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Improved Techniques for Manufacturing the Alpha Solarco Concentrating Photovoltaic System

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E. Schmidt
Alpha Solarco, Inc.
Cincinnati, Ohio

NREL technical monitor: R. Mitchell

National Renewable Energy Laboratory
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Photograph of the Alpha Solarco Proof-of-Concept Array in Pahrump, Nevada. Second generation modules are currently being assembled with on-line connection with the Valley Electric Association to be made in June 1991.

1.0 INTRODUCTION

In an effort to increase the U.S. share in the worldwide photovoltaic (PV) industry, the Solar Energy Research Institute (SERI) is sponsoring the Photovoltaic Manufacturing Technology Project, a two-phase research and development effort directed to the improvement of photovoltaic production and performance techniques. Under SERI Contract # XC-1-10057-9, Alpha Solarco, Inc., has participated in Phase I of the project, which is intended to define current photovoltaic manufacturing capabilities and to identify and evaluate potential manufacturing improvements that can lead to significantly increased production capacities and reduced manufacturing costs.

This report, submitted to SERI in partial fulfillment of the contract requirements, supplements the Interim Report submitted in February and documents the work we performed leading to the successful completion of the four tasks outlined in the Statement of Work:

1. Describe the overall procedure involved in the manufacture of photovoltaic cells and modules.
2. Identify and describe potential cell and module manufacturing processes that can lead to improved performance, reduced manufacturing costs and significantly increased production, and note the long-range potential benefits of these improvements.
3. Identify and describe any problems that may impede the achievement of the long-range benefits.
4. Identify and describe the approaches for solving the identified implementation problems, including time and cost estimates.

This report includes a brief description of the procedures we used to complete each task (Section 2.0). It continues with a discussion of the current procedures used to manufacture our concentrating PV module, and of ways to improve it (Section 3.0). The report concludes with recommendations for the implementation of the most promising suggestions (Section 4.0).

2.0 PROCEDURES

To complete the four tasks described in the SERI Statement of Work, we formed a four-member team to study the current processes used in manufacturing our AS-150 concentrating photovoltaic module (shown in Figure 1), and the tracker system used to accurately position the PV array.

The team included: Mr. Edward Schmidt, President, who led the team, and three outside experts. Mr. Greg Whiteaker, Production Engineering consultant, provided technical support. Mr. Carl Yoder of Gem City Engineering and Machine helped study the manufacturing process and helped develop a plan for incorporating automation into the assembly line. Dr. Vern Risser of Daystar, Inc., assisted in developing methods for measuring the effectiveness of potential improvements.

The team members observed the assembly of the PV module and studied a video tape showing details of the current manufacturing process. Using the tapes, the team identified and timed each step in the assembly process and identified those steps that are particularly time-consuming or repetitious. The team then developed suggestions for improving the procedures and estimated the cost of implementing the changes. Improvement ideas were also solicited from all the production technicians who helped to manufacture the AS-150 modules that we installed at our test site in Pahrump, Nevada, in 1989.

The investigation resulted in numerous suggestions for improving our manufacturing processes, and each suggestion was considered by the team. The evaluation of these suggestions, which was necessarily subjective, was focussed on improvements to the cell assembly because of two practical factors. First, although a larger manufacturing facility is in the planning stages, our current facility is limited in size so that much of the assembly and testing of the module, which is about 10 feet long, must be done in a piecemeal fashion. Second, the manufacture of the cell assembly unit--the heart of our PV module--constitutes about half the total cost of the PV module.

MODULE OUTPUT: 150 WATTS

Figure 1. *Alpha Solarco 150 PV Module.*

2.0 PROCEDURES (continued)

We feel that changes to our cell assembly can be implemented and evaluated at our prototype facility. When the larger production facility becomes available, the cell assembly production line and procedures can be transferred to it without significant changes. Also, a reduction in the cost of the cell assembly manufacturing procedure promises the greatest cost savings for the overall manufacturing process.

To determine a fair estimate of the cost savings in a full production facility, we established a baseline for comparison of production improvement suggestions. We selected 8 MW per year as this production level. Although it might not be practical to expand to 8 MW annual production using our current procedures, it would be possible. Also, a production rate of 8 MW per year is a reasonable goal for the automated production line that is planned for our new facility.

