this equates to 16 cents per watt for the cell cost in ENTECH's concentrator module. Even if the extra gridlines and the two-cell separation required for the ENTECH concentrator cell were to cause the wafer price to double to $9, this still equates to only 32 cents per watt for the cell cost in ENTECH's module. Thus, the marriage of one-sun type cells with ENTECH's 21X concentrator provides a direct path to cost-effective silicon cells.

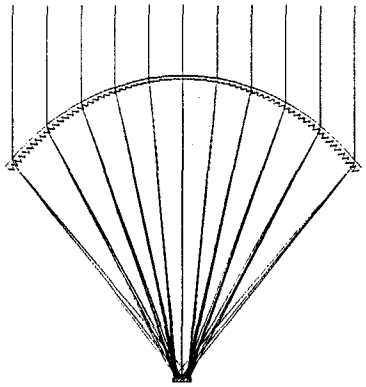


Fig. 6 - Typical Two-Cell-per-Wafer Layout

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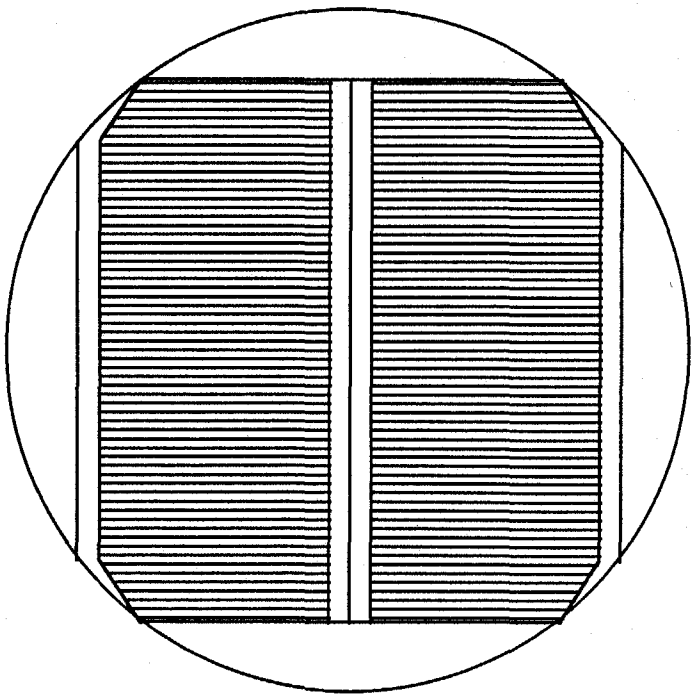

- Standard 125 mm Wafer
- Two Cells per Wafer
  - » Dual Busbars
  - » Parallel Gridlines
  - » Prism Cover Compatible
- Active Area per Cell
  - » 41 mm Wide
  - » 97 mm Long
- Power per Wafer: ~28 W at 19 Suns and 25°C

The measured performance levels of cells from all four suppliers are presented in Section 2.9. Integration of the cells into usable cell packages is discussed in the following section.

2.5 New Cell Package

Figure 7 shows the new cell package (patent pending) which is presently used in ENTECH's fourth-generation concentrator module. ENTECH's cell package has undergone a major evolution during the first half of the 1990's. As late as November 1992, ENTECH's cell package still incorporated more than twice as many parts as the package shown in Figure 7, and production of the package required numerous wet process steps. The latest cell package requires only 8 mass-produced parts, and is produced without a single wet process step. Key features of the new package are described in the following paragraphs.

In prior generation modules, bypass diode protection was provided by a separate diode circuit. This separate diode circuit required soldering, heat sinking, laydown, and encapsulation processes which were nearly as costly as the cell circuit processes. By incorporating rectangular bypass diodes between the top and bottom interconnector ribbons of each cell (Figure 7), this separate bypass diode circuit is completely eliminated. Furthermore, the diodes replace expensive dielectric material which was formerly required between the top and bottom interconnectors. The bypass diodes are very easily made by one-sun cell suppliers on fully metallized solar-grade wafers. For example, BP Solar has provided cost-effective diodes which are made in lots of 26 per wafer.

In prior generation modules, stamped copper interconnectors with multiple fingers were used. These interconnectors were soldered to the cell busbars with flux-laden solder paste. Ultrasonic cleaning was required to remove the flux residue. The new cell package uses interconnectors formed from continuously produced solder-plated copper ribbon. The same ribbon material is used by most one-sun module manufacturers around the world for stringing one-sun cells into module circuits. A mild, no-residue, no-clean flux is used during ribbon soldering to the cell busbars and to the bypass diodes to form the new cell package. No post-soldering cleaning step is required. The triangular shape of the ribbons allows two interconnectors to be obtained from each 10 cm long portion of 2.5 cm wide ribbon. The triangular shape is well matched to the linearly increasing current level in the interconnector as it accumulates current from one end of the cell to the other end. The new solder-plated ribbon costs 80% less than the old stamped interconnector and solder paste materials, and is much easier to handle. In small quantity orders, the triangular ribbon interconnectors cost about a nickel apiece. A small rule die chopper station, developed with PVMaT funding, is used to cut the triangular pieces from a continuous reel of ribbon material at rates equivalent to 10 MW/year.

Fig. 7 - Cell Package: Simple and Inexpensive

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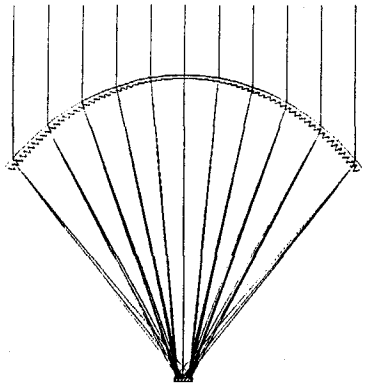

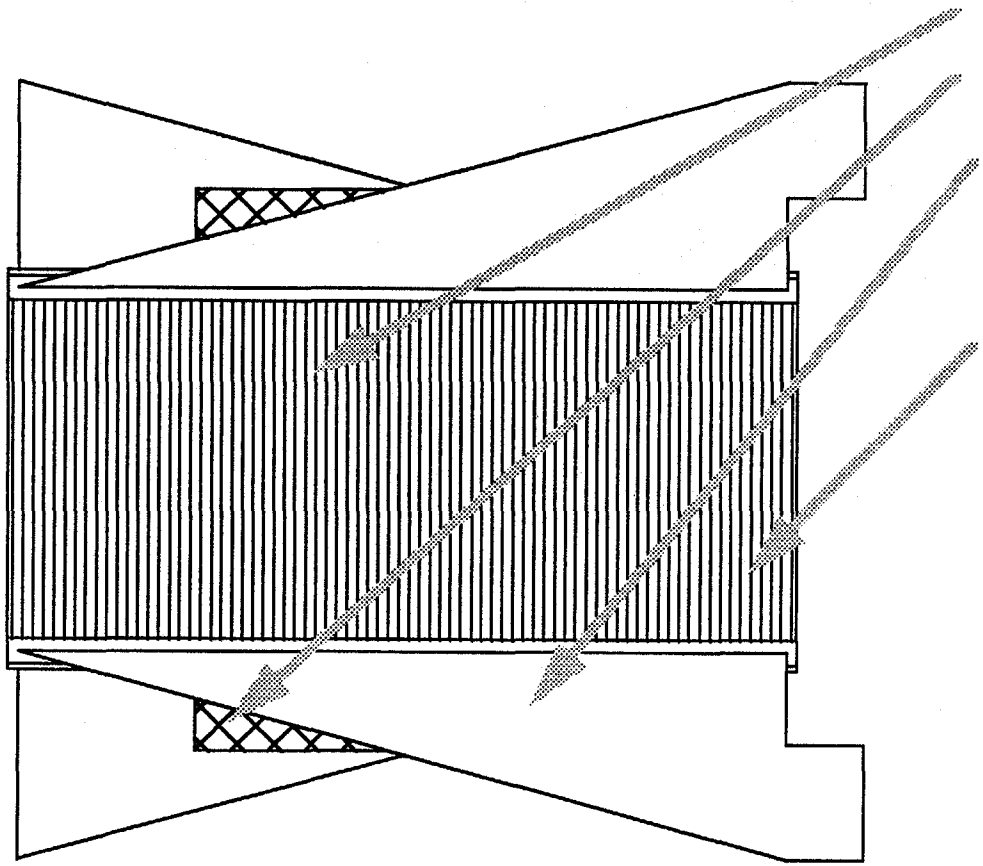

- One Cell
- Two Bypass Diodes
- Four Solder-Plated Copper Interconnector Ribbons
- One Prism Cover
- Eight Mass-Produced Parts
- Cell, Diodes, and Ribbons Are Soldered Together with No Clean Flux
- Prism Cover Is Applied with Pressure Sensitive Adhesive

In prior generation modules, a silicone prismatic cover was bonded to the top of the solar cell using liquid silicone adhesive. This process was messy, labor-intensive, difficult, and slow. The new cell package uses prism cover tape from 3M. Each roll of prism cover tape includes 3,500 precisely die-cut prism covers, each equipped with a pressure sensitive adhesive (PSA) for rapid bonding of the cover to the cell. Using a microscope-aided cover alignment and attachment work station, the new prism cover tape can be applied by one operator at rates faster than one cell per minute. Although this production step could be fully automated for very large production rates (> 10 MW/year), it is more cost effective to use a human operator for current production rates.

A number of problems had to be overcome to develop and implement the new prism cover tape. Many candidate PSA's were evaluated and rejected before the final selection was made. Even with the selected PSA, the silicone prism cover material requires careful corona-discharge surface treatment to enable an aggressive bond to the PSA. In addition, to preclude bubble formation in the PSA due to thermal and humidity cycling, the receiver assembly must be well encapsulated against moisture infiltration. Fortunately, the new receiver assembly process discussed in Section 2.8 is fully compatible with the new prism cover tape.

In the early 1990's, numerous attempts were made by the ENTECH technical team to incorporate dielectric protection and structural support into the cell package. One such attempt used alumina-loaded silicone both beneath the cell and above the interconnectors, all supported in an aluminum pan structure. An automated commercial potting machine was investigated in this effort. These attempts resulted in relatively cumbersome cell packages, which employed numerous parts, which were difficult to interconnect, and which had high levels of thermal resistance between the cell and heat sink. By abandoning these attempts to encapsulate the cell package as a unit, the entire package design has evolved into an elegantly simple assembly.

2.6 New Prism Cover Tape

Figure 8 shows a cross-sectional view of the new prism cover tape. The silicone prism cover optical elements are formed into the upper surface of the tape. The planar lower surface of the silicone prism cover is equipped with a pressure-sensitive adhesive (PSA). To apply the cover to the cell, the operator uses microscopic aids to look through the cover onto the cell before the PSA is allowed to contact the cell. The cover is moved in X-Y-Theta to align the optical elements to the gridlines, and the PSA is then pressed against the cell to form a strong, durable bond.

