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THE STATUS OF PHOTOVOLTAIC CONCENTRATOR DEVELOPMENT*

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ABSTRACT: Several companies in the United States are actively pursuing the commercialization of photovoltaic concentrator technology. Under the auspices of the U.S. Department of Energy's Concentrator Initiative, the Electric Power Research Institute's High Concentration Photovoltaic Program and several privately funded programs, these companies are developing a range of designs from low-concentration linear-focus to high-concentration point-focus cells and collectors. Design details and status of each development program is presented.

1. INTRODUCTION

The concentrator community in the United States is actively pursuing the commercialization of photovoltaic (PV) concentrators for a range of potential markets. The future for PV concentrator technology is bright for both low and high-concentration collectors. In addition to having projected energy costs comparable to or below those for one-sun collectors in volume production, concentrators offer a significant increase in installed capacity for a given cell production capacity. Commercial sales of concentrator systems and technology has already begun. The Concentrator Initiative Program, which is funded by the U.S. Department of Energy (DOE) and managed by Sandia National Laboratories, is playing an important role in developing commercial concentrator cell and collector products for this emerging industry. This paper discusses the status of the cell and collector technologies being developed by the eight Concentrator Initiative Program participants and Sandia's role in that progress. It also briefly reviews the status of other concentrator programs in the U.S. including the Electric Power Research Institute's (EPRI) High Concentration PV (HCPV) program and privately-funded programs.

2. THE CONCENTRATOR INITIATIVE PROGRAM

2.1 Program Origins and Status

The DOE has funded concentrator cell and collector research since the mid 1970's when Sandia demonstrated a 1-kW concentrator array. Program emphasis in the 1970's and 80's was on increasing cell efficiency and developing cell assembly and optical component technology. Significant progress was made in all areas, and towards the end of the decade DOE shifted the emphasis

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of its program more towards support of technology commercialization.

In October 1990, the DOE expanded its concentrator development effort by establishing a $12 million, multi-year Concentrator Initiative (CI) Program that is funded jointly with industry. The CI program participants, four cell and four collector manufacturers, are pursuing programs aimed at producing commercial products. By supporting parallel cell and collector efforts, the CI Program has successfully linked cell manufacturers with collector manufacturers to promote commercial interactions.

All eight CI Program participants are completely committed to product commercialization. Each is committing substantial cost sharing to the product development effort, and all are substantially involved in their own marketing efforts. Additionally, all are working to make their production processes environmentally benign by reducing or eliminating solvents, flux cleaners and chemicals that harm the environment. Two contracts, with Entech and Spectrolab, end early in 1993, the rest are scheduled to end in mid 1994 to 1995. By the end of each contract, participating companies are expected to have developed cell or collector designs that are reliable, cost-effective in volume production, and developed to the point of being ready to put into production. Most expect to market products before the end of their contracts.

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2.2 Sandia Support for the CI Program

DOE's Sandia National Laboratories does more than just monitor the CI contracts it administers. It treats each development contract as a collaborative technical effort, getting actively involved with each one. Sandia provides development support, fabrication process evaluation, and performance and reliability testing at its PV Device Fabrication Lab (PDFL), PV Device Measurement Lab (PDML), PV Technology Evaluation Lab (PTEL) and other facilities.

The PDFL includes complete cell processing capabilities in a class-100 clean room designed to ensure that parametric process studies are unaffected by contamination. To this end, biweekly fabrication runs are made to check all equipment for process stability. The PDML can perform dark current-voltage (IV) and light (one-sun and concentrated) IV measurements, laser beam induced current scans to evaluate spatial responsivity of a cell, optical measurements of gridline dimensions, spectral response measurements, and reflectance for internal quantum efficiency calculations.

Support for a typical CI cell contract includes measuring lifetime of material procured by the contractor, duplicating critical processes in the PDFL to determine process potential, performing parametrized studies to optimize processes, recommending and transferring process technology by hosting technical staff in the PDFL, measuring and diagnosing cell performance in the PDML, and guiding contractor progress.