The team also considered suggestions for the improvement of the module assembly process and the tracker system, but with less emphasis than the cell assembly process. We will continue engineering work related to improved manufacturing of the module and the tracking system, but we plan to delay the implementation of those improvements until appropriate manufacturing facilities are available. With these decisions in mind, the team members asked the following questions about each suggested improvement:

- What are the potential savings in time and money?
- What is the cost to implement the suggestion?
- What fixtures or tooling must be modified or replaced?
- How will the implementation affect other work areas?
- How much engineering development is necessary?
- What is the risk factor?

The team favored those suggestions that could be implemented with little risk, even if the total savings might be less than those requiring more significant changes. Those suggestions that had the potential to yield tremendous savings but also involved tremendous risks were assigned a lower priority than those suggestions involving fewer risks because we wanted to focus on near-term improvements.

The team concluded its efforts by identifying and recommending the five suggestions for improving the cell assembly manufacturing process that have the highest probability of success. Some improvements to module manufacturing and to the tracker / drive system were suggested and are discussed here, but possible benefits in these areas are less well defined because of our emphasis on the cell assembly.

3.0 RESULTS AND DISCUSSIONS

Our AS-150 concentrating PV module contains 24 cell assemblies. One hundred four modules are mounted on a tracker to form the array system shown on the front cover of this report. We are working with Sandia National Laboratories to increase the output of our module. We expect the improved units will produce over 165 Watts at standard operating conditions. The work performed for this project will help increase the module output by producing more consistent cell assemblies and modules. The improvements we plan for both items are discussed separately below.

3.1 Cell Assembly

Our study shows that if we tried to expand to a production rate of 8 MW per year (1,140,000 cell assemblies) without significantly changing our manufacturing procedures, the estimated cost of making cell assemblies would be \$12.68 per unit for parts, supplies, and direct labor. This cost would translate to a selling price over \$6.00 per watt at a systems level--a cost too high to interest major utilities in using our systems. However, our study also shows that if we incorporate the suggestions recommended in this report, we should be able to reduce the cell assembly cost to \$2.83 per unit, which would bring our selling price under \$2.00 per watt. With improvements to the module and tracker areas, and with increasingly automated production, we feel our selling price can be reduced still further to under \$1.75 per watt .

Our current costs and our cost goals for manufacturing the cell assemblies are listed in Table 1. The direct labor costs given in the table are those required to handle the part; they are determined assuming an average production rate of 1,140,000 per year. They do not include engineering, calibration, or maintenance time.

TABLE 1. *Cost Comparisons for Manufacturing the Cell Assembly (8 MW/Year).*

Process	Current Cost (\$)*		Cost Goals* (\$)	
	Materials	Direct Labor	Materials	Direct Labor
Cell	1.70	0.35	1.70	0.10
Heat Spreader	0.22	0.15	0.22	0.01
Top Connector	0.08	0.20	0.08	0.01
Bottom Connector	0.06	0.05	0.06	0.01
Danar Insulator	0.08	0.20	0.08	0.00
SOE	1.20	0.07	0.15	0.07
Solder	0.09	0.15	0.09	0.00
Sylgard Primer	0.07	0.15	0.07	0.00
Sylgard	0.06	0.10	0.15	0.00
Tacks	0.17	0.30	0.30	0.00
Shoulder Washers	0.24	0.00	0.00	0.00
Testing	0.00	0.34	0.00	0.00
Alcohol	1.71	0.10	0.00	0.00
Water	0.76	0.02	0.00	0.00
Flux	0.09	0.00	0.10	0.00
Shield Gas	1.93	0.00	0.00	0.00
Suits	1.66	0.00	0.05	0.00
Gloves	0.15	0.00	0.01	0.00
Charge for Automation	0.00	0.00	0.00	0.10
Totals	\$10.27	\$2.41	\$2.52	0.32

*These costs do not include management, sales, or administrative costs associated with operating our business.

