MAR 30 1998

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SAND98–0208
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UC–1209

Development of the SEA Corporation Powergrid™ Photovoltaic Concentrator Array

Neil Kaminar, Don Curchod, Shandor Daroczi, Marianne Walpert, James Sahagian, and Janis Pepper

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Prepared by Sandia National Laboratories Albuquerque, New Mexico 87185 and Livermore, California 94550 for the United States Department of Energy under Contract DE-AC04-94AL85000

Printed March 1998

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Category UC-1290

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Contract #40-8941C

ABSTRACT

This report covers the three-phase effort to bring the SEA Corporation's Powergrid™ from the concept stage to pilot production. The three phases of this contract covered component development, prototype module development, and pilot line production. The Powergrid™ is a photovoltaic concentrator that generates direct current electricity directly from sunlight using a linear Fresnel lens. Analysis has shown that the Powergrid has the potential to be very low cost in volume production. Before the start of the project, only proof-of-concept demonstrations of the components had been completed. During the project, SEA Corporation developed a low-cost extruded Fresnel lens, a low-cost receiver assembly using one-sun-type cells, a low-cost plastic module housing, a single-axis tracking system and frame structure, and pilot production equipment and techniques. In addition, an 800-kW/yr pilot production rate was demonstrated and two 40-kW systems were manufactured and installed.

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EXECUTIVE SUMMARY

This report covers the a three phase effort under a Concentrator Initiative program funded in part by Sandia National Laboratories (Sandia), contract 40-8941C. The final phase was cost shared with the California Energy Commission (CEC) Energy Technologies Advancement Program (ETAP) and SEA Corporation. The purpose was to bring the SEA Corporation Powergrid™ from the concept stage to pilot production. The three phases of this contract covered component development, prototype module development, and pilot line production.

The Powergrid is a linear-focus, single-axis-tracking PV concentrator. The receiver uses one-sun type cells mounted on an aluminum heat sink. Twelve plastic modules are mounted to a stationary frame to form a panel. The modules are mounted with pivot bearings at the ends and move in unison to track the sun. The tracker is powered by the panel. The Powergrid is sold as a complete panel with everything needed to generate dc electricity. At commercial production levels, SEA Corporation's analysis indicated the Powergrid could provide distributed electrical power during peak load times that could compete economically with traditional peak generation systems.

Objectives

The overall purpose of this project was to bring the SEA Corporation Powergrid from a concept stage to pilot production. The specific technical objectives of the project were to:

1. Develop the lens extrusion technology
2. Develop receiver technology such as encapsulation
3. Develop panel technology such as a tracking system
4. Develop a pilot line capable of a pilot production at 100 KW per year rate
5. Generate a quality assurance / quality control (QA/QC) manual
6. Have production modules pass the Sandia Qualification Tests
7. Demonstrate the Powergrid through beta site sales

Results

The key results of the project were:

1. Extruded lenses of 10, and 15 inch widths were developed and production runs of lenses made
2. Lens transmissions of 86% for specific samples and 76% in production were achieved
3. One-sun type cells were developed that could be use at up to 6 suns concentration
4. Receivers were developed that were low-cost, reliable, and manufacturable
5. Pressure sensitive adhesive systems were developed for cell attachment and encapsulation
6. A low-cost tracking system was developed that was powered from the panel
7. Prototype modules were built and test outdoors for years without significant degradation
8. A panel structure was developed, and prototypes were built and tested
9. An automated receiver assembly station was developed, built, and tested
10. The components were environmentally tested following the Sandia Qualification Tests
11. Production rates of 800 KW per year were demonstrated
12. Two 40-KW installations were completed
13. A QA/QC manual was written and distributed to all key personnel
14. The Powergrid was brought from concept stage to pilot production

Problems experienced during the project were:

1. Delivery problems with a new, wider lens prevented Qualification Tests from being carried out on the new module, although all the components were evaluated using the Qualification Test procedure.

2. The automated receiver assembly station produced inferior receivers and manual assembly was resorted to for production.

Two beta-site 40 KW systems were sold, one to the Sacramento Municipal Utility District (SMUD) and one to Clean Air Now (CAN). The SMUD system is a grid-connected, roof-mounted system with an inverter. The CAN system, manufactured during the pilot line demonstration, is a low-voltage, high-amperage system used to generate hydrogen gas for use as a fuel in maintenance trucks that comply with Southern California's zero-emission vehicle requirements. The modules in these installations range between 8% and 10% efficiency at normal operating cell temperatures.

Conclusions

Extrusion offers an effective lens manufacturing method. The method is the lowest cost process available and has shown reasonable results. But, a dedicated in-house state-of-the-art system is needed to reach the full potential of this process.

An automated receiver assembly station is needed to achieve the low labor cost necessary for commercial production. A second-generation automated receiver assembly station is needed to produce reliable receivers.

Because of the high performance to cost ratio, one-sun cell technology is an effective method to manufacture cells for PV systems in the 6 to 20 suns concentration range. Most one-sun cell manufacturers can adapt their manufacturing line to make cells for the Powergrid resulting in cells in the 13% to 19% range. Low concentration offers a way to quickly and cheaply expand one-sun cell manufacturing capacity and increase the effectiveness of the limited supply of solar grade silicon feed stock.

Cost calculations indicate that a complete DC Powergrid panel can be manufactured under two dollars per Watt in volume production. Because of the straight forward development issues involved, very little capital or time is required to reach this cost. This should enable the Powergrid to compete in the distributed peak power generation market and should enable the DOE commercialization goals to be reached ahead of schedule.

The success of this program has allowed SEA Corporation to obtain investment and follow-on contracts to work toward the goal of a production capability of 50 MW/year in two to three years. Future plans include developing a second generation automated receiver assembly station, an in-house state-of-the-art lens extrusion system, and other improvements to the manufacturing process. Unrestricted commercial sales are planned for the fall of 1997.

CHAPTER 1
PROJECT OVERVIEW

This report covers a three-phase effort under a program funded in part by Sandia National Laboratories (Sandia). The final phase was cost shared with the California Energy Commission (CEC). The purpose was to bring the SEA Corporation Powergrid™ from the prototype stage to pilot production. The program with Sandia was under the Concentrator Initiative Program, contract 40-8941C. The program with the CEC was under the Energy Technologies Advancement Program (ETAP).

1.1 INTRODUCTION

The Powergrid is a photovoltaic (PV) concentrator which generates direct current (dc) electricity directly from sunlight using a linear Fresnel lens. The Powergrid consists of tracking modules mounted to a stationary frame. A module is the basic generating unit which is complete and capable of making electricity. It consists of the plastic Fresnel lens which is attached to a receiver by plastic module sides. The ends of the module are closed by plastic end caps which have provisions for pivots to allow the module to rotate to track the sun (Fig. 1). The receiver converts the sunlight to electricity and consists of an aluminum heat dissipater to which the solar cells are mounted. The receiver also includes the electrical connections for collecting the current generated by the cells. Each receiver produces about 18 volts.

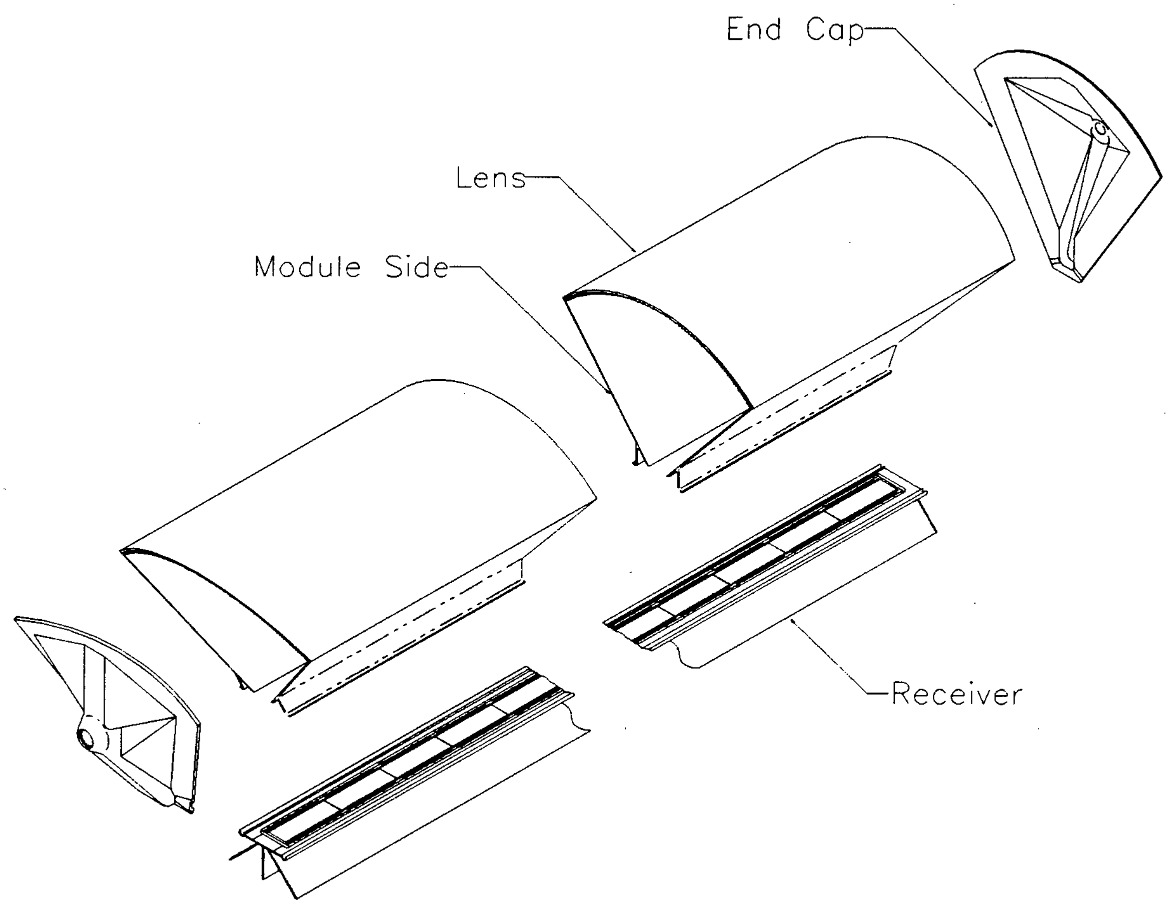


Figure 1 - A Powergrid Module

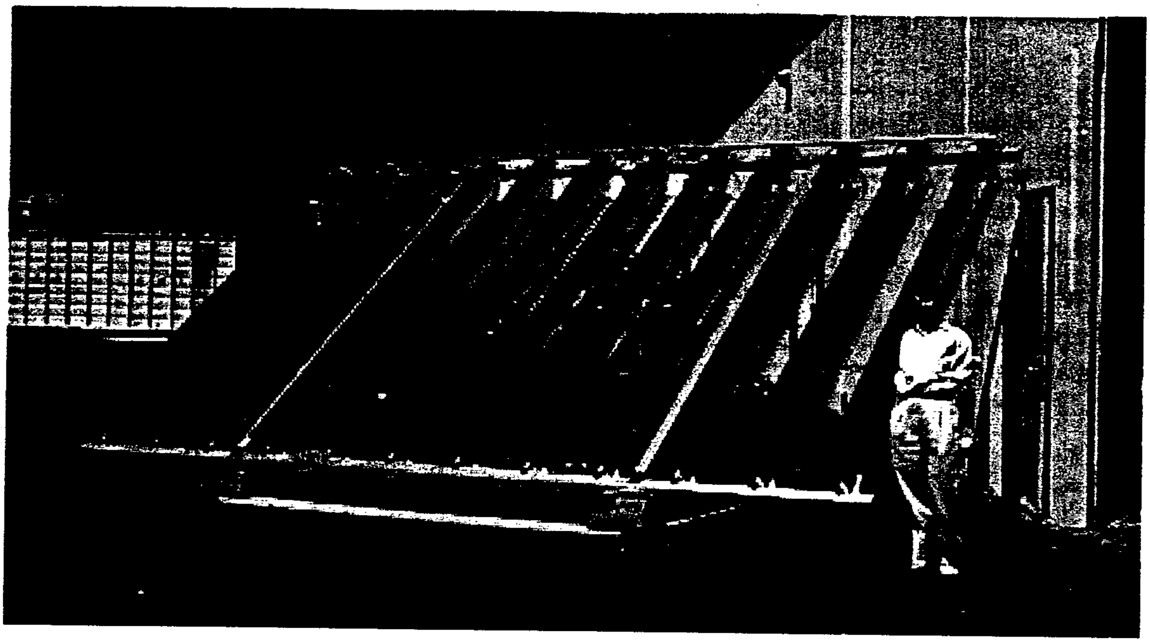


Figure 2 - SEA Corporation Powergrid™ Panel

Eight to twelve modules are mounted to the stationary frame to form a panel (Figs. 2 & 3). The modules move in unison via a drag link driven by a single tracking unit (tracker) which is also mounted to the frame. The panel is a complete system capable of stand-alone operation. The tracker is powered by the modules, eliminating the need for batteries or other external power sources. The Powergrid is sold as a complete panel with everything needed to generate dc electricity.

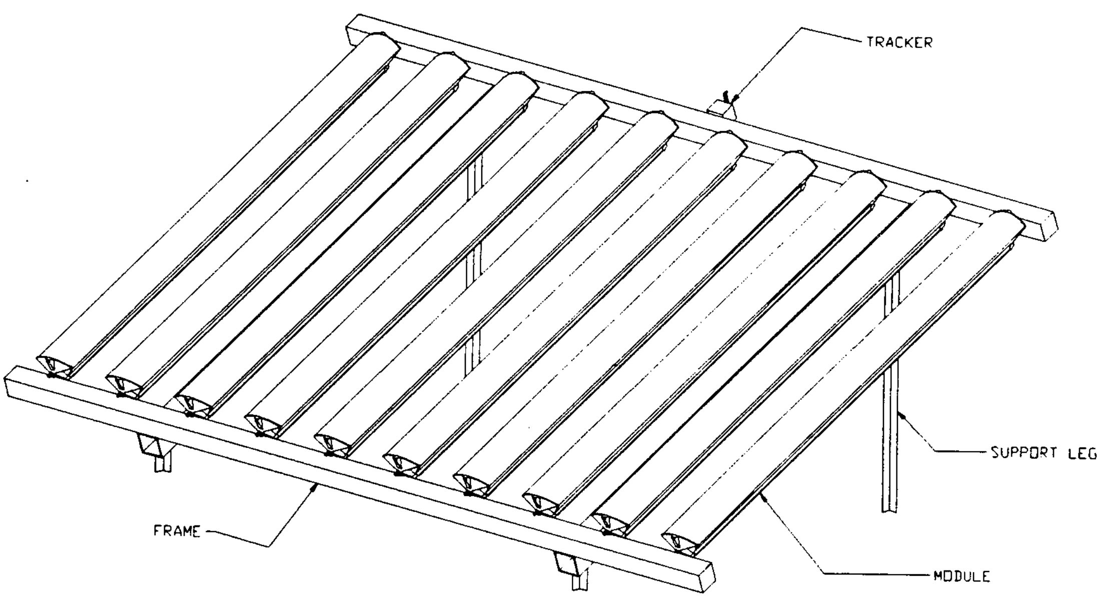


Figure 3 - A Powergrid Panel

The Powergrid panel can operate independently as a stand-alone unit or it can be wired together with other panels to form complete arrays. The modules can be wired in the panels and the panels can be wired in the arrays in various series and parallel combinations to provide almost any multiple of module current and voltage. A detailed technical description of the Powergrid components is provided in Chapter 2.

The Powergrid has the potential, once in full-scale production, to produce non-polluting, renewable electricity at a cost that is less than that of traditional sources of energy. Cost savings in the design result from using one-sun cells under light concentration, low-cost and light-weight components, and one-axis tracking to increase power production.

SEA Corporation's design philosophy from the beginning has been to develop a low-cost, high-volume PV system that will be extremely cost-competitive. Using low concentration, the system can use one-sun cells, achieving cost savings from using fewer cells than conventional flat-plate one-sun designs. The concentrator design uses low-cost plastic parts. At high volume manufacturing levels, the system has the potential to be very low cost.

There are a number of potential barriers to commercialization. These could include scientific uncertainties, economic hurdles, environmental constraints, resource constraints, and future regulatory and institutional impediments. One of the major barriers for photovoltaics is achieving significant product cost reductions to make PV more competitive with other energy sources.

This project provided an opportunity for SEA Corporation to address one of the key barriers toward commercialization of this product: cost reduction through mass manufacturing. Cost is the major barrier to large scale commercialization of PV in general (Fig. 4). The Powergrid, through the efforts of this project and follow-on projects, attempts to address this barrier through mass manufacturing.

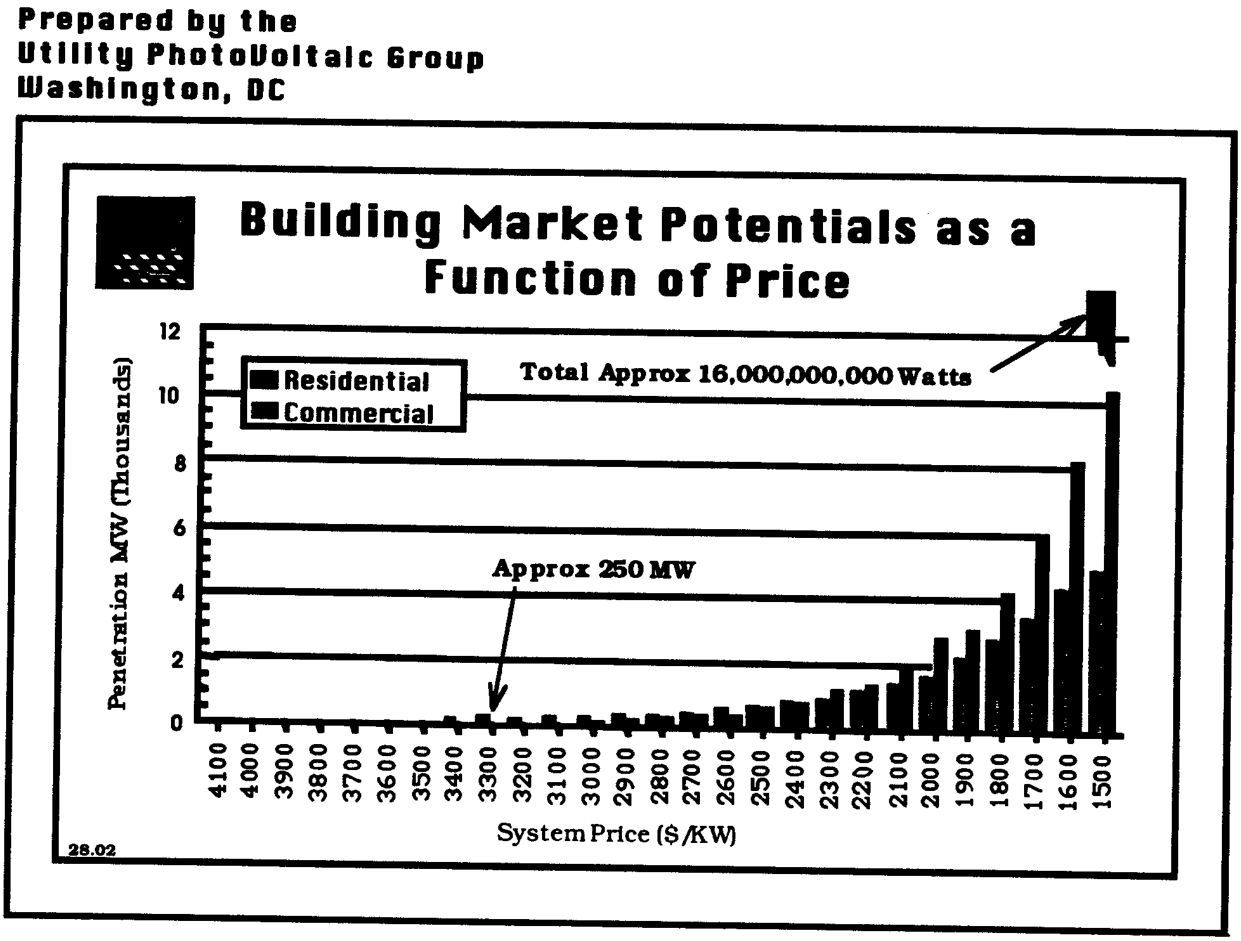


Figure 4 - PV Market at Various Price Levels (Source: UPVG)

A number of improvements were made in the manufacturing process during the pilot-line effort which, when implemented in a high volume production environment, will provide overall cost savings of 89% over previous practices, which were basically manual assembly and prototypical manufacturing. The savings are due to reduced labor, reduced material cost, improved scrap rate, and increased power output of the system. Explicit details on these manufacturing improvements and their effect on cost savings are found in Tables 20, 21, and 22 in Chapter 5.

Table 20 (in Chapter 5) summarizes the manufacturing techniques, expected direct cost savings, the pilot-line efforts, and the next step efforts. Savings are due to reduced labor, reduced material cost, improved scrap rate, and increased power output, and are calculated from the dollars per watt for each manufacturing scenario. Table 21 summarizes how each manufacturing technique will decrease unit costs and how the pilot-line effort will lead to these improved manufacturing techniques. Table 22 breaks down the cost savings into those due to reduced labor, reduced materials, improved Powergrid output, and reduced scrap.

1.2 OVERALL PURPOSE OF THE CONTRACT

The overall purpose of this contract was to bring the SEA Corporation Powergrid, a photovoltaic concentrator system, from a conceptual state into pilot production. The Powergrid had potential as a low-cost source of non-polluting, renewable energy if it is manufactured in mass quantities.

The goals and objectives were broken into three phases for this project. The key goals for each phase were as follows:

Phase 1:

- Construct complete linear focusing modules using SEA Corporation's concept for a light-weight inexpensive module

Phase 2:

- Revise the module design to:
    * improve efficiency and reliability
    * reduce the cost of manufacturing the module
- Produce an automated assembly receiver station
- Produce a Quality Assurance/Quality Control (QA/QC) manual

Phase 3:

- Improve the optical and electrical efficiency of the PV modules
- Develop a pilot production line capable of a production rate of 100 kW/year
- Have modules produced on the pilot line pass the Sandia "Evaluation Tests for PV Concentrator Modules and Receiver Sections"

The first phase emphasized the ability to extrude lenses that met SEA Corporation's goals for transmittance and efficiency. A number of iterations were made as new information was gathered from each try.

The second phase moved on to revising the module design in Phase 1 to reducing the cost in Phase 2 while simultaneously improving its performance. In addition, an automated assembly receiver station was pursued to move down the path to volume production. Manufacturing procedures for a production environment were developed in the QA/QC manual.

The iterations from the first two phases led to further improved modules for the last phase. This phase demonstrated volume production of the pilot plant, exceeding the production rate goal eight-fold. In -house testing of the components and modules were performed before submitting the product to Sandia for testing.

1.3 APPROACH

The overall approach in this project was to review and improve the design of the Powergrid, and to demonstrate pilot production. This included improving the lens; developing a reliable, mass producible receiver; and achieving a production rate of 100 kW/year in a pilot production mode.

Improvement in module design spanned all three phases. This started with work on the receiver, including the heat sink design, encapsulation methods for the cells, and sizing of the components. During the course of the project, different encapsulation methods were tried and tested to determine the most suitable procedure. Samples were manufactured and tested both in-house and at Sandia. The other critical design work was on the Fresnel lens. The objectives were to improve the optical transmission of the lens through improved lens design, and then manufacturing a lens that could achieve this improved transmission.

Work focusing on the Powergrid panel components started up in Phase 2. These included developing a sheet steel frame to support the panel, which included wiring run through the frame.

Attachment pieces for connecting the modules to the frame were developed and tested. The single-axis tracker was designed and the logic optimized to permit the Powergrid to maximize its energy production.

An automated receiver assembly station was designed and tested in Phase 2 to begin work on manufacturing cost reduction strategies. The preparation of a QA/QC manual was also accomplished in Phase 2 in preparation for the transition to a production environment.

The final phase focused on continued improvement in the lens efficiency and designing and constructing a pilot production line. The cost efficiency of the 10" lens was evaluated and the move toward a higher concentration lens was made. A 15" lens was developed to improve the energy production and cost effectiveness of the product.

1.4 PROJECT ACCOMPLISHMENTS

The project was very successful in that the primary objective of demonstrating pilot production of the Powergrid at a rate of 100 KW/yr was exceeded over eight-fold.

The specific assessment for the individual tasks making up the project are described below. Details are given in Chapter 3 of this report.

A) QA/QC Plan

The SEA Corporation Quality Assurance / Quality Control (QA/QC) manual was written to reflect the controls and procedures necessary for a pilot and full-scale production environment. It was distributed to all key personnel.

B) Module Design

The design of each module component was carefully evaluated and prototype samples made. Tests conducted at SEA Corporation and Sandia Labs pointed out deficiencies in product components, allowing improvements to be made. Each part of the module was redesigned and additional prototypes made to test product improvements.

The cost-efficiency of the current design was reviewed and revised to reflect changes in product design. The effects of additional product improvements from this project were evaluated to determine their effect on product cost. The Powergrid design was revised to optimize the performance of the components and correct problems discovered in field tests. The Powergrid design drawings were revised to reflect design changes.

C) Pilot Line Design

Existing equipment and designs were reviewed, including the automated receiver assembly station and other tooling developed previously. Available off-the-shelf and custom equipment were surveyed for possible use in the pilot line. In-house designed equipment was also considered. A design layout was completed of the pilot production line. Design drawings of the pilot production line were made.

D) Pilot Line Fabrication

A pilot assembly line was built to fabricate the Powergrid. The line evolved over time to improve production efficiency and incorporate product design changes. The demonstration objective was to produce at an equivalent 100 kW/year rate, which was exceeded as SEA Corporation achieved a production rate of 830 kW/year.

The production rate was limited by the receiver production. The objective was to use an automated receiver assembly station, but this was abandoned for several reasons, the most important of which were: 1) the change from the sheet metal heat sink to the extruded heat sink would have required substantial changes to the automated receiver assembly station; and 2) the yield from the automated station was unacceptable, requiring extensive rework. The receiver was assembled by hand for the pilot line.

E) Sandia Qualification Testing

Testing of component parts took place throughout the project. Samples of receivers, using different encapsulation methods, were subjected to Sandia's tests. Prototype lenses were also tested for transmission efficiency.

Qualification testing at Sandia of the pilot line-produced modules was not finished during the project. Complete qualification testing of modules requires approximately 6 months. Because of delays in getting lenses for the modules, lenses have not been sent to Sandia until now. However, in-house testing was performed on various components which allows the company to test different product iterations.

F) Lens Development

Several lenses were designed, tooling made, and parts fabricated through a sub-contractor. Specific samples have achieved 86% transmission, but production lenses have fallen short of this, achieving around 76% transmission. The extrusion sub-contractor took an excessive amount of time designing the tooling for the new lens, which resulted in an inability to utilize the new design in the pilot production because of time constraints. SEA Corporation is planning to bring the extrusion process in-house to have greater control over the process and the outcome.

The 15" lens used during the pilot run had low transmission due to two causes: form factors and diffraction losses. The diffraction losses are due to lines in the die caused by the wire electric discharge machining. These can be eliminated by polishing, hardening, and finishing the die after it has been fully developed. The latest version of the die is undergoing this procedure to improve the transmission of the lenses it produces.

A single piece lens and module side extrusion, originally planned for Phase 3, was a concept that was intended to eliminate two glue joints. However, during the course of this project, evaluation of the extrusion process for the lenses and the sides revealed quite different extrusion parameters for the two pieces. Also, the cost-optimum type of plastic used for the two parts was discovered to be quite different. In addition, the glue joint was developed to the point that it is now very reliable. SEA Corporation abandoned this concept because the requirement was eliminated and the approach was impractical and not cost-effective.

G) Program Review

Yearly program reviews were conducted by SEA Corporation. These reviews included projected production cost, QA/QC program, structural design, pilot line, and test results.

H) Beta Site Test Sales

One 40 kW system was installed at the Sacramento Municipal Utility District (SMUD) and one 40 kW system was installed at Clean Air Now (CAN) in Los Angeles. The SMUD system is a grid-connected roof-mounted system with an inverter. The CAN system, manufactured during the pilot line demonstration, is a low-voltage, high-amperage system. These two beta sites provided the opportunity to gain information on structural failure modes, tracker performance, dust accumulation, alignment requirements, foundation methods, and more.