Sandia uses the capabilities of the collector development project and the PTEL to support the development of collectors and to evaluate delivered hardware. Sandia's engineering support is a continuous process throughout the iterative collector design phase. Its engineers can use Sandia's finite element models to optimize collector thermal design and its optical models to design the primary and secondary lenses. Materials and components are tested well beyond the range specified in Sandia's evaluation sequence, often to failure, to provide data necessary for product improvement. Hardware is subjected to accelerated environmental exposure including thermal and humidity/freeze cycling and ultraviolet radiation exposure. Collectors are subjected to environmental extremes including hail impact, water spray, and loads, and they are measured for electrical breakdown and current leakage. Non-destructive imaging (ultrasound, x-ray, and thermal imaging) is used to evaluate fabrication process quality. Failure analysis resources include scanning electron microscopy, scanning auger, and gas and mass chromatography.

Much of the early CI Program support has been to identify reliable soldering, electrical isolation and adhesive bonding materials and processes. Later support is shifting to collector and array evaluation. The PTEL facility measures lens, lens/cell, module, and array electrical performance as a function of environmental conditions and solar alignment not only at design conditions but also at off-design conditions to ensure adequate design tolerance. Once hardware is developed it is subjected to a rigorous evaluation. The PTEL has evolved a thorough evaluation sequence for cell assemblies and concentrators comparable to the EC Specification 503 Qualification Test Procedure for PV Modules used for one-sun collectors. The most recent version is documented in [1]. Figure 1 charts the sequence for collectors which involves four electrical performance evaluations and requires six modules and a minimum of 16 weeks.

2.3 CI Cell Development

Details of the four CI Program cell designs can be found in Table 1. All use float-zone silicon, although Solarex is also investigating Czochralski (CZ) and multi-crystalline silicon (m-Si).

Applied Solar Energy Corporation (ASEC) and Spectrolab are developing similar passivated-emitter solar cells (PESC) sized for the Sandia Baseline Module III (SBM3) type collectors developed by Alpha Solarco and Solar Kinetics, Inc. (SKI). ASEC licensed the microgrooved PESC technology (Fig. 2) developed by the University of New South Wales (UNSW), while Spectrolab is developing their design internally. To ensure rapid transfer to production, Spectrolab has performed all development fabrication on their one-sun space cell production line using production technicians and equipment.

Both have achieved good efficiencies with low-cost processing compatible with below-50¢/W cell production. With Sandia's help, Spectrolab solved an early shunting problem by adding a thick field oxide (Fig. 3), and ASEC solved a contact resistance problem with slight process changes. Another 1-2% (absolute) increase in efficiency is expected for both. Spectrolab has achieved over 20%

at 50 suns and over 19% at 200 suns with its 3-mask process. Using a prismatic-cover parallel-grid design ASEC has already achieved 21.4% at 150 suns (measured without the cover; equivalent to 23% with cover) [2]. Soon ASEC will convert to a new non-prismatic-cover chevron grid design. It incorporates a redundant circumferential grid line suggested by Sandia to improve performance in case of a broken line or non-uniform illumination. Sandia transferred the image reversal process to ASEC which has resulted in sharper, less-reflective microgrooves. ASEC plans to use the same process to reduce the shading of its grid lines, further increasing cell current. Although ASEC has already achieved an impressive 91% yield (minimum 20% efficiency) on its 5-mask process, both ASEC and Spectrolab can further improve costs by increasing yield, the number of cells per wafer, the wafer size, and production volume.