The PV cells cost \$1.70, and we do not forecast a significant reduction in this cost in the near future. The heat spreader is milled from one-eighth inch rolling stock. In 1990, we paid \$0.32 per heat spreader--milled, polished, and cleaned--for an order of 3,000, and \$0.10 per spreader was needed for inspection and handling. The top connector is manufactured in-house from 0.010 inch copper. The formed and cleaned top connector costs us \$0.11 each in lots of 3,000, and the bottom connector costs \$0.09. The Danar template, solder, Sylgard, tacks, and washers cost \$1.26 for each cell assembly. The SOE is subcontracted from an area glass company at a cost of \$1.70 per unit in small prototype lots, but the direct labor for handling and alignment adds \$0.09 per unit. The biggest potential cost saving could be realized by changing the soldering process to a fluxless ultrasonic soldering method. This will eliminate the multiple cleaning steps that are now required and reduce the supplies cost by over 95%. The total parts cost for the cell assembly is estimated to be \$10.27 when purchased in lots of 1,140,000. The direct labor associated with the parts adds \$2.41, for a total cost of \$12.68.

We discuss the current manufacturing methods of the cell assembly in Section 3.1.1 and the suggested improvements in Section 3.1.2.

3.1.1 Current Procedures for Cell Assembly Production

Currently, 12 steps are required to make the cell assembly. Each step has been analyzed to determine whether it can be eliminated or to estimate possible savings in time and parts that might be obtained with improved handling, batch processing, newly designed tooling and fixtures, automation, and changes in processing that allow the reduction of cleaning steps. Approximate manufacturing labor time is indicated (in seconds per cell assembly) for each step.

Step 1. Procuring Cells and Raw Materials

The parts that are used to manufacture a cell assembly are a float zone crystal silicon cell, a heat spreader, a top conductor, a bottom conductor, a secondary optical element (SOE), and a template made of Danar, a high-quality electrical insulator. The relation of these parts is shown in Figure 2.

The silicon cells are procured currently from Applied Solar Energy Corporation (ASEC P/N 60-7046). The float zone single crystal silicon cells, with an active area of 0.164 square inches, are metallized on the bottom and have a specially designed grid pattern made to our specification. In 1990, we paid \$4.00 per cell for a quantity of 24,000. Each cell was tested initially by the supplier, but the cost does not include internal handling and testing of the incoming cells. (0).

Step 2. Acceptance Testing of I-V Cells

For the small lots that we have been buying, we have individually tested every PV cell using a computer-controlled flash tester that is used to measure the I-V curve of each cell. The output of the cell is measured under 400 suns and the maximum power point is calculated. Any cell that does not exceed 16 percent efficiency under the test conditions is rejected.

The cells are placed on the test jig by hand; the probes are set in place temporarily and data is taken so the characteristic I-V curve can be plotted. This testing process takes about 20 seconds per cell. To test 1,140,000 cells would require about 1,000 man days. (20).

CELL ASSEMBLY COMPONENTS

(A) Copper Heat Spreader	(B) Bottom Connector	(C) Electrical Insulation Film
(D) Concentrator Cell	(E) Top Connector	(F) Shoulder Washer (2)
(G) Metal Piercing Tack (2)	(H) Secondary Optical Element.	

Figure 2. The Alpha Solarco Cell Assembly.

Step 3. Applying Solder to the Back of the Cells

Each cell is "tinned" by putting solder paste on the back of the cell and melting it at 179°C. Forty-eight cells are processed at one time. The cells are placed by hand in a fixture, the solder is applied through a screen to the back of each cell, and the fixture is passed through a belt furnace where the solder is melted to obtain a uniform solder layer on the back of the cell. The cells are then removed from the solder fixture and stored until final cell assembly. They are then cleaned in an ultrasonic cleaner using Isopropyl Alcohol (IPA) for a period of 3-5 minutes before final assembly. (3).

Step 4. Cleaning and Inspecting the Heat Spreader

Next, the heat spreader is selected and cleaned in an acid bath followed with distilled water and IPA rinses. The heat spreader is inspected and then stored. The cleaning and inspection process is entirely manual and must be performed on every heat spreader. (10).

