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Final Technical Report
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National Renewable Energy Laboratory
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Golden, Colorado 80401-3393
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NREL technical monitor: R. Mitchell

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On September 16, 1991, the Solar Energy Research Institute was designated a national laboratory, and its name was changed to the National Renewable Energy Laboratory.

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ENTECH's PVMaT Phase 1 Final Technical Report

Prepared Under SERI Subcontract No. XC-1-10057-13

June 1991

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1.0 INTRODUCTION AND SUMMARY

This final technical report documents the key results of ENTECH's Phase 1 contract under the Photovoltaic Manufacturing Technology (PVMaT) program, sponsored by the U.S. Department of Energy, and administered by the Solar Energy Research Institute. Under this program, we have prepared a detailed description of our current manufacturing process for making our unique linear Fresnel lens photovoltaic concentrator modules (Section 3.1). In addition, we have prepared a detailed description of an improved manufacturing process, which will simultaneously increase module production rates, enhance module quality, and substantially reduce module costs (Section 3.2). We have also identified potential problems in implementing the new manufacturing process, and we have proposed solutions to these anticipated problems (Section 3.3). Before discussing these key results of our program, however, we will present a brief description of our unique photovoltaic technology (Section 2.0).

The key conclusion of our PVMaT Phase 1 study is that our module technology, without further breakthroughs, can realistically meet the near-term Department of Energy goal of 12 cents/kWh levelized electricity cost, provided that we successfully implement the new manufacturing process at a production volume of at least 10 megawatts per year (Section 4.0). The key recommendation from our Phase 1 study is to continue our PVMaT program into Phase 2A, which is directed toward the actual manufacturing technology development required for our new module production process.

2.0 ENTECH'S PHOTOVOLTAIC TECHNOLOGY

2.1 Background

The ENTECH management and engineering team has been together since the mid-1970's. From 1975-1983, the team comprised the solar energy division (the Energy Technology Center) of a billion-dollar corporation (E-Systems, Inc.) in Dallas. In 1983, the team concluded a leveraged management buyout of the division from E-Systems and formed ENTECH, Inc., a small business chartered in Delaware and headquartered at the Dallas-Fort Worth International Airport. The principal owners/managers of ENTECH are Walt Hesse (President), Mark O'Neill (Exec. V.P.) , Bob Walters (V.P. Marketing), A.J. McDanal (V.P. Engineering) , and Jeff Perry (V.P. Manufacturing), all veteran engineers as well as entrepreneurs. Our management team also includes John Scott (Controller), an experienced accountant, and Mark Jackson (Manager International Marketing), another qualified engineer.

Our involvement in photovoltaics dates back to 1978, when we submitted a proposal under DOE's PRDA-35 photovoltaic application experiment procurement. We proposed to design, develop, and deploy a turn-key 25 kW linear Fresnel lens photovoltaic concentrator system at the Central Utility Plant of the DFW Airport. Our photovoltaic concentrator module for this program used our newly developed, patented, transmittance-optimized, error-tolerant, arched acrylic linear Fresnel lens [1, 2, and 3]. The 3 foot wide by 8 foot long lens focussed sunlight onto a water-cooled string of 53 ASEC silicon concentrator cells, each 1.44 inches wide by 1.78 inches long. We manufactured 110 of these 12-13% peak efficiency 25X modules in 1982 to form the 245 sq.m. DFW concentrator system [4]. Our DFW system achieved the highest annual solar-to-electric conversion efficiency (about 8%) of any of the photovoltaic systems (flat-plate or concentrator) of that era [5]. In addition, our system showed exceptional reliability for experimental first-generation equipment. In Sandia on-site performance tests, which were conducted annually for a number of years, no measurable performance degradation was ever detected in any of the 11 source circuits [5].

In the early 1980's, under Sandia-funded programs, we developed second-generation modules (both water-cooled and air-cooled) using 3 foot wide by 10 foot long lenses focussing sunlight onto 54 ASEC silicon concentrator cells, each 0.9 inch wide by 2.15 inches long [6 and 7]. We manufactured over 100 of these 13-14% peak efficiency 40X modules for experimental systems, including a 22 kW system at Sandia-Albuquerque [8].

In the late 1980's, using our newly developed, patented prismatic cell cover (which eliminates gridline shading losses for heavily metallized concentrator cells), we began to use low-cost, large-area, modified one-sun type cells in our concentrator modules [9 and 10]. These cells, made by Solarex, ARCO Solar (now Siemens), AstroPower, and others, are about one-tenth as costly per unit area as the previously used ASEC concentrator cells. With our prismatic covers, these low-cost cells are now able to achieve performance levels better than the previously used expensive cells. Our latest modules use a 3 foot wide by 10 foot long lens to focus sunlight onto an air-cooled string of 31 of these cells, each 1.6 inches wide by 3.8 inches long. The increased cell width maximizes both lens efficiency and cell efficiency. Our production lenses achieve over 90% net optical efficiency and production cells from Solarex average 18% conversion efficiency under 20 suns irradiance. During 1989, we manufactured 720 of these 15.5-16% peak efficiency 22.5X modules for deployment in a 300 kW system at 3M

Company's new Austin (TX) Center [11]. Development and deployment of the unique 3M/Austin system was funded under a cooperative program involving DOE, 3M, the City of Austin, the State of Texas, Sandia National Labs, and ENTECH.

The 2,000 sq.m. 3M/Austin system was dedicated in March 1990, and was independently tested in April 1990 by the Southwest Technology Development Institute, which established a system operational DC power rating of 261 kW (@ 60C cell temperature and 1,000 w/sq.m. irradiance) and a peak DC power rating of 301 kW (@ 25C cell temperature and 1,000 w/sq.m. irradiance) [12]. These ratings correspond to a 13% operational collector field efficiency and a 15% peak collector field efficiency. Both of these values are significantly higher than ever before achieved for a utility-scale photovoltaic power plant of any kind.

In 1990-91, we manufactured and deployed a 20 kW emerging-technology (EMT-1) system for the PVUSA project, which is jointly funded by DOE, Pacific Gas & Electric Company, the California Energy Commission, and the Electric Power Research Institute. Our PVUSA system uses advanced Solarex cells in a 3M/Austin type module. Our EMT-1 system represents the only concentrator array presently included in the PVUSA program. Our array has been operational since March 1991 at the Davis, California, PVUSA test site. Performance measurements by ENTECH, Sandia, and PVUSA all indicate module peak efficiency values of about 16% (@ 25C cell temperature) for the 60 modules comprising our PVUSA array. Our module peak efficiency is easily the highest of all of the photovoltaic technologies being tested under the PVUSA program.

In summary, ENTECH is the leading photovoltaic concentrator manufacturing company in the world, in terms of longevity, cumulative production experience, proven manufacturing capacity, and production module efficiency.

2.2 Production History and Capacity

As described in more detail in the preceeding section, from 1982-1988, ENTECH produced several hundred concentrator modules for use in a number of experimental systems. Our annual production output during those years never exceeded 25 kW.

In 1989, under the 3M/Austin project, we established our first relatively high-volume production line at our DFW Airport plant. The schedule-pacing item for module production is the photovoltaic receiver, which comprises 31 cell assemblies bonded to an extruded aluminum heat sink, with appropriate electrical interconnection and encapsulation. At the peak of the 3M/Austin production run, we were manufacturing about 10 photovoltaic receivers per day. Since each receiver is rated at about 450 peak watts, this production rate corresponds to over 1 MW per year. (Using these completed photovoltaic receivers, we were able to assemble modules at a temporary facility in Austin at a much faster rate of 40 modules per day, which equates to 20 kW per day or about 5 MW per year.) Although our current production capacity is over 1 MW per year, our actual production history during the past two years is limited to about 370 kW worth of modules produced for the 3M/Austin system and the PVUSA system.

We used 30-40 temporary workers to manually perform most of the manufacturing processes for the 3M/Austin production run. Based on this valuable experience, we learned that we must automate several of the key manufacturing processes to simultaneously achieve high production volume, superior product quality, and low manufacturing cost. In Section 3.0 of this report, we further explain our need to automate certain processes, and our plan to accomplish such automation. The DOE/SERI/Sandia Photovoltaic Manufacturing Technology program meshes perfectly with our plan to automate our production line and expand our manufacturing volume.

The following section presents a brief description of our concentrator module.

2.3 Concentrator Module Description

Figure 2-1 shows a cross-sectional sketch of ENTECH's current 22.5X linear Fresnel lens photovoltaic concentrator module. Figure 2-2 is a photograph of an actual hardware model of this module cross-section. (This model has been delivered to SERI under this PVMaT Phase 1 contract.) After more than a decade of development and refinement, the current module is very simple in design and construction [10 and 11]. The key features and advantages of the module are summarized in Figure 2-3. A single-piece arched acrylic lens provides nearly 3 sq.m. of aperture area, giving this module by far the highest power rating of any photovoltaic collector on the market. The lens is unequaled in optical efficiency and provides an outstanding tolerance for shape errors, due to its unique symmetrical refraction configuration [1, 2, and 3]. Our lens can tolerate 100 times larger slope errors than a conventional flat Fresnel lens, for equal image de-focussing [2]. Low-cost, one-sun type silicon cells (Czochralski, polycrystalline, or dendritic web) are used instead of the more sophisticated (and more expensive) concentrator cells used in most other concentrator modules. Prismatic covers substantially enhance the performance of these large-area cells, by allowing heavy gridline coverage on the top surface of the cells (20-40% typical), without the usual gridline obscuration loss [9]. With over 25 amps of short-circuit current output, these cells need heavy gridline coverage to function effectively. The cells are bonded directly to an extruded aluminum heat sink with a thermally conductive, electrically insulating adhesive. The total parts count within the module is relatively small. Only one lens, one heat sink, two sidewalls, two endplates, and 31 cells are needed to make a module rated at nearly half a kilowatt. Due to its linear focus configuration and its substantial tolerance for real-world operational inaccuracies, the module has been adapted to a very large, low-cost, roll/tilt tracking array. In fact, our current arrays are by far the largest photovoltaic tracking units ever built, with 1800 sq.ft. of aperture per array. These arrays also offer excellent aperture-to-ground coverage ratio (28% at the 3M/Austin installation discussed in the last section) [11].

Our present production modules have peak efficiency levels (@ 25C cell temperature) averaging about 16%, easily the highest yet achieved for production photovoltaic modules of any kind. Future modules will have substantially higher performance, as the recent impressive cell technology improvements pioneered at SERI, Sandia, industry and university laboratories make their way to the commercial cell production lines around the world. Three years ago, we put a 23% efficient laboratory silicon cell (made by Dr. Martin Green of the University of New South Wales) into one of our 22.5X modules and achieved over 21% combined lens/cell efficiency in an outdoor test [13]. Dr. Green's latest cells are several points higher in efficiency than the one we used 3 years ago. Several firms have licensed Dr. Green's technology, including Solarex and BP Solar. We are working closely with Solarex and Sandia under the DOE-sponsored Concentrator Cell Initiative Program to implement this exciting new cell technology at Solarex. In addition, we are collaborating with BP Solar on their version of Dr.