3M makes the prism cover tape to ENTECH specifications (U.S. Patent No. 4,711,972). Each roll of prism cover tape contains 3,500 precisely die-cut prism covers. The PSA side of the each cover is attached to a release liner in the same manner as a roll of labels for a laser printer. To protect and rigidize the silicone optical elements, each prism cover also has a removable liner on the optical element surface (the upper surface in Figure 8). In megawatt quantities, the new prism cover tape costs about 30 cents per cell. For typical production cells from ASE, the prism cover tape increases the bare cell output of 8 W to about 14 W for the prism covered cell assembly. Thus the 6 extra watts of cell power cost about 5 cents each, for an enormous benefit to cost ratio.

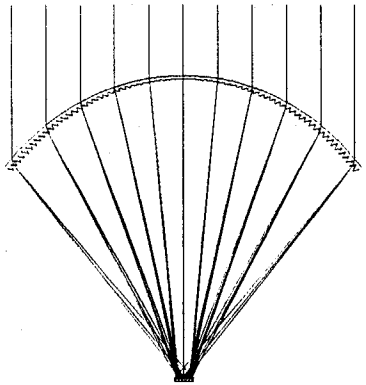

Fig. 8 - Cross Section of New Prism Cover Tape

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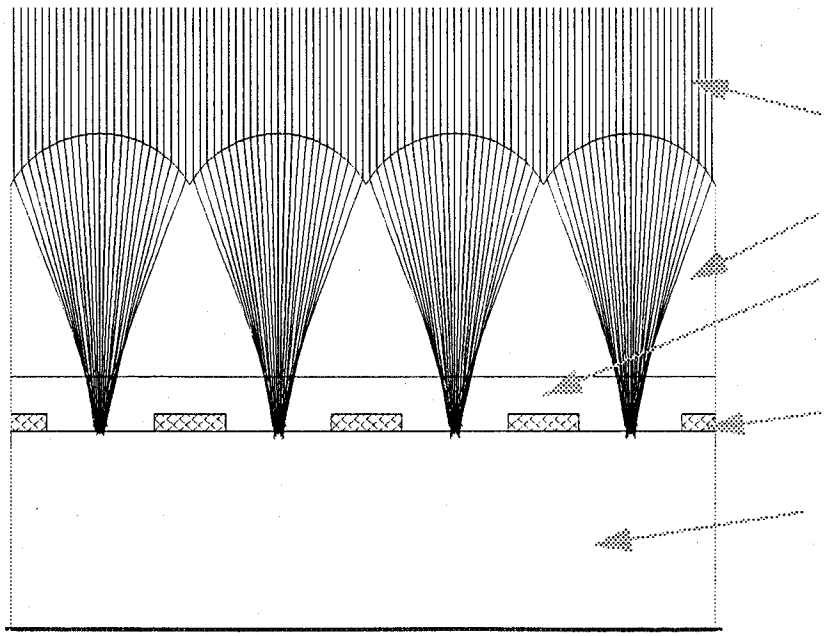

- Incident Rays
- Silicone Optics
- Pressure-Sensitive Adhesive
- Gridlines
- Solar Cell

2.7 New Heat Sink

The new heat sink was described in some detail in Section 2.1. The aluminum extrusion is made to ENTECH specifications by Columbia Aluminum. As shown in Figure 2, the heat sink includes 11 fins, each 15 cm long. The fins are tapered in thickness from the root to the tip, with an average thickness of about 2 mm. The fins are arranged in a star-burst radial pattern, which is very efficient from a thermal conduction viewpoint. A solid semi-circular bulb is formed at the base of the fins, with a flat top for cell package mounting. A 3.7 meter long heat sink weighs about 55 kg (120 pounds). In 1994, ENTECH purchased about 600 heat sinks for commercial orders at a price of about $1.25 per pound. Thus, the heat sink cost is equivalent to about 30 cents per watt of module output.

As previously described in Section 2.1, the new heat sink provides total fin area which is 4 times the module aperture area. This large ratio of heat dissipation area to energy collection area results in low cell operating temperature levels, even under the most adverse conditions (low wind, high ambient, high irradiance). As described in more detail below, side-by-side tests at both ENTECH and Sandia have shown that the module and cell temperature levels are now very similar for the ENTECH concentrator module and for one-sun modules. Compared to the ENTECH third-generation concentrator modules at the PVUSA test site in Davis, California, the new heat sink provides more than twice the heat transfer area to aperture area ratio.

Figures 9 through 11 present Sandia's side-by-side thermal test results for the fourth-generation concentrator module versus three different one-sun modules (Siemens, Solarex, and Mobil [now ASE America]). All of these modules were mounted on the same two-axis tracker at Sandia. The one-sun modules all had their back surfaces fully exposed to the atmosphere to enhance convective cooling. Figure 9 shows the measured module temperatures at low wind speeds for ENTECH, Siemens, and Solarex modules, all corrected to PVUSA reporting conditions as shown in the figure. The ENTECH module temperature was measured in the bulb of the heat sink, just beneath the cell string. The one-sun module temperatures were measured on the back surfaces of the modules. Note that the measured module temperatures are all the same within about a 10C spread, which is about the same as the variation in the measurements for each module. These data show that the module temperatures are all about the same.

Figure 10 shows the estimated cell temperatures for the same three modules. Sandia estimates the cell temperature based on open-circuit voltage measurements for all three modules. These data show that the ENTECH cell temperature is typically about 10C

Fig. 9 - Module Temperature vs. One-Sun Modules

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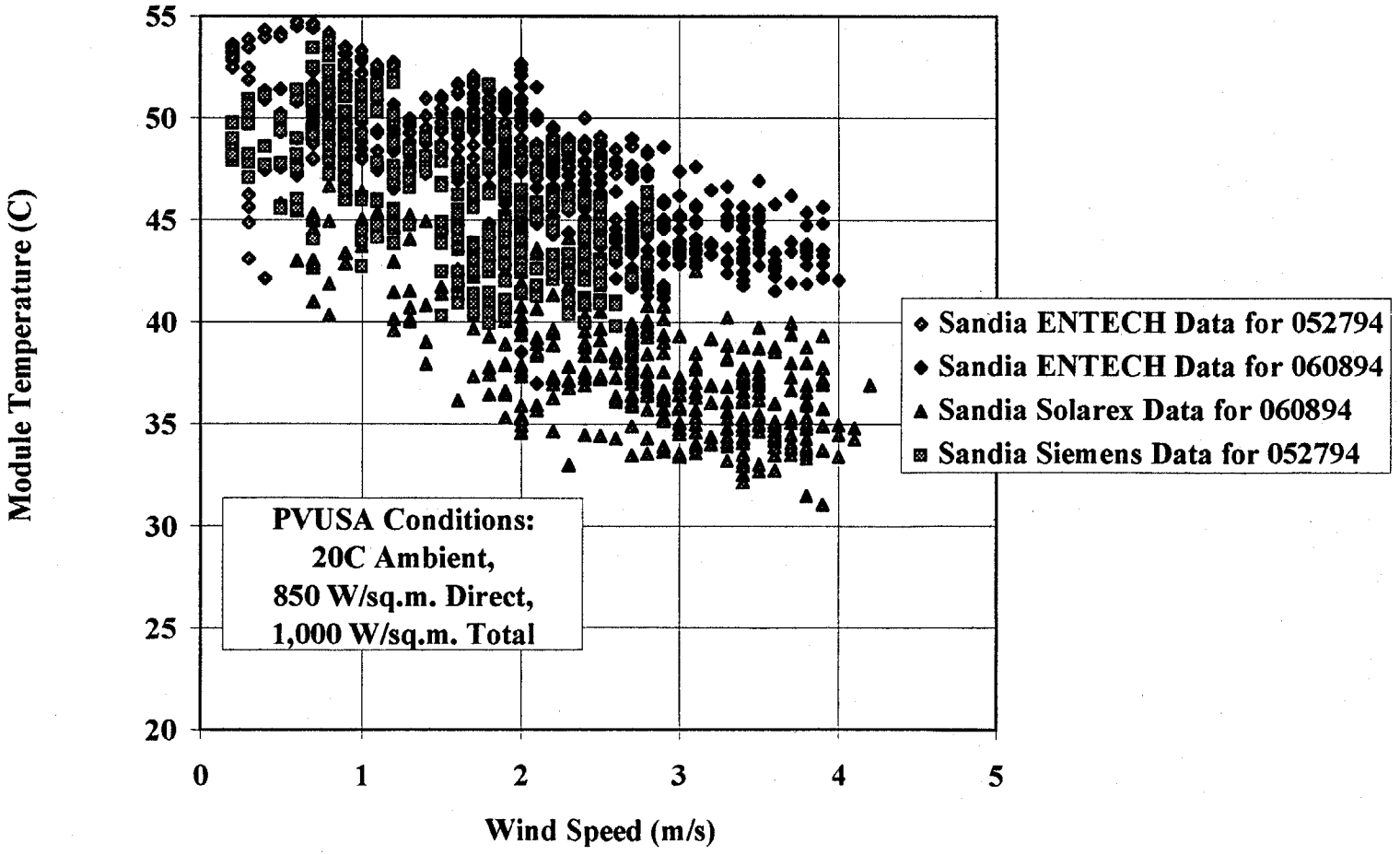
Module Temperatures at PVUSA Conditions for ENTECH's Concentrator and Two Flat-Plates Based on Sandia Side-by-Side Measurements



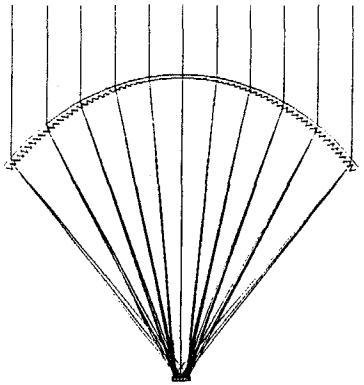
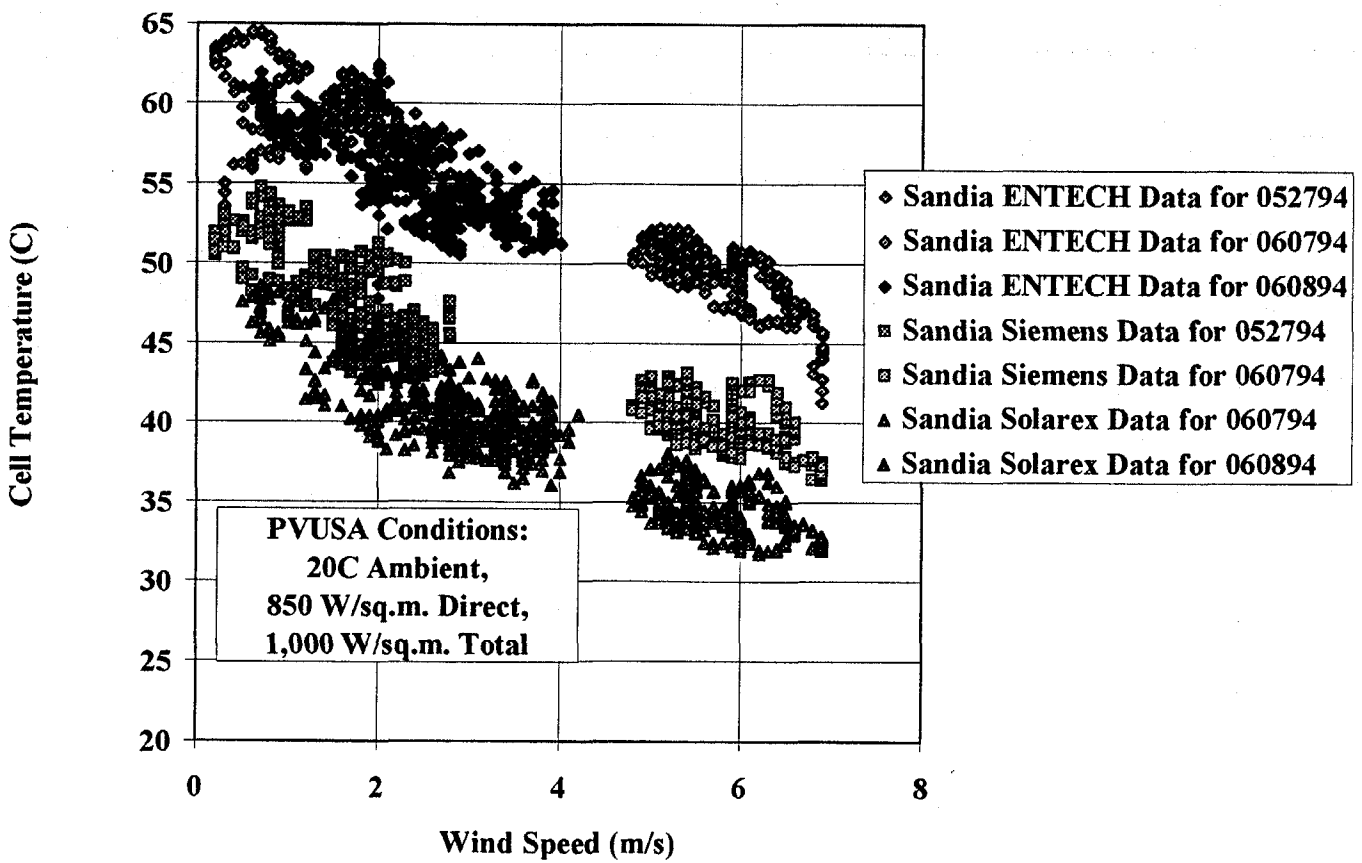