Step 5. Applying Solder Flux on the Heat Spreader

Solder flux is applied by hand to the center area of each heat spreader where the cell is to be attached. The heat spreader is now ready to accept the Danar template. (5).

Step 6. Affixing the Danar Cell Template

A 0.005 inch thick transparent dielectric material known as Danar, with a square hole punched out of its center, is placed over the heat spreader. The square hole is an alignment guide for the PV cell. (5).

Step 7. Aligning the Cells on the Heat Spreader

Using the Danar template as a guide, we place the PV cell by hand in the middle of the template. (5).

Step 8. Manufacturing and Preparing the Connectors

The bottom and top connectors are stamped from 0.010 inch thick copper sheet in a 5 step process that includes the shaping of "finger" connection holders for the wire that interconnects the cell assemblies (see Figure 3).

The top connector is cleaned and prepared for soldering. The solder is applied through a screen to the fingers that make contact with the PV cell. The connector is heated to 179°C to melt the solder, then cleaned by passing it through the ultrasonic IPA cleaner.

The top connector is placed on the heat spreader, aligned on the PV cell, and tacked in place using a rivet and washer. The bottom connector, which has been solder screened, is transferred with the assembly to the soldering station. This entire operation is done by hand. (120).

Step 9. Heating the Cell Assembly and Solder

The cell assembly (consisting of the PV cell, heat spreader, top and bottom connectors), is placed on the belt furnace and heated to 179°C to melt the solder. The cell assembly is then cleaned. The cell assembly is quickly tested for shorts and each connection from the top connect to the cell is tested for adequate solder bond. If the cell assembly fails, it is reworked. The cell assemblies are ultrasonically cleaned for at least five minutes to remove flux. (20).

Step 10. Testing the Solder Bond

The integrity of the solder bond between the PV cell and the heat spreader is critical to the longevity of the cell assembly. If there are voids beneath the PV cell, heat transfer will be decreased and, in the worst case, the PV cell may actually burn.

Therefore, we test each cell assembly to determine the bonding of the PV cell to the heat spreader. If the bonding is less than 90 percent, the cell assembly is rejected and reworked. We use an ultrasonic scanning technique to test the bonding. The cell assembly is immersed in water and the ultrasonic instrument scans the cell area, recording any solder voids by distinguishing the character of the reflected soundwave. Each cell assembly has to be processed individually. (180).

Figure 3. *Top Connection Showing "Fingers".*

Step 11. Testing the Cell Assembly Output

The cell assembly is rinsed and tested under 400 suns to determine the output of the PV cell. The minimum acceptable performance efficiency is 16 percent. The short circuit current and the current at the maximum power point are used for module matching. (20).

Step 12. Cleaning, Inspecting and Attching the SOE

The SOE is inspected for flaws, and cleaned. Optical quality adhesive is applied to the bottom of the SOE and the element is placed by hand over the PV cell. The cell assembly with the SOE is then placed in an oven for 60 minutes to cure the adhesive. 48 assemblies are cured at one time. (15).

Summary of the Current Cell Manufacturing Process

Using the current procedures with batch processing to achieve a manufacturing rate of 1,140,000 cell assemblies per year, we estimate that the total time required to make and test a cell assembly is 10 minutes. Using the suggested manufacturing improvements discussed below, we estimate that we can cut the time to 11 seconds per unit. The manufacturing time is allotted as shown in Figure 4.

The improvements that we feel can led to these projected cost savings in both materials and time are discussed in the next section.

CURRENT

Total Time: 10 Minutes

IMPROVED

Total Time: 11 Seconds

Figure 4. Manufacturing Time per Cell Assembly.

3.1.2 Suggested Improvements for Cell Assembly Manufacture

The team discussed and evaluated many suggestions for reducing the cost and improving the throughput of the cell assembly manufacturing process. In terms of reducing materials costs, we can realize the biggest cost savings by altering our manufacturing procedure to eliminate or reduce the need for supplies, cleaning materials, and testing time. The change could result in a savings of over \$7.00 per cell assembly. We believe this can be accomplished by introducing a cleaner fluxless soldering process. The use of fluxless solder would eliminate the need for a cleaning process after each solder application (Steps 3, 5, 8, 9). An added benefit would be the elimination of the problem of disposing of solvents.