SEA has installed a 4 kW system at Arizona Public Service under the UPVG (Utility PhotoVoltaic Group) TEAM-UP program. Additional TEAM-UP installations combined with an educational exhibit on photovoltaics are planned at two to three museums in the U.S.

CHAPTER 2
DESCRIPTION OF TECHNOLOGY

Most photovoltaic modules generate electricity by exposing solar cells to sunlight without the aid of any optical system. The SEA Corporation Powergrid uses a linear Fresnel lens to focus sunlight on a series of solar cells placed at the focal line of the lens. Current generated by solar cells is generally proportional to the amount of light to which the cells are exposed. By using the lens, a smaller number of the expensive solar cells are needed to generate the same amount of power than without the lens.

The use of the Fresnel lens requires that the Powergrid follow (track) the sun through the day. Due to its low concentration ratio (the ratio of the lens width to the cell width) the Powergrid needs only single-axis tracking for most applications. The effect of tracking on output depends on the local climate. For Sacramento, California, a stationary flat-plate system, tilted at the local latitude, will produce approximately 72% of the energy of a two-axis tracking flat-plate system. For the same location, a single-axis tracking Powergrid will produce 87% of the energy produced by a two-axis tracking Powergrid and a single-axis Powergrid whose tilt is adjusted twice yearly will produce 98% of the energy of a two-axis tracking Powergrid. For this location, the single-axis tracking is the most cost effective because it adds significant output with little added cost and avoids the high cost and complexity of a two-axis tracking system.

The main components of the Powergrid are the receiver assembly, which contains the solar cells bonded with an adhesive encapsulant to the heat sink; the plastic extruded lens; the balance of the module, including the module sides and end caps; the frame assembly; and the tracker assembly.

2.1 RECEIVER ASSEMBLY

The receiver consists of an aluminum heat dissipater (heat sink) to which the solar cells are mounted (Fig. 5). It also includes the electrical connections (cell leads), the adhesive to bond the cells to the aluminum, and encapsulant to encase all the electrical components. The heat sink dissipates waste solar energy to the surrounding air. This is important because solar cells operate more efficiently at cooler temperatures. The adhesive bonds the cells to the heat sink and also provides electrical standoff and heat transfer from the cells to the heat sink. The encapsulant provides environmental protection and electrical standoff in case the receiver gets wet from condensation or moisture intrusion.

The cell leads are soldered to bus areas on the edges of the cell. Leads are placed along the entire length of the top and bottom edges. The cells are wired in series in the receiver, with the top lead of one cell connecting to the bottom lead of the next cell.

Solar Cells

The Powergrid receiver is designed to take advantage of the existing volume production of solar cells for the one-sun market. This enables it to use commercially available cells from a variety of sources, lowering cell costs compared to using a custom cell designed for concentration.

One-sun type cells are designed to be used at one-sun solar radiation levels. They are not designed to carry the current that concentrator type cells have to carry. For this reason, they can use a relatively low-cost metallization on the top and bottom surfaces. The metallization is used to conduct the electricity from the top and bottom of the cell to the cell leads. The low-cost metallization used for these one-sun cells is a metal-frit paste that is put on the cells using low-cost silk-screen printing and then fired to fuse the frit.

Within the last 10 years, in an effort to improve one-sun cell efficiency, various changes have been made by one-sun cell manufactures that allow one-sun type cells to be used in the Powergrid at low concentration. This includes improvements in metallization, doping, and other design changes. The only difference between one-sun cells and one-sun type cells for use at low concentration is the design of the metallization on the top of the cells and the size of the cells. Usually a single one-sun cell is made from each silicon wafer, but for the cells used in the Powergrid, three cells are cut from each wafer. One-sun cells, so modified, can be used up to about 15 times one-sun illumination (15 suns) before their current carrying capacity starts to limit their performance.

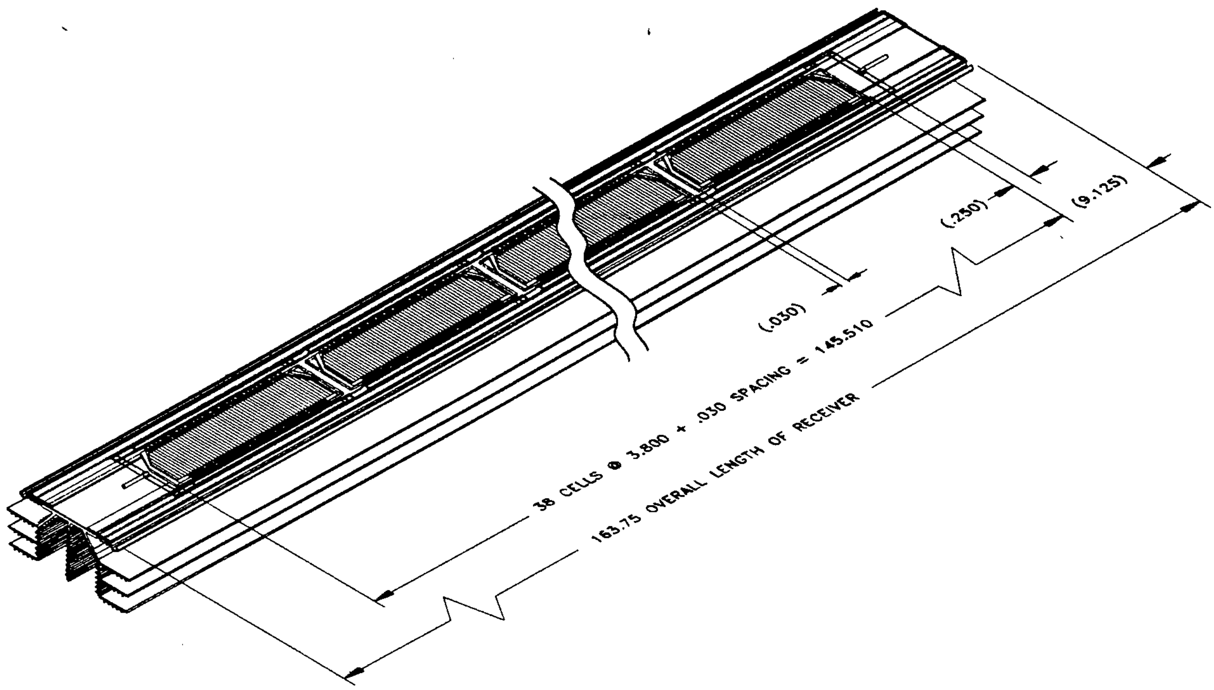


Figure 5 - Receiver Assembly

On the other hand, concentrator cells designed for higher than 20 suns are made using more complex and expensive processing than one-sun type cells. Typically, high concentration cell metallization is deposited by evaporation rather than by screen printing. Additionally, one or more mask alignment and photolithographic steps are generally used for high concentration cells. These cells are very efficient at 100, 200 or greater suns but they are also more expensive. Also, they are currently not being manufactured in quantity and are therefore not readily available.

Other expenses associated with higher concentrating PV systems include more exact optics, a more complex heat dissipation system, a more accurate tracking system, and a stiffer structure.

The Powergrid cells, made from one-sun single-crystal silicon wafers cut in thirds, are 1.30 inches wide by 3.35 inches long (Fig. 6). They have bus areas the length of the cells on both edges and grid lines which are closely spaced to collect the current. The metallization on the back of the cell is solid. Both the top and bottom metallizations are applied using silk-screen printing, which is subsequently fired.

Heat Sink

Solar cells operate more efficiently at lower temperatures. The exact rate of change in efficiency with temperature varies from cell to cell but is about 0.06 percentage points per degree centigrade (0.06 %/°C). That means that for a cell which tested at 16.0% efficiency at 25°C, the cell would reduce to 14.2% at 55°C.

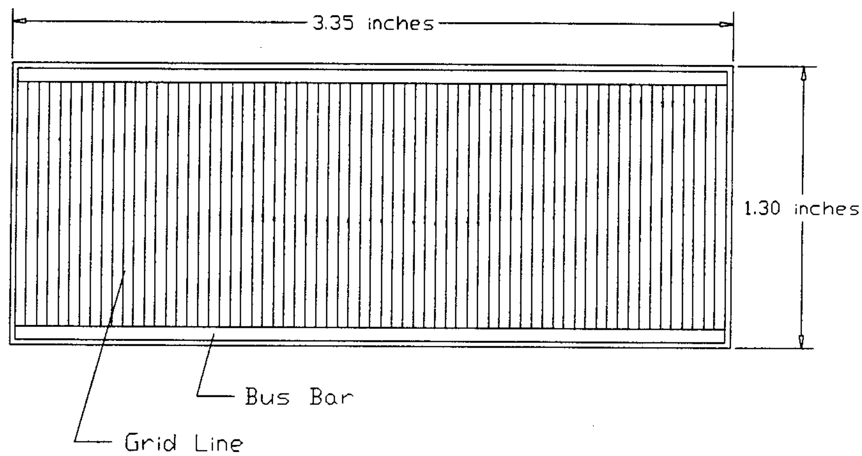


Figure 6 - Powergrid One-Sun Type Solar Cell

At first glance, then, it would seem reasonable to reduce the temperature of the cell to the lowest value possible. For instance, using a huge heat sink could substantially reduce the cell temperature. However, a huge heat sink is expensive. In practice, the heat sink is a compromise between the cost of the heat sink (and supporting structure) and the value of the electricity produced.

An extruded aluminum heat sink is currently used for the Powergrid. The Powergrid heat sink is extruded in a shape designed for maximum heat dissipation (Fig. 7). Three fins radiating from beneath the cell center and two module side wall attachments dissipate the heat. The heat sink was designed using a finite-element heat-transfer computer program. The heat sink uses bumps on the surface of the fins to increase surface area and break up the air flow which assists heat transfer. There is a 0.006-inch step in the heat sink designed to accommodate the cell bottom leads.

The module sides are attached to the heat sink by crimping the heat sink over the attachment foot on the module sides. The heat sink is meant to be installed once, but can be removed by de-crimping if necessary for repair.

Adhesive/Encapsulant System

The adhesive serves three functions: 1) it attaches the cell and cell leads to the heat sink; 2) it provides a heat transfer path from the cell to the heat sink; and 3) it provides electrical standoff between the cell and cell leads and the heat sink. The Powergrid uses a proprietary adhesive system to serve these functions. It is a pressure sensitive adhesive (PSA) tape system that can simply be rolled onto the heat sink, providing immediate tack for placing the cells. It increases in adhesion with time, has a long life, and is not affected by moisture or ultraviolet (UV) radiation.

The adhesive remains pliable, accommodating differential thermal expansion rates between the cells and heat sink. It has a high dielectric strength and is penetration resistant. Dielectric strength is important for electrical standoff, and penetration resistance is important so that sharp edges on the cell leads or solder spikes do not poke through to ground on the heat sink. The adhesive provides over 5000 dc volts standoff. The PSA system eliminated the previous wet adhesive system that was messy, had a long cure time, and required a separate fixturing system to place the cells.

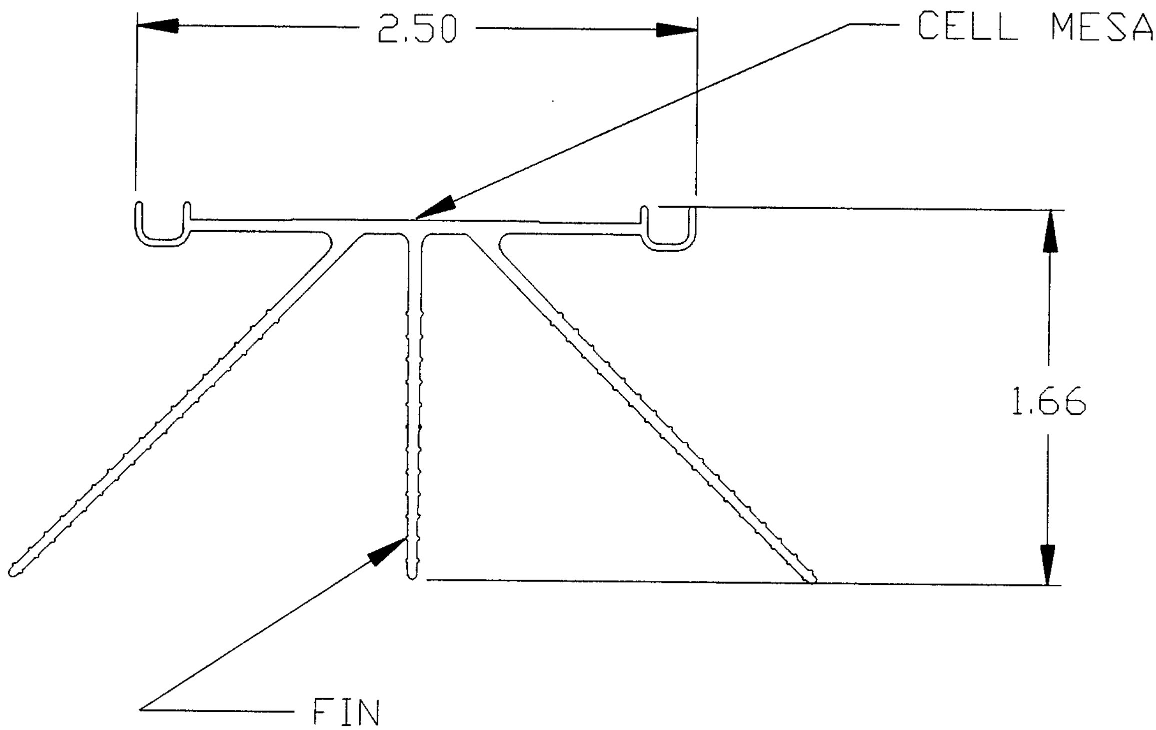


Figure 7 - Cross-Section of Extruded Heat Sink

Heat conduction is important but not as critical in the Powergrid as with higher concentration systems. The PSA system is not filled with heat conductive materials such as alumina or iron oxide. Its heat conduction constant is an order of magnitude lower than those materials that do have the heat conduction fillers. Even so, because of the low concentration, the temperature drop across the adhesive is only approximately 3°C at normal operating cell temperature. The temperature drop does not change significantly going from 10X concentration to 15X. Filled adhesive would have a temperature drop of approximately 1/2°C. This is another economic reason for choosing low concentration.

The encapsulant system has undergone evolution during the program and is still being revised. The purpose of the encapsulant is to encase the cells and other electrical components in a protective shell that will let in light but not moisture or air. Initially, a standard silicone encapsulant was applied as a liquid and allowed to cure. However, liquid silicone encapsulant has two major drawbacks: 1) it is considered a hazardous material until it cures; and 2) it takes approximately 24 hours to cure. The silicone encapsulant, however, passed environmental testing at Sandia and was approved for production.

The next development was a tape material similar to the adhesive tape which could simply be rolled over the top of the cells and leads. This also worked well during environmental tests at Sandia. It was simple to apply and quick, not requiring a drying cycle. This tape system was used for initial production. In the field it was discovered that the tape system was allowing water intrusion via folds and creases in the tape. This provided a path for shorting to the grounded heat sinks, causing the receivers to fail high-potential (hipot) testing in the field.

The current method again uses the liquid silicone encapsulant, which is giving excellent results during wet hipot tests. The entire receiver is submerged in water while applying 2,200 Volts. There must be less than 5 microamps (5μA) current at this voltage for the receivers to pass this test. However, the former problems still remain with this system, namely the hazardous material issues, the high labor content of the procedure, and the long cure time. The company is continuing to search for alternative materials which will eliminate these problems.

2.2 EXTRUDED LENS

The Powergrid uses an acrylic Fresnel lens that is manufactured using extrusion technology. Extrusion is a continuous process and is the lowest cost method of forming plastic. Dried acrylic pellets are fed from a hopper to a screw that operates similar to a pasta maker. The screw is heated so that the pellets melt in the screw. The molten plastic is forced by the screw through a die that imparts the shape to the lens. The plastic is then cooled and sawed into lengths for use. A puller, operating on the hardened plastic, pulls the lens from the die.

The extrusion process is not an exact science and SEA Corporation has invested years of development to obtain quality optical parts. Key to obtaining good parts is understanding the non-Newtonian flow of plastic through the die. Finite element analysis of the flow is essential but the final die shape comes down to cut-and-try techniques. SEA Corporation has developed 7-inch wide, 10-inch wide, and 15-inch wide lenses, and is presently developing a 20-inch wide lens. A cross-section of the current 15-inch lens is shown in Fig. 8.

The first extrusion attempts were encouraging but had low performance, with only approximately 50% transmission. The best 15-inch lens provides over 85% transmission at about 8.7 to 1 concentration ratio and 75% transmission at about 13 to 1. The concentration ratio of 13 to 1 corresponds to the present configuration using 15-inch lenses and 1.3-inch wide (1.15-inch active area width) cells.

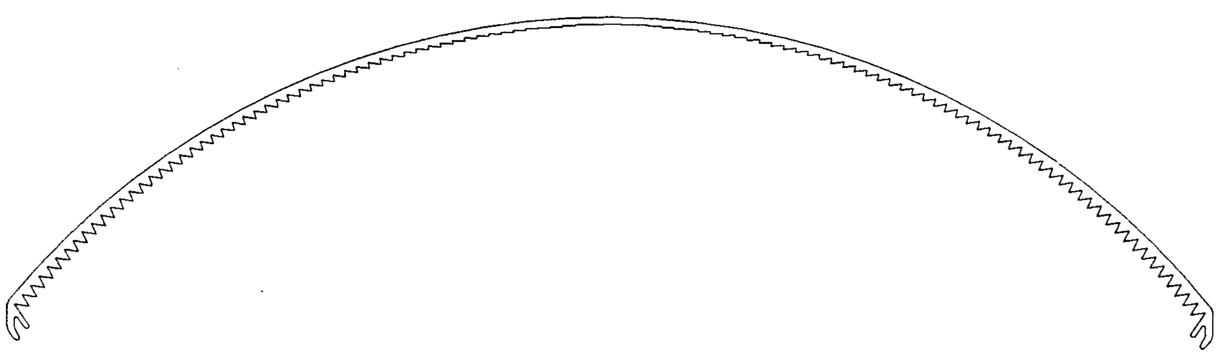


Figure 8 - Cross-Section of 15-inch Lens

As concentration ratio increases, lens transmission decreases. This is because the light has to focus to a narrower line. The next most costly technology, available in rolled sheets, provides excellent transmission even at much higher concentration ratios. However, these lenses are approximately 4 to 5 times more expensive per unit area than the Powergrid extruded lenses at large volume production rates. SEA Corporation believes that, given sufficient development, the extruded lenses can have optical transmissions equivalent to the more expensive lenses, especially at lower concentrations, which is another economic reason for using low concentration.

An impact modified acrylic can be used to make lenses. This gives the lens more impact strength, reducing breakage during manufacturing and use. Impact resistant plastics have slightly less optical transmission, slightly less stiffness, and are slightly more costly than standard acrylic plastics. Lenses tested for hail stone resistance in the past were just on the edge of being strong enough. These lenses did not have impact modifier. The present lenses are thicker and stronger than the lenses that were tested and may pass the hail stone test without the impact modifier. Additional testing is needed.

2.3 BALANCE OF MODULE PARTS

Module Sides

The module sides serve three functions: 1) they provide closure for the module to keep out dust and moisture; 2) they serve as structural elements; and 3) they enhance optical performance. A reflective film is applied to the inside surfaces of the sides to reflect light towards the cells that would normally be lost. This enhances optical transmission of direct and diffuse light during both on- and off-axis tracking. The reflective sides increase power production and reduce cost by reducing the required accuracy of the tracker, required stiffness of the structure, and required assembly tolerances.

The module sides are made from extruded acrylic plastic. Extrusion is the least costly method of forming plastic and the acrylic is not affected by UV radiation, outdoor moisture, or normal temperatures.

End Caps

The ends of the Powergrid module are closed with plastic end caps manufactured from acrylic. The end caps are presently manufactured using vacuum forming, but are designed to be injection molded, which is a lower cost method in large volumes. Injection molding is planned once the production volume justifies the expense of the tooling, which is expected at a production volume of 5 MW/year.

SEA Corporation has improved the design of the end caps during the period of this project. Originally, the pins about which the module rotates were installed in the end caps and self-aligning bearings were mounted on the frame. The pins were inserted into the bearings when the module was mounted on the frame. The original end caps were also made from thin material. The combination of two factors made the end caps prone to breakage: 1) the pins installed in the end caps imparted high moment stresses to the end caps; and 2) the thin material could not withstand the stress. The improved end caps have self-aligning bearings installed in the end cap and pivot pins mounted on the frame. The material thickness has been increased by a factor of three. The self-aligning bearings are plastic balls that mount into sockets in the end caps. These bearings do not impart any moment loads to the end caps. To date, no breakage of the new-design end caps has occurred.

A second pin is installed in each end cap for pointing the module. This pin is attached to the common tracking drag link on the end of the panel. Although only one of the module's two endcaps is attached to the draglink, both endcaps are manufactured with the drive pin to enable any module to be used in either orientation for different array series/parallel wiring configurations and to reduce manufacturing cost associated with managing two versions of the endcap.

2.4 FRAME ASSEMBLY

The stationary frame assembly consists of two horizontal members and two slanted members (Fig. 9). The members are presently manufactured from extruded aluminum, but are planned to be made from roll-formed galvanized steel as soon as the production volume justifies the cost of roll-forming tooling. A production volume of 5 MW/year would justify moving to roll-formed steel. The members are hollow square tubes serving as an "electrical conduit" for wiring and panel bypass diodes. Wires from one end of a row of panels can be fished down the entire length of frame members to the other end of the row. The frame members of neighboring panels are joined by couplers.

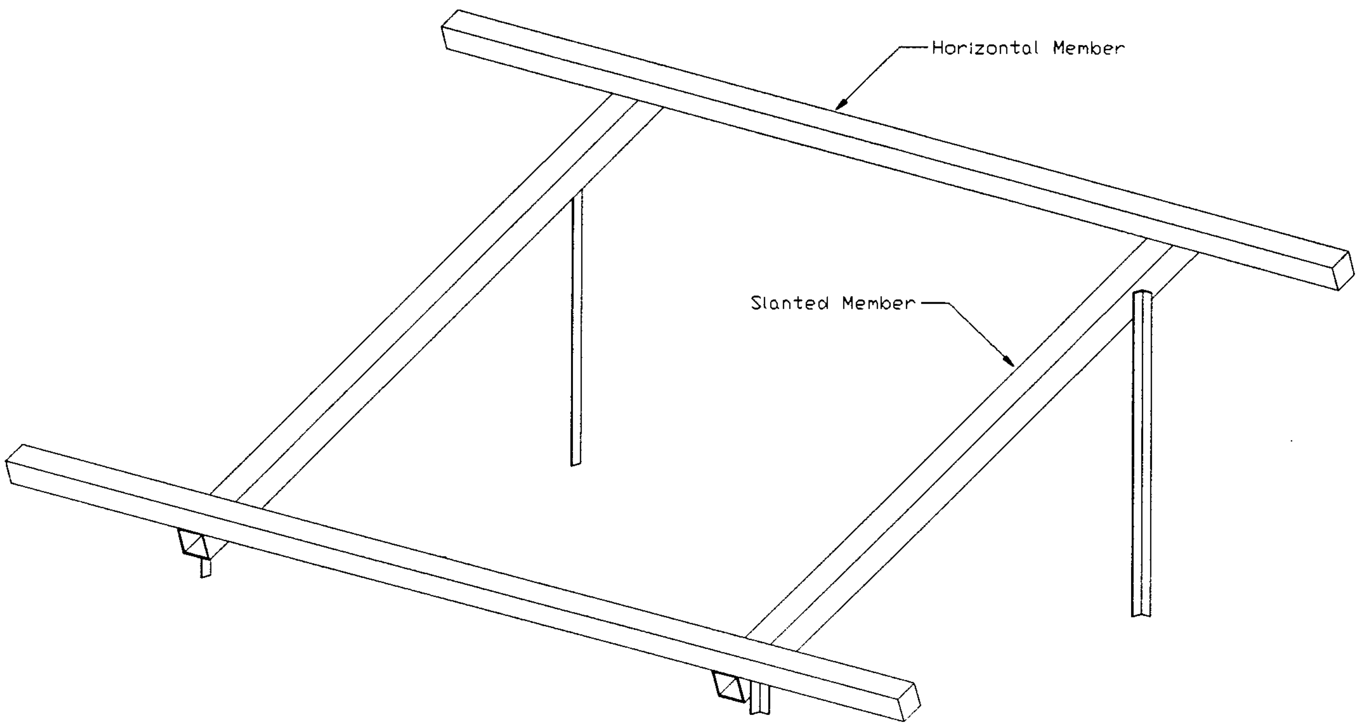


Figure 9 - Frame Assembly

One bypass diode is provided for each panel connected in series with other panels. Stand-alone panels and panels connected only in parallel with other panels do not need bypass diodes. The diodes allow current to go around the panel in case the panel is in shadow or otherwise rendered inoperative. This prevents the modules from being damaged from overheating when current is dissipated in a shaded section. The diodes and associated wiring reside within the frame members.

Additional diodes are built into the modules to protect the individual cells. One diode protects 12 to 13 cells in series in each module, for a total of 3 diodes per module. SEA Corporation tested the diode designs for both the modules and different panel configurations to validate their effectiveness.

Wiring for each module exits the frame members through holes in the frame. There is a grommet for each hole that prevents damage to the wire and keeps water from entering the frame.

Connection to the module wire is made through a crimp connector which is then pushed into the frame.

The stationary frame allows the panels to be mounted on roofs. The loads are distributed to the footings, spaced every 4-feet, and can easily be attached to a building's framing structure, similar to a fixed flat-panel system.

2.5 TRACKER ASSEMBLY

The tracker assembly consists of a gear motor, a circuit board, and a sun sensor (Fig. 10). The circuit board contains the logic for controlling the tracking function and for controlling the stow function. The stow function is used to stow the modules at night and during times when dark clouds are present. The lenses face up in the stow position. The sun sensor senses where the sun is in the sky and also when the light levels fall below a threshold value that controls when the modules stow.

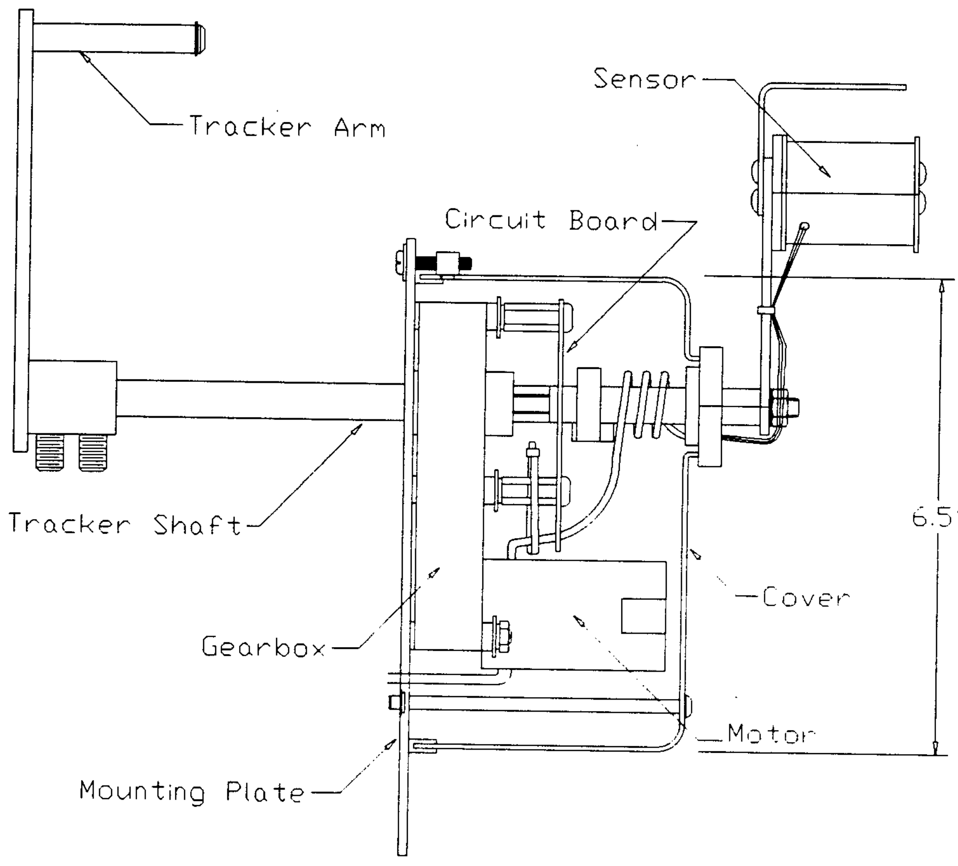


Figure 10 - Tracker Assembly

The tracker is powered by the panel itself. Power requirements for the tracker are very low, less than 6 watts. There is enough power generated when the modules are not pointed at the sun to run the tracker. This has proven to be a very reliable system and has worked flawlessly after some minor changes to the logic. The changes have consisted of raising the threshold light levels for the stow function and adding a latch circuit in the stow function to eliminate oscillation between stow and tracking modes.