SunPower is a small company formed by Richard Swanson and Ron Sinton of Stanford University. It has successfully transferred the record 27% Stanford back-contact cell technology to a production environment. Funded by the CI Program, EPRI, and venture capital, SunPower established a dedicated Cell Pilot Line (CPL) inside a 370 m^2 clean room. By modifying the fabrication process to eliminate hazardous chemicals and solvents, SunPower received an unprecedented and cost-saving commercial building occupancy rating for its CPL. The baseline cell fabrication process has been established and is now carried out completely in the CPL. The process eliminates the ultraviolet (UV) degradation problem experienced by the Stanford cells at the cost of several efficiency points. Baseline cell efficiencies of 23% at 100 suns and 21.5% at 200 suns have been achieved, but a modified design recently boosted results significantly higher, to 25.5% at 100 suns and 25.0% at 200 suns. The back-contact design (Fig. 4) eliminates any grid shading loss, but to incorporate the cell into current point-focus collector designs requires an alumina wafer cell mount to interface the electrical interconnects. Although such a mount has been developed by Cummings Engineering under an EPRI program, cost of the combined cell and mount is high. The cell is promising for advanced collector designs such as the Sandia Concept-90 [3] and EPRI's Integrated Array where the mount is unnecessary.

Amonix, created in 1989, is another small company formed to commercialize the Stanford back-contact technology. Although not part of the Concentrator Initiative, it is funded by EPRI to provide cells for its Integrated Array and has successfully commercialized the process using available silicon foundries for processing. Amonix has produced cells which achieve 24% at 260 suns and maintain 21% to 500 suns. The use of available foundries as needed rather than a dedicated cell fabrication line not only reduces cost but enables very rapid scale up.

Solarex provided CZ cells for the 300kW of 22X line-focus collectors Entech built for the 3M/Austin system and the 20-kW of collectors Entech built for the PVUSA program. Under the CI Program Solarex is working very closely with Entech to develop an advanced cell and prism-cover design for Entech's new 21X collector. Solarex licensed the UNSW buried-contact FZ process

(Fig. 5), and it recently subcontracted UNSW to help it modify the process for CZ and m-Si material. Although Solarex is still early in the process development stage, it has so far achieved 15.4% one-sun efficiency on FZ, equivalent to over 18% at concentration after prismatic covering. Its eventual goal is to achieve over 20% efficiency on prismatic-covered cells (18% for CZ). It is working to optimize the AR coating material and reduce series resistance. Instead of using a laser to form contact grooves, Solarex has successfully developed a potentially lower-cost saw-cut method to form 25 micrometer-wide by 40 micrometer-deep grooves.

2.4 CI Collector Development

The CI Program is cost-sharing the development of four collector designs. Collector characteristics are given in Table 2 along with measured or expected collector efficiency using presently available cells as well as cells being developed under the CI program. Of the four collector manufacturers, Entech is the furthest along the path towards commercialization. Its 20kW PVUSA system is producing dc operating efficiencies (10-12%) and capacity factors (20-35%) that are above those of all the other participating collectors, including crystalline silicon and amorphous one-sun systems. Entech's CI program is geared towards refining its collector design to improve quality, efficiency, and production cost. Improvements made to this fourth-generation design include a new housing size to accommodate 3M Corporation's new one-piece, one-meter wide Lensfilm®, a longer housing (3.66 vs. 3 m) to reduce area costs, improved heat sink and prismatic cover for higher cell efficiency, and an improved endplate with an adjustable pivot assembly which eliminates the need to counterbalance modules. The housing is designed to ship flat and snap together on-site.

Entech has also made a major design change to the receiver section that will not only enable automation of the most labor-intensive production process, but may also change the way Entech does business. Instead of assembling the entire receiver section and then encapsulating it to survive high-potential (hipot) and wet insulation resistance (WIR) tests, Entech is automating the assembly and encapsulation of individual PV cell assemblies (PVCAs) on aluminum pans. PVCAs become products that can be purchased from Entech and assembled into collectors fabricated by companies in developing countries. The PVCA fabrication process is being automated using a surplus encapsulation machine Entech obtained with Sandia's help.

Entech was selected as one of seven companies to participate in the DOE-funded PV Manufacturing Technology Initiative (PVMaT) to develop volume manufacturing processes and equipment. Under PVMaT subcontracts, 3M developed a solvent-free, in-line Lensfilm® lamination process and a prismatic-cover tape fabrication process. Resulting products eliminate labor-intensive production processes previously performed by Entech: laminating Lensfilm® to a superstrate material and molding prismatic covers. As a result of both the CI and PVMaT programs, Entech is drastically cutting production costs of its collector.