Fig. 10 - Cell Temperature vs. One-Sun Modules

ENTECH, Inc.

Cell Temperatures at PVUSA Conditions for ENTECH's Concentrator and Two Flat-Plates Based on Sandia Side-by-Side Measurements



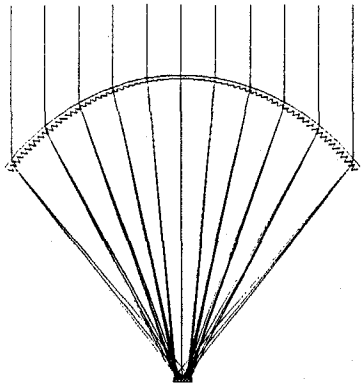
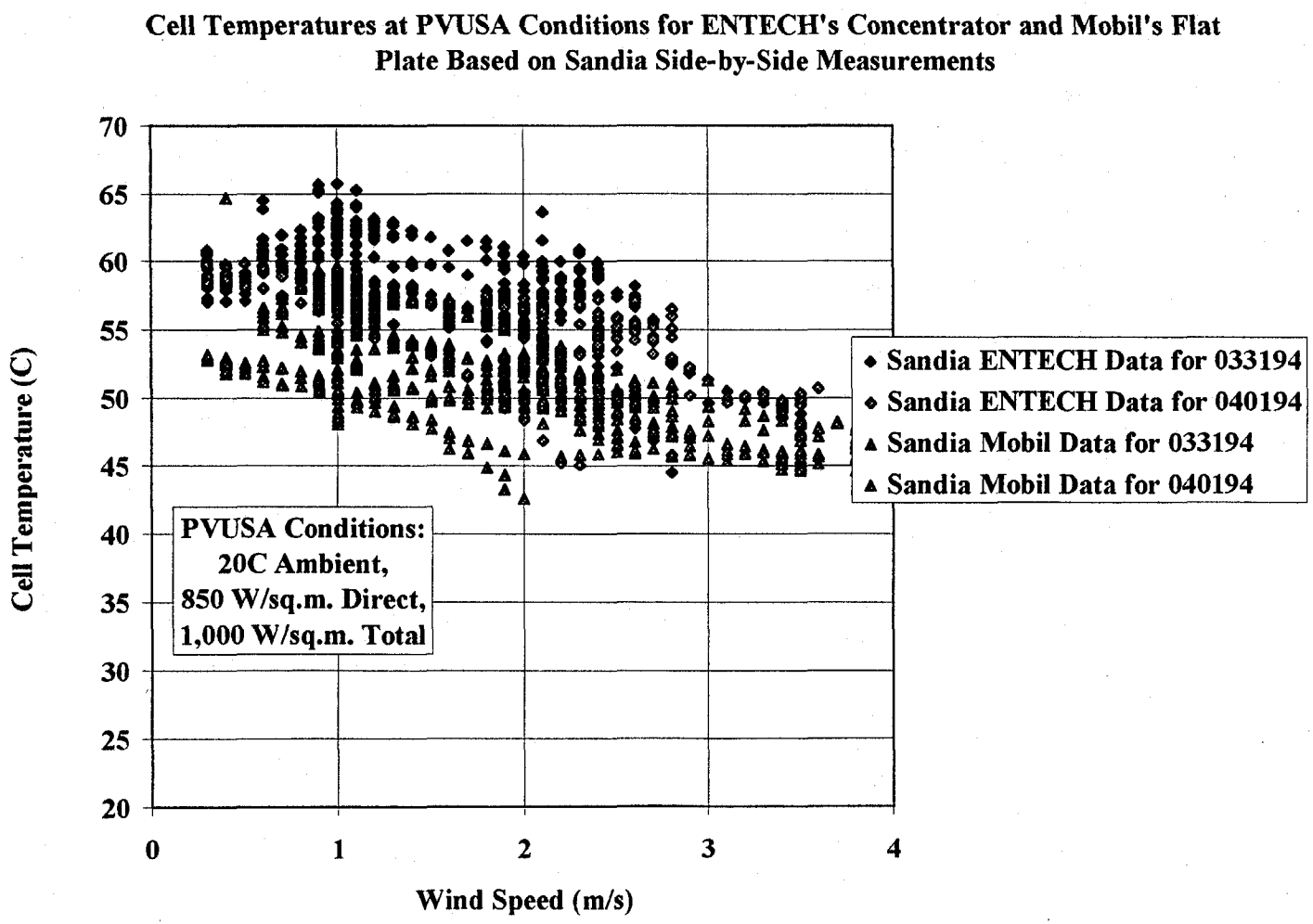


Fig. 11 - Cell Temperature vs. One-Sun Module

ENTECH, Inc.



warmer than the Siemens cell temperature, which is slightly warmer than the Solarex cell temperature. The slightly higher cell temperature for the ENTECH module than for the one-sun modules is due to the heat transfer between the cell and the heat sink. The waste heat in the concentrated solar flux must be conducted through the dielectric layer beneath the cells into the aluminum heat sink in the ENTECH module, with a resulting temperature differential between the cells and the heat sink. Thus, although the heat sink is at the same temperature as the one-sun modules (Figure 9), the cells are slightly warmer in the concentrator module (Figure 10).

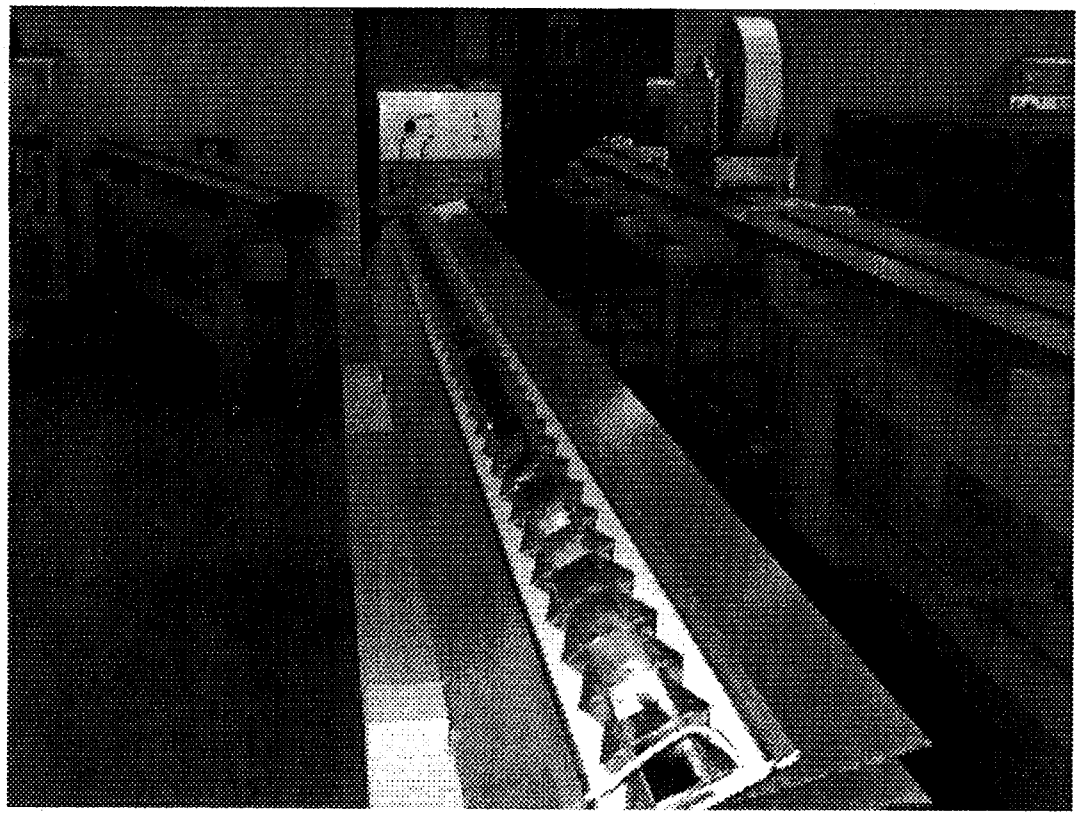
Figure 11 shows more side-by-side Sandia data, comparing the ENTECH concentrator to the Mobil (now ASE America) one-sun module. These data show the estimated cell temperatures to be almost the same. The data of Figure 11 were taken around the beginning of April, while the data of Figures 9 and 10 were taken around the beginning of June. The slightly lower sun elevation angles for Figure 11, coupled with the glass-on-glass construction of the Mobil module, may explain why the ENTECH cell temperatures are closer to the Mobil cell temperatures than to the Siemens or Solarex cell temperatures. In any case, the data of Figures 9 through 11 show that the new heat sink provides excellent cell cooling performance under all wind speed conditions. Under typical operating conditions (~ 3 m/s wind, 20C ambient, 850 W/sq.m. direct irradiance), the ENTECH cell temperature is 50-55C.