CHAPTER 3
WORK PERFORMED BY TASK AREA

This chapter discusses each major task area for all three phases of the project. Phase 1 focused on designing and qualifying the module, including the lens, receivers, and module housing. Phase 2 emphasized development of the array, continued improvement of the module, and designing, testing, and evaluating the receiver assembly station. Phase 3 focused on the pilot production facility.

The major tasks which are discussed here include:

- Writing the QA/QC manual
- Revising the module design
- Developing the extruded lens
- Developing an automated assembly receiver station
- Constructing a pilot production line to manufacture at a rate of 100 kW/year

3.1 QA/QC MANUAL

Work on the QA/QC manual was started during Phase 2 and completed in Phase 3. The QA/QC manual was delivered to the CEC and Sandia. It serves as a reference manual for the company covering such things as qualifying vendors, issuing drawings, engineering change orders, etc. All key employees were issued copies of the QA/QC manual. The importance of this reference is becoming more clear as the company grows and more people are added to staff.

The QA/QC manual was updated and expanded to reflect the procedures necessary in the production of the current product line. Copies of it were delivered to the funding agencies in March 1994.

3.2 POWERGRID MODULE DESIGN

This section describes the work that was done each component that makes up the Powergrid module and testing on the complete module itself.

Module design work was done during all phases of the project. During Phase I, the main goal was to construct a complete linear focusing module. This consisted of:

- revising the cost summary for the module
- revising the module design
- fabricating prototype receiver sections and delivering them to Sandia for qualification testing
- fabricating complete concentrator modules and delivering them to Sandia for qualification testing.

During Phase 2, the main goal for module design was to revise the design to 1) improve the efficiency and reliability and 2) reduce the cost of module manufacturing. This consisted of tasks including:

- changing the module design to improve cost efficiency based on knowledge gained in Phase 1
- designing the array structure and tracking mechanism
- developing encapsulation systems for the receiver
- producing additional modules for evaluation testing by Sandia.

During Phase 3, the goals were to continue improvement in module efficiency.

Cost

The revision of the Powergrid design was based upon cost optimization. At the start of the project, a design review meeting was held to critique the design and set the direction for further work. The review focused on the areas of lenses, heat sinks, mechanical strength, tracker performance, and wiring. The design review meeting was organized as a separate task.

The Powergrid design was continually revised during the project as new information came to light. Much of this information was obtained from field testing. Other information came from testing at the factory, computer analysis, and from experience in the pilot line.

Existing production and projected costs were calculated throughout the project. Where possible, the projected material costs were determined based upon quotes from vendors. Existing labor costs were determined from tally sheets. Projected labor costs were calculated based on assumed levels of automation. Several sources were used for projected labor costs to assure reasonableness.

Table 1 is a summary of the direct material costs for different buys. Material costs refer to a complete Powergrid dc system with modules, frame, tracker, etc. but no ac (inverter) or installation costs.

Table 1 - Summary of Direct Material Costs

Buy	**Material Costs**	**Module Configuration**
Original Proposal (100 MW/yr)	0.36 $/Watt	10, 10-inch modules
Pilot Line Demonstration Buy (40 KW)	6.51 $/Watt	12, 10-inch modules
Next Buy (50 KW)	4.16 $/Watt	12, 15-inch modules

The original proposal was based on a 10-module panel with 10-inch wide lenses. The pilot line demonstration buy is based on a 12-module panel with 10-inch wide lenses. The next buy is based on a 12-module panel with a 15-inch wide lens.

Direct labor costs during the pilot line demonstration were about $760 per panel. This is expected to be reduced as more automation is introduced. From an analysis of a 50 MW/yr facility, the cost per panel would be about $50.40. The original proposal forecasts direct labor costs of $39.95 per panel for a 100 MW/yr facility.

Cells

Phase 1

During Phase 1 of the project, AstroPower cells were used. AstroPower has made low concentration cells, using screened metallization, for use in these concentrators. The manufacturing process is essentially the same as that used for one-sun cells. A special gridline pattern and low resistivity material is used.

Two batches of cells were delivered. The first batch of cells were made on polycrystalline material. The best fill factor for these cells, measured at Sandia, was 72.2% at a flux level of approximately 600 mW/cm^2 (6-suns), which is excellent for screened metallization on polycrystalline material. However, current was limited by material qualities and the best efficiency was 9.9%.

The second batch of cells were made on single-crystalline Czochralski wafers. For the second batch of cells, a maximum of 12.7% efficiency was measured at 6.05 suns concentration. This cell has a fill factor of 77.9%. This is a significant result for a cell with screened metallization used at low concentration. Efficiencies were expected to improve when these cells were encapsulated, due to better matching with the AR coating which was designed to be used with a cover. Sandia tested the cells without the conformal coating. When these cells were tested at AstroPower, with a temporary coating, a maximum fill factor of 81.2% and a maximum efficiency of 14.7% was measured at a flux level of approximately 500 mW/cm^2 (5-suns).

Phase 2

For Phase 2, cells from Siemens were used. Siemens proposed their standard one-sun cells with a different grid line design which they tested at low concentration and achieved over 17% efficiency. Siemens provided preliminary calculations for cell efficiency verses concentration, shown in Table 2 below. The concentrations listed apply to cells that fit on their standard wafer. The efficiencies are without any changes to the cell structure or processing, and just have a different cell mask.

Table 2 - Siemens Cell Efficiency versus Concentration

Number per wafer	Width (inches)	Concentration (suns)	Efficiency (%)	Fill Factor (%)	Grid Spacing
1	4.05	5.1	14.53	69.7	30
2	2.03	10.6	15.84	72.0	35
3	1.35	16.4	16.06	71.8	35
4	1.01	22.7	15.90	70.2	35
5	0.81	29.4	15.58	69.8	30
6	0.67	36.7	15.17	67.4	30

Phase 3

For Phase 3, cells were purchased from Siemens Solar Industries. The cells were purchased on wafers. The wafers were diced into 3 cells by a subcontractor and then flash-tested at SEA Corporation.

Cell grouping and rejection during the flash test was based on the amount of current flow through a fixed resistor. The cells were grouped into 9 current groups. The cells were rejected if they were broken or if current was less than 91% of average current. The reject rate was less than 5% based on these criteria.

Cell efficiency ranged from 13% to 16% at 25°C, 600 mW/cm^2 (6-suns) illumination, and AM 1.5D spectrum, with the average cell efficiency being approximately 15%. Cell performance was very consistent through the project.

Soldering

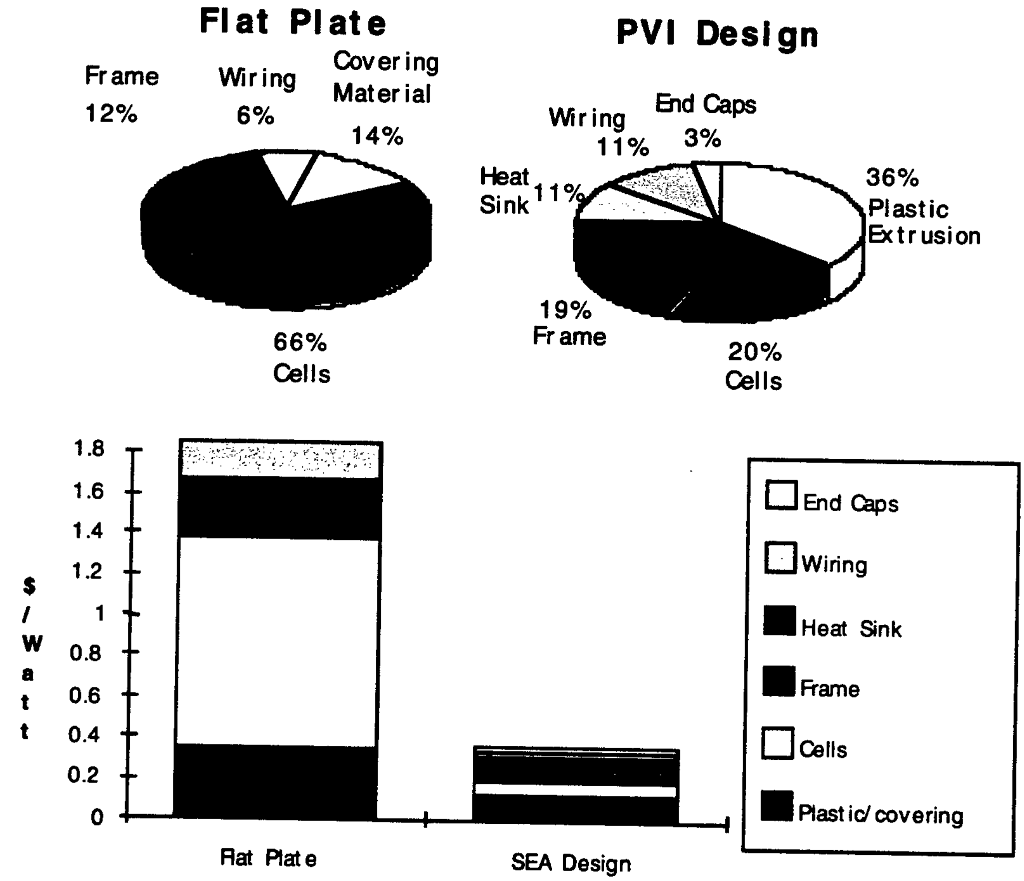
The screened metallization used for one-sun cells is usually more difficult to solder and more susceptible to damage during soldering. The metallization can be damaged by using soldering temperatures that are too high or soldering times that are too long. The metallization damage takes the form of de-wetting of the solder and reduction of adhesion of the metallization to the cell.

If the soldering is done with the correct temperature cycle, the metallization on the Siemens cells works well. The method that must be used is a quick cycle to just above the melting point of the solder. A eutectic lead-tin-silver solder gave the best results. A no-clean flux was used which eliminated the necessity of cleaning the cells after soldering. This was especially important when the automated receiver assembly station was used because the soldering was done on the heat sink and there was no opportunity to clean the cells after soldering.

Cost Considerations

Because of the small quantities of cells purchased during this project, the cost of the cells was relatively high. It is anticipated that the cost of cells will come down in the future, when larger quantities of cells are purchased.

As Fig. 11 shows, the advantage of the SEA Corporation Powergrid design, when compared to the flat plate design, is that the proportion of cost from the cells is much less. Since the cells are the most expensive part, this lowers the overall cost considerably.



NOTE: The above costs are based on identical medium volume production rates.
Flat plate data based on private conversations with a flat plate manufacturer.
Powergrid data base on costing study done at SEA Corporation.

Figure 11 - SEA Powergrid Cost Structure vs. Flat-plate Cost Structure

Heat Sink Optimization

Sheet Metal Heat Sinks

During Phase 1, the first full size receivers were built. Previous receivers were one foot in length. The receivers made during Phase 1 were from sheet aluminum. Thin-section extruded heat sinks were not available and the sheet aluminum heat sinks represented the lowest cost per watt option.

The heat sinks made in Phase 1 had steps formed to accommodate the bottom cell leads. Previous heat sinks had been flat.

Extruded Heat Sinks

During Phase 2, the heat sink design was reviewed in light of recent developments in the technology of aluminum extrusion allowing much thinner sections than previously available. Aluminum extrusions can now be made 0.04 inches thin. Heat sink performance is determined more by the heat transfer to the air rather than by heat conduction in the heat sink. This has been confirmed by testing where the measured temperature drop from the fin to ambient air is at least 5 times the temperature drop along the fin. For best cost-effectiveness, the heat sink fins should be thin. A finite element analysis program was used and tests on sample heat sinks made to compare extruded heat sinks to sheet metal heat sinks, and to optimize the extruded heat sink design.

SEA Corporation employed a finite-element heat-transfer computer program to model the heat sink. This computer program calculated steady state temperatures of user defined elements using an reiterative process. Heat input was calculated based upon solar insolation, optical transmission, and cell efficiency. Heat dissipation was calculated based upon convective and radiative heat transfer to the surrounding environment. Because forced convection was assumed, the program would not give accurate answers for wind speeds less than approximately one meter per second (m/s). The convective heat transfer coefficients for the appropriate elements were calculated based upon the user-inputs for atmospheric temperature, wind speed, and geometry of the heat sink and the calculated temperatures of those elements. Sea level was assumed. The program periodically recalculated the convective heat transfer coefficients as the element temperatures were changed during the reiterative process. Radiant heat transfer was calculated based upon the element temperatures, atmospheric temperatures and user-input coefficient of emissivity. The program terminated calculations when the changes in element temperatures were small and the quantity of heat dissipated was approximately equal to the quantity of heat into the cells. The results of the finite element analysis predicted a cell junction temperature of 55°C under normal operating conditions (20°C ambient temperature, 1 meter per second wind speed and 1000 watts per square meter insolation).

The extruded heat sink provided better heat dissipation and the cells ran about 17°C cooler than the sheet metal heat sink at normal operating conditions. This was because the fins on the extruded heat sink radiate from under the cell while the fins on the sheet metal heat sink were at the edges, requiring the heat to travel much further (Figs. 12 & 13). The cooler cell temperature provided about 10% additional power output. In addition, small bumps on the heat sink increased the heat transfer to the air.

The extruded heat sinks are also much stronger. They provide a backbone for the module and a stable platform for receiver assembly. These are important considerations when looking at yield losses and stress considerations. The heat sinks will be more of a structural element in the 20-inch lens module design, allowing further cost reduction of other components.

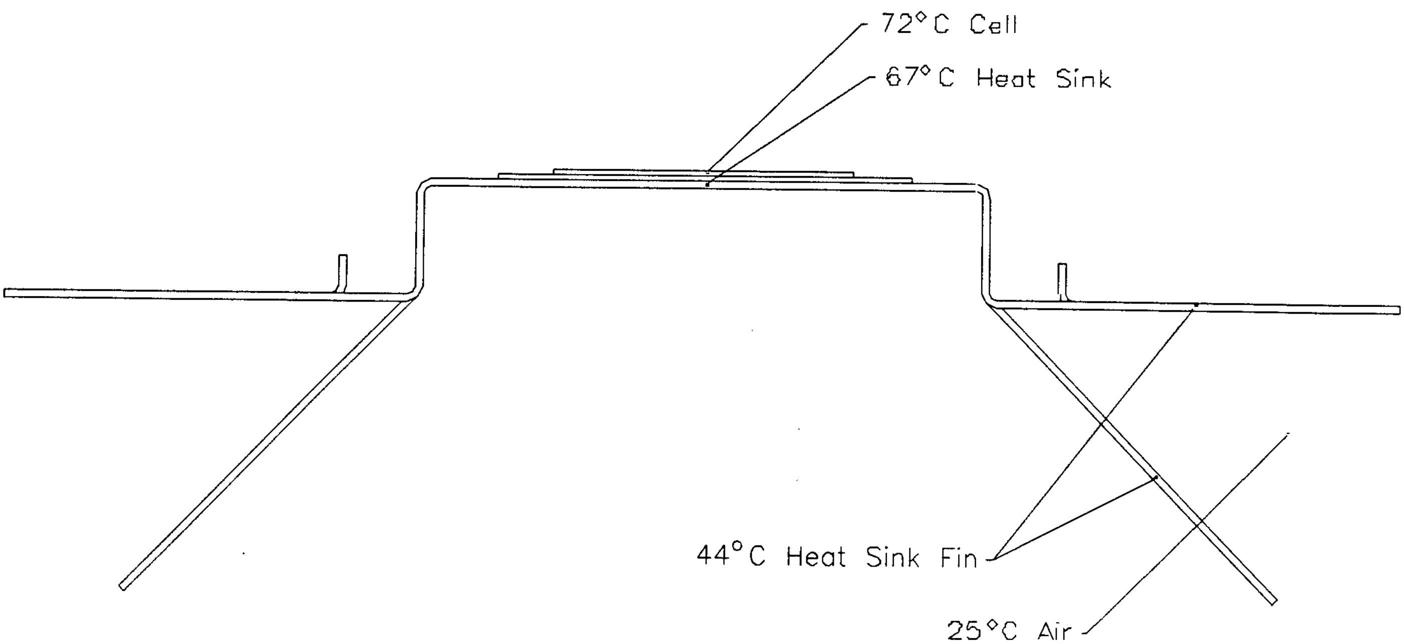


Figure 12 - Sheet Metal Heat Sink Typical Operating Temperatures

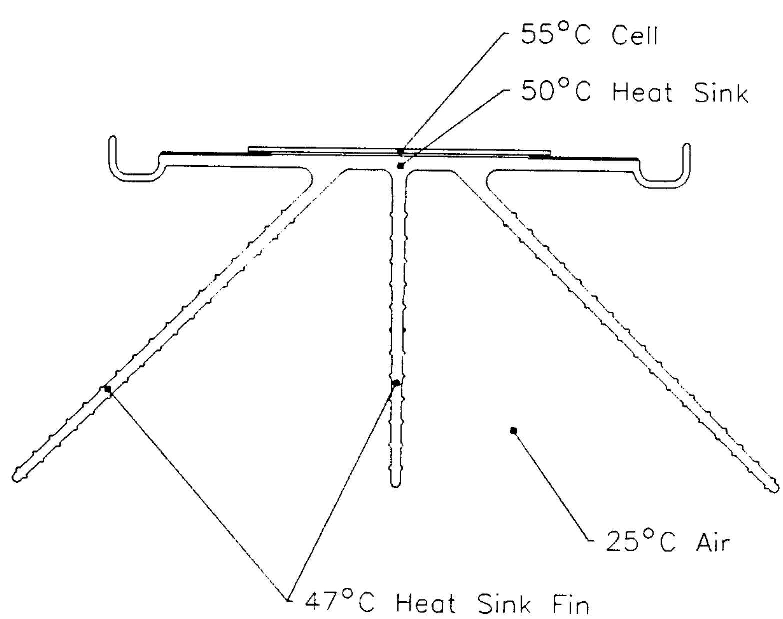


Figure 13 - Extruded Heat Sink Typical Operating Temperatures

Encapsulation

Small, one-foot-long receiver sections had been manufactured under a previous contract with Sandia. These sections were hand assembled using heat-conducting silicone rubber to bond the cells to the anodized heat sink and silicone rubber to encapsulate the electrical components. Concentrator cells with evaporated silver metallization were used. These receivers performed well during the Sandia qualification testing. SEA Corporation felt that it was important to proceed with assembly and testing of full size modules to discover any potential problems that would not be present for the short receiver sections.

Base Line Method

The previous adhesive and encapsulant materials and procedures were retained as a "base line design" during Phase 1. At the same time, new materials and procedures were sought that would be better suited to manufacturing, would reduce cost, and would improve reliability. The liquid silicone rubber adhesive and encapsulant are not well suited for low-cost manufacturing because it is difficult to handle while uncured and requires a long time to cure. Reliability was lower than desired because they allow water absorption which could lead to early failure, and because voids were prevalent under the cell, in the lead area, and in the encapsulant.

Materials and methods were sought that would perform the functions of the base line materials but at a lower cost and with improved reliability and manufacturability. The new materials would have to have the following features:

- Be easy to apply and preferably be dry when uncured
- Perform the bonding and encapsulation functions
- Provide, along with the anodization, the necessary electrical standoff
- Be low cost
- Improve the manufacturability of the receiver
- Survive the expected environment of the receiver for 20 years
- Be environmentally benign

Wet and Dry Methods

A number of cell bonding and encapsulation methods were tested during the project. The first tests were conducted in Phase 1 on ten test receiver assemblies. These were delivered to Sandia to be tested per the Sandia Qualification Test Procedure. Five used the standard "wet" RTV method of cell bonding to the aluminum heat sink. The other five assemblies used a new "dry" method of bonding. The dry process had many potential advantages over the wet process in production. All receivers used AstroPower cells.

For the first group of receivers, a single layer of Emerson and Cuming 4952 Red RTV, 0.005 to 0.007 inch thick, in conjunction with Emerson and Cuming S-11 primer, was used to bond the cells to the heat sinks. Adhesion was found to be inadequate and hipot currents were excessive: up to 24μA before thermal cycling. One breakdown failure was experienced. General Electric SR-900 conformal coating was used, which remained tacky after curing, causing dust and dirt to stick to it.

General Electric SS-4155 primer, together with two layers of Emerson and Cuming 4952 Red RTV, was used for the second group of receivers. Adhesion was much improved and hipot currents were much reduced: 0.1μA to 0.5μA, and no failures were experienced. A vacuum chamber was used for the second group of receivers to de-air the RTV prior to application, and a "double Y" RTV pattern was used, causing marked decrease in voids to be observed. Dow Corning 1-2577 conformal coating was used for the second group of receivers. It cured without tack. No bypass diodes were used in the second batch of receivers. Electrical degradation after the evaluation testing was an average of 3.65%, less than the allowable 8%.

The third batch of receiver sections were identical to the second batch except that a space under the bottom cell contact leads was provided. For the first and second batch of receivers, the leads were causing the RTV bond line to be non-uniform in thickness by standing off the cells in this area. AstroPower cells, with screened metallization, were used. Also, bypass diodes were installed. These diodes, 2.5 mm by 10 mm, allowed multiple contacts for reliability.

The fourth batch of receiver sections were identical to the third batch except that an experimental, proprietary, dry adhesive system was used. This system had advantages in manufacturing. It was tacky when uncured, allowing robotic assembly of the components directly on the heat sink. Soldering could be done *in situ*, after which the adhesive could be cured rapidly at low heat.

Electrical Evaluation

Electrical evaluation after thermal cycling showed that the currents were significantly reduced. This was thought to be due to a problem with the cell lead contact to the back of the cell. Failure evaluations were made at SEA and Sandia of the test receiver assemblies. These receivers used the AstroPower cells with screened metallizations. The performance of the bonding system and encapsulation were acceptable, but the receivers did not pass the electrical tests after temperature cycling and freeze/humidity cycling.

The failure mechanism was determined to be the separation of the screened metal from the front surface of the cell. Possible causes were mechanical stresses, moisture intrusion, and cell process problems.

Lead System

During Phase 3 tests were done to determine what could be done to make the existing lead system more reliable. From these tests it was determined that there was too much solder pre-tinned on the leads and that the mylar insulation was not long enough to cover the possibility of shorts.

The receiver encapsulation has improved significantly and all later receivers passed the SEA Corporation submersion wet hipot tests. Further work remains to move from a hand-assembly process to an automated production process. Even though prototype hand assembled receiver samples passed evaluation testing, receivers initially assembled in the production environment did not.

Lens Width Optimization

Lens width was optimized based upon performance and cost. Performance was calculated from optical transmission and cell efficiency at operating temperature. The lens size was increased from 10 inches wide to 15 inches wide, and a 20-inch wide lens is now under development. The cell size has remained the same during this time leading to increased concentration ratio. For the 10-inch lens, the concentration was 8.7 to 1; for the 15-inch lens it is 13 to 1; and for the 20-inch lens with planned wider cells, it will be 15 to 1. As the width of the lens increases, the general focusing ability of the lens must improve because of the increased concentration ratio. For the optimization study, it was assumed that the lens efficiency was based on a lens at a relatively mature development state.

As the width of the lens increased, other factors must be considered. The heat dissipation must be increased. In addition, the cell efficiency is affected, although most degradation in cell performance can be eliminated by manufacturing a different cell designed for the higher concentration ratio. The motivating force was a reduction in cost per watt. A larger lens added very little cost while increasing the module output significantly.

Table 3 shows module performance and cost at the different lens widths.

Table 3 - Module Performance and Cost at Different Lens Widths

Lens Width	**Lens Efficiency (%)**	**Cell Temper-ature**	**Cell Efficiency at Temperature (%)**	**Powergrid Relative Cost**	**Powergrid Relative Output**	**Powergrid Relative Cost per Watt**
10	85	58	13.0	1.00	1.00	1.00
15	83	65	12.0	1.15	1.35	0.85
20	81	72	11.0	1.25	1.61	0.78

Note: For these calculations, the cell active width was held constant at 1.15 inches. Uniform cell illumination was assumed.

In order to make a fair comparison, lens efficiencies at each width are based on lenses at a relatively mature development state. The company hopes to achieve higher lens efficiencies than used in this table through changes in the extrusion process. For this table, the lens design was kept constant leading to an increase in costs with increasing lens width. By improving the design, SEA Corporation is lowering parts cost with the 20-inch module. In reality, the 20-inch module should not cost much more than the present design.

The cell efficiency in Table 3 is based on tests of the present cell. Cell efficiency should improve with time. Since the Powergrid uses one-sun cell technology, the present work being done worldwide to improve one-sun cells should benefit the Powergrid.

The heat sink design was held constant for this table but scaled according to lens width. Improved heat sink design should lower cell temperature and thus raise cell efficiency.

Improved cell efficiency, lens transmission, and heat sink design, along with the economics of the wider lens and improved design, will make the Powergrid significantly more cost effective in the future.

Module Testing

The Phase 1 task of fabricating and delivering modules to Sandia was accomplished. Three complete concentrator modules and one mechanical sample module were delivered in October 1991.

During Phase 2 the modules were tested. Specific areas with deficiencies were identified:

- The module venting system needed improved rain rejection. A drip feature was added to route water away from the vents.
- The module connector was eliminated and a strain relief feature added. The connector was a possible source of failure (fire, insulation breakdown) and did not conform to certain electrical

codes which required a tamper-proof box for the connector. It was more cost-efficient to move the connector to a tamper-proof box on the array frame.

- The reflective film adhesive system was improved. Delamination was noted during thermal and freeze-humidity cycling. Candidate alternative adhesive specimens were assembled and sent to Sandia for evaluation.
- Encapsulation needed to be revised to improve wet-insulation resistance. The modules did not pass the wet-insulation resistance test which was added to the Sandia Qualification Tests. SEA added this test to the QA/QC program.
- Plasticizer needed to be added to the lens material to improve hail ball survivability. Samples of plasticized acrylic were sent to Sandia for evaluation.
- The module sides were molded from polycarbonate to improve hail ball survivability. The 1/16-inch thick acrylic sides were too weak for hail ball resistance. Samples of 1/16-inch thick polycarbonate sheets were sent to Sandia for evaluation.
- The end joint between the receiver and the end cap was improved to eliminate interference during differential thermal expansion. Tolerance build-up caused this area to be a butt joint where a lap joint was planned. The design was improved to be more tolerant to dimensional errors.
- A stiffening feature was added to the heat sink to reduce bowing.

Two modules that underwent evaluation testing at Sandia were returned to SEA Corporation. Tests also showed that one module developed a lens image that was skewed in relation to the cell string. Inspection by Sandia did not reveal any twisting in the module but there was a considerable amount of distortion in the plastic parts.

Module Bowing

An interesting result of the thermal cycling was that the module developed a longitudinal bow. This bow was concave as viewed from the bottom of the module (Fig. 14). One possible explanation was relative movement of the tabs that attach the heat sink to the plastic parts of the module during thermal cycling, resulting in residual compressive stresses in the plastic parts and residual tensile stresses in the heat sink. To test this theory, the tabs were loosened, allowing any residual stresses to be relaxed. After the tabs were loosened, the bowing increased (from 0.380 to 0.423 inch in 96 inches), indicating the bowing was caused by residual stresses in the plastic parts alone.

The plastic portion of these prototype modules was made from three different parts: the extruded acrylic lens, the sheet acrylic sides, and the extruded polycarbonate Z-bars. Samples of these components were placed in an oven at 80°C for 48 hours to test for growth. (Stresses are placed in plastic parts during the fabrication process and heating will tend to relax these built-in stresses.) The extruded acrylic lens grew by 0.18% in the middle but had no change on the sides. The Z-bar grew by 0.31%. The acrylic sheet shrank by an average of 0.15%. These changes in sizes of the plastic parts explained the bowing.