In terms of reducing manufacturing time, some savings can be realized by changing procedures to alternatives more compatible with high-volume production. For instance, the ultrasonic technique used to test the quality of solder bonds (Step 11) is adequate for prototype units but not for higher volume production. It must be replaced by another method, such as thermographic analysis.

Other large savings can be realized by introducing automation into the production line. For any step in which handling or precision alignment is required, the use of automation would significantly reduce cost and improve quality and, therefore, performance of our PV arrays. Areas in the current process in which automation would yield large savings are aligning the PV cell and connectors on the heat spreader (Step 7, 8) and testing the PV cells (Steps 2, 10, 12). For example, the cells are tested two times in the current manufacturing process: first for acceptance, and second after the ultrasonic test of the solder bond. Automating this procedure would reduce the manufacturing time by over 30% per cell assembly and decrease costs by two thirds. Finally, increased scale batch processing will be applied to those processes amenable to batch processing, such as oven curing adhesives.

All of these ideas were applied to the development of a plan for an automated production line. The planned manufacturing system is shown in Figure 5 with an artist sketch of the automation line shown in Figure 6.

Figure 5. Automated Cell Assembly Manufacturing System.

PROPOSED
ALPHA SOLARCO
AUTOMATED
CELL ASSEMBLY
MANUFACTURING
SYSTEM

Figure 6. *Sketch of Automated Cell Assembly Line.*

alpha **SOLARCO**

**PROPOSED AUTOMATED
CELL ASSEMBLY SYSTEM**

The fully automatic system is monitored and controlled by computer. It consists of a primary transfer line with eight fully automated stations, six of which are supplied by secondary lines, and 8 idle stations (even numbers) to be occupied by a worker during manual operation or repair periods. The primary line is a modular "power and free" conveyor system utilizing pallets to transport the cell assemblies to the work stations. We will describe the equipment and the work done at each station.

Station 1. This station, where the heat spreader is loaded onto a numbered pallet, is supplied by a secondary line originating at a cleaning station. A robot picks up the heat spreader from the secondary transfer line, dips the heat spreader into a solder pot to be tinned. The robot removes the heat spreader from the solder pot and loads it onto a pallet on the primary transfer line. Because the process uses a fluxless solder, no solvent cleaning is required.

Station 3. At this station a photovoltaic cell is automatically loaded onto the heat spreader. The station is supplied by a secondary line that includes the station that automatically tests and accepts or rejects each incoming PV cell. A robot picks up an accepted cell from this secondary line and dips it into a solder pot for tinning of the back surface. The robot then removes the cell from the solder and loads it into a shutter mechanism that drops it into position on the heat spreader. No post-solder cleaning is necessary.

The automated cell testing station on the secondary line would include "pick and place" equipment to handle the PV cells. This equipment produces a computer-controlled I-V curve output and stores the results for comparison with results taken after further processing. The equipment uses specially designed fixtures to align and maneuver the part and has automated synchronization for making probe contact with light control. Using full automation should reduce the test time per cell by a factor of 10 over current procedures.

Station 5. The Danar insulation strip is automatically loaded onto the heat spreader at this station which is supplied by a secondary line originating at a reel with two spools of Danar film. The Danar is stripped from the spool and fed into a die set where alignment holes are punched. The insulation film is then fed into the work station on the primary transfer line. The Danar template is punched from the strip and loaded onto the heat spreader. The scrap is automatically fed to a shredder for discharge from the line area.

Station 7. The top connector is loaded onto the Danar covered heat spreader at this station. A secondary line originating at a press station feeds the primary station. The top connector is cut from a die set and dipped into a solder pot for ultrasonic tinning. It is then delivered to the work station on the primary transfer line where it is snipped from its carrier strip and loaded onto the heat spreader. The carrier strip is discharged into an automatic scrap shredder and saved for recycling.

Station 9. At this station the bottom connector is loaded onto the heat spreader and the entire cell assembly is soldered. Current testing may eliminate the need for the bottom connect and this station would then be used for soldering the cell assembly only.