2.8 New Receiver Assembly Process

Figure 12 shows a photovoltaic receiver assembly, which consists of 37 series-connected cell packages mounted to one extruded heat sink. With materials help from DuPont, ENTECH has recently developed a proprietary new process (patent pending) for assembling the photovoltaic receiver. This process involves two dry film processes to mount and encapsulate the cell package circuit. The first dry-film process is used to mount the cells to the heat sink, with a thin layer of Tefzel dielectric film between these parts. The second dry-film process is used to encapsulate the upper surface of the cell package circuit with another layer of Tefzel dielectric film. Both film processes are accomplished using commercially available tape and film dispensing and application equipment from 3M. The dielectric isolation between the cell package circuit and the heat sink is excellent, as is the isolation between the cell package circuit and the surrounding atmosphere. The thermal resistance between the cell packages and the heat sink is very low, resulting in only a 10-13 C cell-to-heat sink temperature difference under peak irradiance conditions as confirmed by Sandia. The new receiver assembly process has eliminated more than 300 parts per receiver compared to the previous receiver assembly process. The elimination of all wet silicone layers in the receiver assembly process has been a joyful experience at ENTECH. The details of the new process will not be made public until the pending U.S. patent is published. Since the U.S. Patent Office has already allowed claims in the pending application, patent publication is anticipated within the next year. Although the process details cannot yet be disclosed, ENTECH is pleased to report that the new process is simple, streamlined, and rapid, with significant quality advantages and cost savings.

Fig. 12 - Photovoltaic Receiver Assembly

ENTECH, Inc.



- 37 Cell Packages
- 1 Extruded Heat Sink
- Dielectric Tapes/Films
- 430-480 W Output

2.9 Cell and Module Performance

Figure 13 shows the relationship between module efficiency and cell efficiency for the fourth-generation concentrator. The measured lens optical efficiency is 90%. The measured Tefzel encapsulating layer transmittance is 94%. The cell package to receiver packing factor is 98% (i.e., the total active length of all 37 cells is 98% of the lens aperture length). The product of these three factors times cell efficiency provides an accurate estimate of module efficiency. With 17% cells, the module efficiency is about 14%. With 19% cells, the module efficiency will be about 16%. With 22% cells, the module efficiency will be about 18%.

Figure 14 shows the present status of cell efficiency for the four cell suppliers. Solarex, BP Solar, and ASE have delivered cells which have been independently measured by Sandia to be 18.9% efficient at 19 suns irradiance (Air Mass 1.5 Direct [AM1.5D] spectrum) and 25C cell temperature. Siemens has delivered cells which have been measured by Sandia to be 17% efficient under the same conditions. All cells were tested in cell packages, including prismatic cell covers and copper ribbon interconnectors, as described in Section 2.5.

The data of Figure 14 don't tell the whole story of cell efficiency. These cells are representative of the best-performing cells from all four suppliers. A more meaningful performance index is the lot-average cell efficiency for a large production run of cells. ENTECH has just completed two 100 kW module production runs, using over 20,000 cells from ASE. The lot-average efficiency of the cell packages produced with these cells is slightly over 17% at 19 suns irradiance and 25C cell temperature. The measured outdoor performance for two modules using these production cells is shown in Figure 15. Both modules used mild-focus SCL-1000 lenses from 3M, as described in Section 2.3. Two different lens thicknesses were utilized, with no impact on module performance. Note that the operational power output of each module was just under 400 W at irradiance levels of 920-940 W/sq.m. and an ambient air temperature of 5C. Sandia later tested both modules very thoroughly, and rated each at about 430 W at standard test conditions (STC) of 1,000 W/sq.m. direct irradiance and 25C cell temperature. Since the module has an aperture area of 3.1 sq.m., this 430 W power level equates to a module efficiency of about 14%, in close agreement with the data of Figure 13 for 17% efficient cells.

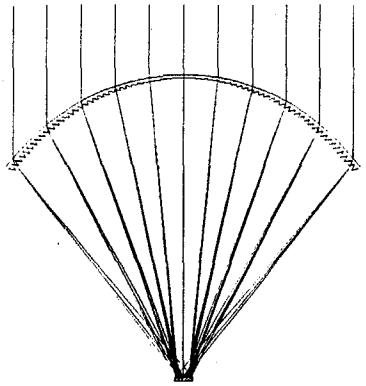


Fig. 13 - Concentrator Module Performance

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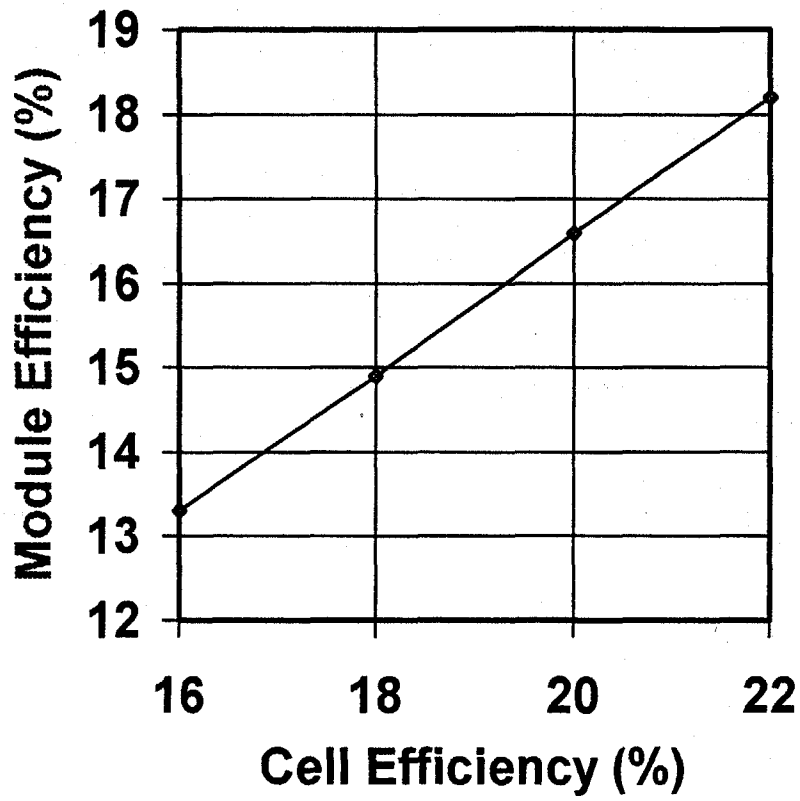
- **Four Multiplicative Factors Determine Module Efficiency**
  - » **Lens Optical Efficiency**
    - – **Presently 90%**
  - » **Encapsulating Layer Optical Efficiency**
    - – **Presently 94%**
  - » **Cell-to-Receiver Packing**
    - – **Presently 98%**
  - » **Cell Efficiency Under Lens Irradiance**



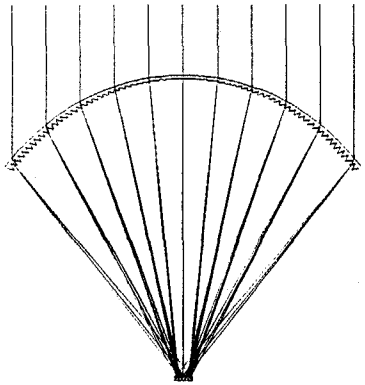


Fig. 14 - Sandia-Measured Prism-Covered Cell Performance at 19 Suns and 25C

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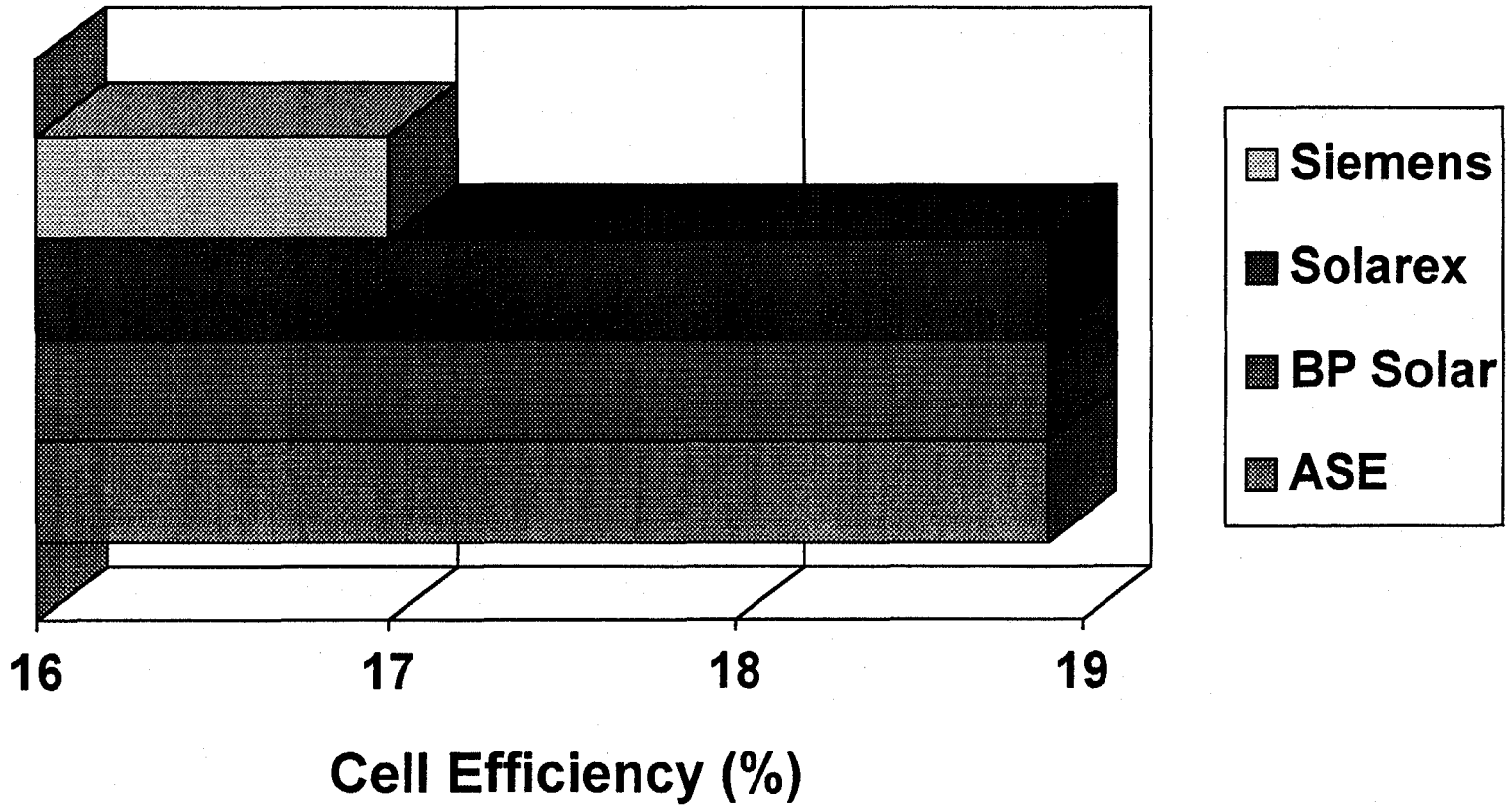