Present modules are not susceptible to bowing or warping. The plastic parts for Phase 2 consisted of two parts, both extruded, that grew by approximately the same amount, eliminating most of the module bowing. The bowing did not cause reduced performance in these prototype modules. The optical system accommodated such bowing without any degradation. Also, the cells bent by this slight amount without any breakage.

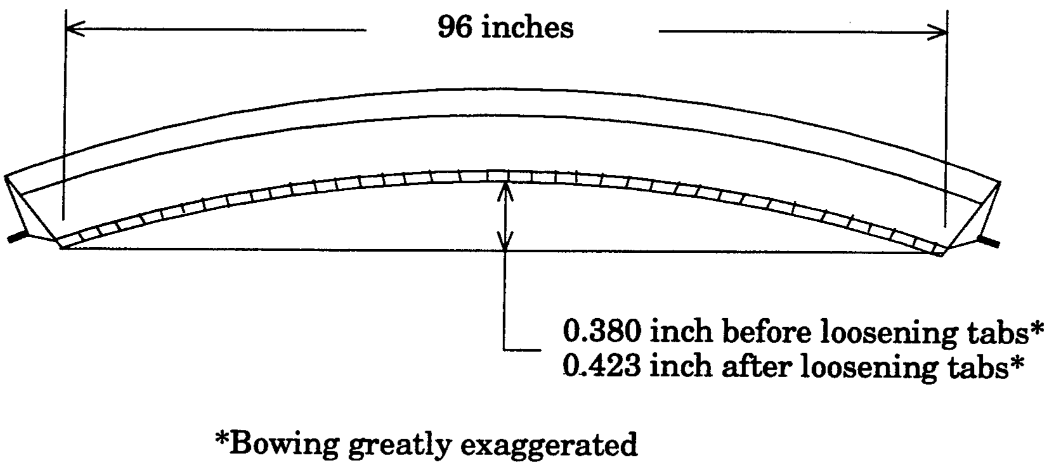


Figure 14 - Module Bowing

Module Length

The ongoing optimization study determined that the module length should be increased to 10 feet. This brought the calculated electricity cost down to approximately 3 1/2 cents per kilowatt-hour. The 10 foot length was not used previously because of the availability of plastic sheet in this size. Since SEA Corporation extruded the sides of the module for Phase II, this enabled moving to the 10 foot length. Additionally a company was found to make the 123-inch-long heat sinks required for the longer module.

End Caps

During Phase 3, the mechanical design of the module was tested in the field. Based upon the results of these tests, the end cap and module-to-receiver crimp joint were improved. The changes were based upon stress analysis, sand bag loading, and wind testing on top of a vehicle. The improved modules were installed in the field for further testing.

Wind loading is the most severe loading situation for the Powergrid module. A violent winter wind storm occurred at the Sacramento Municipal Utility District (SMUD) site, which stressed the modules to their breaking point. Weather data from surrounding areas indicated that the wind peaked at 80 miles per hour. Approximately one-quarter of the modules were damaged.

Analysis of the damaged modules showed that the end caps were weak in the pivot pin area, the glue joint to the module sides, and the bottom of the module near the receiver (Fig. 15). The initial stress calculations on the end caps did not catch these flaws, and the loads were underestimated. The beta test site provided an opportunity to discover this problem. When tested at the factory, these modules failed at about 50 pounds dead weight per end.

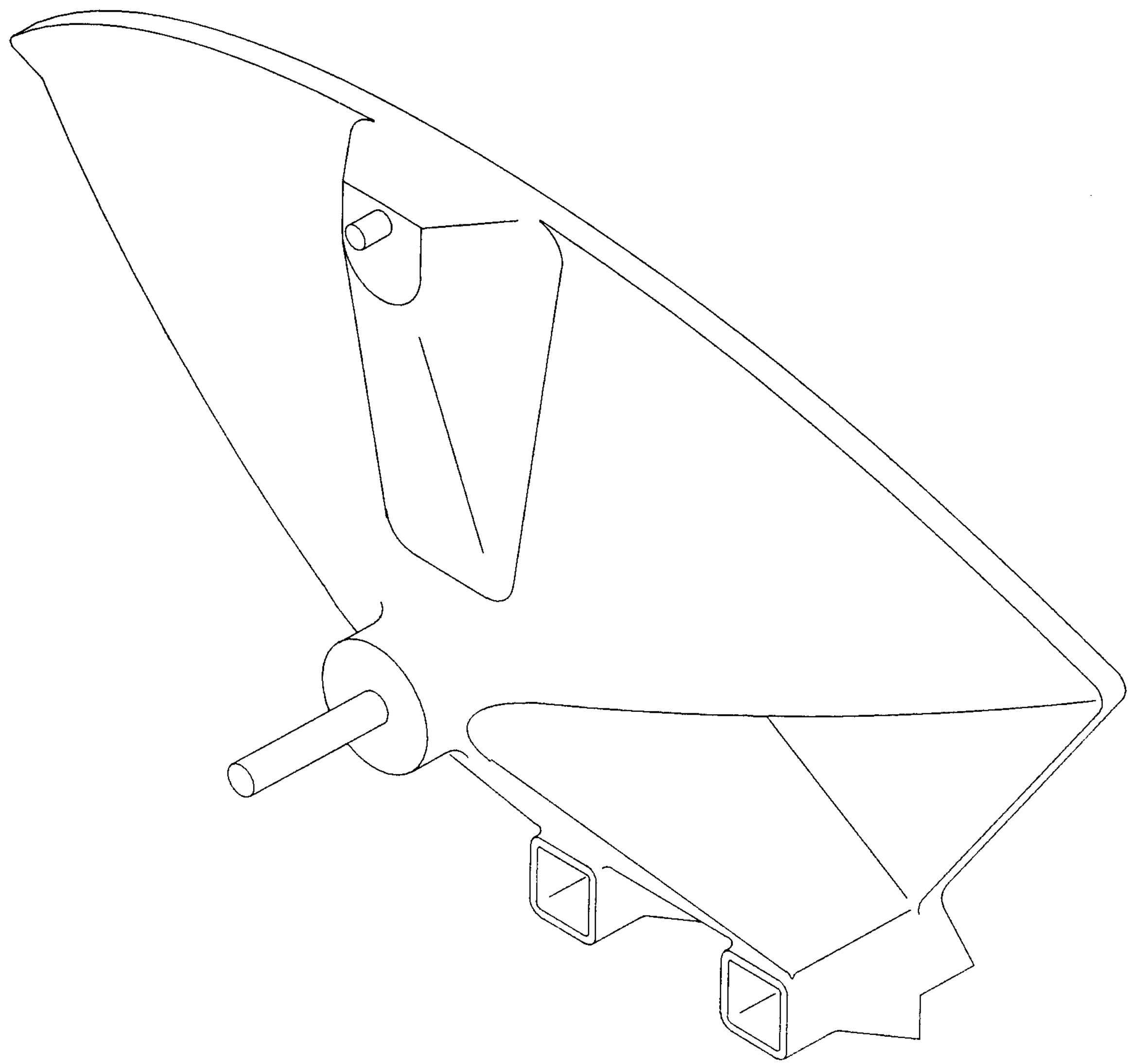


Figure 15 - Old-Style End Cap

The end caps were re-designed and new end caps manufactured. The new end caps incorporated many improvements. The pin was moved to the frame while a ball joint was installed in the end cap, thus eliminating moment loads in the plastic. Material was added to the end cap and module sides near the receiver. The glue joints were strengthened by increasing the adhesive filler. The thickness of the end cap was increased (Fig. 16). Static tests on the new end caps indicated that they could withstand about 200 pounds dead load which is four times the previous design. Tests where the module was mounted on top of a truck indicated that they could withstand about 80 miles per hour wind load with the wind coming perpendicular to the side of the module, which is the weakest part of the module.

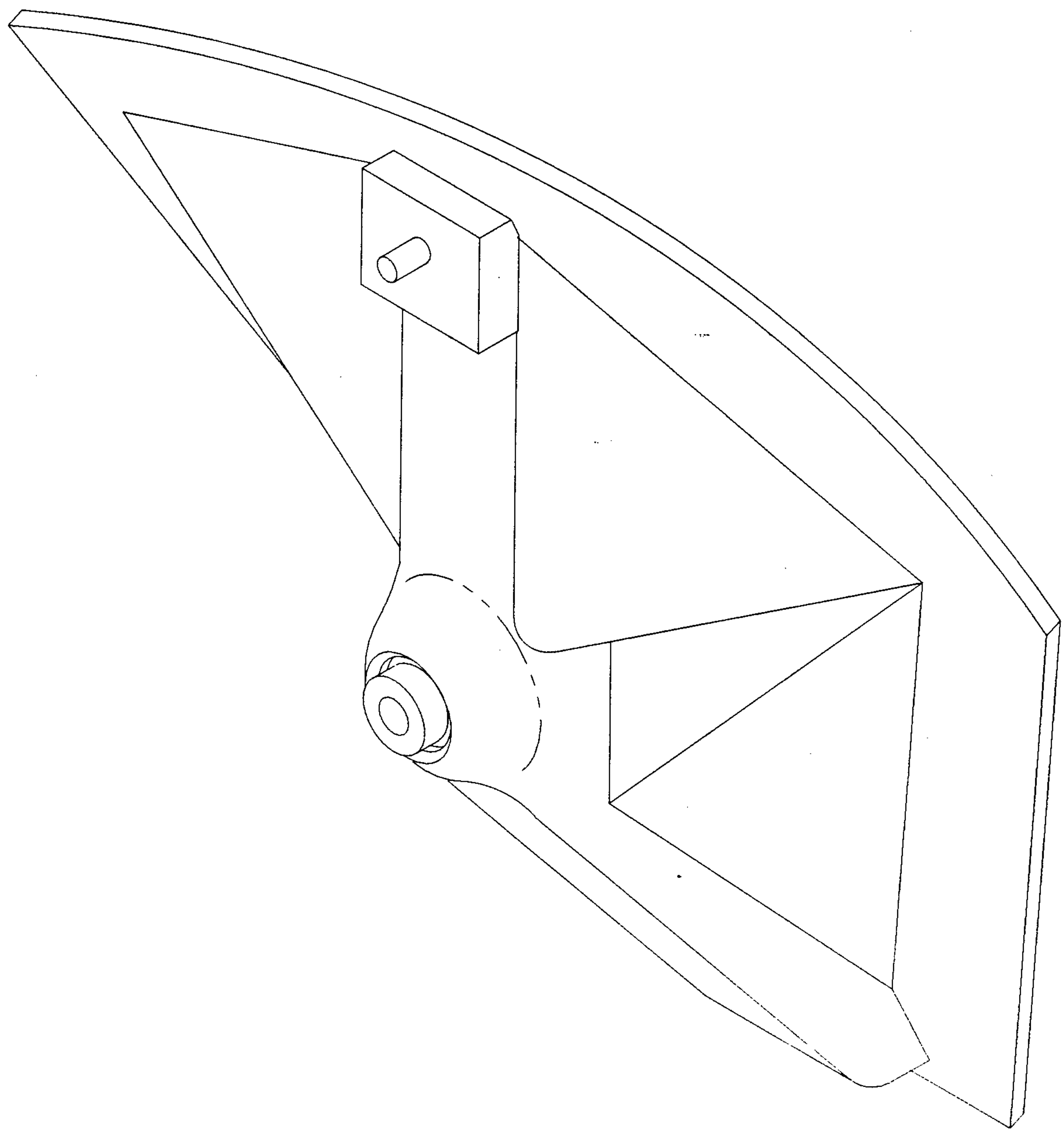


Figure 16 - New-Style End Cap

Attachment of Heat Sink to Module Sides

The attachment of the sheet metal heat sink to the module sides was also determined to be weak. This was vastly improved by eliminating the small clips used on the sheet metal heat sink and replacing them with a continuous crimp used on the new extruded heat sink. No structural failures have occurred with the new design.

Tracker

The majority of work on the tracker drive occurred during Phase 2. The tracker circuit was designed to take energy from the array with no external sources or batteries. The power produced by the array when not pointed at the sun is enough to drive the circuit and the gearmotor. The circuit uses two inputs, a sun sensor and a position sensor. The sun sensor doubles as an intensity monitor. The array tracks in a jog mode, minimizing parasitic loads, and stows in an upward position when the intensity drops to a preset level. Initially, the preset level was set so that the array stowed when a dark cloud obscured the sun. The array required less than 45 seconds to re-acquire the sun.

The total part cost of the tracker electronics is less than six dollars. Size of the circuit board is less than 2 inches by 4 inches. The circuit board is mounted in the gearmotor housing along with all the sensors. The electronics and motor are electrically floating at up to 500 volts, depending on where the array is in the field circuit. This requires special isolation requirements similar to the module.

The power requirements for the Powergrid tracker are small, less than 6 Watts. This allows the use of a small, low-cost gear motor and control electronics. The wide acceptance angle of the module allows the use of a simple sun sensor and electronics circuit. These components have worked better than expected providing better than ±1/4° tracking accuracy, measured at the modules. The sun sensor is not affected by clouds or other bright objects and has a ±130° acceptance angle, measured on panels, so that it can acquire the sun in the morning from the stow position.

Prototype Testing

The first prototype tracking electronics were built and tested. The test pointed out weaknesses in the design. An updated tracker drive was manufactured. This drive had the stow capability and fit into the gearbox housing as originally designed.

The performance of the Phase 2 version of the tracker drive was outstanding. The concept of using the panel to power the tracker worked extremely well. Several improvements to the tracker drive were made during this phase.

Phase 3 Field Tests

The original tracker gear motors failed in the field. The cause of failure was overload of the final output shaft. The size of the gear motor was increased to a 1/2-inch diameter shaft as opposed to a 1/4-inch diameter. This increased the strength by four times. No subsequent failures have been noted.

Part of the failure of the shafts was due to oscillations in the original tracker drive that were caused by the gain being too high. The oscillations only occurred when the panel was not loaded down and the voltage was high. The tracker motor was designed to operate at 12 volts, whereas the actual voltage could be 24 volts when the panel was operating open circuit. The solution to this problem was to install a voltage regulator on the tracker circuit board to keep the motor at 12 volts. This slowed down the response and thus the gain, eliminating the oscillations. An additional safety measure was going to a lower gear ratio in the tracker gear box.

The stow function was improved. Initially, the stow time was set too late in the day resulting in insufficient sunlight to move the lens up to stow position. The modules would be west facing in the morning and would not acquire the sun until late in the morning. The stow light level was adjusted by changing the controlling resistor in the circuit board. This eliminated the late stow but introduced another problem, oscillation between stow and tracking.

The oscillation between stow and tracking was caused by the response of the sensors. As the light level decreased in the evening, the panel would move towards the face-up stow position. The sensors would then acquire more light and start to track towards the west where they would again sense low light and again move towards stow. This continued until the light level was too low to move the modules and they would again be facing west in the morning.

The solution to the oscillation between stow and tracking was to add a latching circuit to the tracker board. This circuit prevented the tracking mode from being re-activated until the stow function was complete. Once the modules were face-up in the stow position, the sensors would sense low light and the module would stay in the stow position.

The tracker was cycled for the equivalent of over 200 years (76,245 cycles, equivalent to 209 years assuming 365 cycles/year). The test was stopped when the tracker failed to move in one direction. The failure mechanism was traced to one of the sensor wires fatiguing at the tracker board. There was no strain relief for this wire. The design was changed to add a strain relief for these wires. With this correction, the tracker could operate for many more cycles. There was no noticeable wear on the tracker gear motor after these cycles.

A dc to dc isolated converter was added to the tracker circuit. This eliminated a potential shock hazard and a potential high voltage insulation breakdown. The nominal voltage for the panel is 18 volts. This does not normally represent any shock hazard or high voltage breakdown problem. However, the panels are wired in series to provide a reasonable working voltage for the inverter. This voltage is typically 360 volts at the operating point or over 420 volts open circuit. Each tracker takes the differential voltage of the two leads of the panel to which it is attached. For the last panel in the series string, the negative pole of the panel is 342 volts and the positive pole is 360 volts. The differential voltage is 18, but the high sides of the circuit and motor are operating at 360 volts above ground. The dc to dc isolated converter changes the 342 and 360 potentials to 0 and + 12 volts. Over 2,200 volts isolation is provided by this device.

Wiring

The wiring was also reviewed for cost-effectiveness. The original Powergrid was designed using bus bars and complicated electrical connections for the panel wiring. The cost of this design turned out to be very high. A more traditional wiring harness assembly was investigated. The present wiring is very simple and low cost by comparison. Multiple strand, 12 gage, sunlight resistant Underground Service Entrance (USE) wire is used with watertight crimp connectors to connect the module wiring to the panel wiring. When a module is replaced, the connectors are cut off and new ones installed. The connectors are fed through the frame, which functions as a conduit, and are held in place by a grommet which also protects the wire. This system has proven to be very reliable, tamper-proof, and cost-effective.

Two grounding straps are provided for each module. These are flat, braided, multiple-strand wires without insulation. The braided wires are soldered at the ends and drilled so that sheet metal screws can fasten the wires to the heat sinks and the frame members. Anti-corrosion compound is used between the copper wire and the aluminum heat sinks and frame members. The copper wire is tin plated.

The routing of the wire from the module to the frame was found to be critical. If the routing is not correct, there can be strain concentrations at the ends of the wire which considerably reduce the number of cycles before failure. The best design stresses the wire uniformly throughout the length. This optimum routing was discovered by trial-and-error with the small test panel. The proper strain on the grounding straps is a twisting movement along the entire length of the straps. This reduces the strain levels to a minimum and allows the grounding straps to be cycled well beyond a 200 year equivalent life time.

Additional improvements are being made to the wiring to allow easier field installation. The #4 cable used to hook panels together is very stiff and hard to work with. It is difficult to do this work within the confines of the frame. SEA Corporation is re-designing this area to provide a large, rain-proof box for hookup. The design is a compromise between the cost of the components and the cost of installation and maintenance.

3.3 LENS DEVELOPMENT

Lens development during all three phases focused on improved lens efficiency. During Phase 1, the goal was to improve the existing 73% efficiency to 76% for the 10-inch lens. In Phase 2, the goal was to bring the efficiency to 80%. Phase 3 sought to continue to improve the optical efficiency to 83% or above.

Development of an extruded lens is essentially a cut-and-try process. The correctness of the first cut depends on the experience of the extruder. AllWest Plastics, SEA Corporation's sub-contractor under this project, is the foremost extruder of linear focus Fresnel lenses in the world.

Lens Extrusion

Figure 17 shows the lens being extruded. The heated die is protected with cardboard from the air flow used to cool the lens. As shown, the lens shrinks considerably during the first few inches. It continues to shrink as it cools. Plastic extrusion, as usually applied, is not an exact science.

During the course of this project, SEA Corporation endeavored to make the lens extrusion more of a science by asserting greater control over the design and manufacturing process.

Extrusion Die Design Process

The lens design is given to the extruder who then designs a die. Since the final lens form is defined by how the plastic flows after exiting the die, the die shape is not a direct copy of the design shape, but is modified to give the desired lens form after extrusion. The extruder transfers the die design to computer-aided-machining (CAM) code. This code cuts the die using a wire electric-discharge-machining (wire EDM) milling machine.

A trial run is then made using the new die and the lens is tested for optical transmission, focal length, allowable tracking error, and flux distribution. There are a number of proprietary methods to modify the die to improve the lens form. Alternately, the CAM program can be modified and a new die cut on the wire EDM machine.

Once a die is obtained that gives an acceptable lens, then, with proper process control, miles of lenses can be produced that will be nearly identical. One die can give over 25 MW worth of lenses per year. Additional production capacity can be added simply by producing additional dies using the same CAM code. Additional improvements in optical transmission can be obtained by using a proprietary method that polishes and hardens the die.

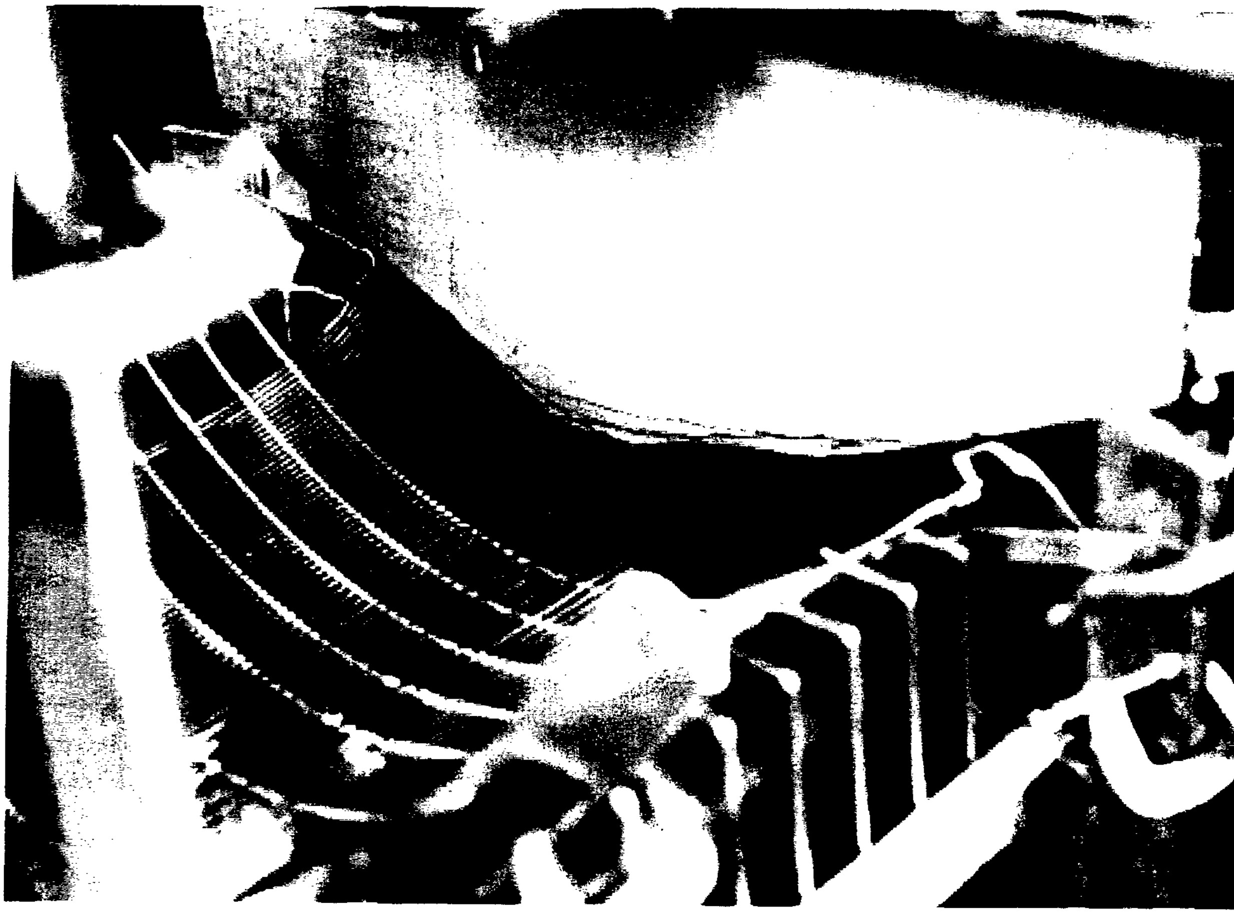


Figure 17 - Close-up of Lens Extrusion

SEA Ray-Trace Program

SEA Corporation maintains a computer ray-trace program which designs a lens based upon input parameters and then calculates performance of the lens under different operating conditions such as tracking error, airmass number, etc. The lens must be designed with the limitations of the extrusion process in mind.

During the project the use of a tertiary optical element (TOE) was investigated. (The module sides operate as a secondary optical element.) The TOE design was added to the SEA ray trace program. The computer ray trace program was also revised to more accurately model the extruded lens. The program now gives the same performance figures as the actual lens. Computer studies indicated that there was no economic advantage to the TOE.

<u>Die Numbers 1 and 2</u>

During Phase 1, SEA Corporation worked closely with the lens extrusion sub-contractor. Because of limited funds for Phase I, it was decided to modify the existing die to test various ideas on how to improve the lens form rather than make a series of new ones. The objective was to reduce the convex shape of the lens facets. The modifications went too far as the facets became concave. A sample lens produced from this die was tested at SEA. The lens gave approximately the same optical transmission as the lens samples produced before the modifications, approximately 76%.

After all modifications were performed that could be done to improve the optical transmission, a proprietary method was used to polish and harden the lens.

The first trial runs on the new die were encouraging but some modifications to the die were necessary. Die number two was cut wrong at the electrical discharge machining (EDM) shop. The EDM shop has promised a third die at no charge. Die number one was further modified and parts were run. These lenses were tested at SEA and 78% lens transmission was obtained. Sample parts and associated sides and fixturing were sent to Sandia for evaluation.

The lens development procedure followed in Phase 2 was to machine a series of dies, each one modified according to the results obtained from testing the previous die. Modification was achieved by adjusting the software used to cut the die. In this way, the results will be documented and repeatable. The procedure under Phase I was to hand modify the die to get a good part, but when it was attempted to duplicate this die, the results were unsatisfactory.

Also during Phase 2, direct-cut lenses were manufactured by 3M company for use in the module. These lenses were approximately 5 times as expensive as the extruded lenses but served to verify SEA's optical design and as a backup to the extruded lenses. Preliminary tests by Sandia indicated a 92% transmission to the cell without the reflective sides. Truly, these lenses were excellent quality. A cost analysis was performed to determine the cost-effectiveness of the 3M lenses when compared to the extruded lenses. The cost analysis indicated that the extruded lens would have to have a transmission of 57% or greater to be lower cost per watt than a 90% 3M lens.

Die Number 3

A new lens design was generated to cut the number three die. The new lens design had a number of features to improve lens transmission. It incorporated existing facets from the number one die that had almost the correct shape. The other facets were modified to work in conjunction with these existing facets, building on the previous work. The new lens also had been designed for improved performance throughout the year for single axis tracking.

The number 3 die was polished using a special process and trial extrusions were made and tested. The special process uses an abrasive slurry that is pumped through the die to polish the surfaces. After the polishing, the surface is hardened. The surface quality of the lens was much improved using the polished die but the transmission was essentially unchanged. This was due to the fact that most of the losses are caused by malformation of the facets rather than surface finish. It was interesting to note that the flux contribution from individual facets could be seen with the lens from the polished die while this was not true with a lens from an unpolished die. This would indicate that, when the facet shape was improved, the polishing of the die might improve transmission.

The lens was tested at SEA and Sandia (Fig. 18). As can be seen in the figure, up to 85% transmission was obtained at lower concentration while about 71% transmission was obtained at higher concentration.

The portions of the lens near the sides had well formed facets and focused to a narrow line. However, the facets near the center part of the lens were not well formed and the rays from this section diverged.

The 10-inch lens was designed as an equal facet volume lens. That is, the center facets, which are not very high, were made wide to increase the volume. The outside facets, which are the highest, were made narrow to keep the volume constant. It was thought that this would distribute the plastic uniformly across the lens.