Meanwhile Entech is pursuing a variety of markets. Entech is selling 100 collectors using BP Solar buried-contact cells to a South African firm, Irenco, for village power systems providing both electricity and hot water in the Kalahari desert. Entech has also designed a two-collector "kilowatt on a stick" polar tracker system called Sunline for small domestic or remote applications, and it continues to pursue the utility market with its large tilt-roll tracking arrays such as those installed at 3M/Austin and PVUSA.

Two companies, Alpha Solarco and SKI, are pursuing similar medium-concentration point-focus designs based on the SBM3 collector developed by Sandia. Working closely with Sandia, both have developed reliable cell solder bonding processes that use few or no environmentally harmful chemicals. Sandia subjects the cell assemblies to 10 humidity-freeze cycles and 250 thermal cycles (-40 to 110°C) with pre- and post-ultrasound inspection to determine bond quality. With Sandia's help, both are developing encapsulation techniques that will pass Sandia's hipot and WIR tests to ensure safety and resistance to electrochemical corrosion.

SKI uses a non-imaging Fresnel lens and a reflective secondary optical element (SOE) to redirect the light onto the cell in case of mis-pointing, and Alpha Solarco uses an imaging Fresnel lens combined with a refractive glass SOE for the same purpose. Alpha uses a low-cost molding process to produce the glass SOEs, and it is investigating a Solgel process that is showing promise as an even lower-cost process. Both companies are investigating curved-facet Fresnel technology for the primary lens. It reduces the number of facets per lens, increasing optical efficiency. SKI plans to use the lens just manufactured by American Optical (AO) under a Sandia contract to develop a 2-by-2 lens parquet injection molding process. Alpha Solarco, which currently uses a 3M-manufactured point-focus Lensfilm®, has manufactured a curved-facet master for its lens using EDM (electric discharge machining).

SKI has delivered two iterations of collector for evaluation at Sandia and is preparing to send a final one. SKI, which has extensive experience designing and manufacturing solar thermal tracking structures, is now installing its first PV tracking array at its facility and plans to begin quantity production of collectors to explore production issues.

Alpha Solarco, which has had a 125 m^2 array tracking in Nevada for years, expects to deliver a new generation collector to Sandia for evaluation soon. Meanwhile, Alpha Solarco is working closely with a Chinese partner to install a 3MW per year production facility in Qinhuangdao, and it has purchased State Machine Products, a Kentucky sheet metal operation to expand its PV manufacturing capability. Alpha Solarco has spent considerable effort developing test equipment such as solder-bond testers, and cell and collector flash testers to monitor its collector production lines.

Solar Energy Applications (SEA) is developing a low-cost, linear-focus collector designed for volume production and large tolerances. Designed for use on a one-axis polar tracker, the collector tolerates declination angle errors of ±23.5° during the year. Installation is expected to be easier than for one-sun collectors because the collectors are already mounted and wired onto the tracking structure. The array is unloaded, unfolded, aligned to north, staked in the ground and connected electrically to the load. The simple drive system will run off the collector power even when it is not pointing at the sun.

The collector consists of three main parts, an arched extruded Fresnel lens, extruded plastic sidewalls covered with reflective film, and a receiver section using cells fabricated on a one-sun production line. An agreement was recently reached with Siemens for supply of the cells. SEA delivered a first set of collectors to Sandia for evaluation and is making changes to improve hail durability, reflective film durability and cell encapsulation. During the current contract phase, SEA is automating their receiver assembly process to eliminate most of the assembly labor. SEA also plans to deliver their first arrays during the next year and will start selling to organizations interested in evaluating the unit.