FIGURE 2-1

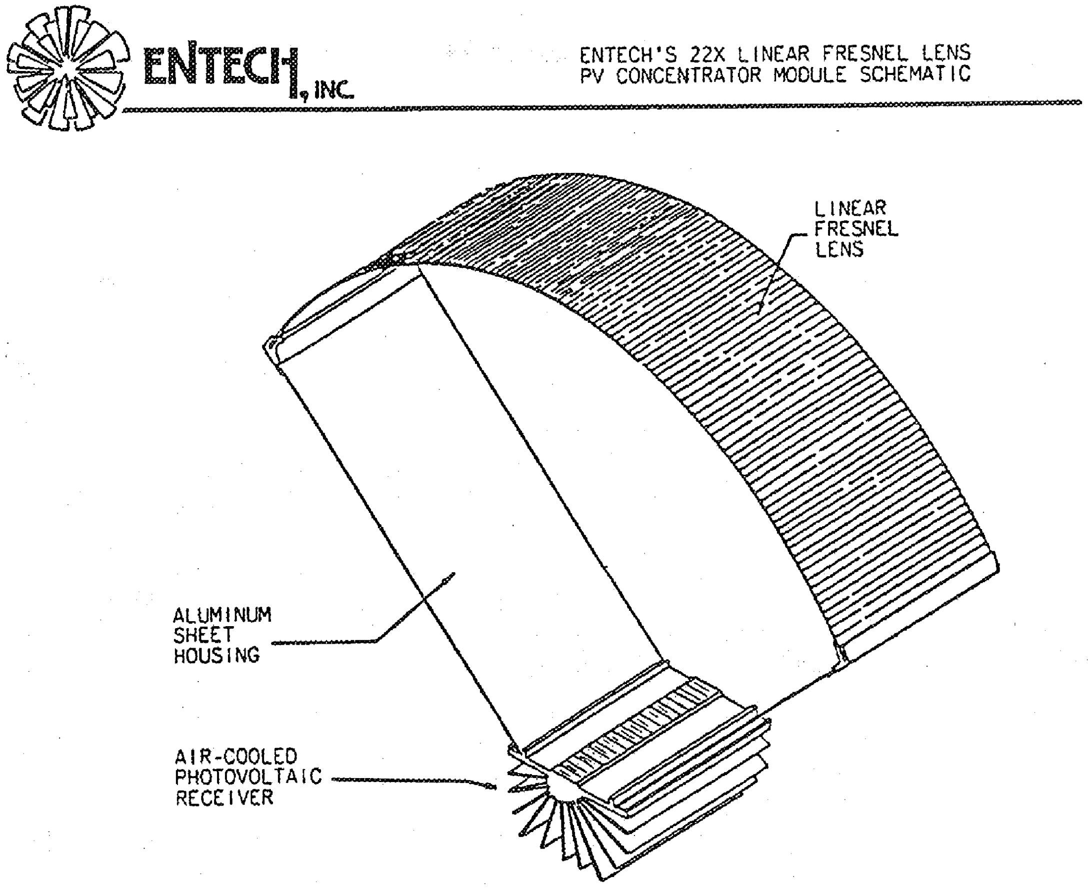


FIGURE 2-2
PHOTOGRAPH OF MODULE CROSS-SECTION

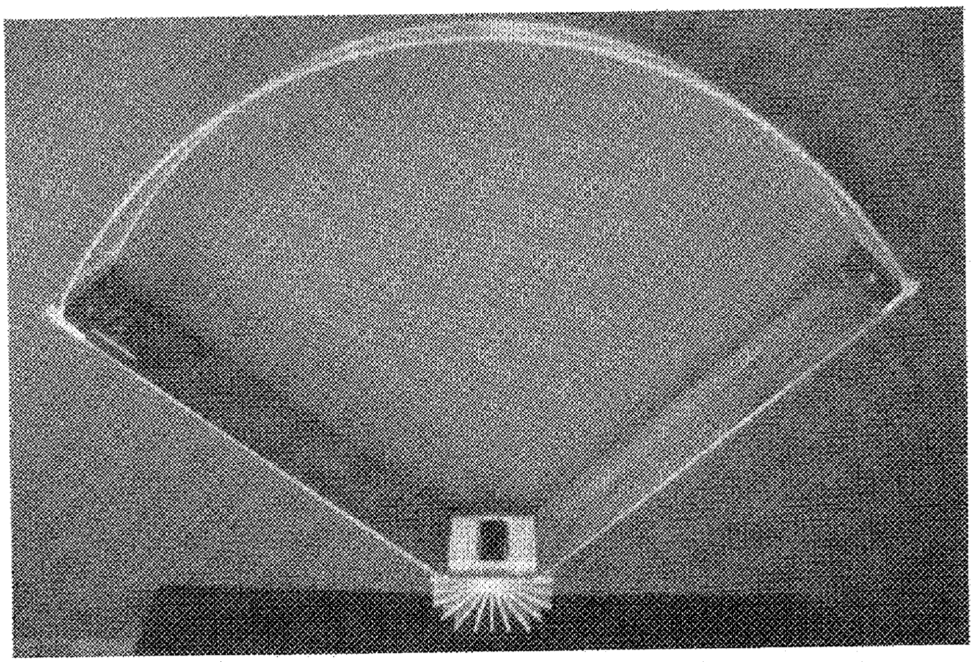


FIGURE 2-3: ENTECH'S LINEAR FRESNEL LENS PV CONCENTRATOR TECHNOLOGY KEY FEATURES AND ADVANTAGES

UNIQUE LENS: THE TRANSMITTANCE-OPTIMIZED LENS PROVIDES 90% NET OPTICAL EFFICIENCY (WITHOUT THE NEED FOR SECONDARY CONCENTRATORS), EXCEPTIONAL TOLERANCES FOR MANUFACTURING AND OPERATIONAL INACCURACIES (E.G., >100 TIMES THE SLOPE ERROR TOLERANCE OF FLAT LENSES), AND IS MASS-PRODUCED BY 3M'S LENSFILM PROCESS.

ONE-SUN TYPE CELLS: THE MODEST CONCENTRATION RATIO ALLOWS THE USE OF LOW-COST, LARGE-AREA, ONE-SUN TYPE CELLS (CZ, POLY, OR WEB SILICON), WHICH ARE ALREADY IN PRODUCTION AT NUMEROUS COMPANIES WORLDWIDE.

PRISMATIC COVERS: CELLS ARE ENCAPSULATED WITH SILICONE PRISM COVERS, WHICH ELIMINATE GRID OBSCURATION LOSSES FOR HEAVILY METALLIZED CELLS.

SIMPLE HEAT DISSIPATION: CELLS ARE BONDED DIRECTLY TO AN EXTRUDED ALUMINUM HEAT SINK WITH A THERMALLY CONDUCTIVE DIELECTRIC ADHESIVE.

LARGE MODULE/FEW PARTS: EACH MODULE PROVIDES 2.787 SQ.M. OF APERTURE (470 PEAK DC WATTS @ 1,000 W/SQ.M. DNI AND 25C CELL), WITH A SINGLE LENS, 31 CELLS, ONE HEAT SINK, AND ONE HOUSING.

SIMPLIFIED TRACKING APPROACH: USING AN OPEN-LOOP, COMPUTERIZED CONTROL SYSTEM, A LIMITED-MOTION TILT/ROLL TRACKING APPROACH, TWO MOTOR-DRIVEN LINEAR ACTUATORS, AND A UNITIZED STEEL STRUCTURE, EACH TRACKING UNIT COMPRISES UP TO 167 SQ.M. OF APERTURE WITH 22-28% GROUND COVERAGE RATIO.

Green's cell technology. In the next 1-3 years, both of these companies, and probably several others (Astropower, Siemens, etc.), should be able to produce our 20-sun cells with peak efficiency levels (after prism-covering) in the 22-24% range. Thus, with little doubt, ENTECH will be producing commercial modules with peak efficiency levels above 20% within the next 3-5 years.

In summary, our modules represent the current state-of-the-art in production photovoltaic concentrator modules.

2.4 Module Cost versus Manufacturing Volume

Based on our 3M/Austin production experience, we have quantified all of the cost elements associated with our module at the 300 kW/year production rate. More importantly, we have extrapolated those costs to higher volume production, assuming that we can automate many of the manufacturing operations to substantially reduce labor costs. The results of this costing effort were summarized in detail in our PVMaT Phase 1 proposal, using the standard Sandia-furnished cost breakdown structure format for concentrator modules. We have shared these proprietary cost data with Sandia, DOE, and selected industry personnel, all under formal non-disclosure agreements. Furthermore, we have presented and explained the backup data for each of the various cost elements to these independent parties. However, since no proprietary data is allowed by SERI to be included in this final report, only the bottom-line module cost data will be discussed below.

The 3M/Austin 300 kW system costs, including a 50% indirect cost markup, correspond to about $3 per peak watt for the concentrator module. Thus, the module cost was relatively low for the 3M/Austin system, especially considering it was our first major production run. However, schedule delays of nearly a year (due to cell delivery problems, as well as rework and repair of various components), coupled with the complexity of installing the arrays 16 feet above the top deck of a parking garage, caused the overall system cost to reach about $10 per peak watt [14].

The following table summarizes the key results of the previously discussed module cost versus production volume study. (A detailed breakdown is included in our PVMaT Phase 1 Proposal, or can be provided anew by ENTECH under a non-disclosure agreement.) The cost/power values are presented for two module efficiency levels: (i) a conservative 17% (only a minor improvement over our present 16% production modules), and (ii) a more optimistic 21% (already achieved in our laboratory module).

Production Rate (MW/year)	Module Price/Aperture ($/sq.m.)	Module Price/Peak Power ($/W)	
		(@ 17%)	(@ 21%)
1	352	2.07	1.68
10	212	1.25	1.01
100	151	0.89	0.72

The table above shows that our module can be profitably sold for about $200 per sq.m. at production rates just slightly above 10 MW per year. The DOE 5-Year Plan near-term goal for concentrator modules requires a 20% efficient module to sell for about $200 per sq.m. to meet a levelized energy price of 12 cents/kWh. Clearly, our module will be able to meet the DOE near-term at a relatively modest production rate <u>without any breakthroughs required in technology</u>. We know of no other photovoltaic approach which can realistically make this claim. Furthermore, our system-level economic analysis shows that the DOE long-term goal of 6 cents/kWh is not out of reach at higher production volumes, as further discussed in the following section.

To meet the near-term DOE goals, we need to (i) achieve large volume production, and (2) develop the manufacturing technology and automation required to lower the labor content of our module. Section 3.0 further discusses our manufacturing technology challenges and opportunities.

While this section has presented <u>module</u> cost and economic data, the following section summarizes our concentrator <u>system</u> economics.

2.5 System Economics

As discussed in previous sections of this report, ENTECH has deployed a number of concentrator systems over the past decade. Additionally, we have bid a number of multi-megawatt utility-scale installations on a turn-key basis. For these large-scale systems, the module price generally equates to about 60% of the total installed system cost <u>for our technology</u>. (The relative module-to-system cost ratio is probably different for other technologies.) The other 40% cost fraction includes our roll/tilt tracking structures, system controls, DC/AC inverters, installation, etc. Using this 60% rule, the module price estimates of the previous section can be extended to system cost estimates.