Station 11. At this station the cell assembly output is tested at one sun and 400 suns. The cell assemblies are accepted or rejected by measured power output. The pallets are encoded corresponding to the accept/reject criteria.

Station 13. The pallet code is read and rejected cell assemblies are routed to a manual inspection area located off-line where an operator can manually inspect the rejected cell assembly and determine whether to scrap or re-work the assembly.

Station 15. The pallet code is read and accepted cell assemblies are routed to a testing station. We are investigating the feasibility of using thermographic analysis to test for voids in the solder. For this technique, a test current of approximately 10 amperes is passed through the cell and a thermograph is taken that visually presents the temperature gradients across the cell area. We are working with XEDAR Corporation in Boulder, Colorado, to develop this technique and quantify the results so that comparisons with ultrasonic test results can be made. Preliminary indications are that the thermograph is consistent and can be used reliably to locate solder voids. Thermographic testing is much faster than ultrasonic testing and would be easier to integrate into the assembly line.

The planned automated production line will reduce the number of steps required in manufacturing the cell assemblies and will also reduce the handling of each unit. The line will incorporate changes in manufacturing techniques, particularly the soldering process, that further simplify assembly and reduce cleaning time. The modular design of the flexible production line will facilitate expansion of the line as product sales warrant. The production can be fully automatic--no operator will be required. The estimated cost for the production equipment, not including design and checkout costs, is \$600,000--the equivalent of \$0.10 per cell assembly for five years. We believe that the automated production line can reduce the cost of making the cell assembly to about \$2.75 each for production of 8 MW per year.

3.2 Current Procedures for Module Assembly Production

If we extrapolate the cost of manufacturing our module (excluding the cell assembly) to a production rate of 8 MW per year using current production techniques, we estimate the cost to be \$106.00 per module for parts, supplies and direct labor. Our study indicates that introduction of automated production techniques should reduce these costs by about 50 percent. These savings, combined with the cost savings realized in the cell assembly manufacture, should allow us to reduce our selling price to less than \$2.00 per Watt.

The evaluation team studied seven steps in the current module assembly process. The methods used in each step were analyzed and suggestions were made for improvements that would decrease production time without sacrificing quality. Each step is described below and suggestions for improvement are presented. The potential benefits to be obtained from suggested improvements are also discussed.

Step 1. Manufacturing the Module Housing

Current Process. The module housing is stamped from a single sheet of 0.063 inch aluminum and measures 114 x 19.7 x 12 inches when finished. Five bulkheads are spaced across the housing at 18 inch intervals to increase the structural integrity of the modules.

Suggested Improvements. This step in the process can be improved in several ways. One is to reduce the material thickness to 0.050. Second improvement could eliminate the large bulkheads and use a smaller, lower cost strut which could be spot welded to the housing. The stamping dies can be modified to make these changes.

Step 2. Mounting the Cell Assemblies

Current Process. Cell assemblies that have met initial testing are current matched for each module group. A layer of Danar is used as an insulator to electrically isolate the cell assembly from the module housing. The Danar, coated with an adhesive, is applied to the bottom of the cell assembly. The alignment of the cell assemblies under the Fresnel lens is critical and must be precise.

Using current techniques, the cell assemblies are placed in the module housing one at a time. A jig picks up a single cell assembly and places it through a template that covers the entire module housing. This procedure must be repeated 24 times for each module.

Once the assemblies are in place, the adhesive used to hold the Danar is cured for six hours at 60°C. After curing and before cell interconnections are made, a hi-pot test is conducted on each cell assembly to ensure adequate insulation from the module housing. A 2,500-volt DC potential is applied between the module housing and the two conductors on each cell assembly. A leakage current greater than 50 microamperes is cause for rejection.

Suggested Improvements. This process can be improved in three ways. First, the cell assembly placement must be more precise. We have developed a system which locates the cell assembly within .002 of the exact center of the lens center. This will reduce misalignment errors. Second, new adhesives are being investigated to eliminate the curing process. Third, many hi-pot tests are performed on each module during the manufacturing process, we plan to automate this test as well as all cell and module I-V testing.