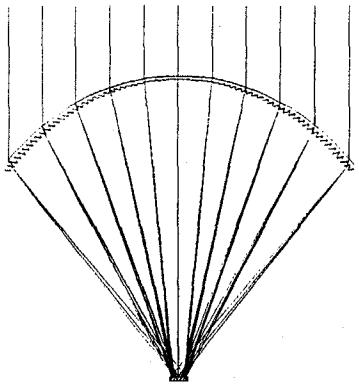

Fig. 15 - Measured Performance of Two Fourth-Generation Modules

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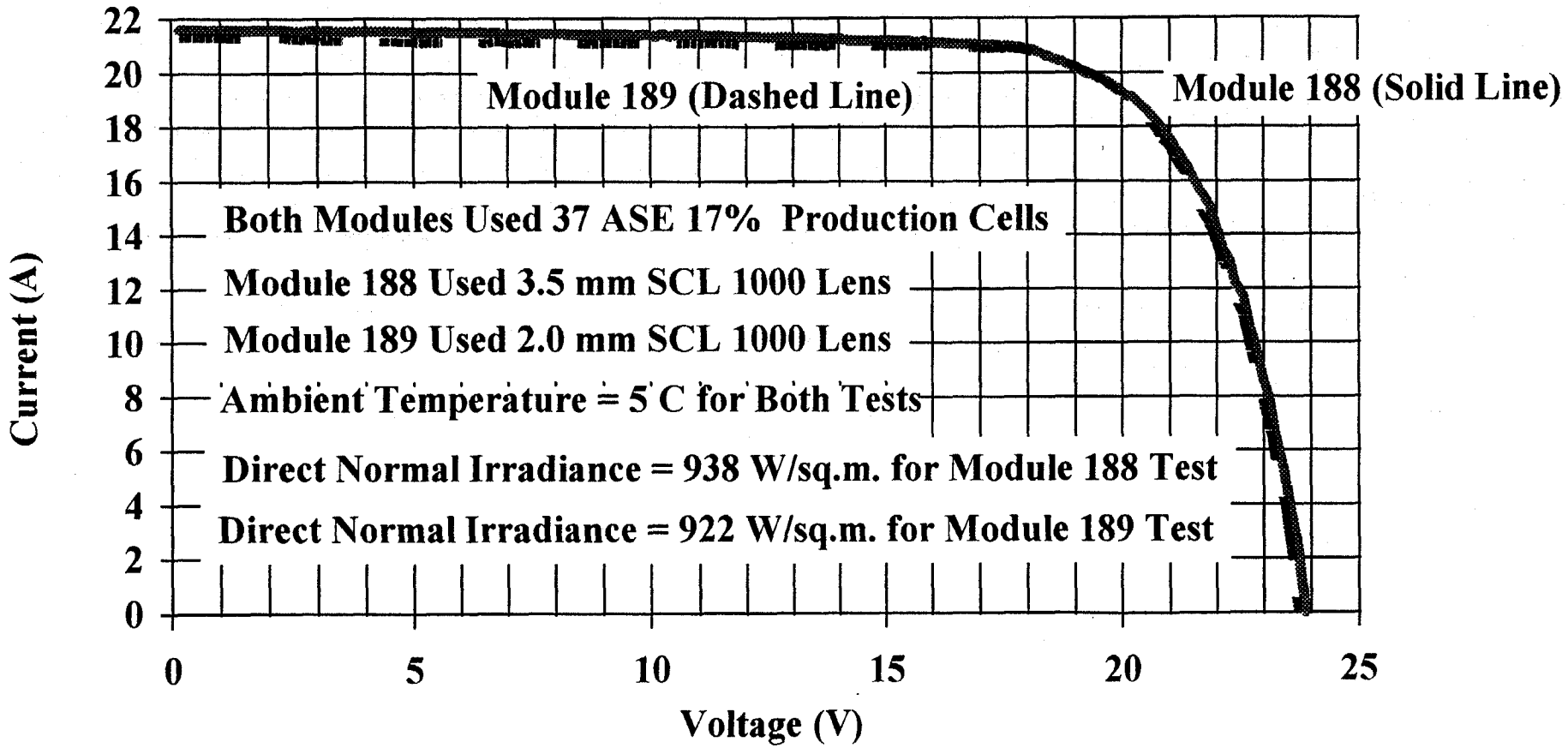

All four of cell suppliers are continuing to make gains in cell performance. Solarex has provided quotations to ENTECH related to 20% lot-average efficiency levels. BP Solar likewise expects to reach the 20% threshold with their latest laser-grooved cell technology. ASE has provided sample cells with various performance-boosting features which will keep their cells in the competitive range with the other suppliers. Other cell suppliers have also proposed designs and/or provided samples of their advanced silicon cells. Thus, module performance levels are expected to continue an upward trend for the foreseeable future.

3.0 ARRAY DEVELOPMENT

In addition to the module development work described in the previous Section 2.0, ENTECH also developed a new array drive and control system for use in fourth-generation concentrator systems. The new drive and control system was developed to overcome recurring problems with the third-generation drive and control system installed with ENTECH's 20 kW array at the PVUSA test site at Davis, California. At the Davis site, the ac power grid is subject to transients caused by large nearby variable loads (e.g., canneries) and by several on-site inverters which convert the solar-generated power from dc to ac. Significant voltage disturbances on the ac grid have been monitored by the operators of the site. ENTECH's third-generation controller and drives were both ac-powered. When line disturbances occurred, the solid-state relays which controlled the power to the tilt and roll drive motors would malfunction, causing the motors to try to run in both directions at once. A number of failures of solid-state components, ranging from fuses to logic chips, occurred over the first 3 years of system operation. To overcome this problem for future systems, ENTECH proposed to Sandia the development of an all-dc control and drive system, completely de-coupled from the ac grid during the daylight operating hours. The proposed system would use 12 V lead-acid batteries to provide energy for the controller and drives. At night, a small trickle charger would be used to replace the energy drawn from the batteries during the day. The rationale behind this design approach was simple: an all-dc system would be immune to ac line disturbances and would provide a built-in uninterruptible power system (UPS) for the tracking controller and for emergency stow functions. Sandia approved the ENTECH proposal for funding. The following sections describe the implementation of the new drive and control approach for several recently installed large arrays, which ENTECH calls SolarRows.

3.1 SolarRow Large Array Description

Figure 16 shows a typical SolarRow large array of ENTECH's fourth-generation concentrator modules. The SolarRow is believed to be the world's largest two-axis photovoltaic sun-tracker. The SolarRow contains 72 modules with a total aperture area of 220 sq.m. and a total operational power output of about 25 kW. Figure 17 shows another view of the SolarRow. Each row is over 100 meters long in the east-west direction, and represents a unitized steel structure. The structure tilts from north-to-south via shafts and bearings on 13 posts. The 72 modules mounted in the SolarRow frame roll from east-to-west in Venetian blind fashion via shafts and bearings on both ends of each module. The measured power output for each of four SolarRows, under typical operating conditions, is provided in Figures 18 and 19.

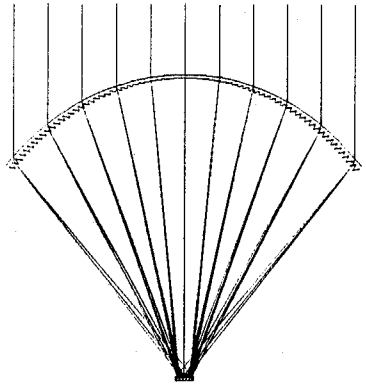

Fig. 16 - SolarRow Array at TUE Energy Park

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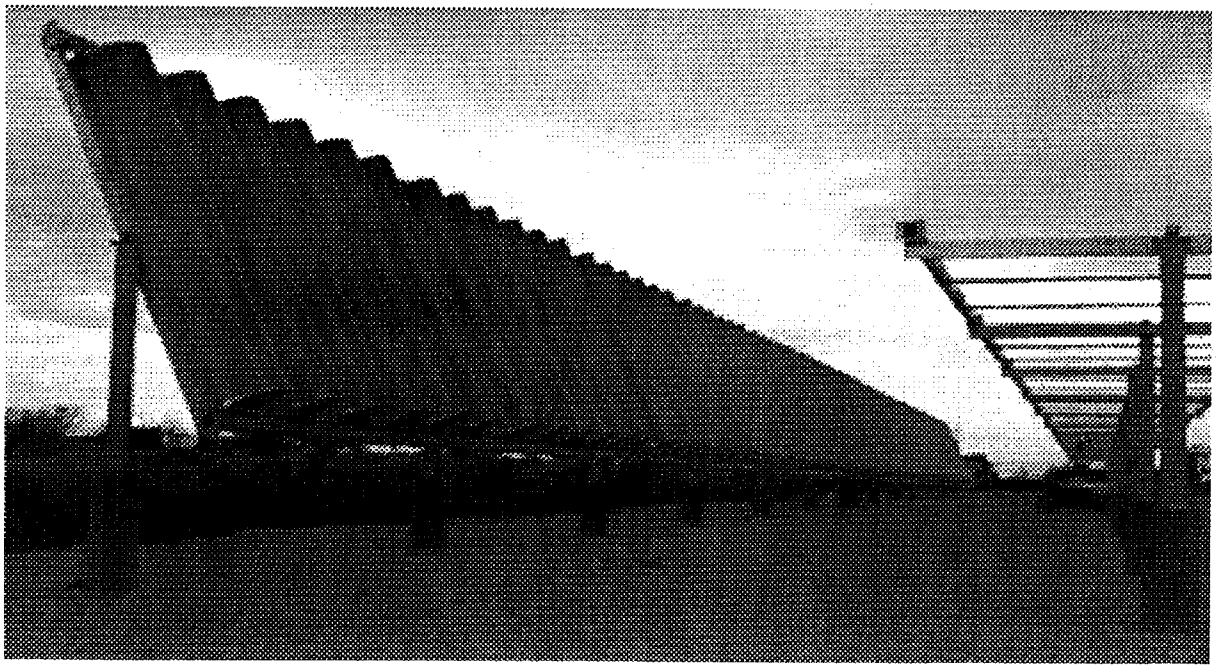

- 72 Modules
- 220 sq.m. Aperture
- Full Sun Tracking
- Galvanized Structure
- > 25 kW Output
- Easy to Install