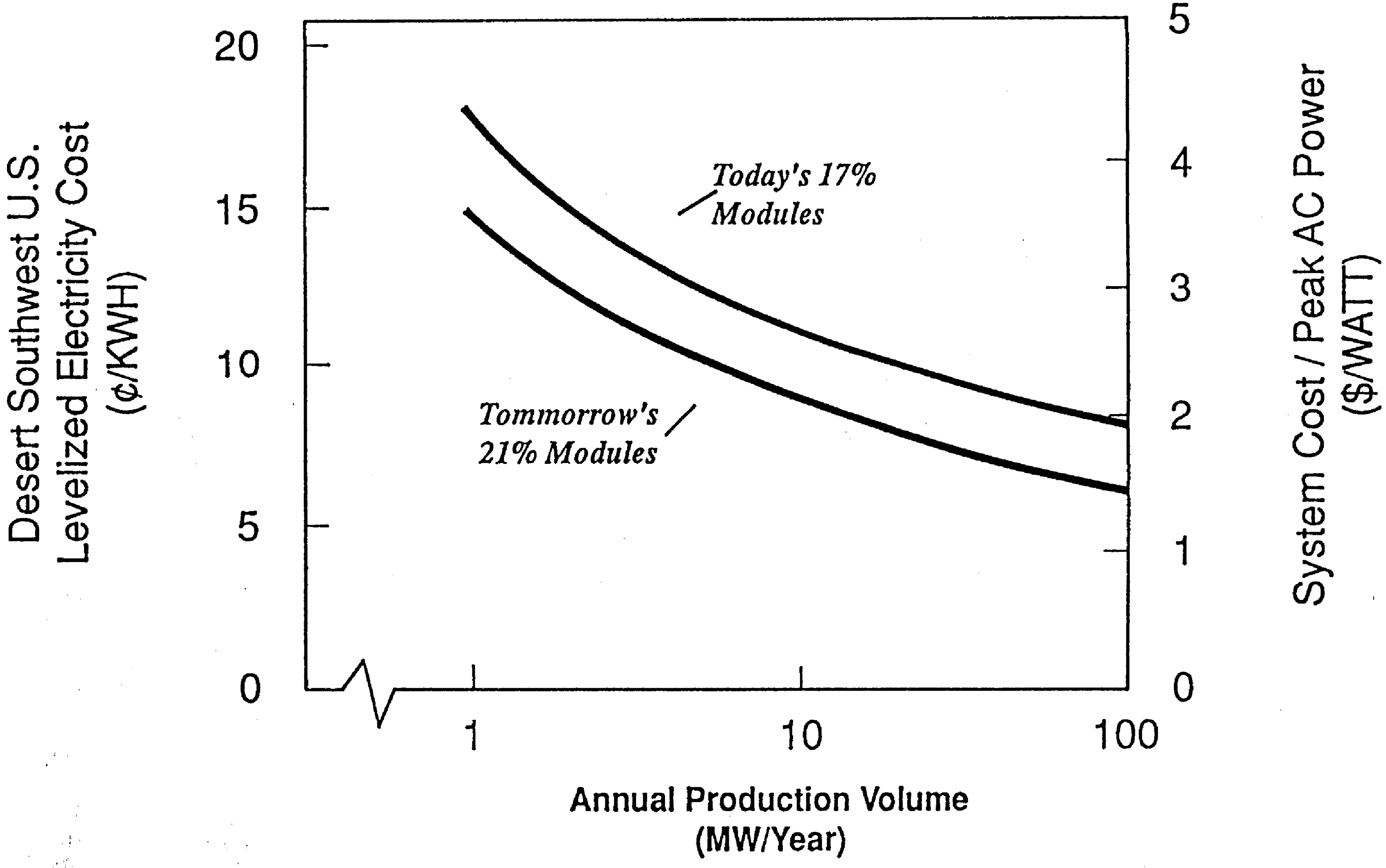
Figure 2-4 shows the estimated turn-key system cost (in dollars per peak <u>operational AC watt</u>), and the corresponding levelized electricity cost (in cents per kWh), versus production volume for both current-technology (17% efficient production modules) and near-term improved technology (21% efficient production modules already demonstrated in the lab). The operational AC watt rating is 80% of the peak DC watt rating, reflecting the combined power degradation due to operational cell temperature, wiring/mismatch losses, and inverter losses. The levelized electricity cost assumes an Albuquerque-type environment (2,600 kWh/sq.m. annual direct normal irradiance) which provides an annual capacity factor of 26.7% after tracking/shading losses. The levelized energy price also assumes a 10% annual fixed charge rate.

Figure 2-4 shows that our technology can meet the DOE near-term energy price goal of 12 cents/kWh at a production rate of about 10 MW/year, even at today's module efficiency levels. Furthermore, with tomorrow's more efficient modules, we can see a clear path toward the DOE long-term goal of 6 cents/kWh at production rates of about 100 MW/year. We know of no other photovoltaic technology which can realistically make a similar claim. In addition, our technology exists today - no further breakthroughs in materials, processing, stability, or efficiency need to be discovered for our technology to meet the DOE goals.

Clearly, from Figure 2-4, we must reach relatively large production levels to provide the system cost and the levelized electricity cost needed to compete against conventional energy sources. Fortunately, these production rates are not

FIGURE 2-4

Linear Fresnel Lens Photovoltaic
Concentrator System
Estimated Energy Economics



large by utility standards (1,000 MW conventional power plants are not uncommon). Unfortunately, we have not yet been successful in convincing a utility company to buy a multi-megawatt photovoltaic concentrator system. Also, we have not yet identified any niche markets for small photovoltaic concentrator systems, like those markets presently sustaining the flat-plate photovoltaic industry (e.g., walk lights, fence chargers, buoy lights, etc.). However, considering the recent Persian Gulf War, the growing environmental movement, and DOE's renewed commitment to photovoltaics, we are optimistic that we will have the orders to sustain large-volume manufacturing within the next 2-5 years.

We view the PVMaT project as a key element of our plan to reach such large-scale production. We also see the Sandia Concentrator Module Initiative program as another key element in our plan. The Concentrator Module Initiative program provides the path for module design improvements and qualification testing. The PVMaT program provides the path to develop the manufacturing technology needed to mass-produce the improved module. The remaining elements of our plan toward mass-production are our on-going large system marketing effort and our on-going program to raise additional investment capital. Thus, with DOE, SERI, and Sandia assistance, we see this plan toward mass-production as an ideal public/private partnership. With the potential shown in Figure 2-4, we believe that, through this public/private partnership, our technology will be able to contribute in a major way toward providing cost-effective, non-polluting energy in an increasingly environment-conscious world.

The following section discusses our manufacturing technology status, needs, challenges, and plans.

3.0 MANUFACTURING TECHNOLOGY DISCUSSION

3.1 Current Module Manufacturing Process

Figure 3-1 summarizes the current production process for ENTECH's modules. There are three major elements in our module, namely the lens, the photovoltaic receiver, and the sheet metal housing, which are fully discussed in the following paragraphs.

The primary component of the lens is a 3M prismatic acrylic sheet product called Lensfilm, which is made to our design with excellent precision and quality. To maximize throughput and to minimize cost, 3M makes the Lensfilm by a secret process at a thickness of only 0.022 inch, and ships the material to us on rolls of several hundred linear feet. 3M can make more than an acre of our Lensfilm in a single day. To withstand 100 mph wind loads and 1-inch hail impact without damage, the 3M Lensfilm must be laminated to a 0.125 inch thick ultra-violet stabilized acrylic superstrate. The current lens lamination process at ENTECH (Photo 3-A) uses a methylene chloride solvent spray at the interface between the 3M Lensfilm and the acrylic superstrate, as these two sheets are fed between a set of rubber rollers. Appropriate protective gloves are worn by our workers who perform this lamination, and the room is well ventilated with exhausts at floor level to remove the relatively heavy solvent vapors. Portions of the superstrate and Lensfilm which are not to be laminated must be covered with poly sheet and tape. After lamination, an acrylic edge strip (Photo 3-B) is adhesively bonded to each edge of the lens, to later self-index with a slot in the sheet metal sidewalls of the module. The lens assembly processes are all manual at the present time. 3M has been ENTECH's primary lens supplier for more than a dozen years. In 1989, ENTECH and 3M formalized a pair of patent license and lens supply agreements, establishing 3M as the exclusive manufacturer of our patented lenses, subject to a long-term price schedule for the 3M Lensfilm product. The 3M Lensfilm process is the only known mass-production approach to Fresnel lens manufacture which can meet the performance, cost, and volume requirements dictated by the DOE/Sandia near-term cost goals for concentrator modules.

The starting point for the photovoltaic receiver is, of course, the solar cell. We use large-area cells compatible with standard one-sun cell production approaches. Two of our rectangular cells can be sliced from a single 100 mm square polycrystalline silicon wafer or from a single 125 mm diameter circular Czochralski silicon wafer. While Solarex has provided high-quality cells for most of our recent systems, we are also continuing to work with other cell vendors as well. At the modest concentration ratio of our module, we have found that polycrystalline silicon cells, solar-grade Czochralski silicon cells, and even dendritic web silicon cells can provide good performance, provided that the cell metallization system has a low contact resistance with the silicon surfaces. Thus, vapor-deposited metallization (Ti/Pd/Ag or Ti/Pd/Cu) and laser-grooved metallization (with proper groove diffusion) have both proven to be acceptable, but screen-printed silver paste metallization has proven to be unacceptable to date.

For our 300 kW system at 3M/Austin, we purchased approximately 25,000 cells from Solarex for between $7 and $8 each. Since each prism-covered cell produces about 15 watts of power under the 20 suns irradiance produced by our lens, the cell cost for this job equates to about 50 cents/watt. However, to understand the small relative production level represented by this job, Solarex produces more

FIGURE 3-1 - CURRENT ENTECH 22X MODULE MANUFACTURING FLOW CHART

CELL ASSEMBLY FABRICATION

All Manual Processes

1. Procure Cell Assembly Materials (Cells, Copper Interconnects, Silicones, Tape, & Solder)
2. Solder 4 Interconnects to Cell & Add Tape Between Interconnects
3. Mold Silicone Prism Cover & Trim to Final Size
4. Bond Prism Cover to Cell & Check Alignment/Acceptance Angle
5. Flash Test/Group Cell Assembly
6. Select 31 Matched Cell Assemblies --> & Notch Interconnects for Diode Clearance/Soldering

PHOTOVOLTAIC RECEIVER ASSEMBLY

All Manual Processes

1. Procure Receiver Materials (Heat Sink Extrusion, Wire, Diodes, Copper Plate, End Pieces, Silicones, & Solder)
2. Coat Extrusion w/ Dielectric and Hi-Pot Test/Patch
3. Assemble Bypass Diode Circuit incl. Heat Spreaders and Wires
4. Bond Diode Circuit to Heat Sink & Hi-Pot Test
5. Assemble End Pieces/Pigtails
6. Bond Cell Assemblies to Heat Sink and Hi-Pot Test
7. Solder Cell Assemblies Together
8. Encapsulate Receiver --------->---------- & Dry/Wet Hi-Pot Test & Seal/Retest as Required