Step 3. Preparing and Mounting the Bypass Diodes

Current Process. Each module contains three bypass diodes around a string of eight series-connected cells. Each bypass diode is tested individually before being used in the module. The diodes are mounted on an angle bracket that is adhered to the bottom of the module housing. The diodes are electrically insulated from the bracket but thermally attached using thermally conductive adhesive, which helps with heat dissipation. All three diodes are tested after the electrical interconnections in the diode circuitry are made. A power supply is connected to the module to reverse bias the cells and cause the bypass diodes to conduct. The voltage drop versus current is monitored. If the three diodes are functioning correctly, the voltage drop is about 2.5 volts when 10 amperes of current is applied.

Step 4. Interconnecting the Cell Assemblies

Current Process. The cell assemblies are interconnected with #6 wires. The wires are cut, pre-tinned by hand and inserted in the "fingers" on each cell assembly top connection. The fingers are then bent around the wire and a resistance heater is used to solder the wires to each cell assembly. After interconnections are made, another hi-pot test is performed, this time between the module housing and cell string.

This process is necessary to make a secure electrical connection that can withstand damp and possibly flooded conditions, but it results in residue that can soil the cell assemblies. The process is also time consuming and expensive.

Suggested Improvement. This process could be improved by altering the interconnection method. We plan to redesign the top and bottom connectors to eliminate the fingers that must be bent around the wires for each connection. This is a time consuming operation, and we will achieve large savings if we replace it with an automated procedure. We plan to investigate methods of making these connections using the fluxless ultrasonic solder tinning techniques. Additionally, we have replaced the #6 wire with a copper strip equal to a #4 wire to reduce electrical losses. This procedure is adapted from the "Concept 90" module built at Sandia National Laboratories in Albuquerque, New Mexico.

Step 5. Manufacturing the Lens Parquets

Current Process. We manufacture the lens parquets from a Fresnel lens film manufactured by 3M Company. We attach this film to a clear acrylic sheeting, using a solvent bonding process, to give the rigidity required for the lens parquets. We have been unable to achieve yields above 70 percent with the current equipment.

Therefore, we have decided to discard the lens film method in favor of a compression-molding technique. Our initial analysis indicates that the performance, durability and cost of compression-molded lens will be significantly better than the current process..

Suggested Improvement. Compression molded lens are being introduced for our future modules. We are working with the Electric Power Research Institute to develop and evaluate a Fresnel lens manufactured using the Electronic Discharge Machining (EDM) process. We are developing the EDM tooling necessary to build a single lens using a base design that will yield a lens superior to those made with lens film. Approximately 10 single lenses will be manufactured and evaluated. Optical efficiency, consistency, focal pattern and cost will be compared. Costs of the tooling will be tracked and estimates for production level tooling will be made.

Step 6. Preparing the Inside of the Module

Current Process. The interior of the module must be prepared before installation of the Fresnel lens cover. First, a dielectric coating is applied to the bottom and sides of the module housing so that moisture in the module will not degrade performance. Second, a metal reflective radiation shield is installed to protect sensitive areas from concentrated sunlight.

Wet Hi-Pot Testing. During construction and assembly of the module, the module housing is carefully isolated from the electrical subassemblies using Danar. The Danar dielectric material has been tested to 4,000 volts DC with no breakdown under dry conditions. However, to protect against moisture inside the module, we also use a dielectric coating to prime the bottom and inside walls of the module.

Suggested Improvements. A dielectric coating could be applied to the aluminum coil prior to the deep drawing process for making the module housing. This coating would tolerate the draw process of the module housing and eliminate the application of any coatings needed to make the unit electrically safe for maintenance work.

Anti-Radiation Shielding. When the modules for the Pahrump Test Site were manufactured, we found that inadvertent off-axis focusing of the high concentration lens caused some damage to materials surrounding the cell assembly. We installed anti-radiation shielding inside the modules after they had been shipped to the site. This shielding is now installed manually into all of our modules.