Fig. 17 - SolarRow Array at CSW Solar Park

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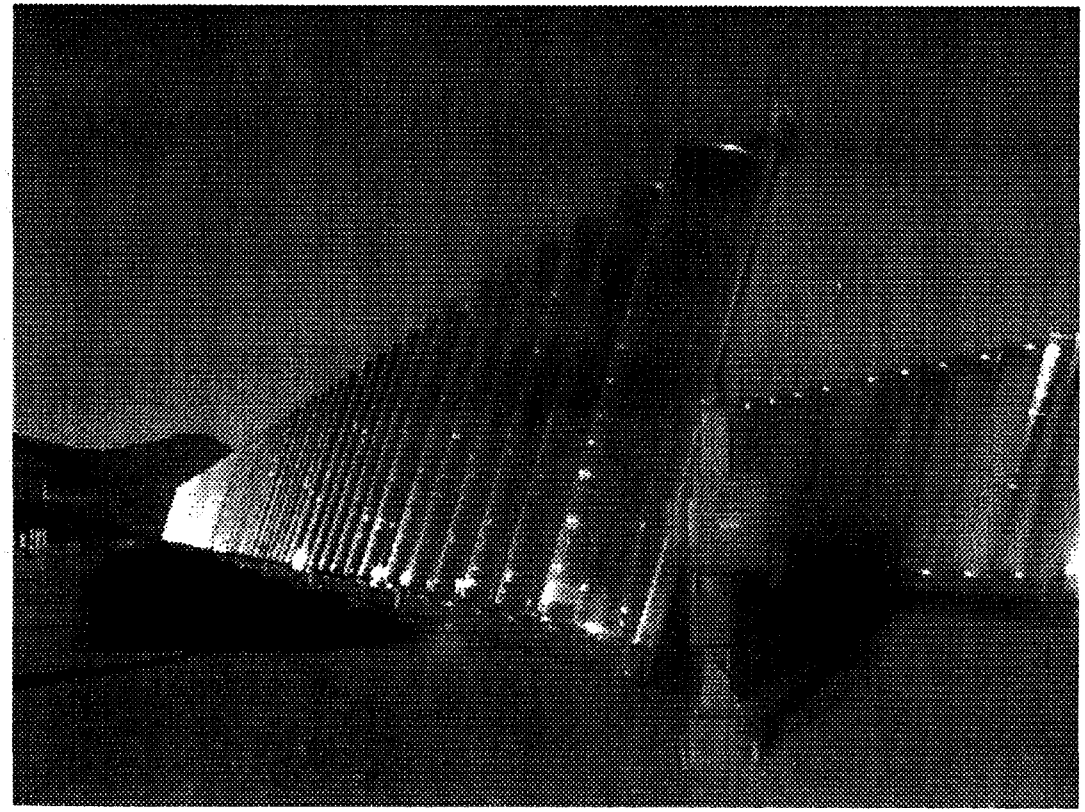

- One of Four SolarRows at CSW Solar Park
- Each 104-m-Long Row Comprises:
  - » 14 Piers
  - » 13 Steel Posts
  - » One Bolt-Together Steel Frame
  - » 72 Modules
  - » Roll/Tilt Drives and Controls

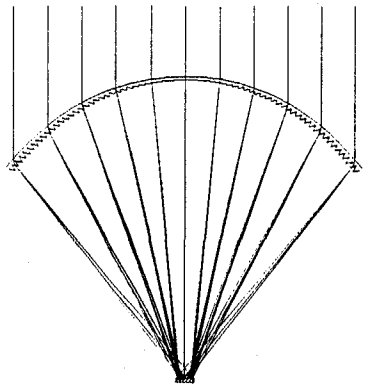

Fig. 18 - Measured SolarRow Performance

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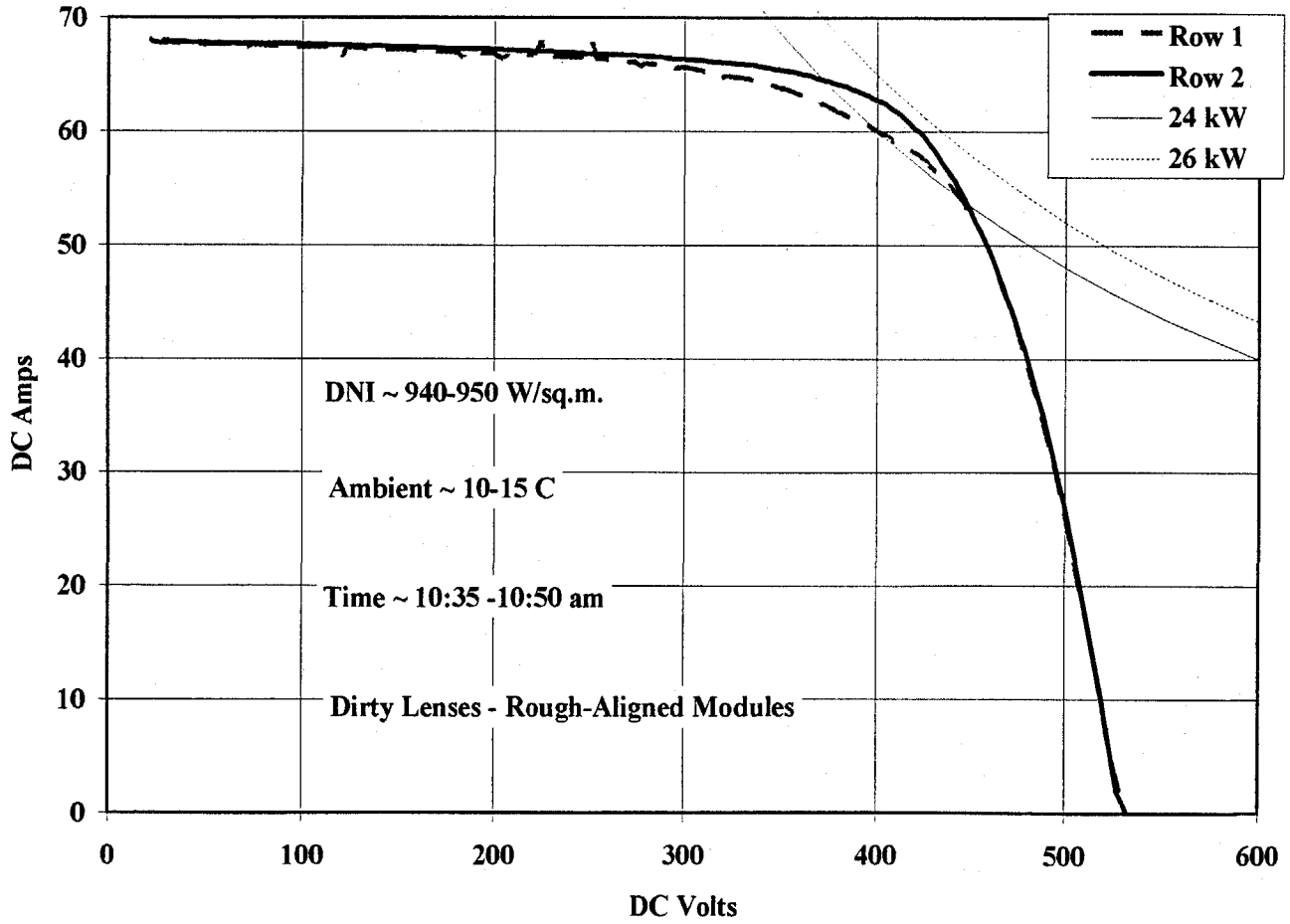

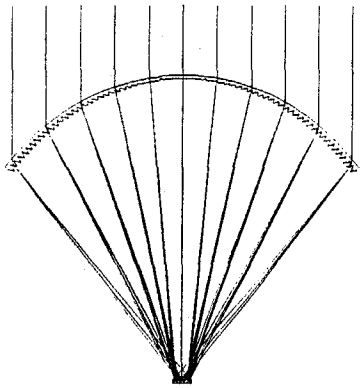

Fig. 19 - Measured SolarRow Performance

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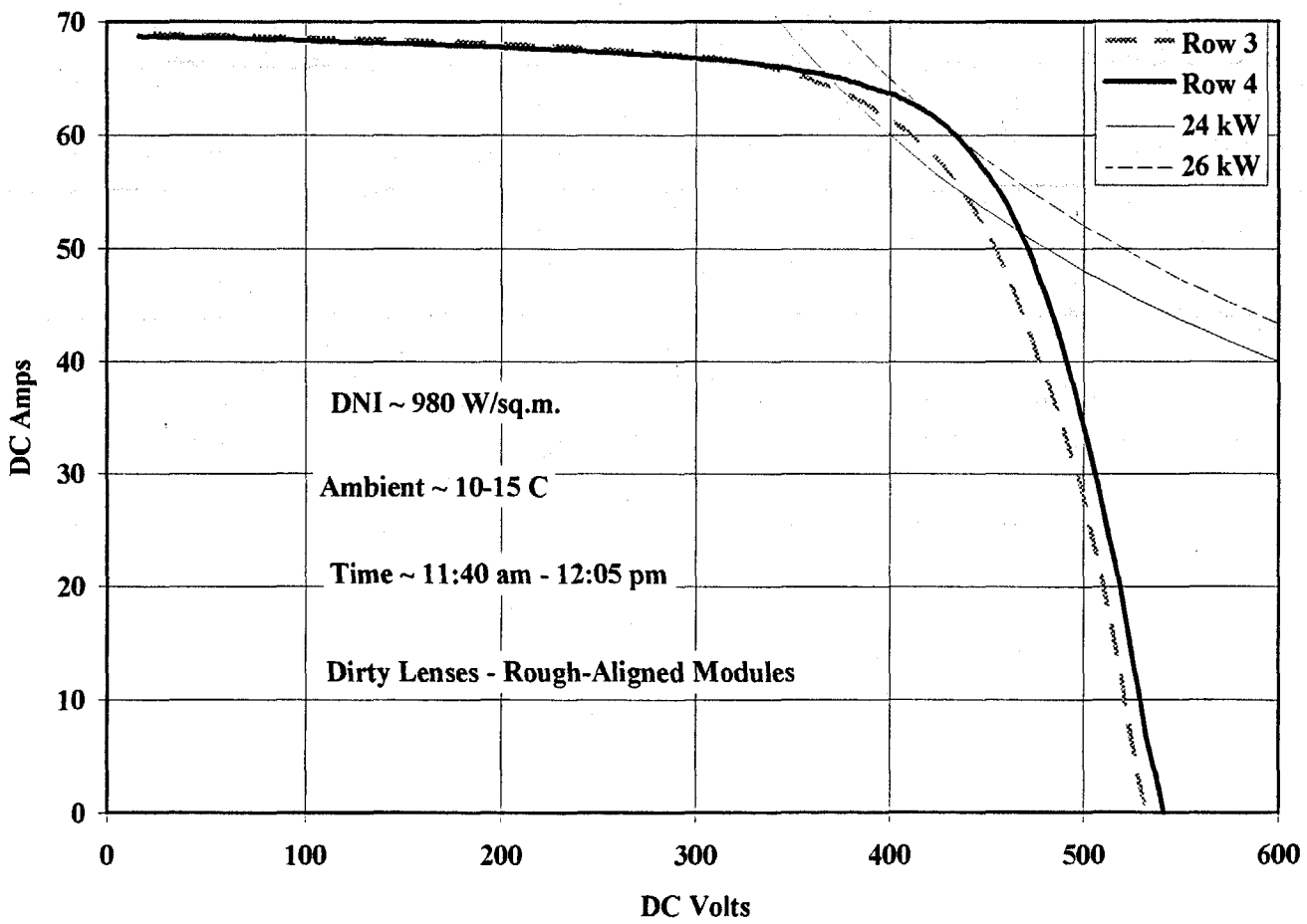
CSW Solar Park - ENTECH Rows 3 and 4 - January 13, 1995



3.2 New All-DC Controls and Drives for SolarRow

Figure 20 shows the center post of a SolarRow, and summarizes the equipment which is installed there. ENTECH refers to this region as the "brains and braun" center of the SolarRow. The microprocessor controller provides the "brains" and the tilt and roll drives provide the "braun" to continuously aim the modules toward the sun. The tilt drive system uses a 10-ton ball screw jack powered by a 240 W 12 V dc motor. The roll drive system uses a 3/4-ton ball screw jack powered by a 100 W 12 V dc motor. The control system is made by Prime Manufacturing Company, and includes all hardware and software required to position the two array drives using reed switch sensors for position feedback. Two 60 AH batteries are used to provide energy for daytime operation. One battery powers the controller and small roll drive motor. The other battery powers the larger tilt drive motor. Each of these batteries is recharged each night using a 1-amp trickle charger, which is switched on via a photocell darkness detector at sunset. Color-coded, non-interchangeable cables with military-style, plug-type connectors are used to connect the drive motors to the controller. In addition, a simple omni-directional, aerodynamic drag-type, high-wind limit switch, used to trigger an emergency stow function, is also connected via cable to the controller.