LENS ASSEMBLY

All Manual Processes

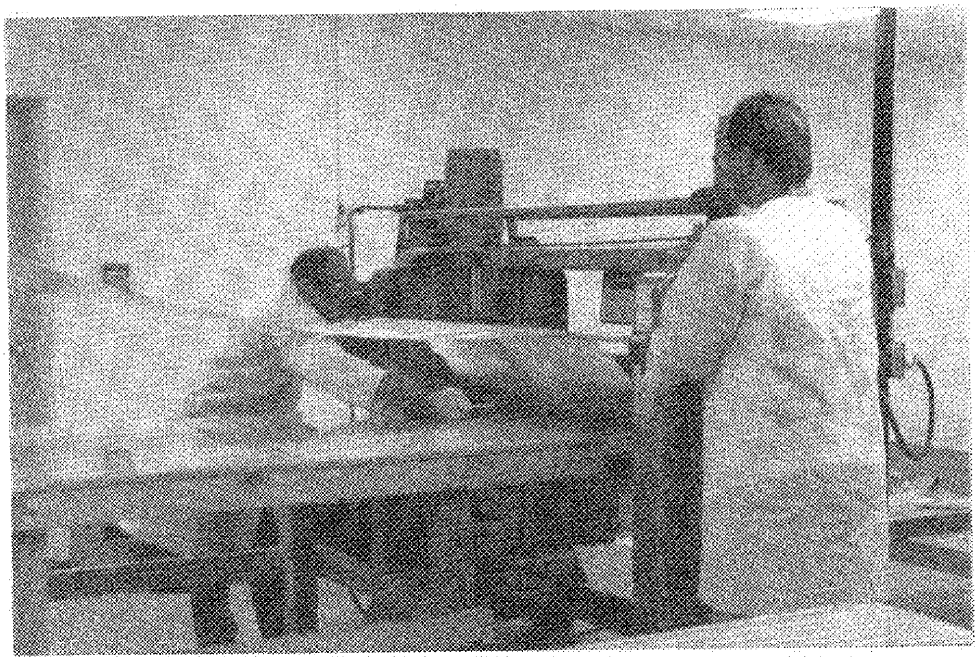
1. Procure Lens Materials (Lensfilm, Superstrate, Edge Strips, Solvent, Tape, & Poly Sheet)
2. Laminate Lensfilm to Superstrate Using Rubber Roller/Solvent Process
3. Bond Edge Strips to Lens -----------> & Remove Poly Sheet/Inspect Lens

MODULE ASSEMBLY

At Power Plant Site

1. Procure Module Materials (End Plates, Sidewalls, Adhesive, Lens Seals, & Clips)
2. Clinch/Stake End Plates to Sidewalls Using Structural Adhesive
3. Attach & Align Lens to Housing Using Clips with Adhesive
4. Attach Photovoltaic Receiver <---------- to Lens/Housing Unit Using Clips with Adhesive

PHOTO 3-A



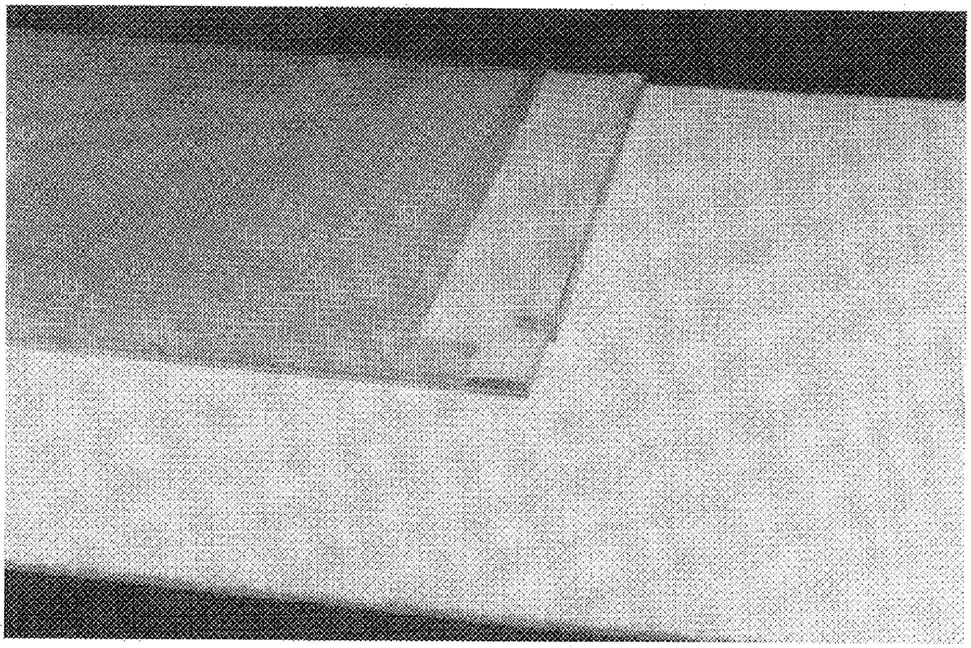


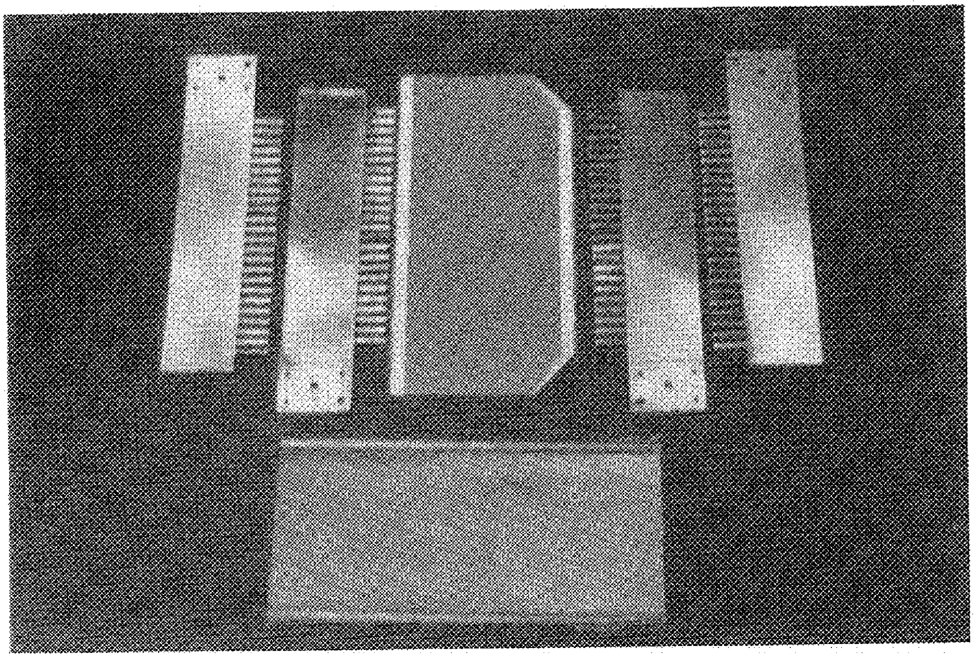
PHOTO 3-B

than his quantity of cells every day at their one-sun cell plant in Maryland! Thus, to achieve cell production economies of scale, we need to increase the cell production quantities by orders of magnitude. We have solicited and received recent quotations for larger quantity purchases of our concentrator cells from three major one-sun cell manufacturers, all of whom indicate that they can meet our cost, performance, and volume targets. Thus, we are not dependent on a single supplier for cells.

Prior to assembling the photovoltaic receiver, we first solder, prism cover, and performance test the vendor-furnished cells into usable cell assemblies. This currently involves manual soldering of four copper interconnects onto both edges of the cell on both the top and bottom surfaces of the cell (Photos 3-C and 3-D). Next, a prism cover, which has been previously molded and trimmed to size, is bonded to the cell to eliminate gridline obscuration losses (Photos 3-C and 3-D). Our patented prism cover comprises an array of parallel microlenses bonded to the top surface of the cell to refract incident light away from the gridlines. The prism cover, which is made from less than 10 cents worth of clear silicone rubber, typically boosts the cell output from about 11-12 watts (bare) to about 14-15 watts (covered), for a 20% metallized 40 sq.cm. cell under 20 suns irradiance. (Since the cell output current is over 25 amps, heavy metallization coverage is essential for good performance.) Completed cell assemblies (Photo 3-D) are then flash-tested at 20 suns irradiance and grouped by peak-power current. Thirty-one cells from the same group are selected for each receiver. The copper interconnects are notched on several of these cell assemblies to properly interface with a bypass diode circuit on the receiver. The labor content represented by all of these manual steps in our current cell assembly fabrication process is inordinately high at the present time. As discussed in the next section, all of these steps are amenable to automation.

The starting structure for our photovoltaic receiver is a 10-foot long extruded aluminum heat sink (Photo 3-E). We have multiple qualified sources for the heat sink extrusion. We manually coat this extruded heat sink with a thermally loaded dielectric silicone material. The coating is then hi-pot tested with a copper plate which is charged to more than 2000 volts relative to the heat sink, and any pin-holes which are discovered during this test are patched. At a separate work station, a bypass diode circuit is assembled from button diodes, copper heat spreaders, and insulated copper wire (Photo 3-F). This diode circuit is then bonded to the heat sink near one edge, leaving room for the photovoltaic cell string at the centerline of the heat sink. The diode circuit is then hi-pot tested to insure isolation from the heat sink. At another work station, plastic end pieces (Photo 3-F) with insulated brass feedthroughs are assembled with insulated copper wire pigtails exiting the end piece. These end pieces are attached to both ends of the aluminum heat sink. The 31 cell assemblies are then bonded to the heat sink and hi-pot tested to insure isolation from the heat sink. The cell assemblies, diode circuit, and end pieces are then soldered together to form a series-connected cell string (Photo 3-G). The receiver is then fully encapsulated with a loaded silicone material (Photo 3-H), and hi-pot tested. In addition to a normal dry hi-pot test, the receiver is also subjected to a wet hi-pot test to simulate condensation and/or rain infiltration into the module. For our PVUSA modules, with Sandia, Bechtel, and PG&E agreement, we placed a distilled water-soaked cloth over the front surface of the receiver, with the cloth draped over the bare aluminum heat sink at both edges. We then applied over 2000 volts between the cell string and the heat sink. When small current paths were discovered (nearly always between cells), we patched them with more