3. ADDITIONAL DEVELOPMENT PROGRAMS

EPRI's HCPV program has supported development of concentrator technology for over a decade. Presently the program is working with Amonix, SunPower, Cummings Engineering and others on an Integrated Array designed to eliminate the module as an independent unit. By using the tracking structure's support beams as the module's enclosing sidewalls, EPRI's design eliminates most of the module housing. Lens parquets are mounted on the array front, and backplanes are mounted on the rear. The backplanes are mass-producible laminates similar to printed circuit boards. Back-contact cells are soldered to a patterned copper conductor layer which is separated by an insulating layer from an aluminum support layer. The first prototype is expected to be tested in late 1992.

SunPower has been developing a reflective dish system on its own using a dense-pack receiver of PV cells. Unfortunately in June 1992 they had to postpone further research until they located a strategic partner to supply additional funding. Preliminary testing of their 1-kW prototype system achieved a 14% overall efficiency using an 80% efficient segmented glass dish reflector and 19% efficient cells. Eight wafers each containing 10 back-contacted cells were mounted to an active cooling system. Non-uniform illumination was a problem at this size.

Midway Laboratories, located in Chicago, is selling Power Source™ point-focus collectors mounted on a Wattsun tracker. Midway uses the same 3M lens used by Alpha Solarco, a glass SOE, and cells by AstroPower at a concentration ratio of 150X. Midway advertises a peak output of 65W per module.

Sun Energy Development Inc.(SEDI, formerly AESI) is developing a 12.5kW turntable array design of 300X point-focus collectors. Each collector contains eighteen ASEC cells having a 1-cm diameter active area, glass SOE's and a 3x6 non-imaging Fresnel lens parquet. SEDI is planning an irrigation pumping project with a firm from India.

4. THE FUTURE FOR CONCENTRATORS

In the U.S. there is a strong commitment to commercialize PV concentrator technology by a number of companies pursuing a range of designs. The missing factor has been products that are cost-effective, reliability-tested, and ready for the commercial marketplace. The CI Program and the EPRI development program are very successfully encouraging the often-difficult link between cell and collector manufacturers while providing the vehicle to take the technology out of the research lab and into the marketplace. Before substantial utility market penetration begins, field experience is required to establish user acceptance. Experience exists with the ten-year old SOLERAS point-focus system as well as the more recent 3M/Austin and PVUSA Entech line-focus concentrator system showing concentrators have high reliability, high efficiency, and a good match to mid-day load profiles. Sandia's substantial development support as well as thorough evaluation and accelerated reliability testing is working to ensure successful field testing of the new CI technologies. However, each user needs to develop his own experience base, and that takes time.

The acceptance process in the low-energy-cost utility market could be greatly accelerated by investing in a jumpstart program to co-fund pilot plants with interested users. Such a program would help overcome reluctance to try a new technology, and it would help raise production volume and bring down costs to self-sustaining levels.

Collector manufacturers are developing commercial systems targeting the utility bulk-power market, but that market is viewed as a longer term one. Meanwhile manufacturers see alternative products including small units for remote applications, product licenses and alternative plant-compatible products as their near-term market that will provide the bridge to the bulk power market.

5. CONCLUSION

PV concentrators represent a viable technology that can contribute significantly to the utility electrical power generation mix. Additionally concentrators can contribute to the nation's industrial base and to the export product base. Over half a dozen collector development programs are underway in the U.S. which are seriously developing commercial products. Concentrator cell manufacturers are transferring recent high-efficiency technology to their production lines and are developing cells for specific collector designs. The resulting concentrator systems are expected to have peak efficiencies between 13 and 20% with field operating efficiencies between 11 and 17% depending on the design. More importantly, the systems under development as part of the CI Program expect to achieve the DOE cost goals of $0.12/kW-hr in moderate production volumes. Additionally they will be tested using Sandia National Laboratories' evaluation sequence which provides a measure of confidence that hardware will not fail prematurely during field operation. PV concentrator hardware is becoming commercially available, and it can be expected to play an increasing role in the world marketplace.