Suggested Improvements. We plan to develop production methods of installing the metallic shielding material required for solar radiation protection. The shielding will be installed after the cell assemblies have been placed, the interconnections have been made, and the dielectric coating has been applied to the inside of the module housing. The shielding material will be held in place with adhesives. We will develop test methods to insure adequate electrical isolation of the shield and the module housing. Additionally, we will perform off-axis focus tests with a full size module to investigate possible damage due to long-term reflection of light energy.

Step 7. Attaching the Lens Parquets and Sealing the Module

Current Process. Installing the lens parquets and sealing the module requires several steps. First, we clean the 2 x 4 Fresnel lens parquets with alcohol and air dry them. Next, we drop the parquets into place using the slot and keys that are cut into the parquets and apply a sealant, high density foam, around the top edge of the parquet. A hi-pot test is performed. Air breathers and a neoprene rubber drain valve are installed. Then, we put a one-piece bezel around the module and crimp it into place holding the lens parquet tightly to the module housing. All of these operations are performed by hand and there is significant room for improvements.

Suggested Improvements. Several methods for improving the placement and sealing of the Fresnel lens have been suggested. We plan to use and test different sealing materials with the bezel, such as butyl caulk, acrylic latex and high density neoprene rubber foam. We will analyze their resistance to ultraviolet light and their differential thermal expansion with respect to the primary Fresnel lens, module housing, and bezel.

A clip attachment that can hold the lens parquet more firmly against the module housing but still allow lateral expansion has also been suggested. Different clip designs will be tested on receiver sections and full-size modules. An alternate method would be to change the configuration of the lens holding area and use a simplified bezel design.

We plan to use a simple screened hole with a dust cap to provide moisture relief. The hole can be drilled in the module housing before the dielectric coating is applied.

A linear parabolic flash tester is being designed. This flash tester would be able to test the entire module under one sun and 400 suns. The I-V curve of the module and its peak power parameters would be used to grade and rate the module.

3.3 Tracker/Controller Considerations

The third area of our investigation, though not its primary focus, was the tracker / drive system. Our system in Pahrump uses a Peerless Winsmith drive assembly with an array tracking controller developed at Sandia National Laboratories. The drive assembly uses a worm-gear set driving a ball screw for elevation movement, and a mutating plate primary gear set driving a planocentric gear for azimuthal movement. Even in large lots, the assembly is expensive. For a production rate of 400 per year (8 MW of production), we estimate the cost at \$5,000 per unit.

The controller uses a microprocessor to compute the position of the sun. The complete controller is built on a 4 x 6 inch circuit board and mounted in the DC switch box on the tracker pedestal. A tracking error of less than 0.1 has been achieved and demonstrated at the Pahrump facility. Performance is adequate and the cost estimate for 50 units is less than \$300 each.

We do not have quantitative estimates of cost savings for the improvements we want to introduce in this area. Our goal is to incorporate the improvements as we manufacture the 400 trackers that would be required to install 8 MW of production.

The currently available gear drive assemblies for tracking the sun are expensive and cost projections for this type of drive do not offer adequate savings even for production levels of 50,000 per year. Therefore, we are studying the use of a Roller Cam based on an epi/hypocyclic mechanism such as shown in Figure 7.

This drive accomplishes its reduction by transferring power from an epicyclic surface to a hypocyclic surface using rolling intermediaries. The design parameters specify that the epi/hypo curves remain in contact with the rollers at all times. This virtually eliminates the backlash found in gear tooth drives. The epi/hypocyclic mechanism was first discussed before 1900 but has not been used because of the perceived cost of machining the mechanism and the vested interest in conventional gear drives. However, this drive can be made economically using the computer controlled machining available today. The cost estimate for 50 units is \$1200 each.

Figure 7. *Alpha Roller Cam (ARC) Drive Mechanics.*

4.0 RECOMMENDATIONS

The investigation into the manufacturing process for our AS-150 PV module resulted in numerous suggestions for improving the cell assembly, module assembly and tracker / drive system production process. As we noted above, the evaluation team reviewed all suggestions but for practical reasons chose to focus on the cell assembly process as the area in which early cost-effective improvements can be made. Figure 8 is a complete process flow chart, a "lights out" automated production facility with an annual capacity of 24 megawatts appears to be achievable within the next three years.

Figure 8. Complete Automated Production Facility.

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