PHOTO 3-C



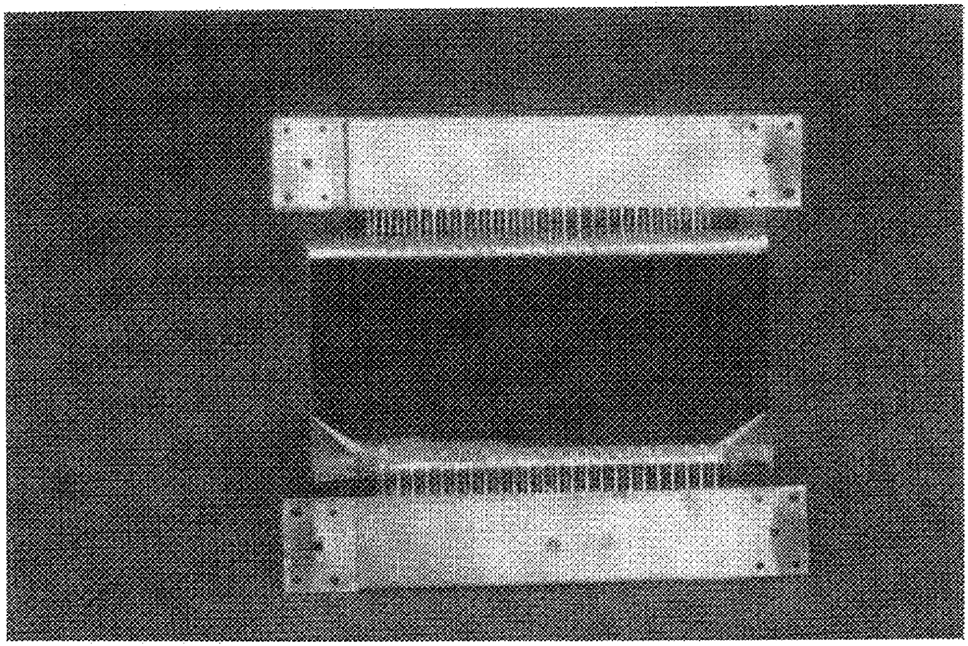
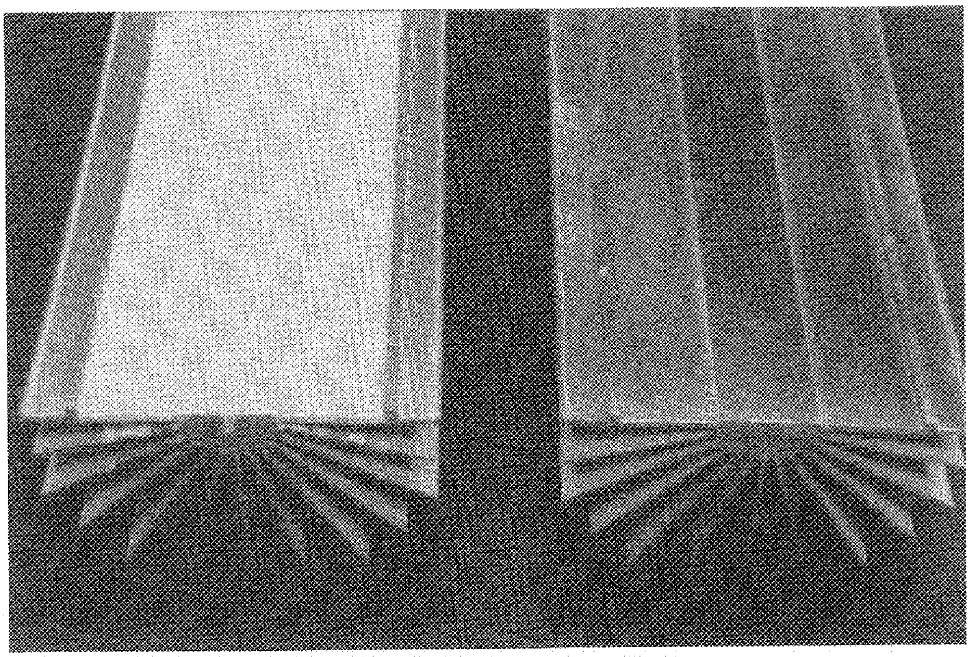


PHOTO 3-D

PHOTO 3-E



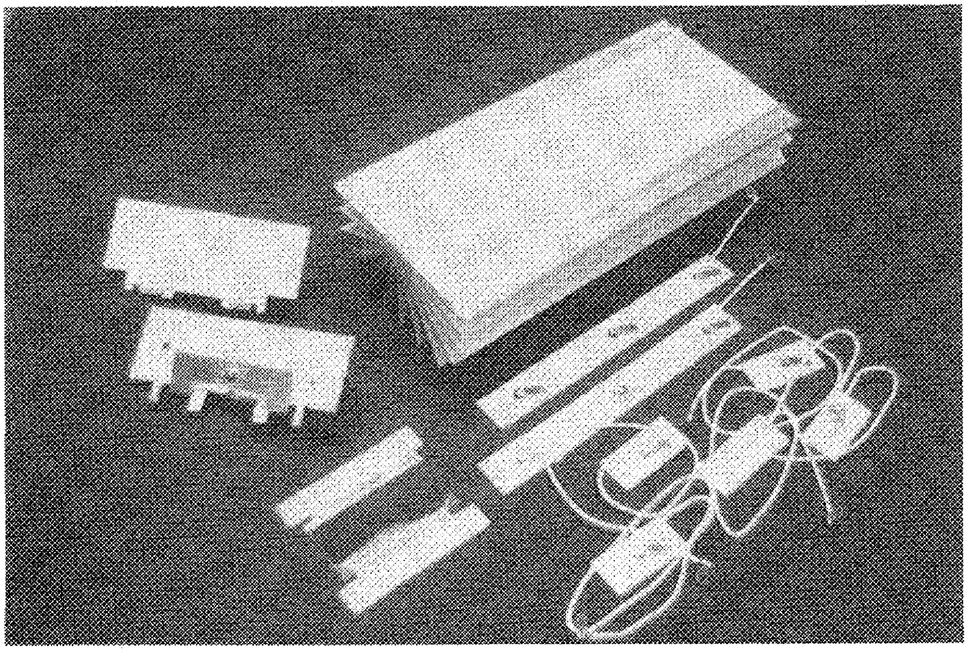
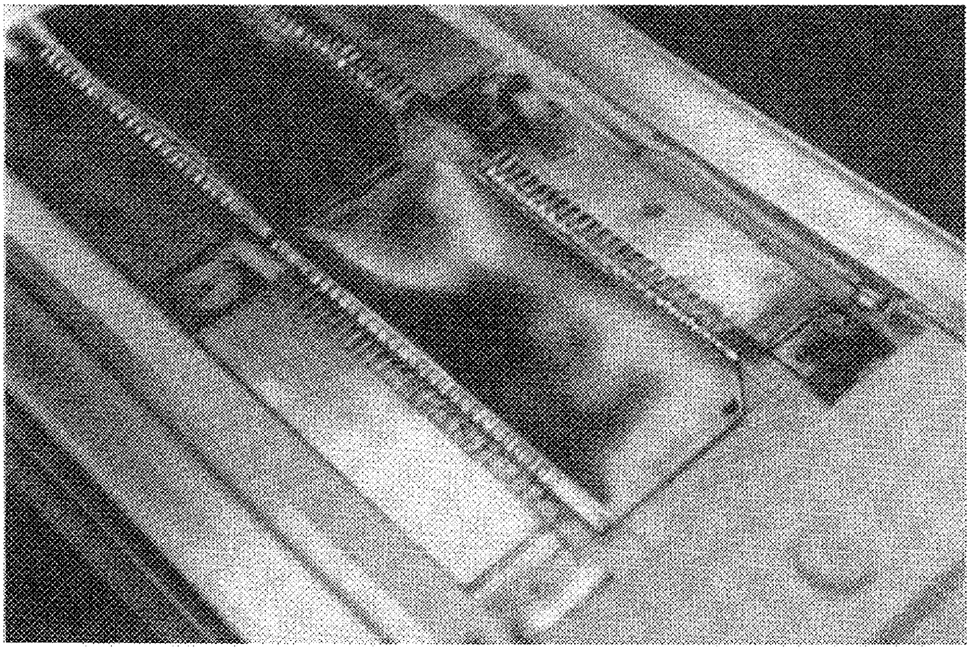


PHOTO 3-F

PHOTO 3-G



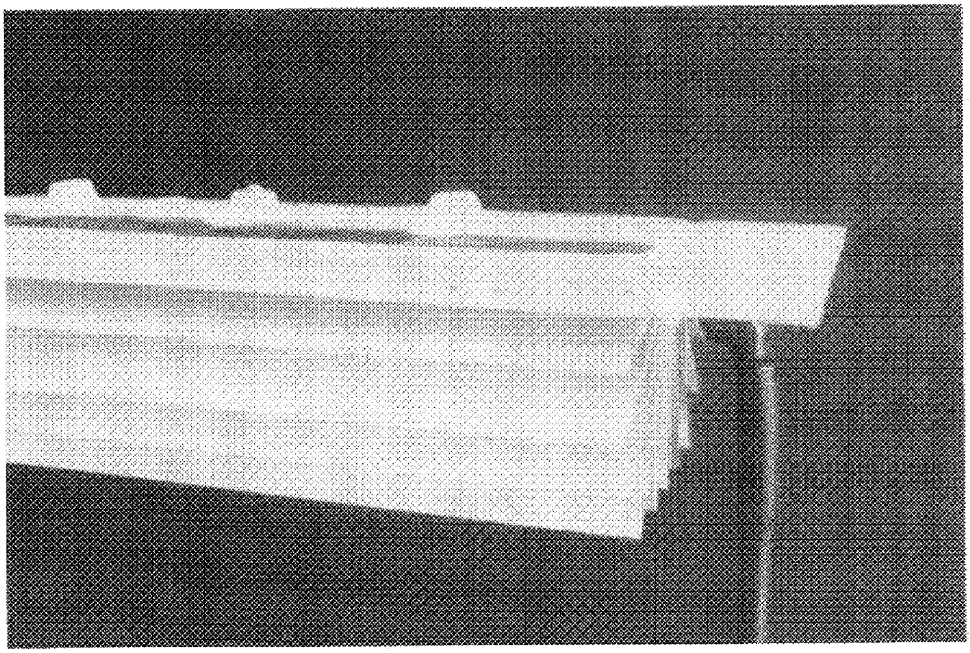


PHOTO 3-H

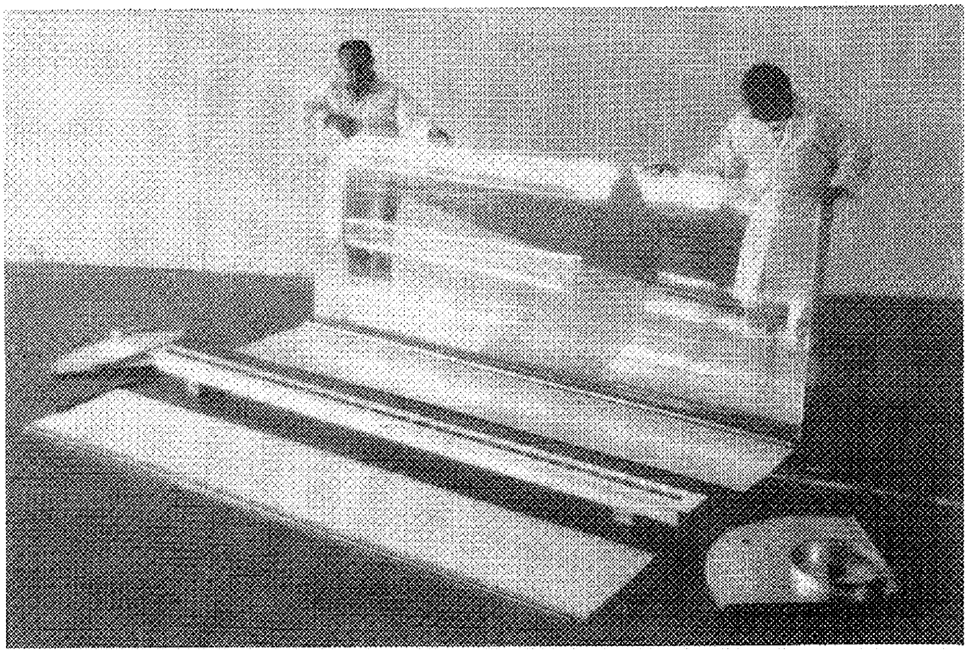
silicone and retested the unit until it had an acceptably small leakage current. This iterative process was both time-consuming and expensive. However, our array passed PVUSA's wet megger testing at first try, unlike most of the other technologies at the PVUSA test site. The labor content represented by all of these manual assembly steps is inordinately high at the present time. Fortunately, by using a new approach for the cell assembly (a fully integrated unit including the cell, prism cover, interconnects, bypass diodes, dielectric, and encapsulant), the labor-intensive steps associated with receiver assembly can be eliminated, as further discussed in the following section.