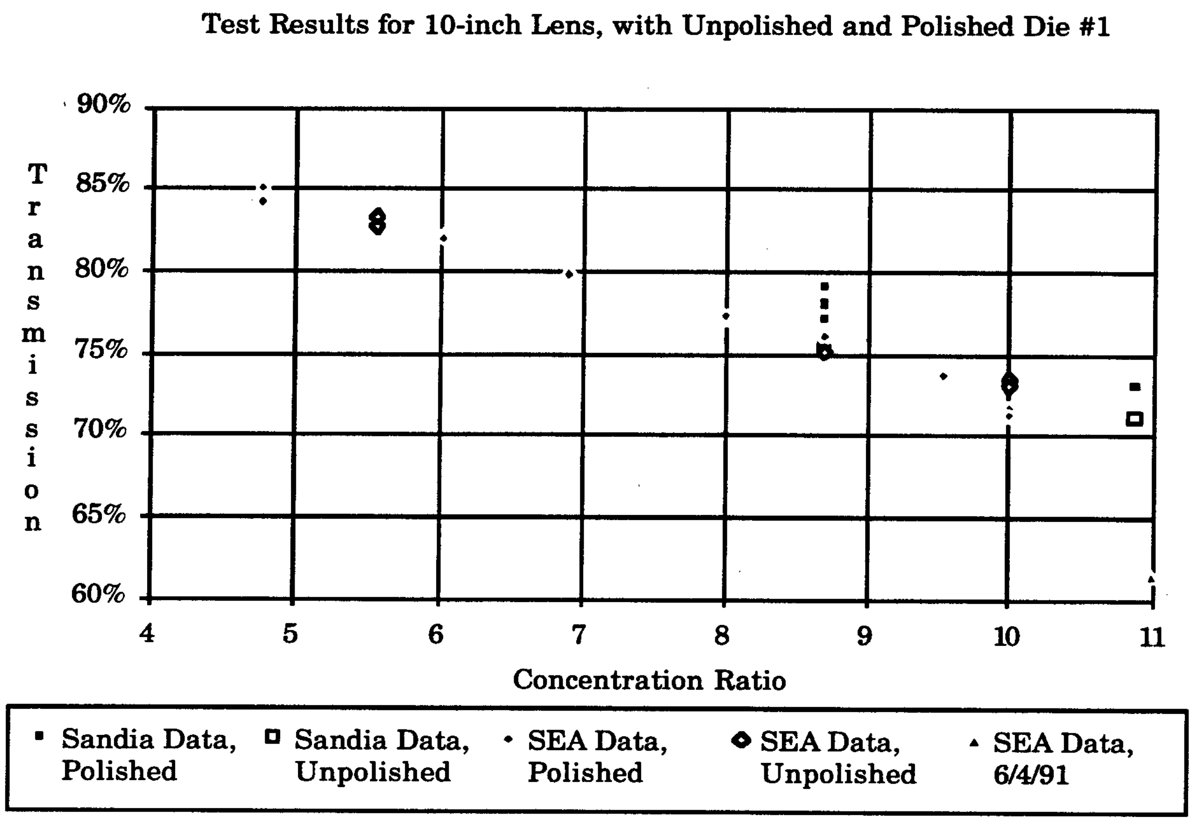


Figure 18 - Transmission from Polished and Unpolished Dies

As it turned out, the wide facets in the center of the 10-inch lens caused the plastic to "blow", which means that the facet surfaces were convex, making then into short focus lenses by themselves. The outside facets were so narrow that the root radii losses were excessive because of the number of root radii.

Design for Maximum Yearly Output

With single axis tracking, the sun is continuously changing the apparent north-south declination sun angle (north-south sun angle). The sun spends relatively little time at the zero north-south sun angle and most of the time at the extremes near ±23.5°. The average north-south sun angle is approximately ±15°. A lens which is designed to work well at a zero north-south sun angle will have a poor average yearly transmission. The lens to cell spacing can be changed to improve output, but the best solution is to design the lens for the maximum average yearly transmission.

Lenses were designed using different north-south sun angles (Fig. 19). These lenses were then ray traced for different east-west tracking errors and north-south sun angles. The average yearly transmissions for these different lens designs were then calculated. The results are summarized in the attached figures. Because the average north-south apparent sun declination angle is approximately 15°, a lens designed for a north-south sun angle of 0° will not have the maximum yearly electrical output when single-axis tracking is used. From the calculations, it is apparent that, with the expected east-west tracking error of from ±0.5° to ±1.5°, the lens designed at 17.5° north-south sun angle will give the best average yearly transmission. This design was used for die number three.

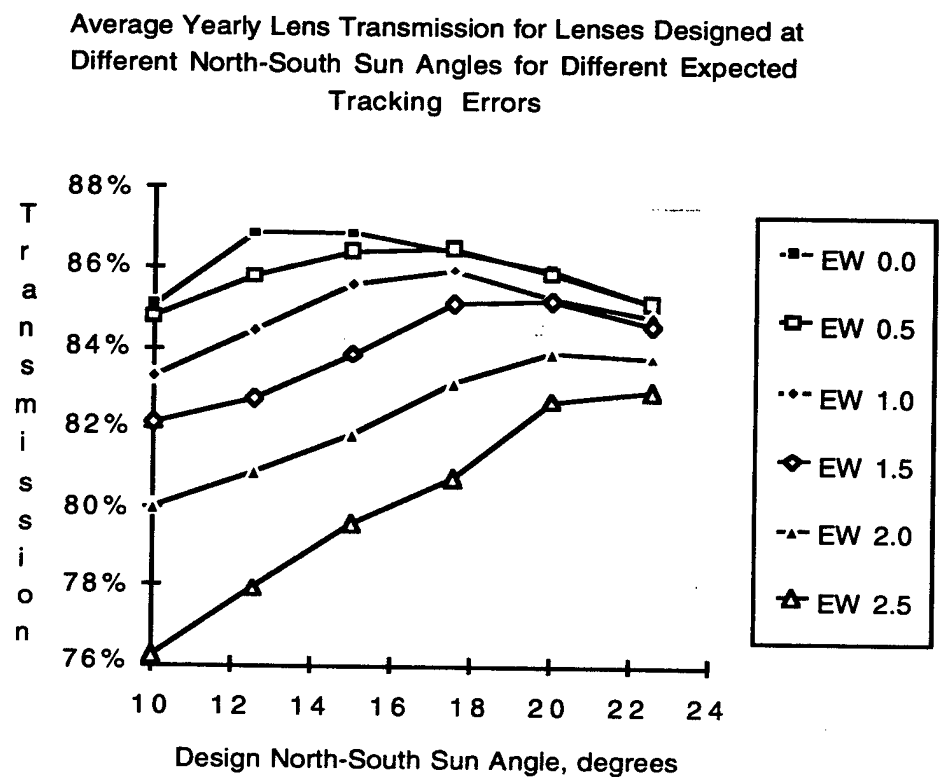


Figure 19 - Lens Transmission at Different North-South Sun Angles

Move to 15-inch Lens in Phase 3

At the start of the project, the Powergrid used a 10-inch lens, and a new 10-inch lens was about to be designed. During Phase 3, it was decided to expand the lens width to 15 inches to improve the cost-effectiveness. The new 15-inch lens was designed to take advantage of the best part of the 10-inch lens and to make the extrusion easier.

For the 15-inch lens design, the 10-inch lens was examined and a facet arrangement was chosen that provided a compromise between too wide and too narrow. The 15-inch lens was designed around this arrangement with a constant facet width. This meant that the outside facets would have much more volume than the center facets. Uniform plastic flow would be accomplished with the design of the manifold that feeds the plastic to the die.

The new 15-inch lens design was given to the extruder to design the tooling. The extrusion company hired a consultant to help with the design of the die and associated tooling. The plan was to extrude the lens as designed and freeze the lens in a vacuum sizer. A vacuum sizer is a device used to rapidly cool the lens as it exits the die and control the final shape. It is water cooled and uses a vacuum to keep the lens in contact with the metal. Top and bottom vacuum sizer pieces were made. The bottom matched the outside radius of the lens and the top matched the facets.

Performance of the die as designed and of the vacuum sizer were disappointing. The bottom half of the vacuum sizer worked well to give the lens a better surface finish and was used on production lenses. However, the top half of the vacuum sizer never meshed with the extruded lens. This was replaced by using rapid air flow along the length of the lens to rapidly cool the lens, but avoid contact with the lens facets.

A second die was designed and made by the extrusion company. The second die was a cut-and-try attempt to solve plastic distribution problems. While it was being made, SEA Corporation did a study of the plastic flow which indicated that the second die would not improve the distribution problems. The second die was not tested.

A third die was designed by SEA Corporation for the 15-inch lens, which was the first time a die had been designed by the Company and not by the extruder. This die had radically different facet shapes than the lens as designed. Lens samples extruded with this die were promising, although the plastic flow in the die was not uniform. The upstream part of the die was machined to force plastic into the starved areas. This proved useful but was not completely satisfactory.

The 15" lens available during the pilot production run had very low transmission, approximately 50%. This was due to two causes: form factors and diffraction losses

Diffraction losses are due to the lines in the die caused by the wire electric discharge machining. These are usually polished out of the die using an extrusion hone process and the die is then hardened and a highly lubricious finish applied. There is often extensive machining to be done on the die after the initial test. The polishing, hardening and finishing preclude any additional machining of the die. This means that these processes are done after all other development work on the die is completed. The polishing, hardening, and finishing can add 10 percentage points to the transmission.

A fourth die was designed by SEA Corporation for the 15-inch lens in consultation with a world renowned extrusion expert. A finite element flow program was used to investigate plastic flow in the die. This showed that there was very little restriction to plastic flow at the edges of the lens where the facets were tall when compared to the center of the lens where the facets were short. The flow was completely modeled and changes were recommended for the die design. The consultant's and SEA Corporation's changes were incorporated into the fourth die. The first samples from the fourth die were the best to date, showing excellent transmission. The die was polished and put into production. Figure 20 shows the history of lens progress and the expected performance in the future.

Attainment of Goals

The goal of designing and fabricating a new lens with 86% transmission was not reached. A new lens was designed, but achieved only 76% transmission. A new lens was designed, tooling made, and parts fabricated through a sub-contractor. Specific samples of extruded lenses have achieved 86% transmission, but production lenses have fallen short of this, averaging 76%. Development time for the new lens was excessive, taking over one year, while the plan was that this step would take only 6 months. This forced development to be cut short toward the end of the project. In fact, the lenses used for the demonstration of the pilot line were of an older design.

SEA Corporation is bringing the extrusion process in-house for the follow-on work. SEA Corporation has hired world-renowned extrusion experts to help develop the in-house equipment and tooling. The extrusion machine will be one of the most advanced systems in the world. The new tooling will allow adjustments while the machine is running, something that was not possible with the previous tooling. The lens facets will be formed by a low-cost die plate insert that can be quickly changed. Advanced post-extrusion tooling will be used to assure accurate facets. SEA Corporation will have sole control over the tooling and equipment development. This work will cost over $1,000,000, a sum that the sub-contractor could not invest. However, SEA Corporation can now invest in this tooling and equipment because of the progress made on other components in this project, and because of additional equity investment.

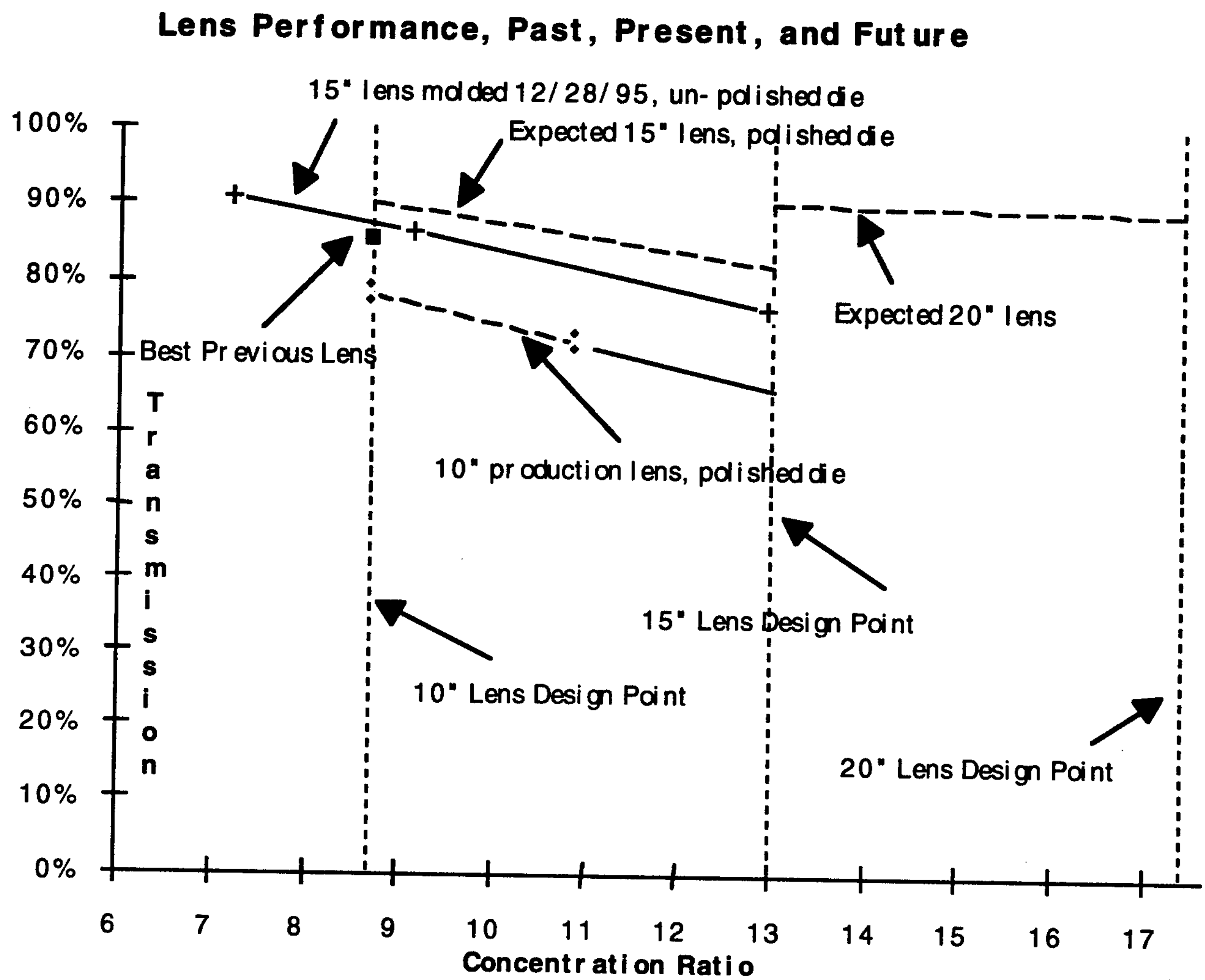


Figure 20 - Lens Progress

Single Piece Lens and Side Wall Extrusion

During Phase 3, SEA Corporation planned to produce prototype tooling to extrude the lens, the module side walls, and the attachment features (used to attach the module sides to the receiver) in one piece. During the project, it became clear that this was not technically feasible nor economically desirable, so this goal was not pursued because of technical reasons.

The single side/lens extrusion was originally planned for a maximum lens width of 10 inches to eliminate two glue joints. However, during the course of this project, evaluation of the extrusion process for the lenses and the sides revealed quite different extrusion parameters for the two pieces, such as screw speed, melt temperature, melt pressure, and puller speed. Also, the cost-optimum type of plastic used for the two parts was discovered to be quite different: the lens needed to be made of a high quality plastic with excellent transmission qualities while a lower cost plastic could be used for the sides. The lens needed to be transparent while the sides could be colored for aesthetic reasons. In addition, the glue joint was developed to the point that it is now very reliable. Finally, the size of the die for the new larger lens is such that a complete lens/side extrusion would be very difficult to produce.

Instead, a single piece extruded module side was developed under this task. The side tooling was based upon standard sheet extrusion technology with the attachment feature. A vacuum sizer was used.

3.4 AUTOMATED ASSEMBLY RECEIVER STATION

During Phase 2, an automated receiver assembly station was designed, assembled and tested with the purpose of assembling receivers. During Phase 3, a number of problems were encountered with this machine and forced a switch to hand assembly towards the end of the project.

The automated receiver assembly station consisted of: 1) a cell lead stamping station; 2) an adhesive applicator; 3) pick-and-place machines for the cells and leads; and 4) a soldering block, all under computer control. A Macintosh computer, running Lab View®, a graphic-oriented software program, was used. This program was used because it was easy to program and easy for the operator to use. It provided a graphic interface for the user to operate the automated receiver assembly station. The adhesive was rolled onto the heat sink to form a pressure sensitive tacky surface. The leads and cells could then be placed on the heat sink in their final position without fixturing. The lead material was supplied on rolls from a stamping company that punched a series of rectangular slots to form a ladder pattern in the copper. The final stamping, done on the station, cut the lead material to length and in half, producing two leads. The rungs of the ladder became the contact fingers for the leads. A pick-and-place machine, using suction cups, grabbed the leads from the punch-bed and placed them on the heat sink. A similar pick-and-place machine placed the cells. The soldering was done on the heat sink with a large copper block that was heated to a temperature determined to produce a good solder joint.

The automated receiver assembly station was designed to assemble a receiver in less than one minute. Soldering was considered the pacing operation. Soldering was completed in about 5 seconds per cell, two seconds for heat up and three seconds for cool down. The cells and leads were placed sequentially. Total operation time was significantly reduced by multi-tasking, such as picking up a stamped lead while the cell was being placed.

The automated receiver station was used to make all the sheet-metal-based receivers for the SMUD project. The knowledge gained from its use is being applied to a new generation of automated machinery that is under design.

The extruded heat sink was used for the CAN project. The automated receiver could not be used with this heat sink because: 1) the problems with this machine made retrofitting for the new receivers uneconomical; and 2) the production rate needed to be increased above that achieved on the SMUD project.

The automated receiver assembly station never did operate near the design rate. The problems with the station were numerous:

a. The automated receiver station kept breaking cells. Very few receivers were built without broken cells, which required expensive and unreliable rework. The cell breakage was caused by the pressure of the solder block. With the new extruded heat sinks, the breakage became worse because of the step in the receiver designed to accommodate the bottom leads. An alternative soldering method was identified using IR lamps. This system could not be developed in time for the CAN project and was problematic for use with the new extruded heat sink. An automated IR process may be used in the future to solder cell assemblies before they are attached to the heat sink.

b. Soldering with the automated receiver assembly was unreliable. This was caused by the soldering method which required heat transfer by conduction from the solder block. Heat was also absorbed by the heat sink through conduction. Since heat conduction depends on pressure, percentage of voids, and cleanliness at the interfaces, both the heat input and heat dissipation were variable.

c. The new heat sinks required new track and feed mechanisms. These were designed and built, but needed hookup and de-bugging. Additional personnel and time were not available to do this for the pilot line demonstration.

d. The lead feed, pick, and place mechanisms used on the automated receiver assembly station were not reliable. This caused a lot of down time while the operator fixed the machine and repaired the receivers.

Switching to hand assembly for CAN increased speed, quality, and yield. However, hand assembly of receivers requires a large number of work stations and introduces inconsistencies into the product. A second generation automated station is the long-term solution.

Several lessons were learned from the automated receiver assembly station. Soldering the cells on the heat sink added an unnecessary level of complexity and uncontrollable variables, which affected the reliability and repeatability of the soldering. The bottom solder joints could not be inspected when bonded to the heat sink. The heat transfer rates from the solder block to the cell and to the heat sink from the cell varied depending on pressure and surface conditions. Soldering to the cell was difficult under the best of conditions. The speed of assembling the receiver was limited because the cell placement, lead placement, installation placement, and soldering all have to happen sequentially for the 37 cells. Finally, a fault in one area resulted in 37 cell/lead assemblies being rejected.

3.5 PILOT PRODUCTION LINE

<u>Pilot Line Design</u>

During Phase 3, SEA Corporation designed a pilot production line for manufacturing the Powergrid at the rate of 100 KW/year. This pilot line was designed as a development tool for the purpose of investigating the different aspects of production.

Included in the pilot line was the automated receiver assembly station, a semi-automated module assembly station, a manual array assembly station, test equipment, inventory control, shipping and receiving, and production management.

Several steps were involved in pilot line design. First, the existing equipment and designs were reviewed. SEA Corporation then surveyed available off-the-shelf and custom equipment for possible use in the pilot line. In-house designed equipment was considered too. Finally, SEA Corporation completed a design layout of the pilot line.

Pilot Line Organization

During this phase, SEA Corporation produced a pilot line for fabrication of the Powergrid. The pilot line became an evolving design with almost constant changes to improve production. The experience of moving to pilot production from prototyping was very valuable as it brought to light new issues to be faced in a production environment.

Powergrid production follows logical grouping of parts and sub-assemblies. As Fig. 21 shows, the receiver is a sub-assembly of cells, cell leads and the heat sinks. The receivers are fully operational as a separate unit and are fully tested before being attached to the plastic parts. The modules are assembled by adding the lens extrusion, side extrusion, and end caps to the receivers. For the pilot production line, most of the parts are manufactured at other facilities. The pilot line is essentially an assembly line.

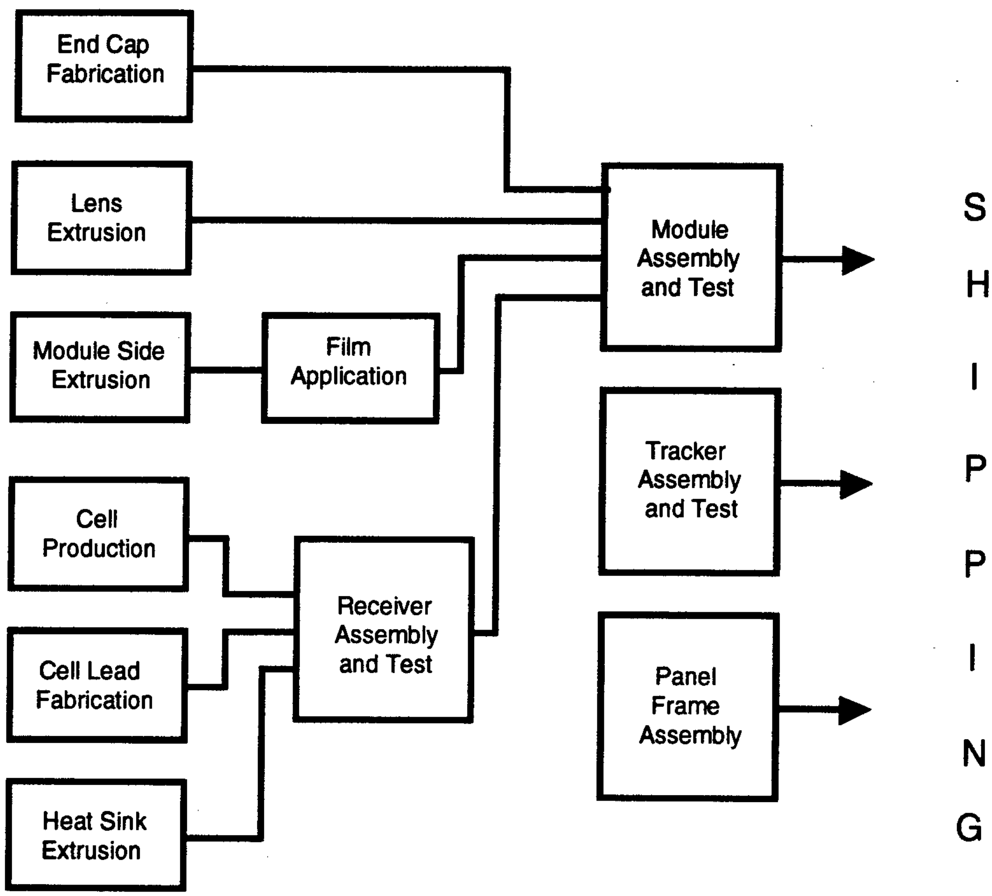


Figure 21 - Powergrid Manufacturing Flow

Automated Receiver Assembly Station

Figure 22 shows the automated receiver assembly station. This station was used to assemble the sheet-metal receivers for the SMUD installation. It was found to be unsatisfactory for assembling the extruded receivers for the CAN installation, as described previously.

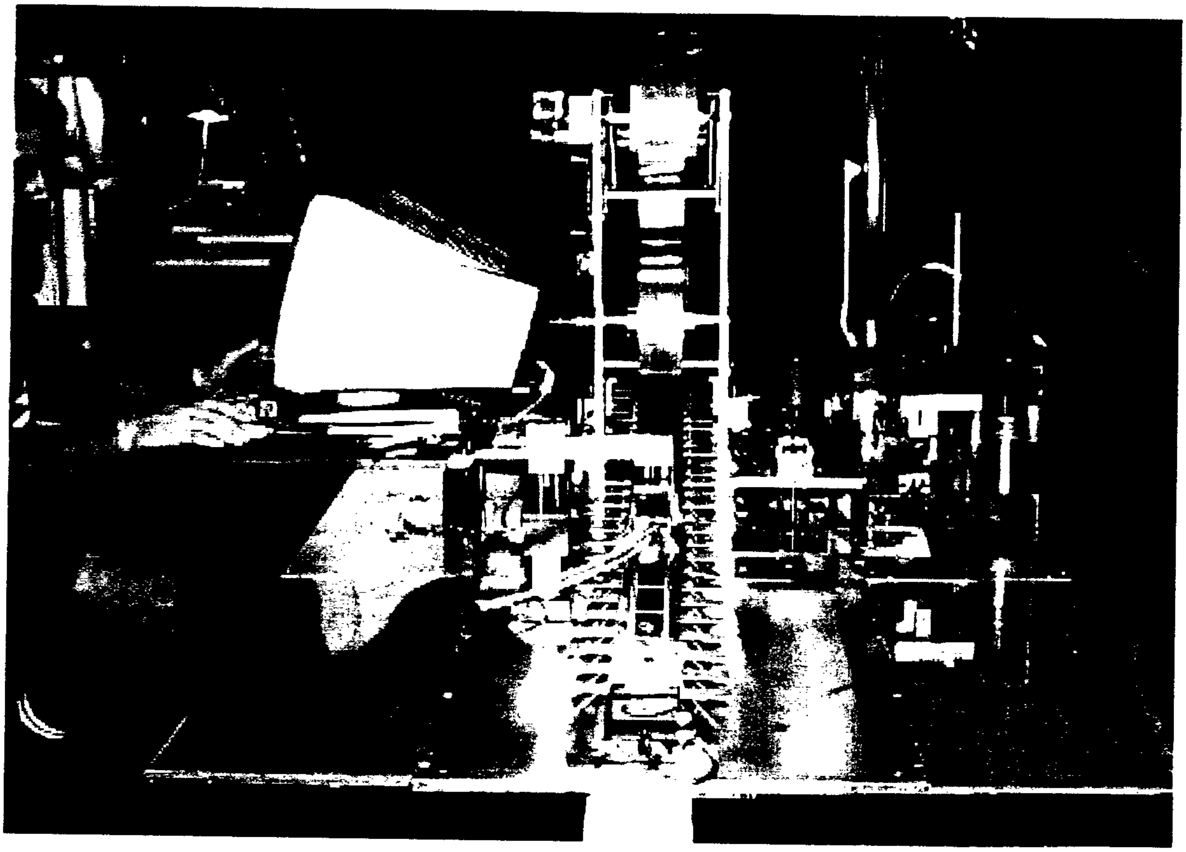


Figure 22 - Automated Receiver Assembly Station

Lens and Sides Trim to Length

The lenses and sides were extruded in a continuous process. The parts were cut to rough length at the extrusion company. They were then shipped to SEA Corporation where they were cut to final length in cutoff stations. The lenses have to be cut at an angle in one plane and the sides have to be cut to an angle in the other plane. Two fixed radial arm saws were used for each of the lens cutoff and side cutoff stations (Fig. 23). The fixed position of the saws assured an accurate cut every time.

Reflective Film Lamination

The reflective film must be laminated to the module sides. This was done before the final trimming of the sides. No commercial lamination station was available that would work on the sides. The company designed and built its own using some parts from a small laminator SEA purchased.

The laminator consists of a set of pinch rollers which press the film onto the sides (Fig. 24). The film was supplied with an acrylic pressure sensitive adhesive (PSA). A stripper roller removed the backing from the film exposing the PSA. The film was supplied from a roll mounted on the machine. Two sides were laminated at one time. There were feed and take-off tables for the sides. Excess reflective material was trimmed after lamination.

The lamination station for attaching the reflective film to the module sides has low yield and produces wrinkles in the film. Plans are to design and build a new lamination station.