Figure 21 shows the controller junction box and the key components found therein. Four fuses, corresponding to the four conductors going to the two batteries, are used to protect the electronics and motors from over-current conditions. Solid-state relays are required to switch the 20 A tilt motor, with drive signals provided by the Prime controller board. The smaller 8 A roll motor is directly switched by a transistor network on the Prime controller board. The entire control system is a replaceable junction box assembly. The unit can be unplugged and removed from the mounting structure within minutes. A replacement unit can then be attached to the mounting structure and plugged in within minutes. The only field data inputs required are the date, time, and home limit switch locations for the roll and tilt actuators. These field data inputs are readily programmed via four buttons with an LCD display providing alphanumeric feedback to the operator. All other parameters can be factory-programmed.

The new all-dc system has been deployed at ENTECH in Dallas, at PVUSA in Davis, California, at CSW Solar Park in Ft. Davis, Texas, and at TUE Energy Park in Dallas. Results to date have been excellent. The controller is reliable and robust. The only significant problem to date has related to an initially undersized roll drive, which formerly used a 600 pound jack, but which has now uses a 1,500 pound jack.

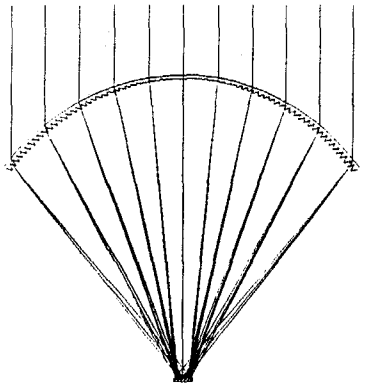


Fig. 20 - SolarRow Brains and Braun Center

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- Located at Center of Row
- One 10-Ton Jack for Tilt
- One 3/4-Ton Jack for Roll
- One Prime Microprocessor Controller
- One 60 AH Battery for Controller and Roll Drive
- One 60 AH Battery for Tilt Drive
- Color-Coded, Non-Interchangeable Cables

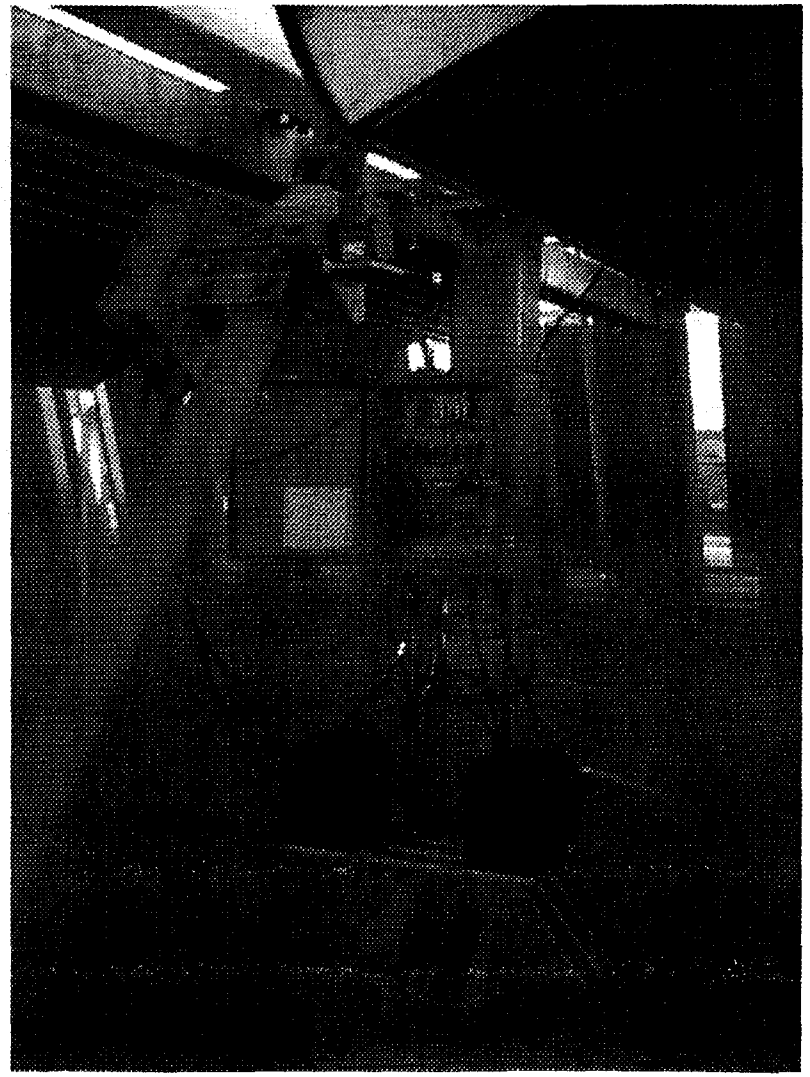

Fig. 21 - ENTECH/Prime All-DC Tracking Controller

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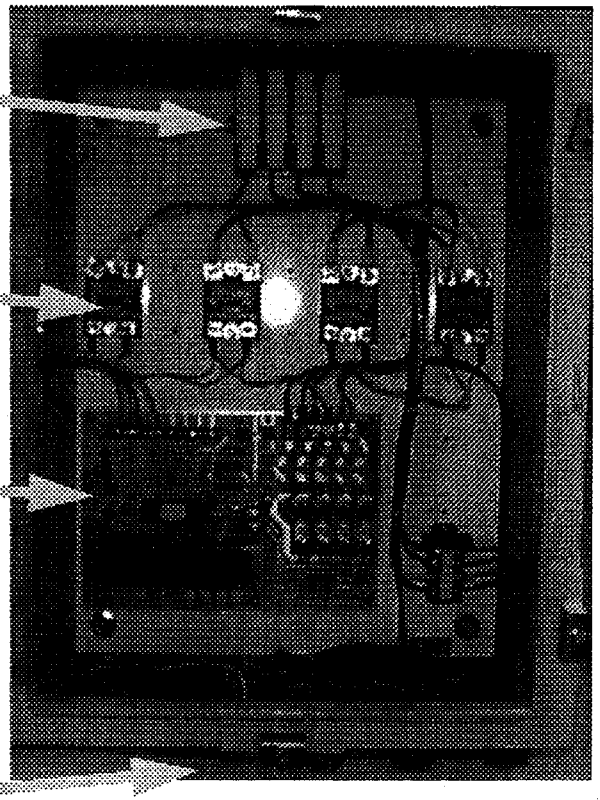
- Fused Disconnects at Top of Panel
- Solid State Relays for Motors with Voltage > 12 V or Current > 10 A
- Prime Controller Board at Bottom Left with LCD Display and Four-Button Operator Input
- Color-Coded Plug-In Connectors to Motors, Batteries, and Sensors



3.3 SunLine Small Array Description

Figure 22 shows a two-module small array, called SunLine by ENTECH. This small array also uses the new all-dc control and drive system described in the last section. The only difference is that solid-state relays are not needed to run the small 30 W 12 V dc motors which provide roll and tilt tracking functions for the small array. The transistor networks on the Prime controller board are sufficient to switch the power for these small motors. Two identical 600 pound jacks are used for both drives on SunLine. A key advantage of the new all-dc controller and drive system for SunLine is that off-grid applications are readily addressed. Battery charging for the single 30 AH 12 V battery used with SunLine is accomplished with a 5-watt one-sun module mounted directly to the galvanized steel frame. This battery/module sizing provides adequate energy for the controller and both motors to tolerate 2-3 weeks of cloudy weather, while also precluding the need for any charge control electronics.

In addition to the Prime controller, ENTECH has also been testing a Sandia-developed SolarTrak controller for several years. The latest SolarTrak unit has performed flawlessly on a SunLine unit at ENTECH for more than six months. ENTECH has been granted a SolarTrak license by Sandia.

In summary, ENTECH has developed an all-dc drive and control system which is applicable to both large arrays (SolarRow) and to small arrays (SunLine). The new approach is much simpler and more reliable than prior generation approaches.

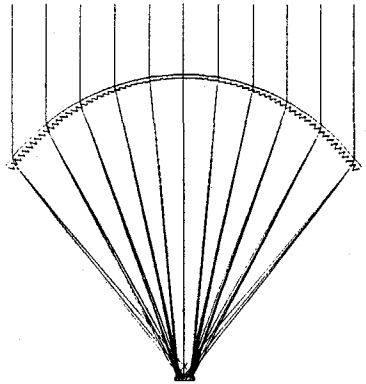


Fig. 22 - SunLine Array

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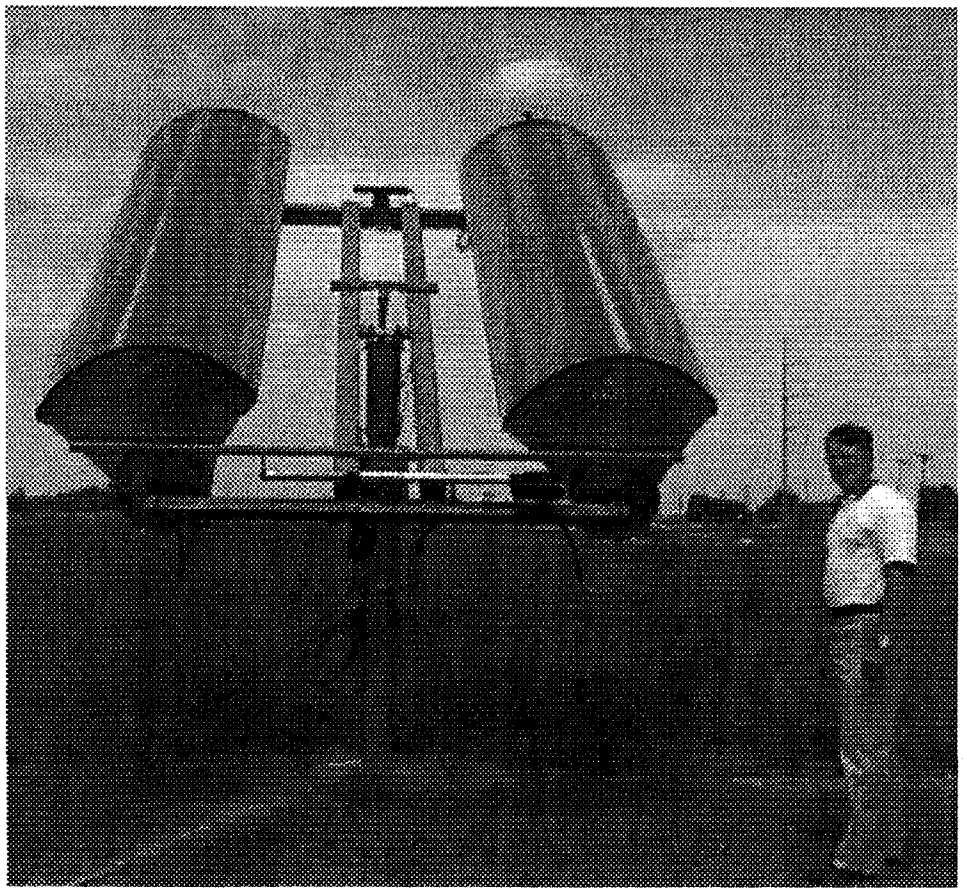

- 2 Modules
- 6 sq.m. Aperture
- Full Sun Tracking
- Galvanized Structure
- > 1 hp Output
- Easy to Install

4.0 NEW SYSTEM COSTS & ECONOMICS

ENTECH's fourth-generation concentrator module manufacturing cost includes the purchased component costs (the lens from 3M, the cells from one of four suppliers, the heat sink from Columbia, the module housing from Consumers, and several small items) and the module assembly costs. Because these items are in production and pricing data have been obtained from the suppliers, these costs are well quantified. They are also strong functions of annual production volume. The lowest curve in Figure 23 shows the module manufacturing cost versus annual production rate. Note that at 10 MW/year, the module manufacturing cost is about $1.50 per watt. The balance of systems (BOS) costs include the SolarRow structure, the dc drives and controls, the foundations, wiring, and the power conditioning system (inverter). For ENTECH's technology, these BOS costs are slightly less than the module costs. The middle curve in Figure 23 includes module costs plus BOS costs. The highest curve in Figure 23 includes module costs plus BOS costs plus a 25% gross profit margin on both. This curve is equivalent to an installed system price. Note that this system price falls below $3 per watt at about 10 MW/year production rate.