The final module assembly is generally done near the site of the solar power plant, to avoid shipping costs associated with assembled modules, which occupy a large volume of space. In addition to the lens and photovoltaic receiver, four sheet metal housing parts are procured from a qualified vendor. These housing parts are two end plates and two side walls, which are made from 0.032 inch marine-grade aluminum sheet (Photo 3-I). (Should aluminum prices again skyrocket, as they did a few years back, we can easily make these housing parts from galvanized steel sheet instead.) While many sheet metal shops could make these housing parts, Consumers, Inc., of Manitowoc, Wisconsin, has been our preferred vendor over the past decade. Consumers has consistently provided high-quality parts at competitive prices. The end plates and sidewalls snap together, and are permanently joined with a simple and rapid clinch/stake operation. The lens snaps into slots in the top edges of the sidewalls, where it is permanently attached with clips and structural adhesive (Photo 3-J). The lens/end plate interface is made with flexible seal, clips, and adhesive. Finally, the photovoltaic receiver is mated to a flange on the bottom edges of the sidewalls and endplates, where it is permanently attached with clips and structural adhesive (Photo 3-K).

We need to stress that our module is unique among all concentrator modules in its ability to tolerate very large inaccuracies in manufacture, assembly, and operation. For example, due to its unique configuration, our lens can tolerate slope errors of 10-15 degrees without any noticeable defocussing. Similarly, due to our large cell size, assembly tolerances on the order of ± 0.125 inch are fully acceptable. Likewise, our latest lens/cell design provides for a full ± 1 degree tracking error in the critical roll angle direction, and ± 10 degrees in the tilt angle direction without noticeable loss of optical efficiency. Furthermore, our module can easily tolerate the relatively huge expansion/contraction phenomena associated with the acrylic lens material. The combined effects of moisture absorption and thermal expansion cause the lens to expand and contract by a full 1% in each dimension, when the lens environment changes from cold/dry to hot/humid. Thus, over the 10 foot length of our module, the lens length can vary by more than an inch. In width, the lens can vary by nearly one-half inch. Such unavoidable lens movements can cause severe problems for point-focus modules in particular, and for conventional Fresnel lenses (point-focus or line-focus) in general. Only the optimized, symmetrical refraction, patented ENTECH Fresnel lens can tolerate these large changes in lens shape without optical performance degradation. We demonstrate this uncanny tolerance for shape errors with a laser ray trace model of our lens.

In summary, the current module manufacturing process is straightforward. However, we are currently using a large amount of manual labor to do repetitive and simple tasks, especially in the cell assembly fabrication and photovoltaic receiver assembly operations. The following section describes our proposed

PHOTO 3-I



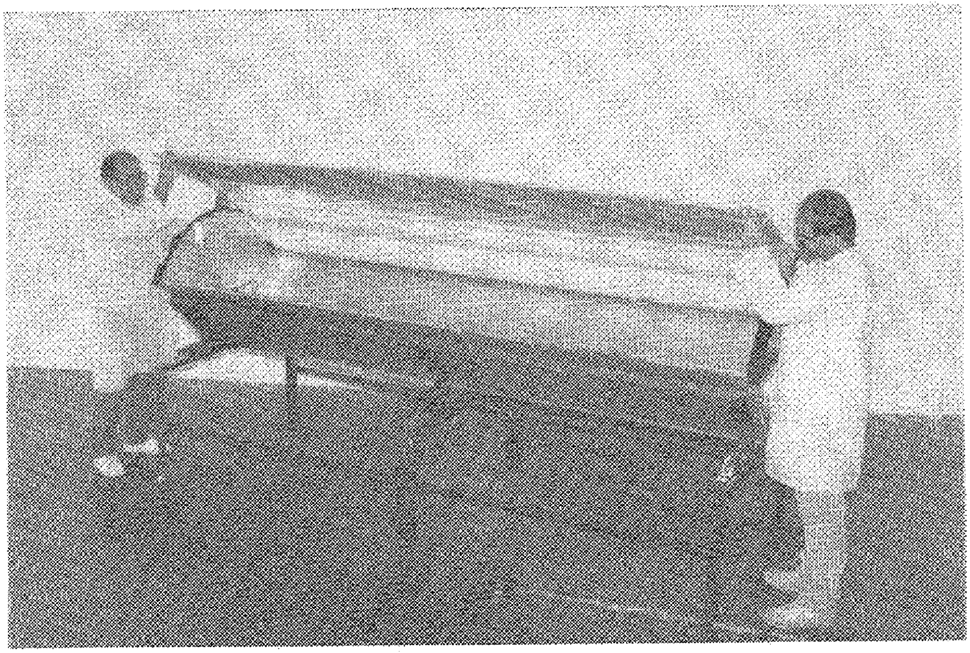
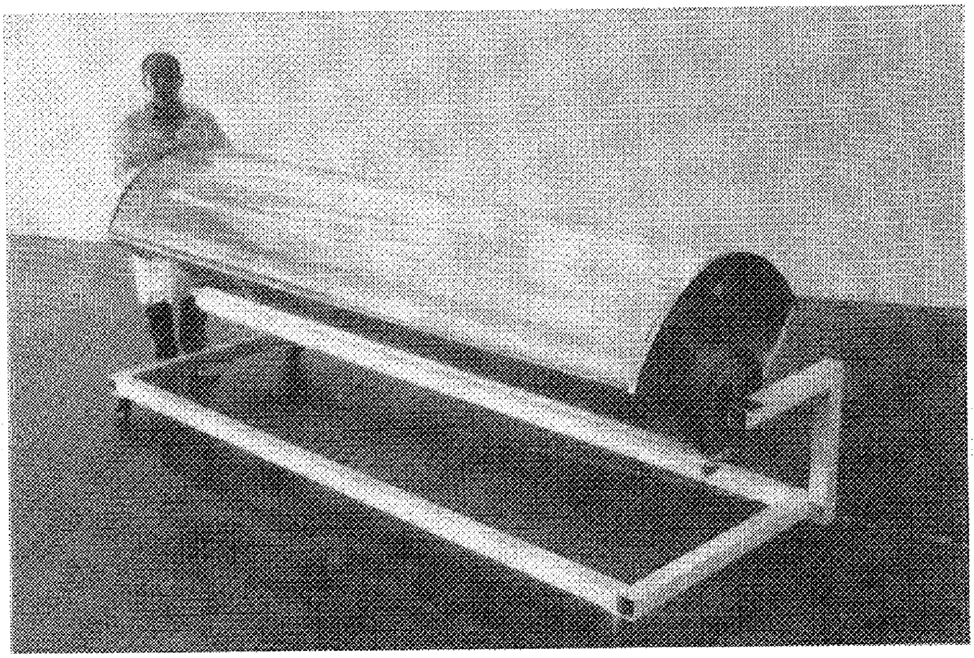


PHOTO 3-J

PHOTO 3-K



approach to module manufacturing to greatly reduce labor content, to dramatically expand production rates, and to vastly improve module quality. The proposed approach to module manufacturing is the result of more than two years of cooperative brainstorming, analysis, and design work involving ENTECH, Sandia, our key vendors (3M, Consumers, Solarex, et al), and our automated manufacturing consultants (Texas Instruments, Integrated Production Systems, Automation & Robotics Research Institute, et al) [15]. With the continued support of the DOE/SERI PV Manufacturing Technology program, we will be able to accelerate the development of this proposed new module manufacturing process.

3.2 Proposed Module Manufacturing Process

Figure 3-2 summarizes our proposed new approach to module manufacturing. The two most important improvements reflected in the new approach relate to the lens and the cell assembly, respectively. The new lens will utilize 3M's recently expanded allowable Lensfilm width of 39 inches. In the past, for each lens assembly, we used two identical pieces of Lensfilm, each 22 inches wide, and each comprising one-half of our lens pattern. The two Lensfilm pieces were taped together at their edges to form a full-width lens pattern, prior to lamination to the acrylic superstrate (as discussed in the previous section). The new wider Lensfilm will provide the full lens pattern on a single sheet. However, due to the 39-inch width limitation, we had to sacrifice a small amount of aperture area compared to our old two-piece Lensfilm approach. Therefore, the geometric concentration ratio of the new module will be 21X rather than 22X. This corresponds to a 33.4 inch wide aperture focussing onto a 1.6 inch wide cell. More importantly, the new single-piece Lensfilm should make possible in-line lamination at 3M's Lensfilm plant. Such in-line lamination would bond the Lensfilm directly to coiled superstrate sheet, furnishing a full thickness product, and completely eliminating solvent lamination at ENTECH's facility. This would not only reduce lens labor content and cost, and improve lens quality, but also eliminate the need for methylene chloride solvent usage within our plant (a major environmental, safety, and health concern). At no cost to ENTECH or the government, 3M has already produced tooling for the new 21X lens, which ENTECH has designed to tolerate a full 1 degree roll angle tracking error without loss of optical efficiency. Under our proposed PVMaT Phase 2A program, 3M will develop the manufacturing technology to perform the in-line lamination. Therefore, the only lens assembly operation remaining to be done at ENTECH will be to attach edge strips to the lens, to properly self-index with the sidewalls of the module housing. This operation is simple and rapid, with miniscule labor content.

The most dramatic improvement in our proposed approach to module manufacturing relates to the new photovoltaic cell assembly (PVCA) concept and its automated production. The new PVCA comprises an integrated assembly of cell, copper interconnects, bypass diodes, prism cover, dielectric, and encapsulation. Over the past two years, working with outside experts from Sandia, Texas Instruments, Integrated Production Systems, the Automation & Robotics Research Institute, and other organizations, we have identified fully automated processes for high-speed assembly of the PVCA, thereby mass-producing a commodity similar to a solid-state electronic component. Conceptually, the new approach first involves stamp-forming of thin-gauge copper coil material into the left/right and top/bottom interconnects. The interconnects are then soldered to both the photovoltaic cell, and also two bypass diodes, which are simply smaller versions of the solar cell turned upside down to reverse their polarity (Photo 3-L). In

FIGURE 3-2 - PROPOSED ENTECH 21X MODULE MANUFACTURING FLOW CHART

PV CELL ASSEMBLY (PVCA) FABRICATION

Automated PVCA Assembly Line

1. Procure Cell Assembly Materials (Cells, Diodes, Copper Coil, Silicones, & Solder)
2. Form and Solder 4 Interconnects to Cell and Diodes
3. Mold Prism Cover Directly onto Cell
4. Mold Silicone Dielectric/Encapsulant Over and Between Interconnects and Over Back of Cell Assembly
5. Flash Test/Group PVCA's
6. Select 31 Current-Matched PVCA's ---> 4.