6. REFERENCES

[1] J R Woodworth and M L Whipple, Evaluation Tests for Photovoltaic Concentrator Reciver Sections and Modules, SAND92-0958, Sandia National Laboratories, June 1992.
[2] Development of Concentrator Cells: Phase I Report, SAND92-7006, Sandia National Laboratories, June 1992. Work performed by ASEC.
[3] A B Maish, T D Hund, and M A Quintana, "The Concept-90 Photovoltaic Concentrator Module," Proceedings of the 10th European Photovoltaic Solar Energy Conference (1991) pp. 988-991.

TABLE 1
CONCENTRATOR INITIATIVE PROGRAM CELL DESCRIPTIONS

Contact/Phone	Type	Focus/ Collector	Concentration	Material	Cell Size: Active (mm)	Cell Size: Total (mm)	Cell Size: Thickness (μ)	Grid	Metal	Anti-Reflection	Texture	Process	Efficiency to Date (%/suns)
Applied Solar Energy Corp. City of Ind., CA Henry Yoo 818-968-6581	UNSW PESC	Point Focus, Alpha Solarco Solar Kinetics	100-300 suns	Low resistivity float zone 0.15-0.2 Ω-cm	10x10	13x15 New cell: 12.5x12.5	280	Linear, Prism cvr. New cell: Chevron	Evap TiPdAg	TiO_2/ Al_2O_3	Micro-grooved	3, 4, or 5 mask	5 mask: 21.4/150[2] 21.0/250[2]
Spectrolab Sylmar, CA Dmitri Krut 818-898-2827	PESC	Point Focus Alpha Solarco Solar Kinetics	100-300 suns	Low resistivity float zone 0.15-0.2 Ω-cm	10x10	13x13	200	Chevron New cell: Radial	Evap/ plate TiPdAg	TiO_2/ Al_2O_3	Random pyramid	1 or 3 mask	1 mask: 18.3/100, 18.2/200 3 mask: 20.3/50, 19.2/200
SunPower Sunnyvale, CA Richard Swanson 408-991-0900	Back-contact	Point Focus EPRI Solar Kinetics	100-300 suns	High resistivity float zone 500 Ω-cm	11x11	12x12	110-120	Trench/ mesa New cell: Pt. contact	Sputter Al Plate Ni/Au	TiO_2/ Al_2O_3	Inverted pyramid	4 or 5 mask	Baseline: 23.0/100, 21.5/200 New cell: 25.5/100, 25.0/200
Solarex Frederick, MD John Wohlgemuth 301-698-4375	UNSW Buried-contact	Line Focus Entech	10-20 suns	Float zone, Czochralski Multi-crystal	45.7x112	53.3x112	275	Linear, Prism cvr.	Plate Ni/Cu/Ag Rear: Evap Al	SiO_2 (non-optimum)[1]	Random pyramid (FZ, CZ) Mech. groove (multi-Si)	0 mask 1-sun proc. Saw-cut groove.	FZ: 15.4/1 17/12[3]

1 = silicon nitride under investigation. 2 = prismatic cover design measured without the prismatic cover. 3 = estimated