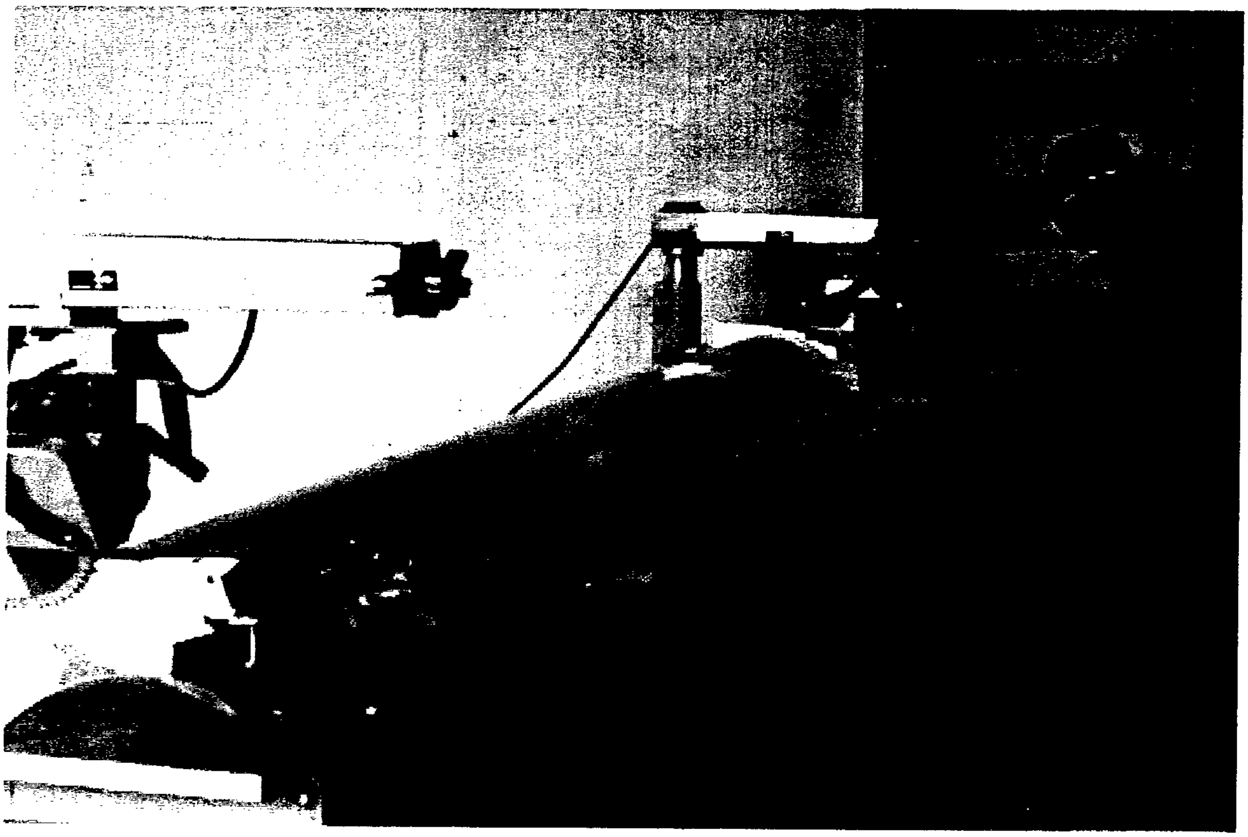


Figure 23 - Lens Being Trimmed to Length

Module Glue Stations

The work stations used to assemble the modules consisted of two glue stations. One station was used to assemble the sides to the lens. The other station was used to assemble the end caps and receiver to the lens/side assembly.

The lens/side assembly was assembled up-side-down in a fixture. A water-thin solvent adhesive, Weldon 5, was used, that wicks into the tongue and groove-type joint where the sides join the lens. The Weldon 5 was initially applied by hand using a syringe (Fig. 25). Later, a pneumatic applicator was used that works similarly to the hand syringe, but was powered by air, has a large remote reservoir, and was easier and faster to use.

The latest version of the semi-automated module assembly station works well and easily keeps up with the receiver production. Several generations of module assembly stations were tried before an accurate module could be produced. Alignment of the lenses was difficult because the lenses have an optical axis that can be different from the mechanical axis. The lenses must be mounted in the same orientation with respect to extrusion direction every time. Lens consistency should improve once the production rate increases and certain process changes are made. The new design for the 20-inch module will have self fixturing features to make the assembly more accurate, lower cost, and faster.

Figure 24 - Reflective Film Being Applied to Module Sides

When the lens/side assemblies were cured enough to move (within a minute), they were moved to the station where the end caps and receiver were installed. The end caps were bonded using Weldon 16, which is a heavy-bodied solvent adhesive. The Weldon 16 was originally applied with a hand syringe, as shown in Fig. 26, and later was applied with the pneumatic applicator, as described above. At room temperature, Weldon 16 takes several hours to cure before handling. This was accelerated to 20 minutes by using heat lamps.

The end caps were originally held in place with a sliding holder that was positioned by hand (Fig. 26). The end caps were held into position with a pneumatic actuator which applied constant force during the curing. The holder positions the end cap in the proper location. A locating device positions the tracking pin. The end caps must be in the proper location with respect to the lens/side assembly for the module to be in focus when mounted on the frame.

The production rate was limited by the long drying time for the end cap adhesive. This problem was temporarily fixed by building additional assembly fixtures and adding heating lamps. Also, the solvent adhesive is a hazardous material. The long term solution to this problem is moving to a solvent-less system, such as ultrasonic bonding or UV-setting adhesive.

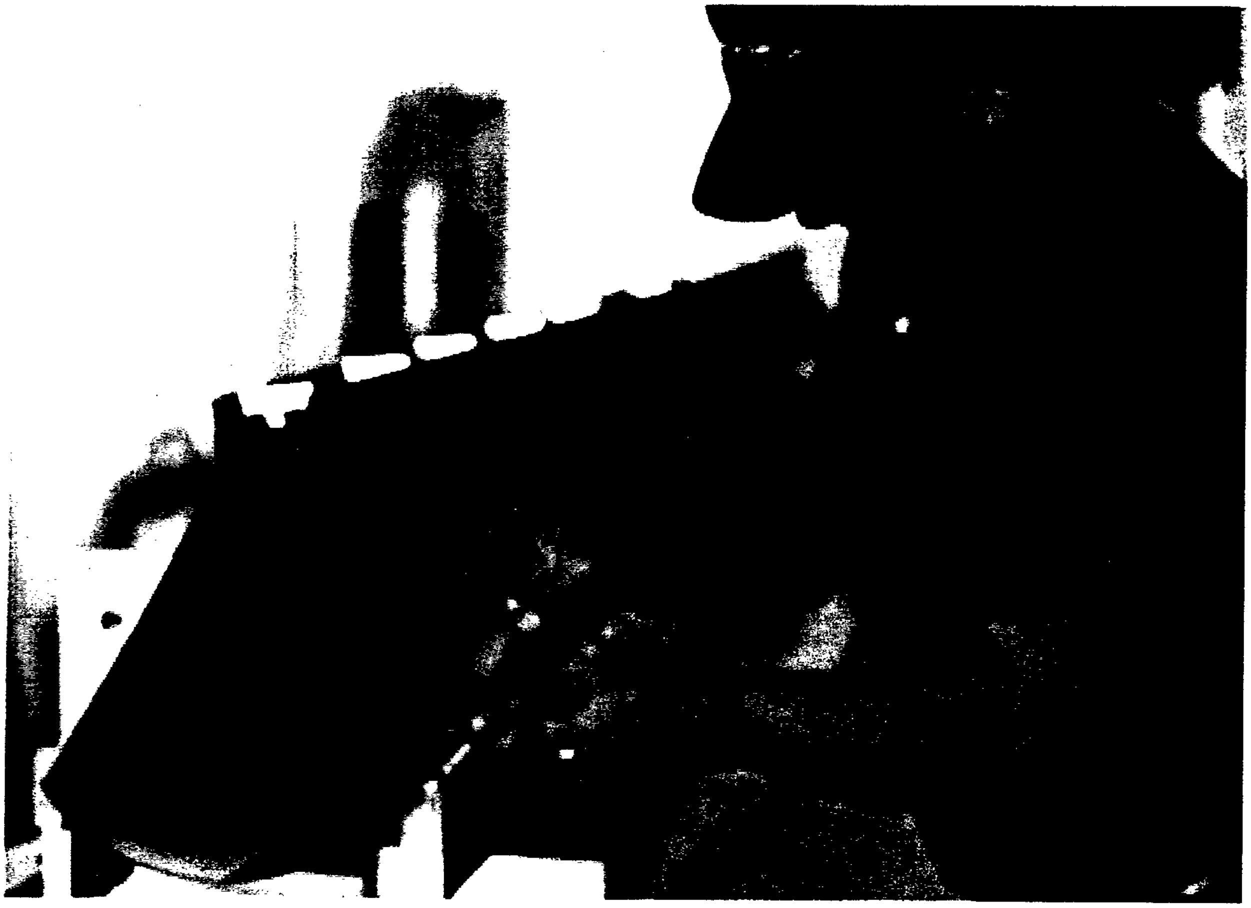


Figure 25 - Application of Solvent Adhesive to the Lens/Side Joint

Module Testing

Several QA/QC testing stations were used in the pilot line:

- The cells were tested for output and grouped according to current.
- After the receivers were assembled (but before encapsulation) the individual cells were tested for shorting and open circuits.
- The entire receiver was then tested for output in a solar simulator and dry hipot tested.
- After encapsulation, the receiver was wet hipot tested by submersion in a tank of water.
- The receivers were then mounted to the plastic parts to form a module which was then tested outdoors for power output.

The incoming cells were tested in a flash tester designed by SEA Corporation. A computer captured the output and displayed the operating current. The operator then grouped the cells according to current. Cells were wired in series in the receiver and therefore must be current matched. The cells were flashed at about 10 suns illumination supplied by a commercial photo flash unit. Electrical contact was made to the cell along the entire length of the bus areas by a multi-fingered contact strip. Electrical resistance along the bus area required contact along its entire length.

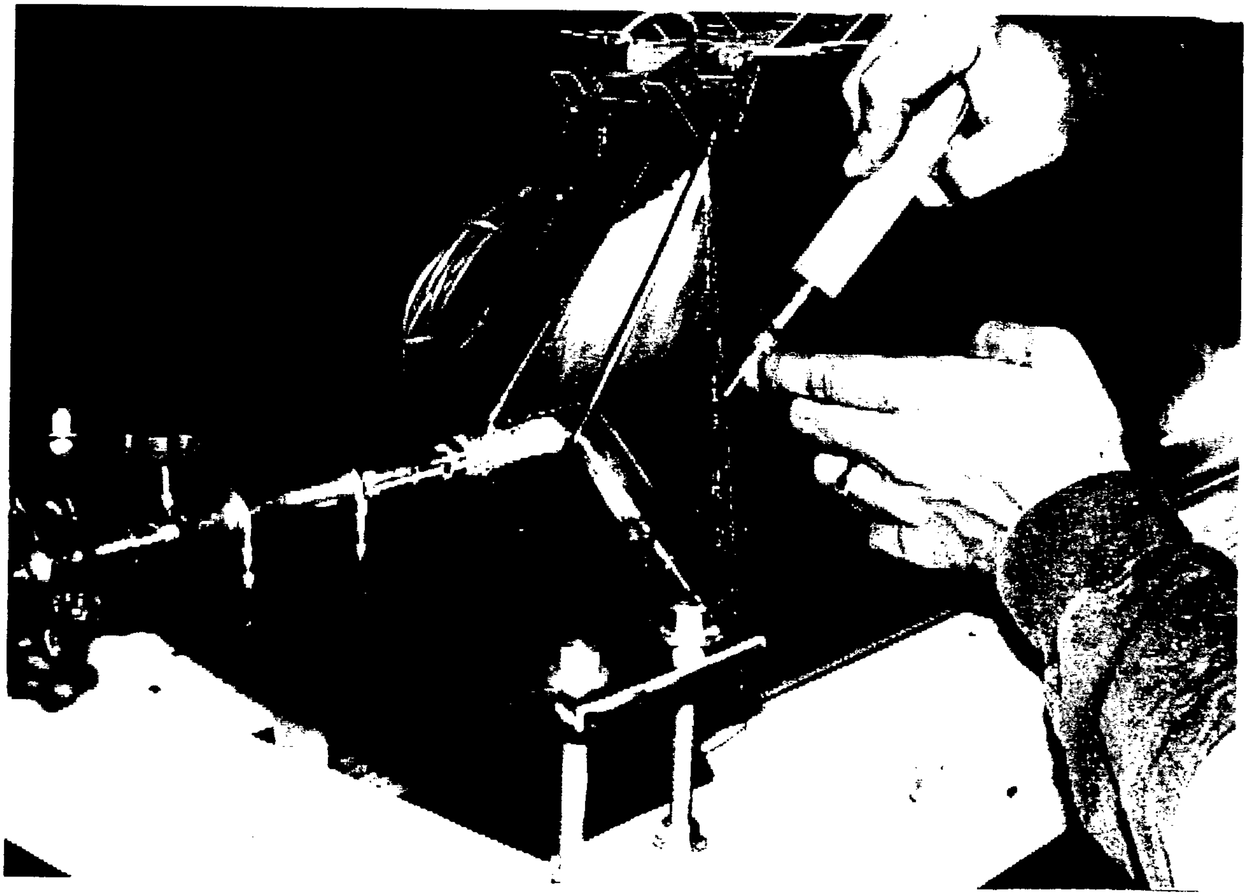


Figure 26 - Application of Solvent Adhesive During End-Cap Installation

The receivers were first assembled but left unencapsulated. An operator then checked for open circuit or shorting in the cells by measuring output from each cell. A dry hipot test was then performed on the unencapsulated receiver. The receivers were subjected to 2,200 Volts dc potential between the electrical components and the heat sink. The company specification required that the current be 5 μA or less under this voltage.

After the receivers were encapsulated, they were wet hipot tested by being submerged in a tank of water. The potential was again 2,200 Volts dc and there must be a current of 5 μA or less.

The completed receivers were subjected to a solar simulator. The simulator consisted of an array of approximately 75 quartz lamps. The lamps were mounted in reflectors which provided approximately ±15° beam spread. The simulator's output was periodically checked with a standard receiver which was calibrated outdoors.

After the receivers were mounted in modules, the entire modules were tested outdoors or in the simulator. A standard module was used to calibrate the simulator. Output of the modules in the simulator was approximately two thirds of that produced outdoors. The ramifications of module testing outdoors vs. testing in an uncollimated simulator is discussed in Chapter 4.

Panel Kitting and Installation on Site

Panels were shipped in kit form. Twelve modules were shipped with a panel frame, a tracker, and a bag of hardware. The kits were assembled on site.

During kit installation, the foundations were installed first. For the CAN project, we used screw anchors as foundations. These were screwed into the soil beneath the parking lot with a hydraulic motor mounted on a small tractor. For the SMUD project, we installed roof mounts through the roofing into the steel frame of the building.

Next, the panel frames were assembled and erected. Once a crew was trained, this went relatively fast. As the frames were assembled, one number four wire must be fished through the frame for the bypass diode, and one number 12 wire must be fished through the frame for the tracker drive. This was made easier by partially fishing the wires through at the factory. Also, one large crimp connection must be made at the site using a hydraulic crimping tool. The bypass diode must also be installed. Once the frames were bolted together, they were erected by a crew of at least three people, two to lift the frame and one to bolt the legs to the foundation. The diagonal wires used for bracing were installed next.

Finally, the modules and tracker were added to the erected frame. The module bearings slip into the top pins on the frame and then pins were installed in the bottom bearings and through the frame. The tracking drag link and tracker were then installed. The module wires were then crimped to the frame wires, the crimp connectors were pushed into the frame, and the grommets were installed. Finally the tracker was adjusted. This finished the panel kit assembly and installation.

The main areas for improvement include: 1) decreasing the amount of field assembly wherever possible, and 2) making field assembly easier for those components that must be assembled in the field, such as the bypass diode assembly.

Shipping

Shipping has been unreliable and/or expensive. During the project, several methods for shipping the Powergrid kits were tried. These included commercial carriers, van line movers, and rented trucks using SEA Corporation personnel. Commercial shipping lines have been unreliable. For example, boxes of modules have been rammed through with fork lifts, and other boxes have been stacked so high that they have collapsed, even when marked "Fragile, do not fork, do not stack". Commercial van line moving companies were the best methods for bulk shipping, but these are expensive.

SEA Corporation has been experimenting with crate design, but no one design has been entirely satisfactory. Several different crate designs were tried, including cardboard, cardboard with wood frames, stacking the module between layers of heavy shipping blankets, plywood with wood frames, and cardboard boxes within plywood and wood frame boxes. The modules are light weight and take up a lot of space. A re-usable custom-made trailer is being considered that could be packed with a Powergrid kit and towed with a full-size pickup truck.

Long-haul shipping will require that components be shipped separately, then assembled near the installation site. The components, such as the lenses, can be nested to reduce shipping volume. In foreign countries, assembly near the site has the added advantage of adding a local component to the Powergrid.

Materials Planning

Steady material supply is very important. In general, this can be assured by proper planning. This lesson was learned during the sixth week, when lead material ran out. However, the major supply problem, the lack of 15-inch lenses, was due to the prototypical nature of our project. This was solved by using the older 10-inch lenses for delivery.

The material supply problems have been solved by installing an MAS (Material Accounting System) computer program to control inventory. SEA Corporation has subsequently hired an experienced purchasing agent and a controller.

Pilot Line Demonstration

A one month demonstration of the pilot line was planned. The demonstration was extended to two months in order to better measure the performance of the pilot line. The demonstration was used to manufacture, deliver, and install a 40 KW system for Clean Air Now (CAN). The goal of the demonstration was to run the pilot line at a rate equivalent to 100 KW per year.

Daily outputs from the key workstations were recorded, as well as delivery and installation outputs.

Program Review

At the end of the project, SEA Corporation conducted a program review which included projected production cost, QA/QC program, structural design, pilot line, and test results. This report is the result of that review.

Beta Site Sales and Demonstrations

SEA Corporation planned to sell arrays to utilities, universities, government agencies, and other interested parties for the purpose of introducing the Powergrid to the market and for SEA Corporation to obtain valuable customer feedback. Customers were to be selected based upon their potential for large scale purchasing, public exposure, and the customer's ability to perform adequate testing. SEA Corporation planned to carefully gather customer feedback and use this information to revise the product as necessary.

Two 40 KW systems were sold to demonstrate the technology, one to the Sacramento Municipal Utility District (SMUD) and one to Clean Air Now (CAN). The SMUD system is a grid-connected roof-mounted system with an inverter. The CAN system, manufactured during the pilot line demonstration, is a low-voltage, high-amperage system used to generate hydrogen gas for use as a fuel in maintenance trucks that comply with Southern California's zero-emission vehicle requirements.

Invaluable information was obtained from these beta sites and the product has been much improved because of them. These sites provided information on structural failure modes, tracker performance, dust accumulation, alignment requirements, foundation methods, and much more. This information could not have been obtained by continuing to build limited quantities of prototypes.

CHAPTER 4
RESULTS AND DISCUSSION

The ultimate focus of this project was pilot production. In addition, various improvements to the design have been made during the project. Improvement of the design is a continuing process at SEA Corporation.

4.1 QUALIFICATION TEST RESULTS

One of the technical goals of the project was to complete qualification testing of the modules at Sandia. This was not completed in time because of the problem of getting lenses on time. However, testing was done on all the various components. This included the cells, cell soldering, cell leads, cell mounting system, receivers, encapsulation system, and lenses. Complete qualification testing of modules requires approximately 6 months. Sandia now has the modules and may elect to do the qualification testing.

SEA Corporation plans to acquire and maintain its own in-house testing equipment to evaluate the product on an on-going basis instead of solely depending on testing at Sandia. SEA Corporation now has its own temperature cycling and freeze-humidity cycling chamber, which it did not have at the start of this project. In-house, on-going testing is important to continually improve the product. Qualification testing at a national laboratory is valuable for independent verification and detailed analysis, but does not substitute for comprehensive in-house testing. Also, qualification testing is only valid for the product at one point in time and, as soon as the product is changed, another qualification test is required. Continuing in-house testing is both desirable and necessary for product improvement. The cost of running the present testing equipment is small (approximately $25,000 per year including labor) compared to the value it provides.

4.2 PILOT LINE PRODUCTION RESULTS

The goal of the demonstration was to run the pilot line at a rate equivalent to 100 KW per year. Actual average production over the period exceeded 225 KW/yr per year for the least efficient process and was as high as 830 KW/yr for module production towards the end of the demonstration.

Although the production rate was limited by the receiver production, the major problems were related to supply of materials and assembly of modules. Process improvements were made during the pilot demonstration program.

The pilot line demonstration was run as part of the manufacturing, delivery, and installation requirements for the CAN project. Daily outputs from the key workstations were recorded as well as delivery and installation outputs.

The pilot line was run on a two shift operation, 10 hours per shift, four days per week. There was an overlap between first shift and second shift. First shift was from 7:00 AM to 5:30 PM. Second shift was from 5:00 PM to 3:30 AM. Because of schedule pressures towards the end of the period, the four day work week was expanded to 5 days. At the end of the project, one 6 day work week was required.

During the initial month of the demonstration, problems with delivery of lenses were experienced. This limited the module production during the first month. It was decided to expand the demonstration one more month in order to report important data that would otherwise be overlooked.

From July 24, 1995 to September 24, 1995, 457 receivers were built, 518 modules were built, and 480 modules were installed. At 82 Watts per receiver, this is equivalent to 225 KW/year production for the receivers. The maximum one day production rate for modules was 830 KW/yr. This clearly met the 100 KW/yr goal.

Most of production was done in batch lots. For instance, the production personnel would laminate reflective film, stocking up sides for module production, then move to another task, such as trimming the sides to length. Most production tasks were very fast, such as bonding the adhesive to the heat sinks. The noted exceptions were receiver production and module production, which were among the key parameters measured.

Figures 27 through 30 show the daily production for the four key parameters. Even though it was low, as Fig. 27 shows, receiver production was fairly constant through the demonstration period. Module production (Fig. 28) picked up during the second month, when all the parts were available. Delivery (Fig. 29) was in lots determined by the size of the truck. Installation (Fig. 30) occurred after delivery and was very fast, with the maximum daily rate equivalent to 1.4 MW/yr.

Figure 31 shows the equivalent rate for each week for the key parameters. The rate is based on the work week, with allowances made for four-day and five-day weeks. Again, receiver production is fairly constant, with exceptions when material supplies were short. Module production starts towards the middle of the period, when parts were available. The module production rate increased toward the end of the demonstration reflecting improvements in the assembly tooling and procedures.

Figure 32 shows cumulative production of the key parameters. Increase in the slope of these curves near the end of the demonstration reflects improvements in the pilot line.

Figure 33 shows the equivalent yearly production rate for several key stations during the demonstration. Increased rates towards the end the period show improvements in the pilot production facility.

Figure 34 shows the fraction of equivalent production at the same key stations. The lack of materials caused receiver production to fall to zero during the week of 9/8/95.

4.3 POWERGRID PERFORMANCE

The original proposal stated that the delivered Powergrid performance would be 743 Watts at 1000 Watts per square meter (W/m^2) direct normal insolation (DNI) for a 10 module panel. This equates to 892 Watts for a 12 module panel (the present number of modules per panel) at 1000 W/m^2 DNI. The present Powergrid output with the production 10-inch lenses is approximately 960 Watts at 1000 W/m^2 DNI. It is expected that the 15-inch Powergrid output will be approximately 1,300 Watts at 1000 W/m^2 DNI. Figure 35 is an IV curve showing the Powergrid output.

Module output is now approximately 8% higher than when the project started. An additional increase of approximately 35% is anticipated when switching to a 15-inch lens.

<u>Beta Site Performance</u>

Total peak output for the SMUD rooftop installation is approximately 34 kW at 1000 W/m^2 DNI and a cell temperature of 25° C. Total peak output for the CAN installation is approximately 51 kW under the same conditions. The CAN installation is shown in Fig. 36.