PHOTOVOLTAIC RECEIVER ASSEMBLY

Semi-Automated or Manual

1. Procure Receiver Materials (Heat Sink Extrusion, Wire, Cell-to-Cell Jumper Tabs, Silicones, Solder, & J-Box)
2. Attach Lead Wires & J-Box to One End of Receiver
3. Spray Thin Adhesive Layer over Bare Heat Sink Extrusion
4. Bond PVCA's to Heat Sink
5. Solder Jumper Tabs between PVCA's and Coat Joints with Dielectric.
6. Perform Dry/Wet Hi-Pot Test ---->--------

LENS ASSEMBLY

3M In-Line Lamination

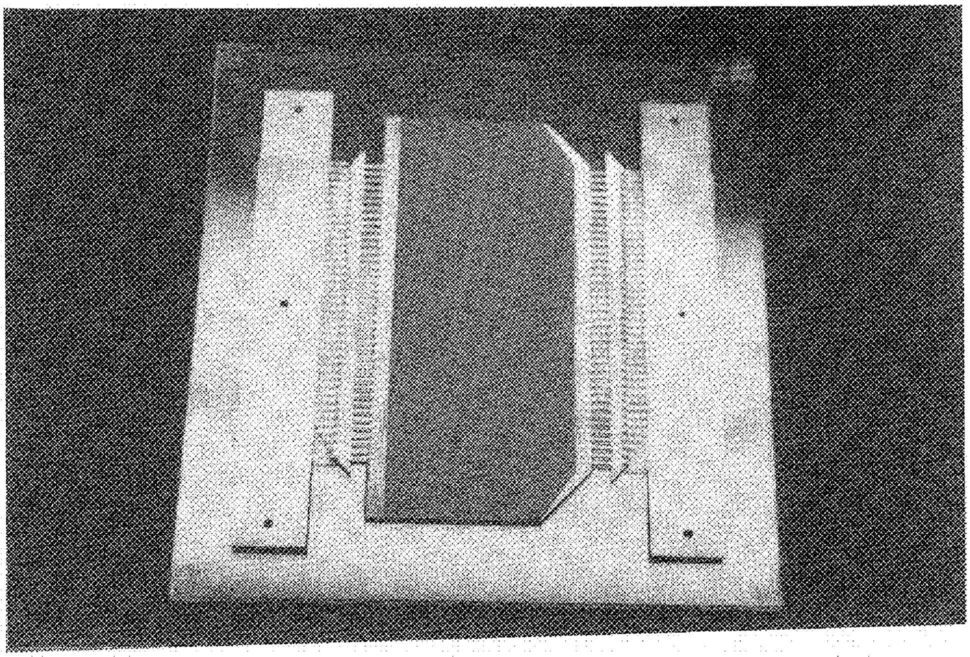
1. Procure Lens Materials (Laminated Lens & Edge Strips)
2. Bond Edge Strips to Lens -----------> 3.

MODULE ASSEMBLY

At Power Plant Site

1. Procure Module Materials (End Plates, Sidewalls, Adhesive, Lens Seals, & Clips)
2. Clinch/Stake End Plates to Sidewalls Using Structural Adhesive
3. Attach & Align Lens to Housing Using Clips with Adhesive
4. Attach Photovoltaic Receiver <----------- to Lens/Housing Unit Using Clips with Adhesive

PHOTO 3-L



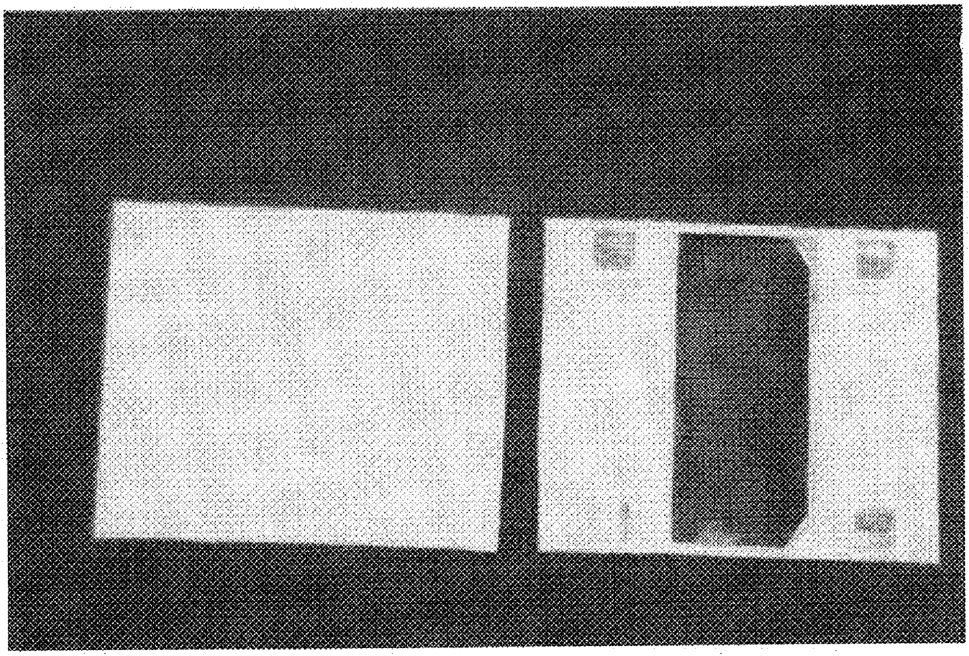


PHOTO 3-M

fact, the diodes can be made from the scrap areas on the solar cell wafer which are normally discarded as scrap. Next the prism cover is molded directly on top of the cell, replacing the two separate steps of prism cover molding and prism cover attachment. Next, the loaded silicone dielectric/encapsulant is molded completely around all surfaces of the PVCA, excluding only the prism cover surface and four small access points for later cell-to-cell conductor attachment (Photo 3-M). The completed PVCA is then automatically flash-tested and current-grouped. The beauty of the PVCA concept is that it not only eliminates the labor content associated with the present cell assembly operations, but it also eliminates most of the labor-intensive steps associated with receiver assembly as well, as further discussed below.

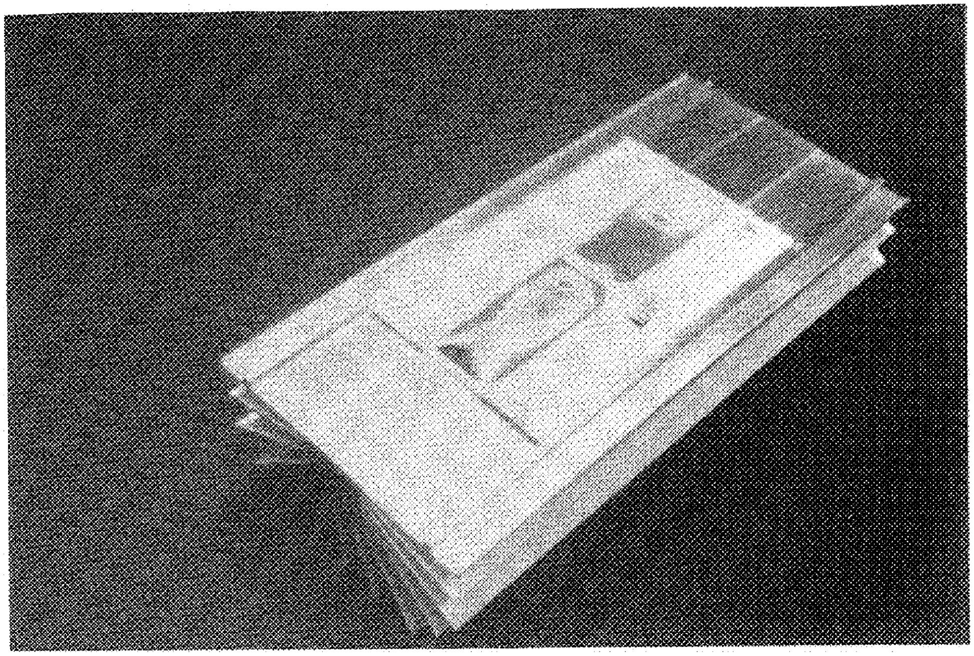
Under the proposed PVMaT 2A program, we will work with Texas Instruments, Integrated Production Systems, and other outside organizations to complete the design and engineering of a fully automated assembly line to produce PVCA's. Furthermore, we will complete the critical laboratory process development work associated with the soldering, prism-cover molding, and encapsulation steps in the PVCA production. Based on the analytical and empirical work done by our team over the past two years, we see no real "show-stopper" problems in successfully implementing the PVCA production line.

In addition to using the new PVCA concept, the new receiver also uses a simpler approach to external wiring. A single junction box (J-box) on one end of the receiver contains both electrical terminations (plus and minus). This is accomplished by running a flat insulated wire under the cell string (in a recess in the heat sink extrusion) from the positive end of the receiver to the negative end (where the J-box is located). This simple change not only reduces receiver cost, but also eliminates our present module polarity distinction. Since our sun-tracking roll drive system uses a pulley on the south end of our module, we presently have two versions of our modules: those with a negative terminal at this south end and those with a positive terminal at this south end. With the new single J-box approach, we will finally have only one version of module, greatly simplifying module book-keeping and field wiring.

With the new PVCA's, the bare aluminum extrusion is simply sprayed with a thin coating of adhesive and the PVCA's are laid down end-to-end to form the cell string (Photo 3-N). Small, insulated, copper jumper tabs are then soldered between cells, with the resultant small joints then coated with an encapsulant. Similar tabs effect the electrical connection to the J-box terminals, completing the receiver assembly process (Photo 3-O). Since the PVCA itself is completely sealed, no problems are anticipated in either dry or wet hi-pot testing of the completed receiver. Receiver assembly can be done in either a semi-automated or manual process. Texas Instruments has proposed a straightforward semi-automated receiver production line at ENTECH. For some applications (e.g., developing countries), however, it may be desirable to use manual receiver production. In either case, the PVCA concept has eliminated most of the difficult processes associated with our present receiver assembly.

The basic module assembly approach (integrating lens, housing, and receiver) will remain the same, although noteworthy improvements are being made in the design, configuration, and materials associated with the module assembly, under our Sandia Concentrator Module Initiative project. For example, new lens seals are under development which will be more effective in preventing water and dust infiltration, while also reducing assembly labor. In addition, we are exploring

PHOTO 3-N



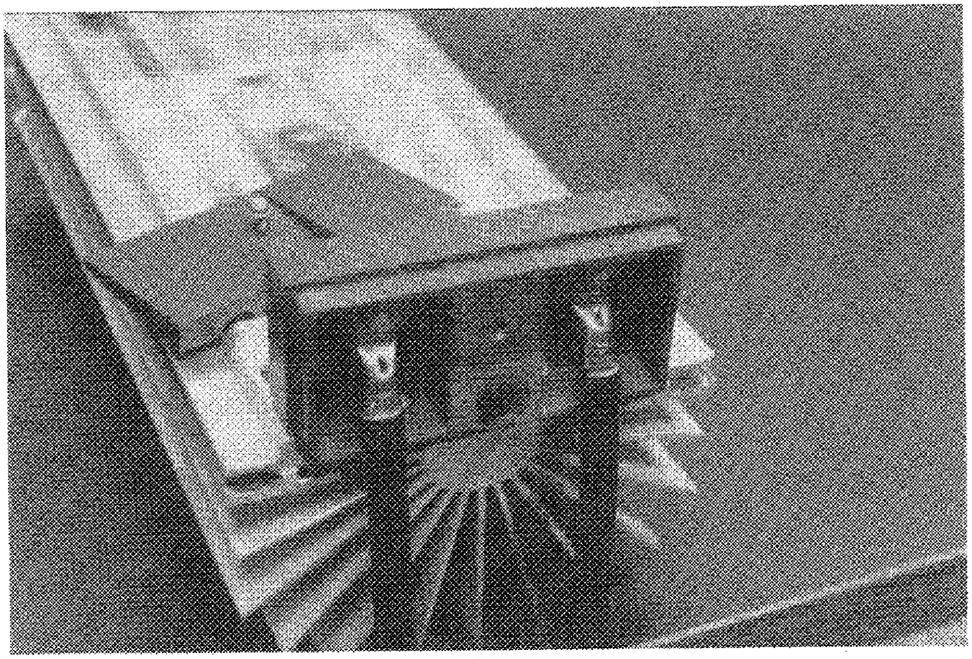


PHOTO 3-O

a longer module assembly (e.g., 12 feet rather than 10 feet) to provide more power output per unit of assembly labor. We are also working closely with Sandia on improvements to our extruded heat sink design, with a goal of lowering cell operating temperature, thereby increasing power output. Our key suppliers (3M, Consumers, etc.) are also working closely with us on these module assembly improvements.