TABLE 2
CONCENTRATOR INITIATIVE PROGRAM COLLECTOR DESCRIPTIONS

Manufacturer Contact/Phone	Focus/ Concentration	Potential Cell Source	Aperture (mxm, m²)	Cells/Mod. Arrange.	Lens Element (cmxcm)	Lens to Cell (cm)	Tracker	Module Weight kg, kg/m²	Heat Exchanger	Operating Cell Temp. (20°C amb. 880 W/m²)	Efficiency: Lens, SOE	Efficiency: Collector (25C cell)	Efficiency: Collector (op. temp)	Avg. Operating Values (20°C amb, 880 W/m²): I_{max}	V_{max}	P_{max}
Entech DFW Airport, TX Mark O'Neill 214-456-0900	Line Focus 21X geom. 16-19 suns	Solarex, BP Solar, Siemens & others	0.85x3.66 3.1 m²	36 1x36 (BP Cells)	NA	72.6 peak 50.6 rim	Tilt/Roll 167 m² Polar/Dec 6.2 m²	77 kg 25 kg/m²	aluminum extrusion, finned	70-85°C	89.5%, NA	16% (18% cell) 20%* (22% cell)	13% (18% cell) 16%* (22% cell)	20A 24A	18V 18V	360W 435W
SEA Corp. Sunnyvale, CA Neil Kaminar 408-720-1804	Line Focus 10X geom. 6-8 suns	Siemens	0.254x3.05 0.77 m²	36 1x36	NA	22.9 rim	1-axis polar 7.7 m²	5.5 kg 7 kg/m²	aluminum stamped, anodized 0.8mm	45-50°C	79%, NA	13%* (16.5% cell) 14.5%* (18% cell)	12%* (16.5% cell) 13.5%* (18% cell)	4.5A 5.1A	18V 18V	81W 91W
Alpha Solarco Cincinnati, OH Don Carroll 513-771-1690	Point Focus 492X geom. 330-400 suns	ASEC, Spectrolab	0.46x2.74 1.25 m²	24 2x12	22.9x22.9 (9"x9")	30.4	Az/El 125 m²	26 kg 21 kg/m²	aluminum backplane sheet, 1.5mm	60-70°C	85%, 92-96%*	14%* (18% cell) 16%* (21% cell)	12.5%* (18% cell) 14.5%* (21% cell)	11.5A 13.3A	12V 12V	138W 160W
Solar Kinetics Dallas, TX Drew Konnerth 214-556-2376	Point Focus 282X geom. 200-240 suns	ASEC, Spectrolab, SunPower	0.345x2.23 0.77 m²	24 2x12	17.3x17.3	25.4	Az/El 15.4 m² or 77 m²	14.7 kg 19 kg/m²	aluminum backplane sheet, 1mm	60-70°C	85%, 98%*	14% (18% cell) 17%* (21% cell)	12.7% (18% cell) 15.5%* (21% cell)	6.3A 7.7A	13.6V 13.6V	86W 105W

*= estimated

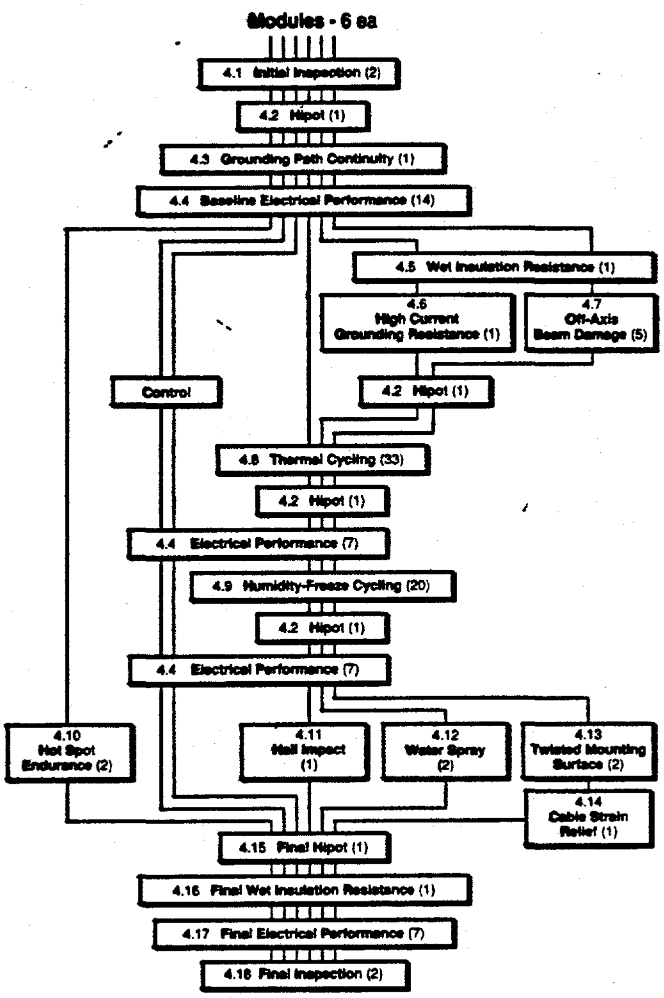

Figure 1 - Sandia's Concentrator Collector Evaluation Sequence (Number of test days in parenthesis).