The energy cost for such systems depends on two additional factors: the system annual capacity factor (at least 21% for a high insolation location like Phoenix, Albuquerque, Barstow, etc.) and the owner's annual fixed charge rate on invested capital. The fixed charge rate depends on many factors, including the sources of funds, tax situation, etc. Two values of the fixed charge rate (5% and 10%) are represented by the two curves of Figure 24. These two curves present the levelized energy cost corresponding to the system prices of Figure 23. For example, at 10 MW/year production rate, the system price is about $3 per watt in Figure 23. For a 5% capital recovery factor, this system price provides electricity at a levelized price of 8.5 cents per kWh, as shown in Figure 24. For a 10% capital recovery factor, this system price provides electricity at a levelized price of 17 cents per kWh, as shown in Figure 24. At higher production rates, these levelized electricity prices continue to fall to lower levels.

These energy prices are substantially lower than for present photovoltaic systems of any kind, including those being manufactured at rates well above 10 MW/year. Furthermore, these energy prices can be obtained without any breakthroughs in materials, manufacturing processes, stability, or efficiency. Thus, the fourth-generation concentrator technology described in this report provides a clear and direct path to much lower electricity prices for photovoltaic systems. Indeed, the near-term electricity prices for this technology are comparable to conventional residential electricity rates in several parts of the U.S. today. What is needed is a sustainable larger annual volume of system production and sales.

Fig. 23 - Module & System Costs & Prices

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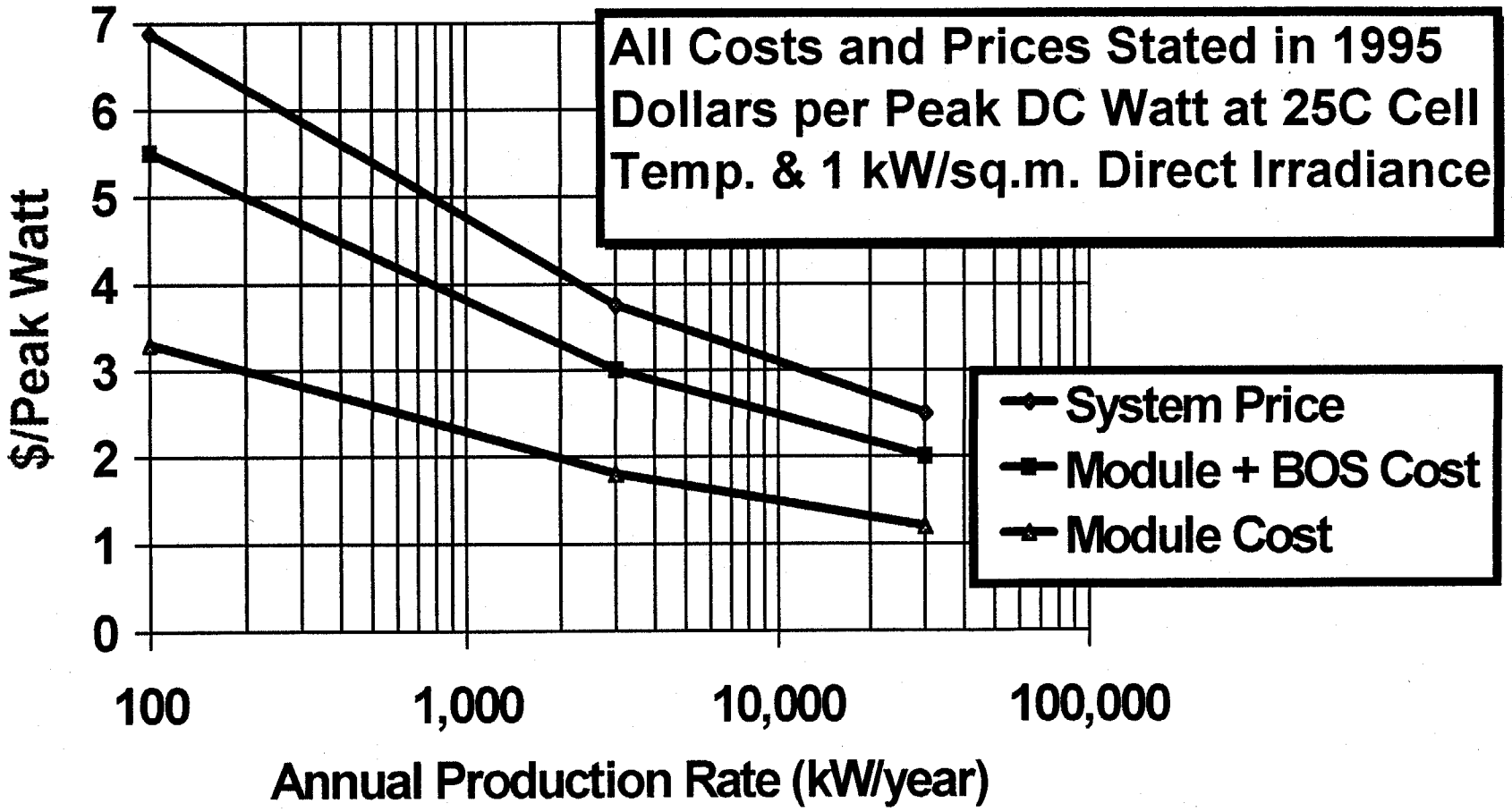

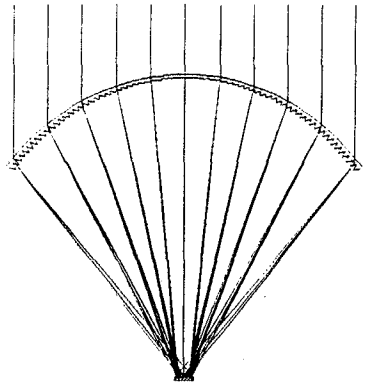

Fig. 24 - System Energy Economics

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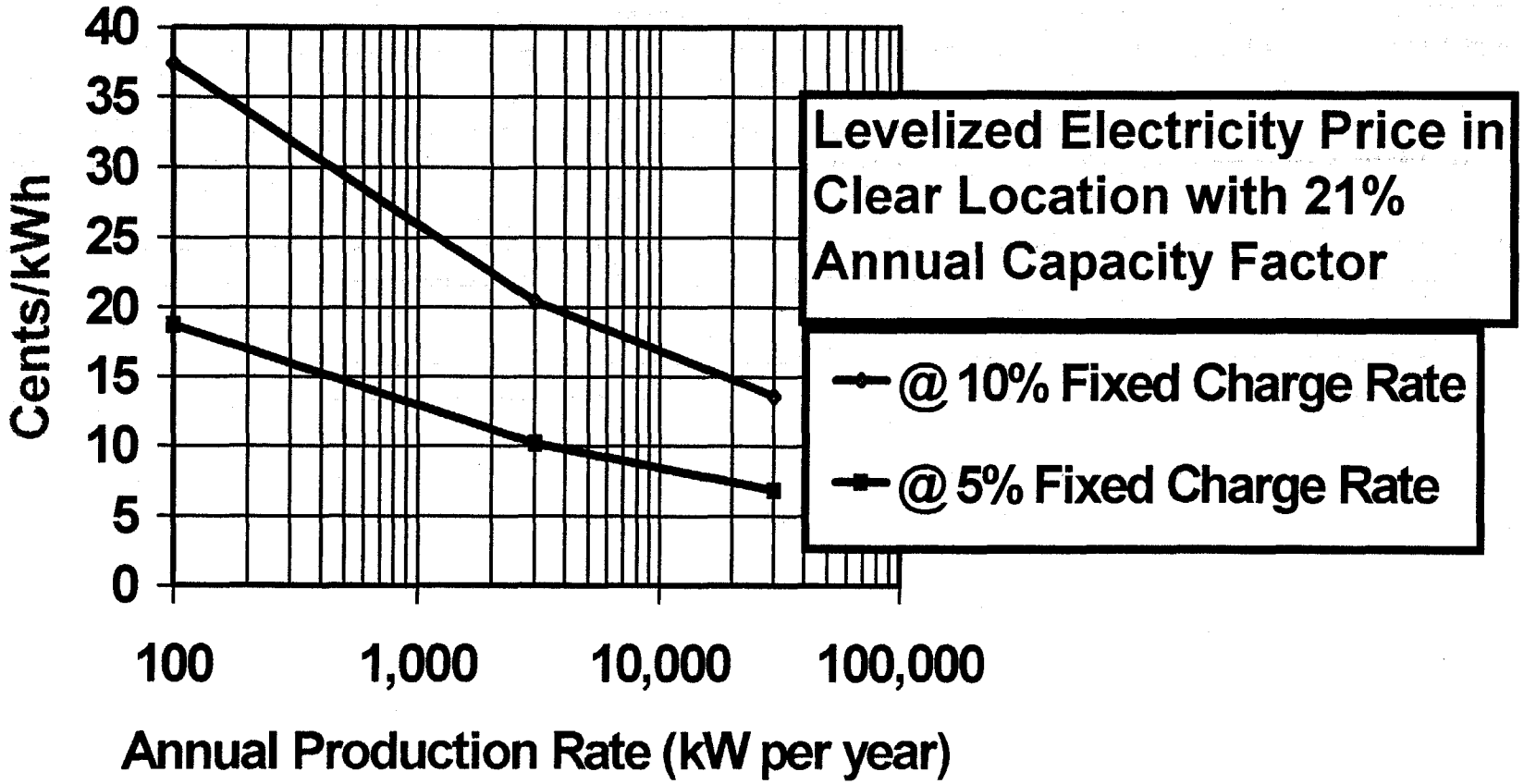

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