3.3 Key Problem Areas and Planned Solutions

The previous section summarized our proposed new module manufacturing process, which will simultaneously increase production rates, reduce manufacturing costs, and improve product quality (resulting in better module performance and longer module life). The following sections describe potential problems which could impede the development of the new module production process, and our planned solutions for overcoming these problems.

3.3.1 PV Cell Assembly (PVCA)

The automated production of PVCA's is essential to our new production process. After thorough review by our technical team (including Sandia, Texas Instruments, and Integrated Production Systems), we have concluded that the key potential problem area is in prism cover molding directly to the cell. The other processes, including interconnect forming, soldering, encapsulation, and flash-testing, have already been successfully accomplished by other companies making similar products with equal or tighter tolerances. However, prism cover molding is unique to our product. While Sandia, ENTECH, and the Automation & Robotics Research Institute have each successfully molded prism covers onto cells in laboratory settings, much work remains to be done to develop a production-worthy process for this task. The two key problems with prism cover molding directly onto the cell are tool-to-grid pattern alignment and de-molding without cell breakage. Our plan to solve the alignment problem includes maintaining the prism cover tool at a constant (elevated) temperature, so that thermal expansion/contraction effects will be mitigated. In addition, a vision system will be used to look directly through peep holes in the prism cover molding tool at the grid pattern on the cell, while the cell is moved relative to the mold, to thereby align the grid pattern to the prismatic optical pattern in the mold. After this alignment is done, silicone will be admitted to the hot mold where it will rapidly cure. Then the de-molding problem arises. To solve this problem, we have developed and verified a strategy using a vacuum to hold the back of the cell against a rigid surface while air is admitted into the space between the mold and prism cover on the front side of the cell. Other tricky areas related to the prism cover molding are mold seals, silicone flow control, tool life, cycle time/temperature relationships, etc. We have an excellent team of experts addressing the prism cover molding problem at the present time. In summary, we are confident of being able to mold prism covers directly against cells in a production environment, but much work remains to be done.

3.3.2 PV Receiver Assembly

The two key potential problems with PV receiver assembly using the new PVCA's are adhesive bonding of PVCA's to the heat sink and electrical joining of the cells into a series circuit. We are working closely with the major silicone adhesive manufacturers (including Dow Corning and General Electric), as well as 3M, on various candidate adhesive systems for bonding the PVCA's to the heat sink. With our new PVCA approach, we will no longer need the adhesive to possess either high dielectric strength or high thermal conductivity. Instead, we plan to use a strong thin (i.e., 0.0005 inch) adhesive layer to minimize the temperature gradient across the bond line. The other key potential problem relates to joining the cells together electrically. While we presently plan to use a no-clean-flux soldering approach, we are also investigating both crimp-type connections and ultrasonic welding. After the joint is made, we plan to dispense a small dab of silicone over the joint to complete the receiver encapsulation.

3.3.3 Lens Lamination

The in-line lamination of Lensfilm to acrylic superstrate material is very desirable for our proposed module manufacturing process, from cost, quality, and environmental, safety, and health (ES&H) considerations. 3M is confident that they will be able to develop the manufacturing technology for the in-line lamination. One key problem relates to coiling of the superstrate material so that continuous lamination can be implemented. 3M has identified a new grade (Im-Plex) of acrylic sheet made by Rohm & Haas that is more impact resistant than currently used grades. Sandia recently ran 1" diameter hail impact tests on 0.092" thick sheets of the new material with excellent results. (In the past, we have needed 0.125" thick superstrates to withstand 1" hail impacting at terminal velocity.) The new material is coilable due to its reduced thickness. The other key problem with in-line lamination is in forming the joint between the two sheets. While 3M is, of course, secretive about their various options for accomplishing this lamination, they are also confident that it can be done. If, however, they are unable to develop the in-line lamination, they have also offered two back-up plans. The first is to use a much less hazardous solvent than methylene chloride in our existing lamination facility, with appropriate upgrading of the facility to a semi-automated work station. The second back-up approach would be for 3M to apply a pressure-sensitive adhesive to the Lensfilm, such that we could laminate it to superstrate sheets with no solvent. In summary, we are confident that a low-cost, environmentally benign method of laminating lenses will be achieved in the near term.

3.3.4 Module Assembly

The module assembly portion of the manufacturing process is the most straightforward of all the production steps. The only significant problem in the current module assembly approach relates to seals between the lens and housing. These seals must accommodate the very large relative expansion/contraction effects between the lens and housing. Going from a cold, dry winter day to a hot, humid summer day, the lens will expand by about 1% in each dimension, due to combined thermal expansion/moisture absorption effects. Thus the seal must tolerate significant movement of the lens relative to the housing. Furthermore, due to its convex shape, the lens is subjected to very large aerodynamic suction forces (about 1,000-1,500 pounds over its 10-foot length) under high winds (80-100 mph) out of the east or west. Thus the seal must tolerate large structural loads. Finally, the seal should minimize rain and dust infiltration over the 20-30 year life of the module. Our present module uses silicone seals with metal clips at the lens/sidewall interface, and EPDM seals with metal clips at the lens/end plate interface. While these seals are functional and have passed Sandia's grueling qualification test sequence for concentrator modules, we are currently developing more elegant solutions to the seal problem. In summary, the module assembly portion of the module manufacturing process is relatively problem-free, with only seals/gaskets representing significant issues.

3.3.5 Vendor-Furnished Parts

Our key vendor-furnished parts are cells, Lensfilm, heat sinks, and sheet metal housing parts. As discussed in previous sections, we are working with a number of the leading cell manufacturers on 20-sun concentrator cell versions of their production one-sun cells. Solarex has been our key supplier of cells to date, and we are working closely with Solarex on the development of their next-generation cell under Sandia's Concentrator Cell Initiative program. We are also working with Astropower, BP Solar, and other companies, to ensure an adequate supply of qualified cells for future module production. We anticipate the purchase of a significant number of cells (e.g., 1,000 each) from several suppliers under our proposed PVMaT Phase 2A program. These cells will be used during the manufacturing technology development work on PVCA's. Thus, we do not anticipate any key problems in the cell supply area. However, cell performance is crucial to our system economics, and the concentrator cell R&D efforts at SERI, Sandia, and industry should obviously be continued, and expanded if possible.

As already discussed, 3M is our key Lensfilm supplier. The 3M product already meets our performance, volume, and cost requirements, as dictated by the DOE near-term goal of 12 cents/kWh levelized electricity cost. Under our proposed PVMaT Phase 2A program, 3M will extend their production capability, as discussed in Section 3.3.3 above.

In the extruded heat sink area, we are working closely with Sandia on new designs which will result in a significantly lower operating cell temperature, especially on hot, windless summer days. This heat sink R&D is very much a manufacturing technology activity. Cost/performance tradeoffs always indicate that we would like to have more fin area than we have in the existing heat sink extrusion. However, extruders are reluctant to extend either the fin length or the total number of fins, for fear of die breakage or yield problems. We have worked with several excellent extruders over the past dozen years, including one firm who provided over 40,000 pounds of extrusions for our 3M/Austin 300 kW system installation. We plan on working with this firm, and others, on more advanced heat sinks for our module, under our proposed PVMaT Phase 2A program. We are also investigating alternative cooling means for our photovoltaic receiver, including heat pipe systems and forced convection systems, under the Sandia Concentrator Module Initiative program. In summary, we do not consider the heat sink to be a key problem area, but we are working toward more efficient heat sinks in the future.

In the sheet metal housing parts area, we are working with our key supplier, Consumers, Inc., on lower cost versions of the end plates and side walls comprising the housing. In addition, we are evaluating longer modules (e.g., 12 feet instead of 10 feet) to amortize assembly-related costs over larger aperture areas (and thus larger power outputs). Since the housing represents very conventional sheet metal technology, with relatively loose tolerances, we do not consider this vendor-furnished equipment to be a problem area, although we are continuing to simplify and improve the housing design.

4.0 CONCLUSIONS AND RECOMMENDATIONS

The key conclusion drawn from our Phase 1 study is that our 21X linear Fresnel lens photovoltaic concentrator module can realistically meet the near-term Department of Energy goal of 12 cents/kWh levelized electricity cost, provided that our proposed new module manufacturing process is implemented at a production scale of at least 10 megawatts per year. Supporting conclusions include:

1. An automated photovoltaic cell assembly (PVCA) production line will eliminate most of the present labor content in our photovoltaic receivers.

2. In-line lamination of lenses by 3M will reduce lens cost and eliminate the need for solvent lamination at ENTECH's plant.

3. With the new PVCA-based receiver and the in-line laminated lenses, the balance-of-module assembly work will be straightforward and cost-effective, due to the extremely large allowable tolerances of this unique concentrator module.

4. No further breakthroughs in materials, module efficiency levels, device stability, or basic manufacturing approaches are needed for this concentrator technology to succeed. Straightforward engineering development and large-volume manufacturing are the keys to meeting not only the near-term Department of Energy goal, but also the long-term goal of 6 cents/kWh.

The key recommendation from our Phase 1 study is to continue our PVMaT program into Phase 2A, wherein our team (including 3M, Texas Instruments, Integrated Production Systems, Consumers, Inc., etc.) will develop the needed manufacturing technology to implement the new module manufacturing process.

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7. Author(s)
M. J. O'Neill, A. J. McDanal, J. L. Perry, M. C. Jackson, R. R. Walters

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
ENTECH, Inc.
1015 Royal Lane
P.O. Box 612246
DFW Airport, Texas 75261

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16. Abstract (Limit: 200 words)

This final technical report documents ENTECH's Phase I contract under the Photovoltaic Manufacturing Technology (PVMaT) project. Under this project we prepared a detailed description of our current manufacturing process for making our unique linear Fresnel lens photovoltaic concentrator modules. In addition, we prepared a detailed description of an improved manufacturing process, which will simultaneously increase module production rates, enhance module quality, and substantially reduce module costs. We also identified potential problems in implementing the new manufacturing process, and we proposed solutions to these anticipated problems. Before discussing the key results of our program, however, we present a brief description of our unique photovoltaic technology. The key conclusion of our PVMaT Phase 1 study is that our module technology, without further breakthroughs, can realistically meet the near-term DOE goal of 12 cents/kWh levelized electricity cost, provided that we successfully implement the new manufacturing process at a production volume of at least 10 megawatts per year. The key recommendation from our Phase 1 study is to continue our PVMaT project into Phase 2A, which is directed toward the actual manufacturing technology development required for our new module production process.

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