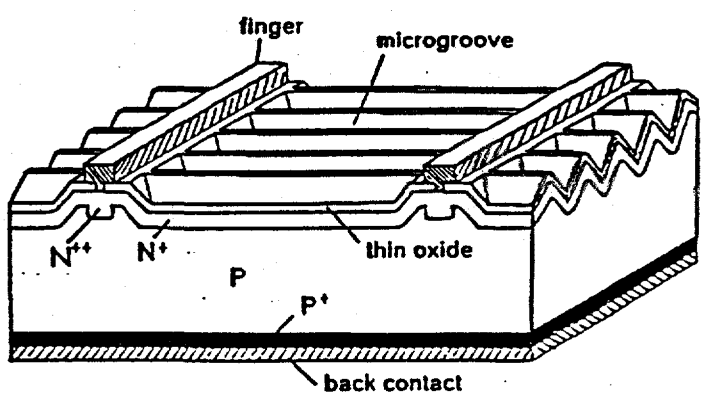

Figure 2 - ASEC Microgrooved Cell Design

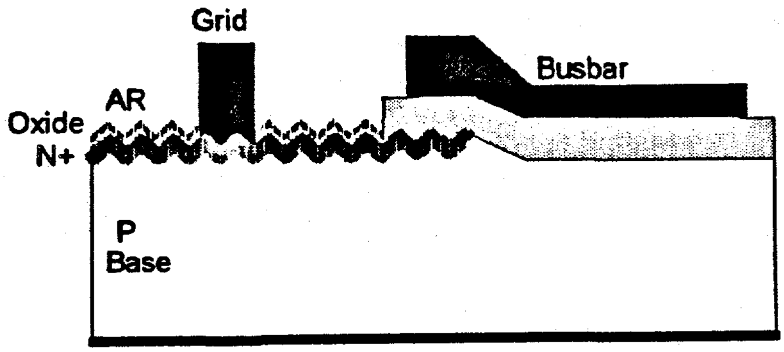

Figure 3 - Spectrolab Cell Design ~~with Thick Field Oxide~~

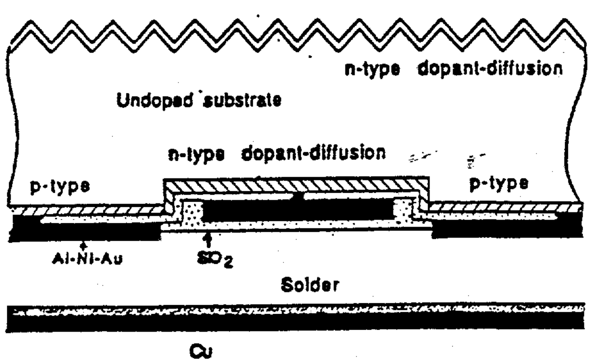

Figure 4 - SunPower Back-Contact Cell Design

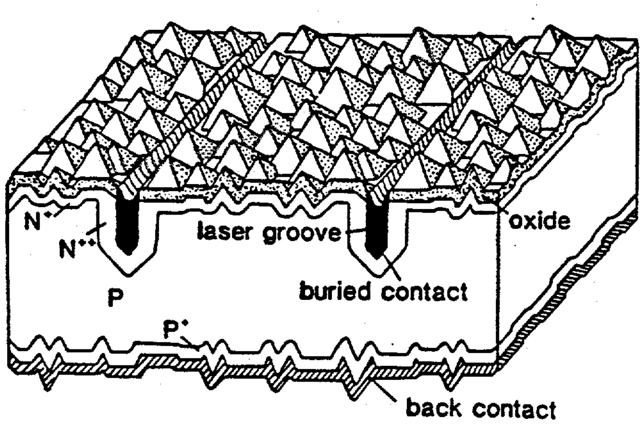

Figure 5 - Solarex Buried-Contact Cell Design