Powergrid Receiver Daily Production

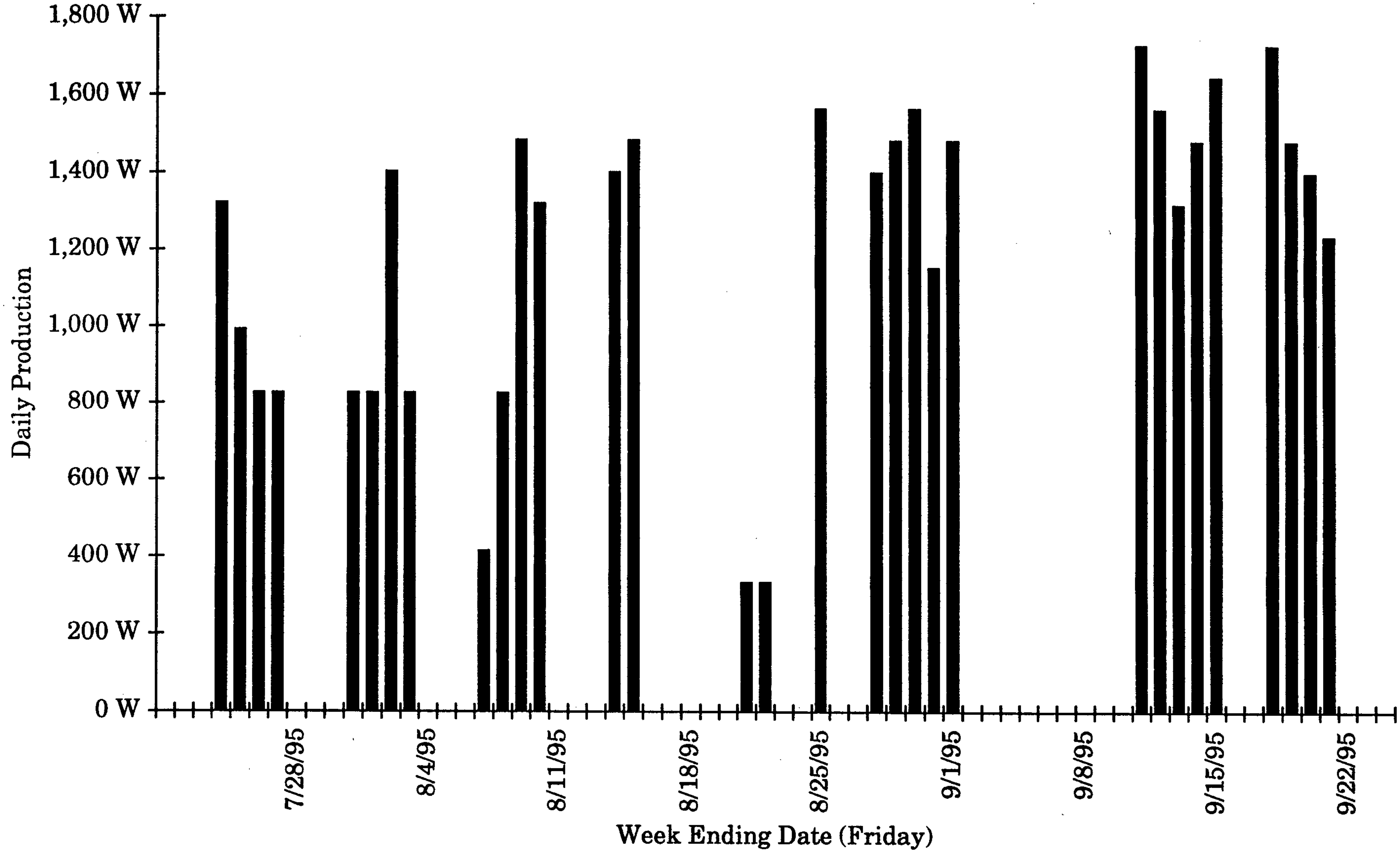


Figure 27, Daily Production of Receivers

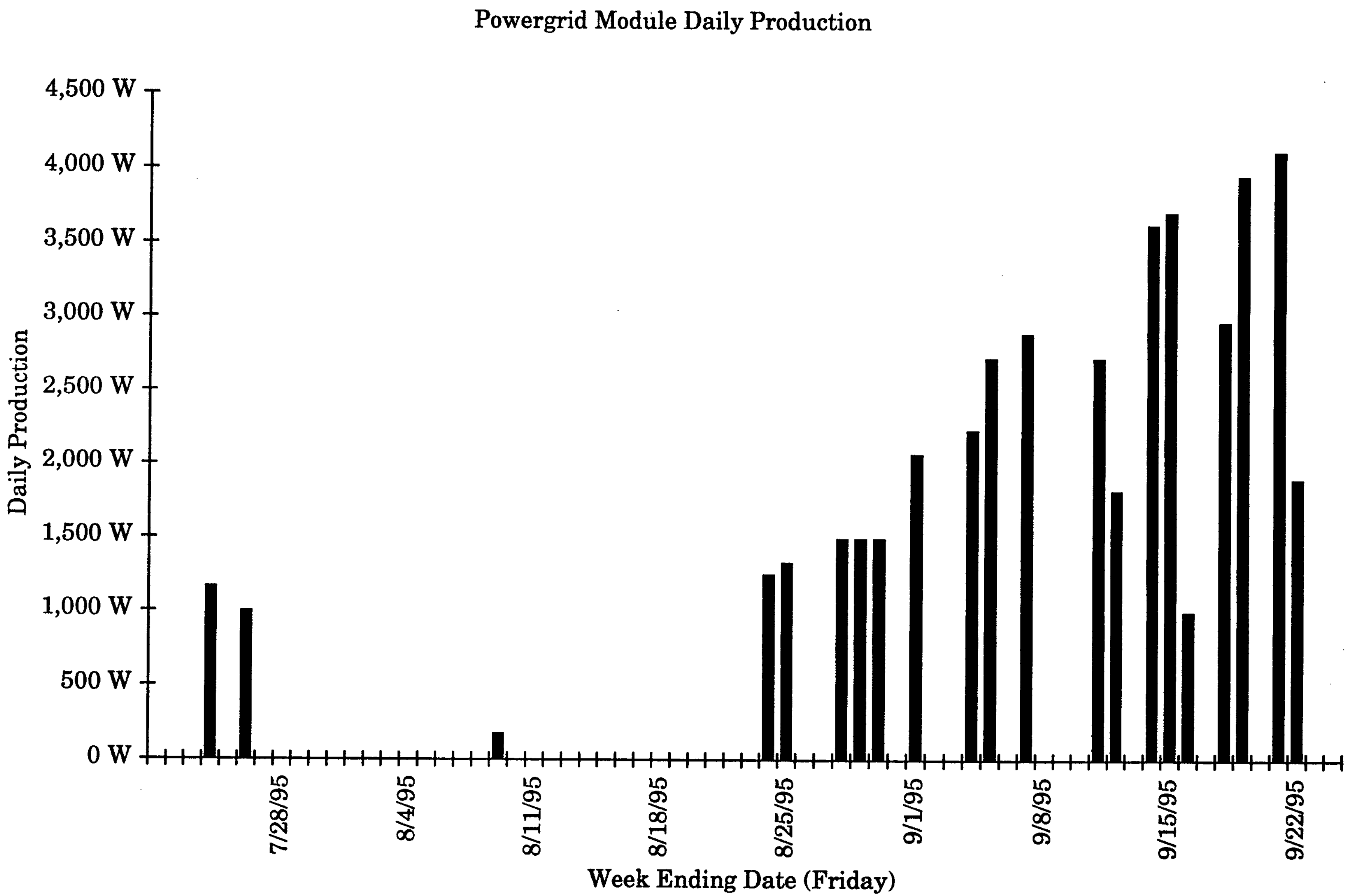


Figure 28, Daily Production of Modules

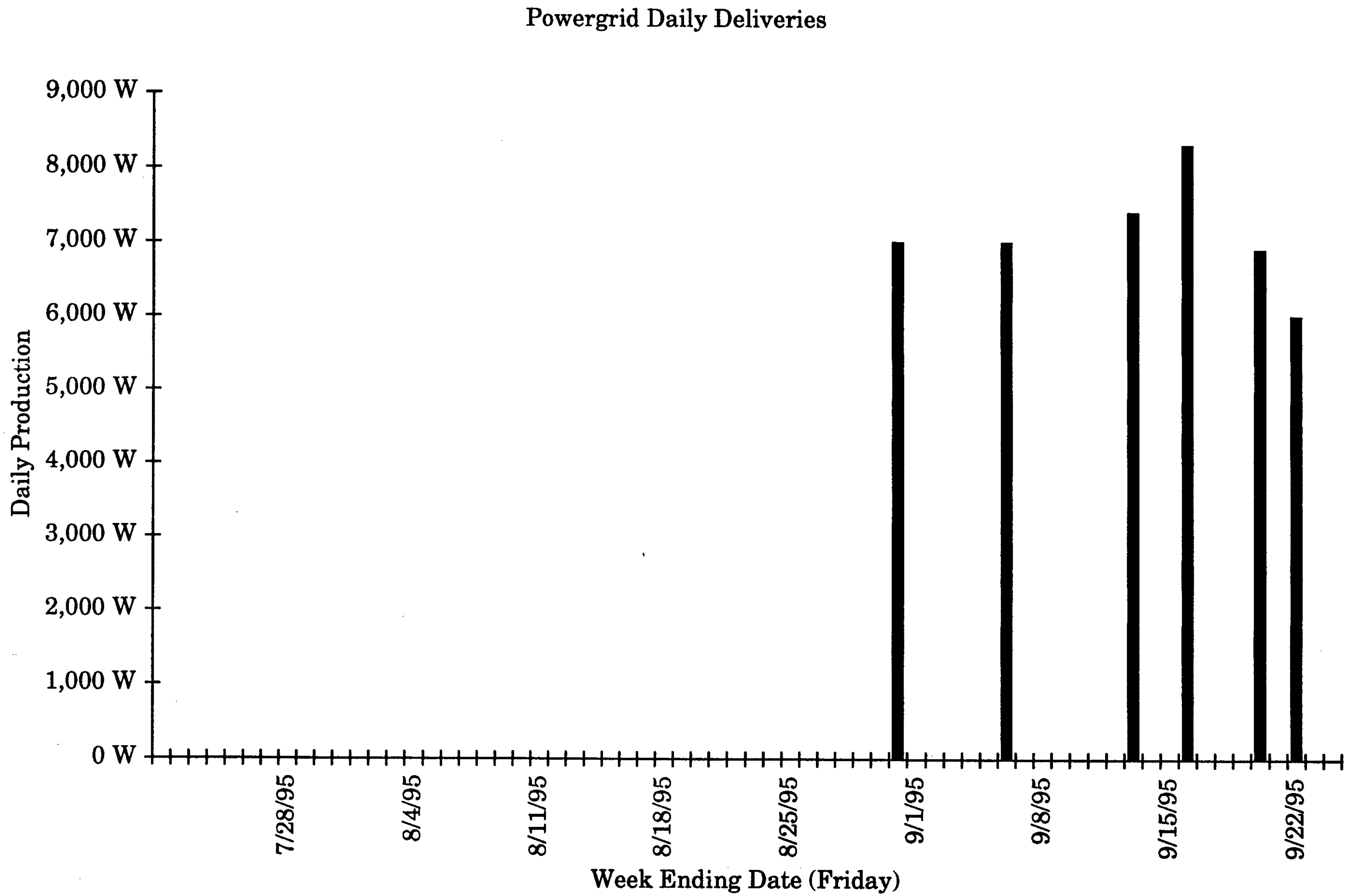


Figure 29, Daily Delivery Rate

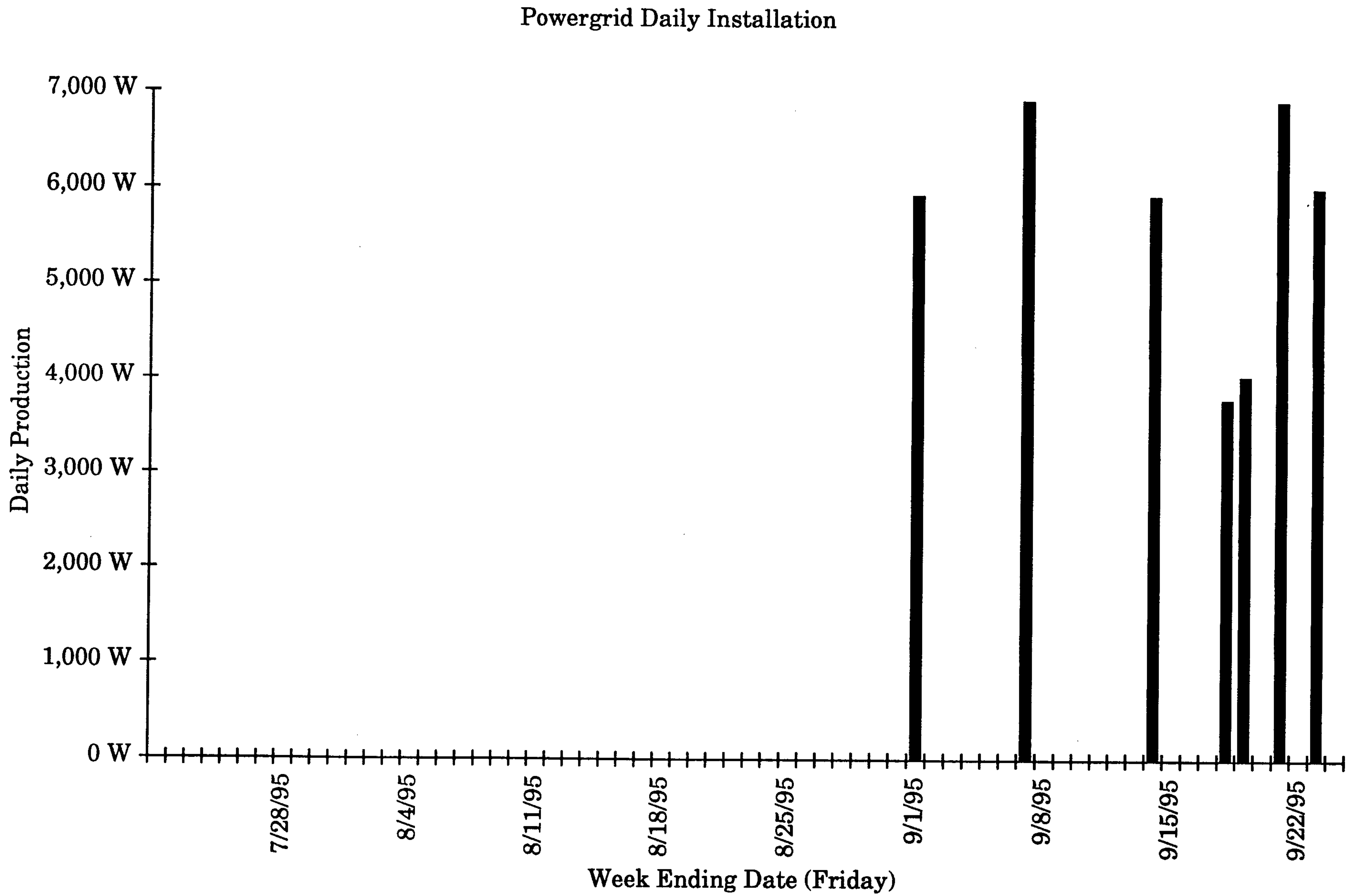


Figure 30, Daily Installation Rate

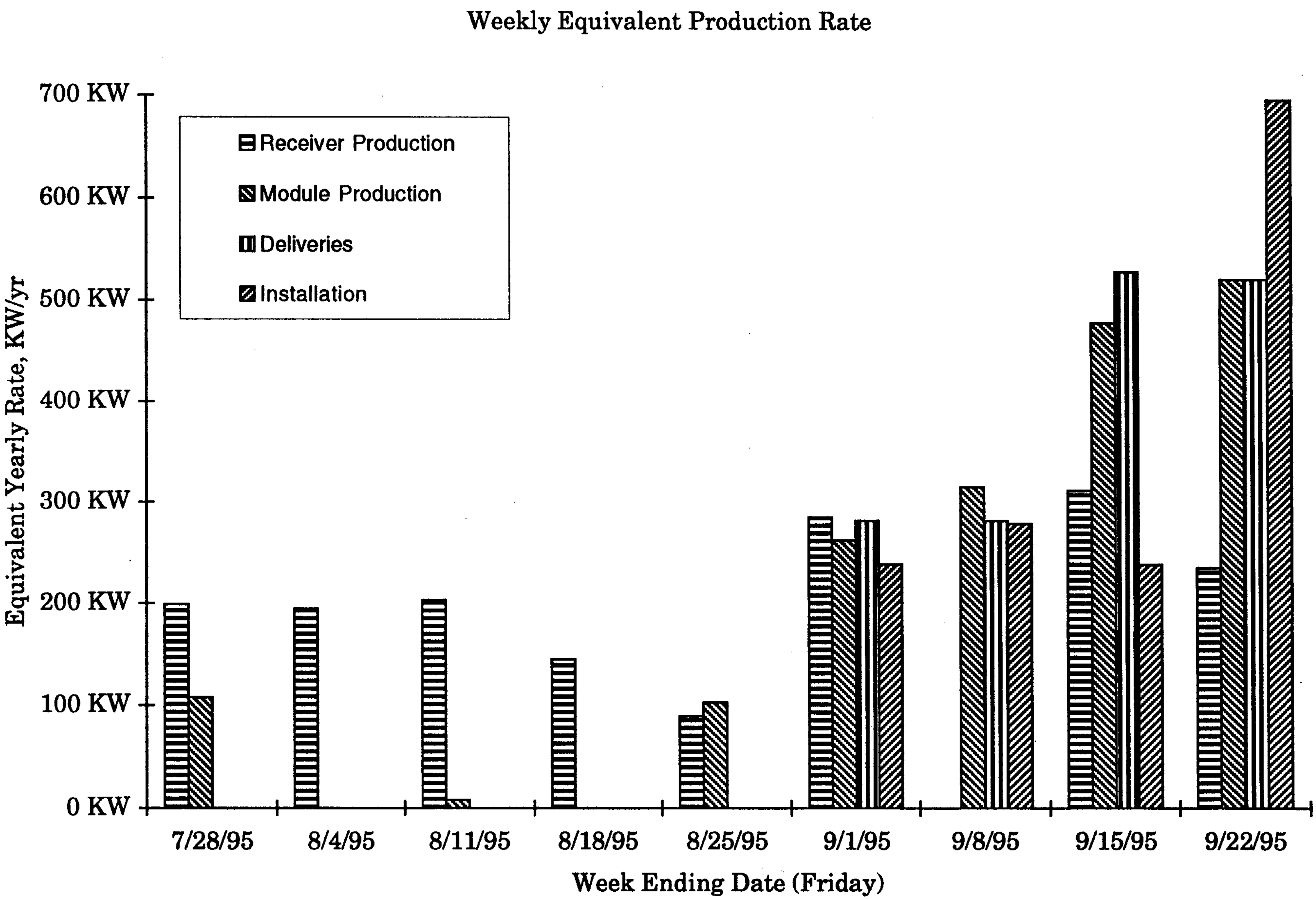


Figure 31, Equivalent Yearly Production Rate of Key Parameters

Cumulative Powergrid Production of Key Parameters

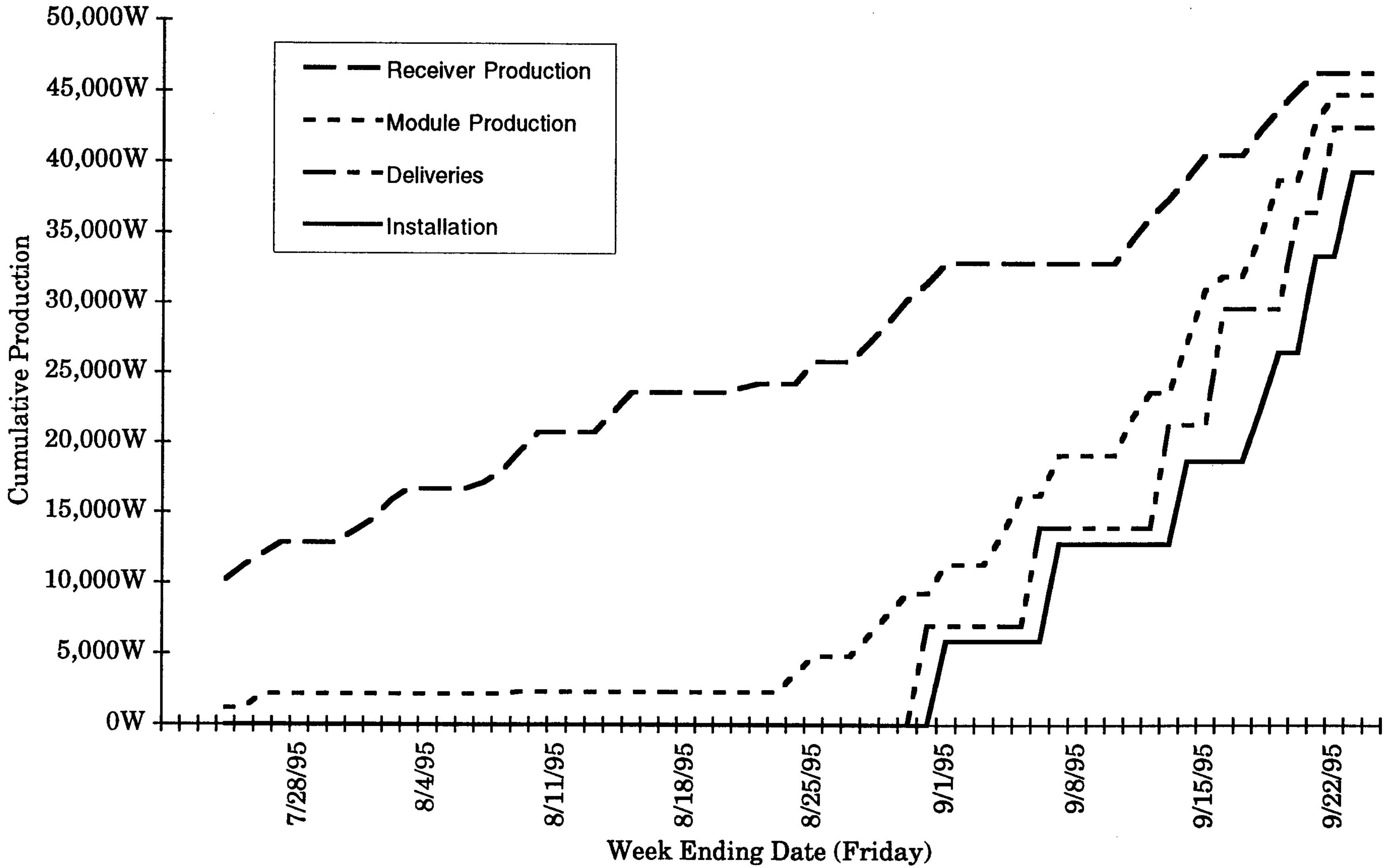


Figure 32, Cumulative Production of Key Parameters

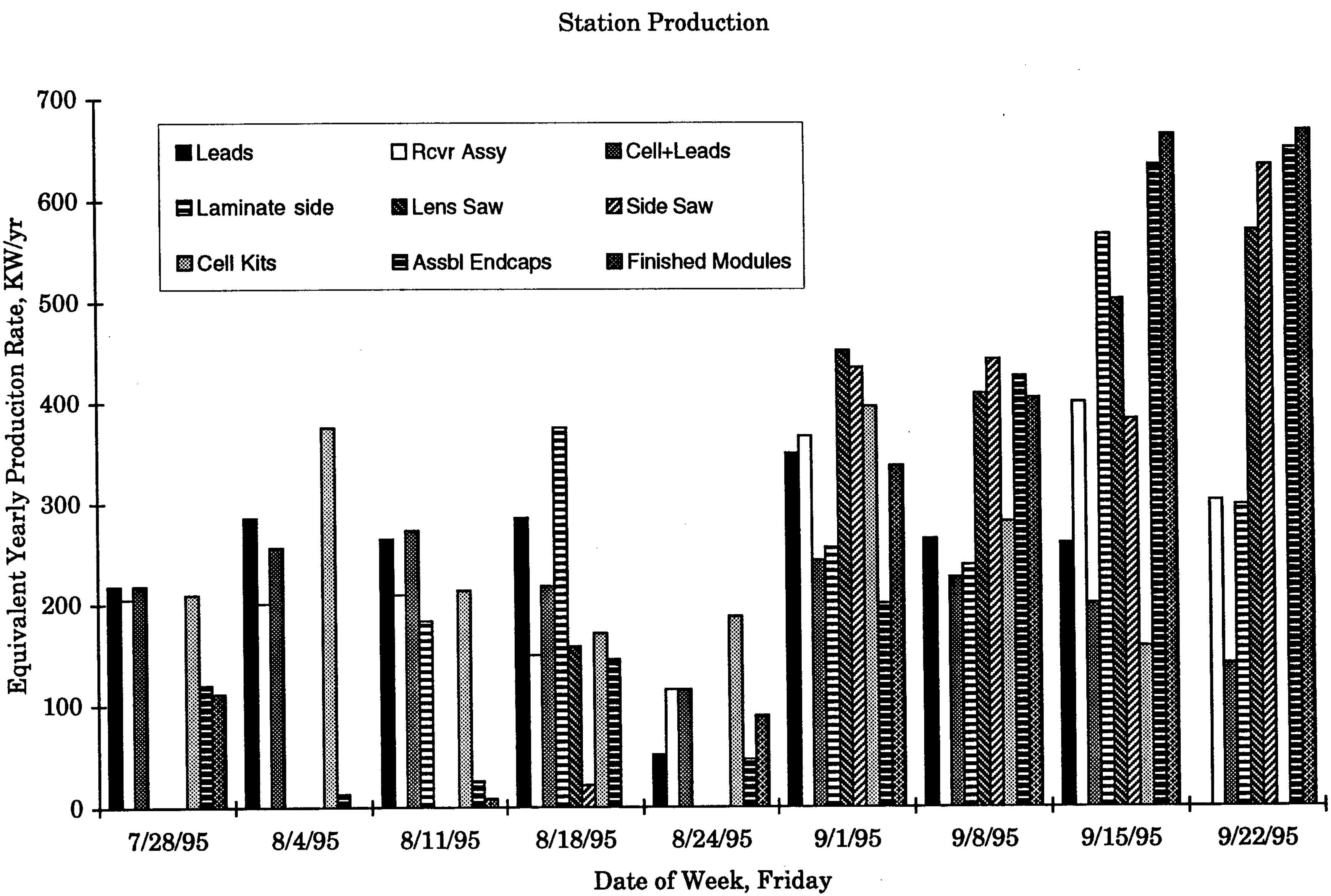


Figure 33, Equivalent Yearly Production of Key Stations

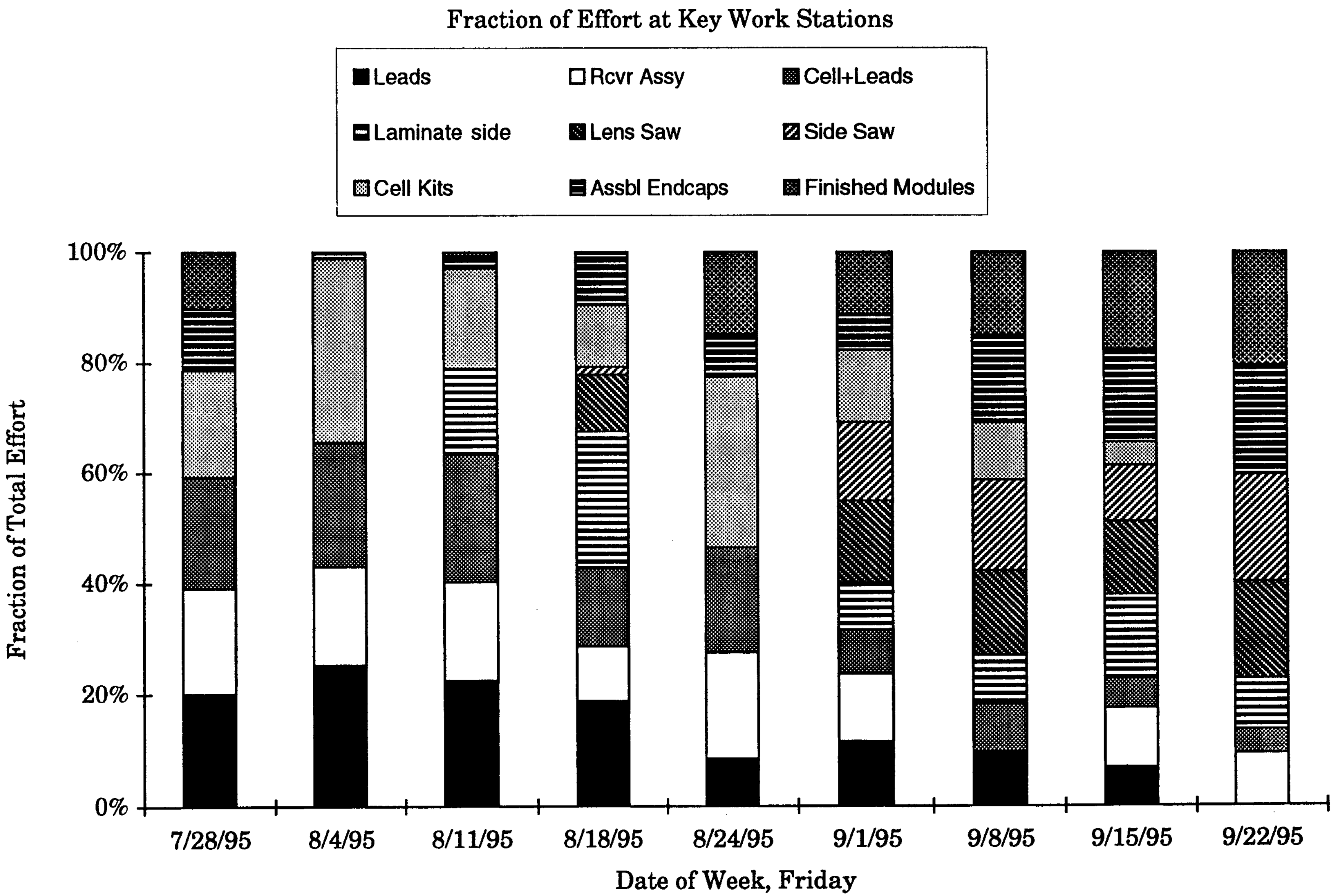


Figure 34, Fraction of Equivalent yearly Production at Key Work Stations

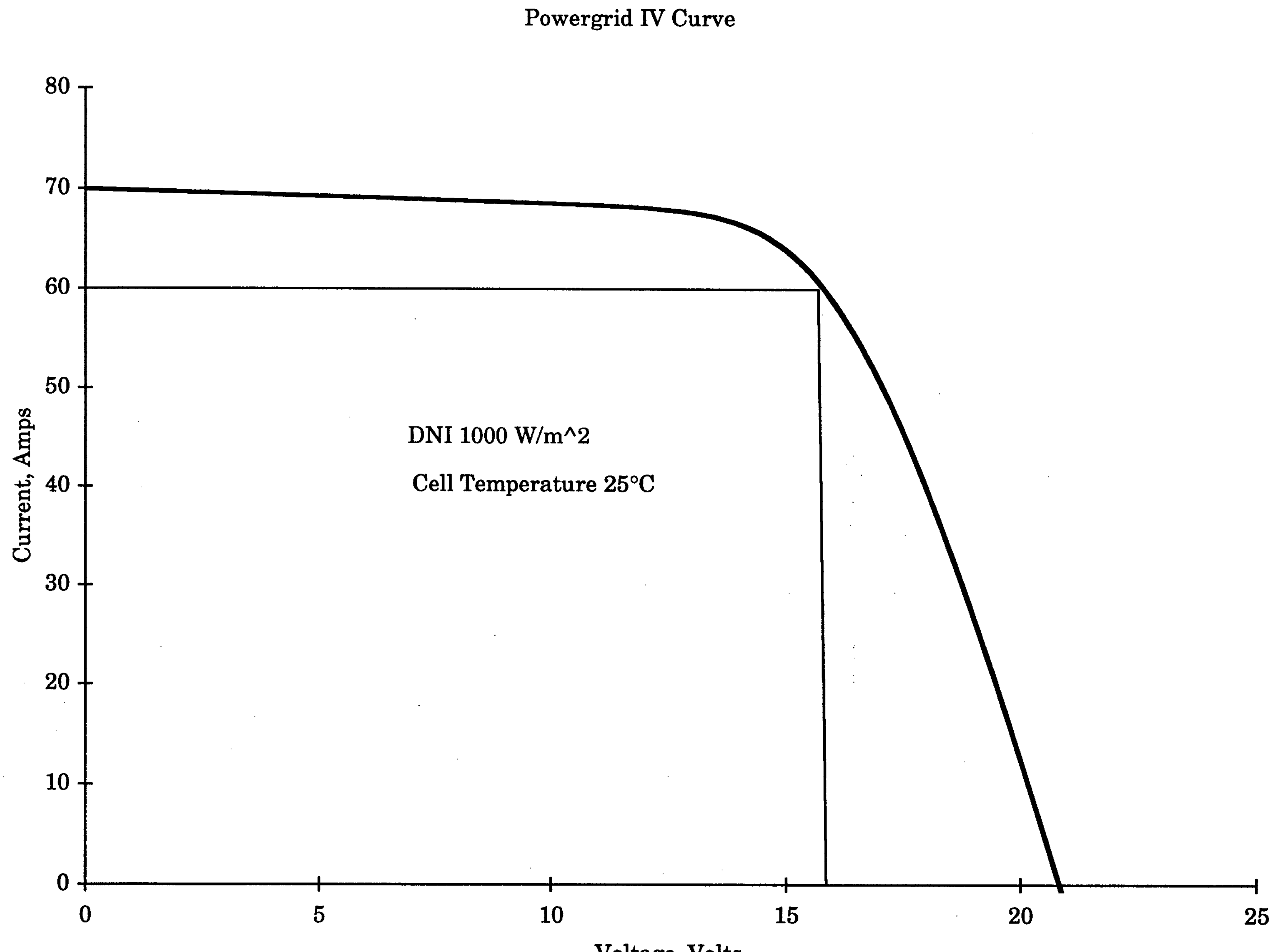


Figure 35, IV Curve Showing Powergrid Output

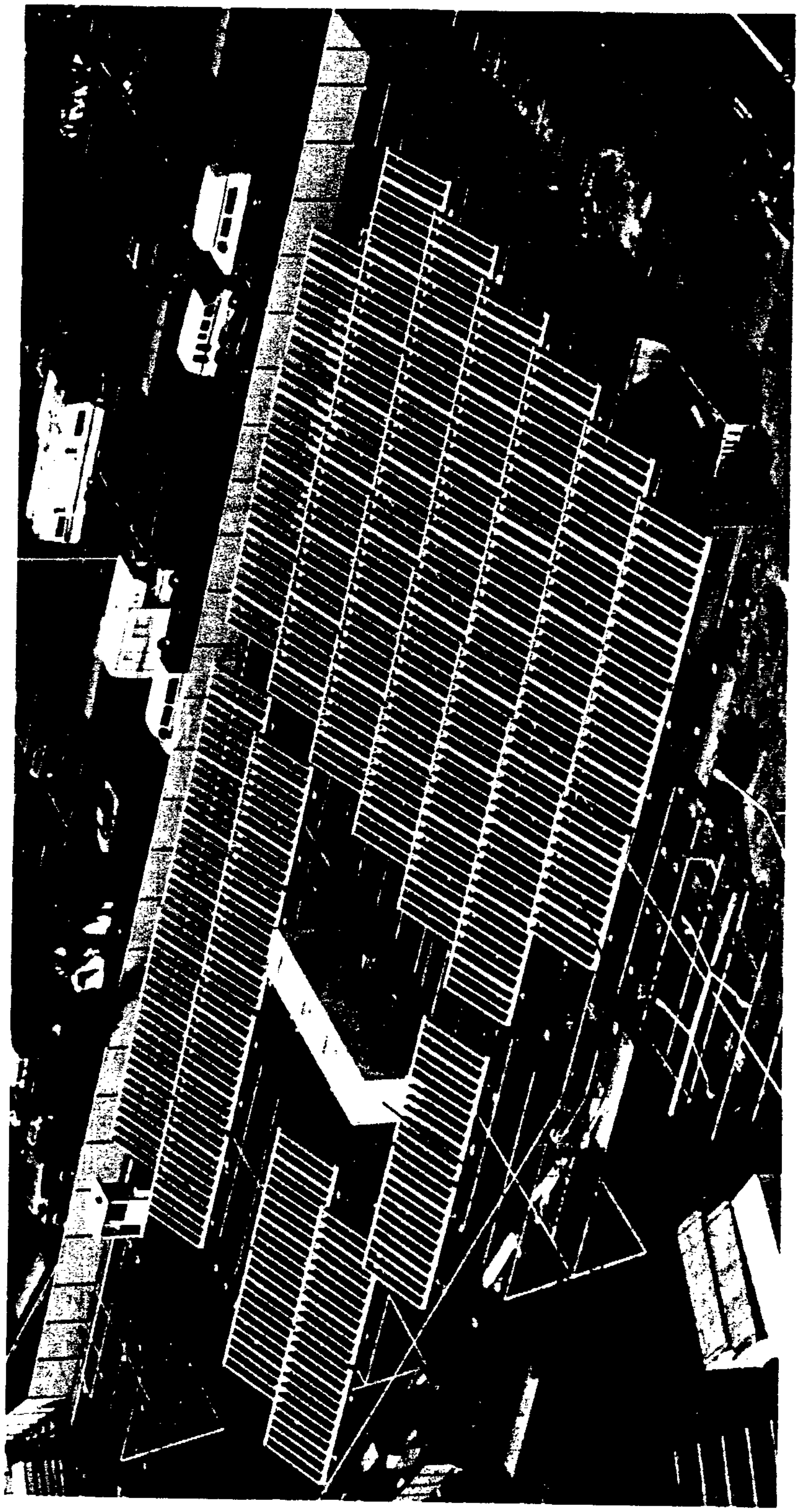


Figure 36 - CAN Installation

4.4 POWERGRID BENEFITS AND ENVIRONMENTAL IMPACTS

Market Penetration

The estimate of PV shipments in 1996 is between 82 and 89 MWp [1]. At an annual market growth rate of 13% [2], estimated shipments should reach approximately 140 MWp. SEA Corporation expects that the entry of its product into the world PV market will open up another market which will eventually be even larger than the current market. Table 4 below shows the estimates of the world market, and the increase of this market with the entry of PVI's product

Table 4 - SEA Corporation Sales and Market Penetration Estimates

Year	Estimated World Market Size (MW)	Estimated SEA Sales (MW)	Increased World Market Size (MW)	Estimated SEA Penetration Rate (%)
1996	85	0.02	85	0.02%
1997	96	0.20	96	0.2%
1998	109	1.50	111	1.4%
1999	123	10.00	133	7.5%
2000	139	50.00	189	26.4%

Table 5 indicates the planned sales of Powergrids by year along with estimated cumulative energy generation. The cumulative energy generation is calculated assuming that the product is available to generate rated capacity for 1,250 hours during the year it is sold and 2,500 hours/year for subsequent years.

Table 5 - Planned Sales and Cumulative Energy Generation

Year	Planned Annual Sales, Kilowatts	Cumulative Sales, Kilowatts	Estimated Cumulative Energy Generation, KW-hr/yr
1996	20	20	25,000
1997	200	220	325,000
1998	1,500	1,720	2,750,000
1999	10,000	11,720	19,550,000
2000	50,000	61,720	111,350,000

Growth in Peak Energy Demand

The California Energy Commission's 1994 Electricity Report predicts that there will be an increase of 14,758 MW in peak demand over the 15 year period from the year 1998 to 2013. This

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[1] Strategies Unlimited in a private report to SEA Corporation

[2] Strategies Unlimited in a private report to SEA Corporation

corresponds to a corresponding growth in energy consumption of 72,787 GWh. On a yearly basis, this would be the equivalent of adding a 984 MW power plant, producing 4,852 GWh each year.

An analysis of meeting this growth in the years 1998 and 2013 using residual oil-fired electricity generation technology results in the following amount of fuel required and the negative impact on the country's balance of payments, as shown in Tables 6 and 7.

Table 6 - Annual Fuel Requirements for 984 MW Oil-Fired Power Plant[3]

Year	GWh of Production	Barrels of Oil Required
1998	4,852 GWh	2,984 billion
2013	72,787 GWh	44,760 billion

Table 7 - Annual Negative Impact on U.S. Balance of Payments for Fuel (Assuming Imported Oil at $20/barrel)

Year	GWh of Production	$ Value of Oil Required
1998	4,852 GWh	$59.68 trillion
2013	72,787 GWh	$895.20 trillion

The corresponding impact on the environment from the addition of 984 MW of oil-fired plant in 1998, and finally 14,758 MW by 2013 is shown in Table 8 below.

Table 8 - Annual Environmental Impact from 984 MW Oil-Fired Power Plant in 1998 and 14,758 MW Oil-Fired Power Plant in 2013

Emission or Resource	Quantity in 1998	Quantity in 2013
SO_x	42.8 million pounds	642 million pounds
NO_x	8.92 million pounds	134 million pounds
CO_2	233.3 million pounds	3,500 million pounds
Particulate Matter	2.62 million pounds	39 million pounds
Total Organic Compounds	0.20 million pounds	3 million pounds
Water Required	15.95 million gallons	239 million gallons

Assuming the Powergrid can meet this increased demand at a 20% level each year, this is equivalent to installing 388 MW of Powergrids each year from 1998 to 2013. At an energy production rate of 2500 kWh/year per kilowatt installed (28% capacity factor), 388 MW of Powergrid can produce 970 GWh per year, or 20% of the energy needed. Increasing this to meet

[3] Assumes residual C oil, with heat value of 18,300 Btu/lb, 8 lbs/gallon, 42 gallon/barrel. Also assumes powerplant heat rate of 10,000 Btu/kWh.

the energy demand by 100%, this is equivalent to installing 1,940 MW of Powergrids each year from 1998 to 2013. This would produce 4,852 GWh per year.

CHAPTER 5
CONCLUSIONS AND FUTURE PLANS

This chapter presents the conclusions from the program and future plans for SEA Corporation.

5.1 SUCCESS OF PROGRAM IN MEETING GOALS

This program has been successful because it demonstrated pilot line production of the Powergrid. This allowed SEA Corporation to obtain investment and follow-on contracts to work toward the goal of a production capability of 50 MW/year in 2 to 3 years. Invaluable information has been obtained in this program which will be applied to future efforts.

Producing the product in a production environment identified new issues and solutions that have improved the Powergrid. The major Powergrid advancements accomplished under this project include the following.

- The new heat sink has increased power output by 10% by reducing cell temperature by 10°C, and the cost has decreased by 80% over the previous heat sink.
- Lens transmission for 15" production parts reached 50% transmission, with rates of 86% achieved with non-production samples.
- End caps strength has been increased to accommodate winds of 80 mph, and static load strength has been increased 400%.
- Module performance has increased 8% since project start, and should increase another 35% once the 15" lens is used.
- The tracker drive gear motor output shaft has been strengthened four-fold to an equivalent service life exceeding 200 years.
- Wiring has been simplified for easier field installation, and costs have been reduced by half.
- Frame design has been improved through a cost reduction of 10% and a strength increase of ten times.
- Installation experience of the Powergrid has been obtained for both ground- and roof-mounted applications.
- SEA Corporation has gained experience in system design.

The automated receiver assembly station was initially used to assemble the receivers, designed to assemble a receiver in less than one minute. The station never operated near this design rate and was abandoned. Hand assembly was substituted for the pilot production line. The automated receiver production process is under review and improvements are underway.

5.2 FUTURE IMPROVEMENTS TO REDUCE COSTS

Cells and plastic are the major cost components of the Powergrid. As these costs are reduced with high volume production, labor costs will become larger in proportion to the overall costs. This points to the need for continued automation development.

<u>Cells</u>

Cells costs have been high because of the small quantities of cells purchased. It is expected that this cost will be reduced as larger quantities of cells are purchased. Progress made in one-sun cell technology will benefit Powergrid performance and reduce costs. Most one-sun cells can be adapted for use in the Powergrid, which represents a wide variety of possible cell sources.

Heat Sinks

The cost-effectiveness of the heat sinks can be enhanced by distributing the same amount of material in a more efficient manner. The major temperature drop in the heat dissipation system is between the air and the heat sink. To enhance performance of the heat sink, thinner fins need to be developed.

The heat sink is continually under review. The fin length has been increased for the 15-inch-lens module to approximately 15 total inches and will be again for the 20-inch-lens module to approximately 20 inches. The present heat sink for the 20-inch module is about optimum in terms of $/W . The finite element program shows that when the heat sink dissipation area is about the same as the aperture area, the cell temperature is about the same as for one-sun flat-panel modules at equivalent air flows.

Adhesive/Encapsulant System

SEA Corporation is evaluating a number of alternative materials which promise to provide excellent encapsulation at low cost, with little or no hazardous material problems, and that have a short work-in-progress cycle time. Samples are being made, and environmental testing and UV testing are being performed. In-house environmental testing equipment has been procured to shorten the testing time. The materials under evaluation are proprietary at the present time.

Lenses

The opportunity for cost reduction due to lens technology relates more to the performance of the lens rather than its cost. As the concentration ratio increases, the lens quality will need to increase even more. SEA Corporation has taken on the responsibility of lens tooling design and manufacture to better control the result, and to assure timely delivery of lenses. The 20-inch lens will be using a radically different process and is expected to yield very good results. The lens will be extruded flat and then curved. Further improvements are anticipated in lens transmission with the 20-inch lens tooling and with planned electronic feedback on the extrusion machine.

There is some opportunity for direct cost reduction of the lens. This will achieved by thinning out the lens. The 20-inch lens tooling will have an adjustable lip on the die exit whereby the lens thickness can be reduced as it is produced. The danger in reducing the thickness too much is a reduction in strength and a reduction in optical quality. The reduction in strength can be largely balanced by changing the plastic formulation to improve the impact strength. Optical performance can be degraded by mis-shaped facets; this can be balanced by using smaller facets.

The electronic feedback consists of a computer that measures key lens geometric and performance factors and uses these factors to control the operating parameters. This system will be implemented within one year. Optical performance will be one of the measured performance factors.

Sides

The plastic sides are a structural element of the module which requires the sides to be relatively thick. Additional steel structural elements have been added for the 20-inch module. This will actually reduce the cost because it will allow thinner plastic to be used. The heat sink will become more of a structural element in the 20-inch module and the end caps will have stamped steel reinforcements (Fig. 37).

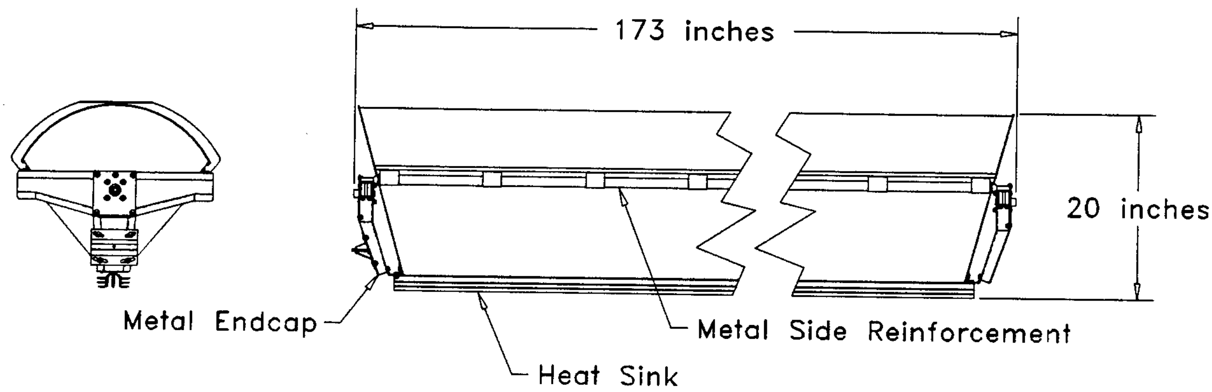

Figure 37 - 20-inch Powergrid Design

As with the lenses, electronic feedback will be used during the side extrusion to control the thickness, and hence the cost. The long-term plan is to directly metallize the sides rather than applying a metallized film to further reduce cost.

Tracker

For the 20-inch module, the tracker electronics are being re-designed to include a microprocessor. This will simplify changing the logic of the tracker electronics by allowing a new PROM chip to be programmed and inserted on the board. The present board requires a wiring change to effect a logic change. The microprocessor will also allow additional features to be added as needed, such as a hail sensor or high wind sensor. Even with these changes, the tracker board will remain a very simple, low-cost component that will still run off the panel itself.

Balance of Parts

As production volume increases, the economics will favor changing from an extruded aluminum panel frame to a steel frame.

The commercial screw anchors for ground- mounted installations are very costly. They are designed for anchoring buildings and utility poles and are grossly overbuilt for this application. This cost will be reduced by designing and manufacturing a Powergrid-specific screw anchor.

5.3 FUTURE IMPROVEMENTS TO ASSEMBLY

Additional process and material development is necessary to reach the short term company goal of a yearly production capability of 50 MW/yr and a cost of less than $2/watt. Areas that need attention are lens extrusion, module side lamination, receiver assembly, and plastic part bonding.

Additional automation is needed to reduce labor cost. As the production volume increases and material costs decline, the labor costs will become a major portion of the overall costs.

SEA Corporation is also working to eliminate all hazardous materials in the production line. This will reduce costs but more importantly, make a more healthy, safe working environment.

Receiver Assembly

The knowledge gained with the automated receiver assembly station is being applied to a new generation of machines which should substantially increase the quality and speed of receiver production. The goal is to reduce receiver assembly time to less than 5% of the previous automated receiver assembly station, with no rejected parts. The cells and leads will be assembled in a separate step (automated cell assembly) using IR heat lamps. The leads will be stamped from a copper strip during this step. This will maintain registration and eliminate an expensive extra stamping step. These cell assemblies will be inspected and tested after soldering. They will then be added to the receiver and soldered in one step, significantly decreasing assembly time. This work is being cost shared under a Department of Energy SBIR (Small Business Innovative Research) grant.

Concept drawings for a new automated receiver assembly station are complete. Test fixtures have been made and tests have been performed on the IR heat lamps and new solder formulation. Thermal cycling and freeze-humidity machines have been acquired to evaluate samples. A consultant was hired to help in the detailed design and development of a working machine in 1996. The machine will be built in functional groups starting with the automated cell assembly. First, small test fixtures will be made to verify the soldering technique using IR lamps. Next, a fixture will be designed and built to automatically solder cell assemblies. The next stage is to fully automate the feed and discharge for the cell assembly station. After that, automatic testing will be added. Finally, fully automated receiver production will be done. The long range goal is to add an improved wire design to the cell assembly, which is being designed under another SBIR grant.

Module Assembly

This project identified the solvent adhesive drying as a production rate limiter, causing high work-in-progress. Alternative adhesives and bonding methods that are faster-acting and are not hazardous materials are being investigated.

With the 10-inch lens, the mechanical center of the lens was not always the optical center of the lens. This is being rectified in the 20-inch lens with the electronic feedback in the extrusion process. If mechanical and optical symmetry cannot be assured, two or more lasers will be used for optical alignment.

As the accuracy of the extruded parts is increased with the electronic feedback, it will be possible to add self-jigging features to the parts. Some self-jigging features are being added to the 20-inch lens module.

Module Testing

An improved solar simulator is needed for module testing. A truly collimated light source will allow more accurate testing of the modules. Additionally, automation will help the throughput. SEA Corporation is presently in the process of improving the data acquisition system with a capacitor load and rapid scanning. This will measure and display an IV curve in under one second, as opposed to the present system which takes several minutes.

Shipping

No completely satisfactory shipping method was found during this project. A satisfactory shipping method must be developed to reach the Powergrid cost goals.

5.4 FUTURE PLANS

SEA Corporation is presently engaged in expanding production with the goal of 50 MW/yr production capacity, at a $2.00/Wdc price by 1999, funded by equity financing and development contracts. The experience gained from the pilot production program will be very valuable when applied to the full-production equipment. The company plans to improve the quality of the product and to lower cost and raise output. The current objective is to be able to offer a quality product that costs approximately half of present day PV systems. Volume production is necessary to achieve this low cost.

The company is presently:

- Installing a state-of-the-art lens extrusion line that should provide 20-inch wide lenses with high transmission
- Installing a state-of-the-art module side extrusion line that will provide high quality module sides
- Developing an improved automated receiver assembly station
- Developing a low-cost roll formed steel frame
- Developing automated module assembly procedures with minimum hazardous materials

This work will be carried out in a new, larger manufacturing facility. Details of this work are presented in the body of this report.

The SEA Corporation plan calls for approximately $6,000,000 to be spent to achieve the high volume production capacity and low-cost objectives. If the cost objectives are met, it should allow the product to dominate the present market for 1 KW and larger systems and expand that market. Research carried out by SEA Corporation[4] has shown that if the price can reach $2.00/Wdc, a new market for PV, distributed peaking power, could expand to $10 billion per year domestically and over $30 billion per year worldwide during the next decade.

While full-scale production is being established, SEA Corporation is continuing to sell demonstration systems manufactured using the pilot production facility. These sales will allow the company to test the product under a variety of conditions and allow potential large-scale customers to evaluate the product. SEA Corporation hopes to have sales of 50 MW/yr by 2000.

5.5 COST PREDICTIONS

An overall cost reduction of 89% over the present manufacturing cost is possible by implementing the lessons learned from the pilot-line effort into the high-volume manufacturing line.

Table 9 below summarizes the manufacturing techniques, expected direct cost savings, the pilot-line efforts, and next step efforts. Savings are due to reduced labor, reduced material cost, improved scrap rate, and increased power output, and are calculated from the dollars per watt for each manufacturing scenario. Table 11 breaks down the cost savings into those due to reduced labor, reduced materials, improved Powergrid output, and reduced scrap.

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[4] Kaminar, Neil, SEA Corporation Internal Research Paper, April 1994, not published.

Table 9 - Total Expected Savings from Improved Manufacturing Techniques

Manufacturing Task	Previous Low Volume Technique	Planned High-Production Volume Technique	Savings	Pilot-Line Effort	Next Step Effort
Receiver assembly	Manual assembly	Fully automated assembly	92%	Develop first generation automated receiver assembly	Develop second generation automated receiver assembly
Lens extrusion	Low output lenses	In-house state-of-the-art dedicated extrusion line using advanced tooling	87%	Improve lens output using pilot tooling	Develop state-of-the-art dedicated extrusion line using advanced tooling
Side extrusion	Hand assembly of different parts	In-house state-of-the-art dedicated extrusion line using advanced tooling	95%	Extruded first one-piece parts using pilot tooling	Develop state-of-the-art dedicated extrusion line using advanced tooling
Cell testing and sorting	Manual testing	Fully automated testing and sorting	92%	In-house designed manual flash test	Automate techniques developed during project
Receiver encapsulation	Manual application of liquid encapsulant	Automated encapsulation using zero hazmat material	97%	Pilot application of zero hazmat encapsulant	Second generation zero hazmat material & application
Receiver testing	Manual testing	Automated testing on assembly line	97%	Pilot processes & equipment	Automate techniques developed during project
Side film lamination	Semi-automated	Fully-automated on extrusion line	87%	First-generation lamination machine	Second generation lamination machine
Cut module sides to length	Manual operation on non-dedicated equipment	Fully automated on extrusion line	99%	Semi-automated operation on dedicated equipment	Automate techniques developed during project, add to extrusion line
Cut lenses to length	Manual operation on non-dedicated equipment	Fully automated on extrusion line	99%	Semi-automated operation on dedicated equipment	Automate techniques developed during project, add to extrusion line
Crimp sides to receiver	Manual operation	Full-automation	98%	Semi-automated equipment	Automate equipment developed during project
Glue sides to lens	Manual operation	Full-automation using low hazmat materials	98%	Develop semi-automated equipment and fixtures	Automate equipment developed during project
Attach end caps to module	Manual operation	Full-automation using low hazmat materials	98%	Develop semi-automated equipment	Automate equipment developed during project
Module test	Manual testing	Automated testing on assembly line	99%	Pilot processes & equipment	Automate techniques developed during project
Frame assembly	Manual assembly	Semi-automation using jigs and fixtures	61%	Pilot jigs and fixtures	Second generation jigs and fixtures
Shipping	Manual, consumable packaging	Bulk loading/ unloading, reusable packaging	92%	Investigate various alternative techniques	Improve techniques developed during project
Receiving, material expediting	Paper records	Computerized	60%	Develop material tracking system	State-of-the-art MAS system
Overall			89%		

Table 10 below summarizes how the each manufacturing technique will decrease unit costs and how the pilot-line effort will lead to these improved manufacturing techniques.

Table 10 - Result of Pilot Line Effort to Reduce Costs and Improve Manufacturing Techniques

Manufacturing Task	Cost Reduction Method	How Pilot Line Effort Will Lead to the Improved Manufacturing Technique
Receiver assembly	Reduce labor cost by 98% Reduce scrap & rework rate by 10%	Experience with the first-generation machine will lead to a much improved second-generation machine
Lens extrusion	Reduce parts cost by 39% Increase output by two fold Reduce scrap rate by 50%	Experience with 15-inch lens tooling will lead to much improved 20-inch lens tooling and a state-of-the-art extrusion line
Side extrusion	Reduce parts cost by 76% Reduce scrap rate by 50%	Experience with pilot tooling will lead to much improved production tooling and a state-of-the-art extrusion line
Cell testing and sorting	Reduce labor cost by 80%	Techniques developed during the project can be automated
Receiver encapsulation	Reduce labor cost by 97% Reduce parts cost by 85% Reduce use of hazardous materials Reduce scrap & rework	Materials and techniques developed during the project, along with new materials and techniques, will be used for an improved encapsulation system
Receiver testing	Reduce labor cost by 92%	Techniques developed during the project can be automated
Side film lamination	Reduce labor cost by 80% Reduce scrap & rework	A second-generation lamination station, installed on the extrusion line, can be based on the station developed during the project
Cut module sides to length	Reduce labor cost by 99% Reduce scrap	Techniques developed during the project can be automated
Cut lenses to length	Reduce labor cost by 99%	Techniques developed during the project can be used to develop an automated flying-cutoff system on the extrusion line
Crimp sides to receiver	Reduce labor cost by 95%	Techniques developed during the project can be automated
Glue sides to lens	Reduce labor cost by 96% Reduce use of hazardous materials	Techniques developed during the project can be automated
Attach end caps to module	Reduce labor cost by 94% Reduce use of hazardous materials	Techniques developed during the project can be automated and the product can be redesigned based on experience gained
Module test	Reduce labor cost by 99%	Techniques developed during the project can be automated and an indoor simulator can be developed based upon the experience gained
Frame assembly	Reduce labor cost by 91% Reduce scrap	Semi-automated second-generation jigs and fixtures can be developed based upon pilot jigs and fixtures
Shipping	Reduce labor cost by 50% Reduce part cost by 83%	Techniques developed on the project can be further improved
Receiving, material expediting	Reduce stand-by time, thus reducing cost throughout the line	Computerize techniques developed during the project to eliminate parts-not-in-stock delays

Additional cost reductions for high-volume production will come from large quantity purchases and improvements in power output. The high-volume module should produce 2.5 times the power output over the present module, which alone will produce a 60% reduction in cost per watt.

Table 11 below presents additional details on the cost savings, which are due to labor savings, material savings, reduced scrap rate, and increased output. The totals for each column include costs not presented in the table and account for the different contributions from the various manufacturing tasks, and therefore cannot be calculated directly from the table.

Table 11 - Manufacturing Cost Reduction Details

Manufacturing Task	Labor Savings	Material Savings	Cost Savings due to Increased Output	Cost Savings due to Reduced Scrap Rate	Overall Cost Savings for Manufacturing Task
Receiver assembly	98%	65%	60%	10%	92%
Lens extrusion	—	39%	60%	50%	87%
Side extrusion	—	76%	60%	50%	95%
Cell testing and sorting	80%	—	60%	—	92%
Receiver encapsulation	97%	85%	60%	0.4%	97%
Receiver testing	92%	—	60%	0.5%	97%
Side film lamination	80%	67%	60%	1%	87%
Cut module sides to length	99%	—	60%	1%	99%
Cut lenses to length	99%	—	60%	1%	99%
Crimp sides to receiver	95%	—	60%	1%	98%
Glue sides to lens	96%	—	60%	1%	98%
Attach end caps to module	94%	—	60%	1%	98%
Module test	99%	—	60%	10%	99%
Frame assembly	91%	-61%	60%	1%	61%
Shipping	50%	83%	60%	0.5%	92%
Receiving, material expediting	—	—	60%	0.5%	60%
Overall	93%	55%	60%	13%	89%

The panels used in high volume production are larger which is part of the reason for increased output. The increased size adds to the frame cost which accounts for the negative savings in the frame assembly task materials.

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M98004403

Report Number (14) SAND-- 98-0208

Publ. Date (11) 199803

Sponsor Code (18) DOE/EE, XF

UC Category (19) UC-1209, DOE/ER

DOE