PVMaT Improvements in the Manufacturing of the PVI Powergrid™

Phase I Annual Technical Report
26 October 1995 - 25 October 1996

N. Kaminar, D. Curchod, P. Hobden, S. Roake, J. Navin, B. Bottenberg, J. Sahagian
Photovoltaics International, LLC (PVI)
Sunnyvale, California

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of the U.S. Department of Energy
Managed by Midwest Research Institute for the U.S. Department of Energy under Contract No. DE-AC36-83CH10093
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PREFACE

This is the Annual Technical Progress Report for Phase I of a three phase effort to improve the manufacturing of the PVI Powergrid concentrator. It covers the work done from October 16, 1995 to October 26, 1996 under DOE/NREL Subcontract #ZAF-6-14271-11.

The following personnel at PVI have significantly contributed to the efforts covered in this report.

Garlton Salter, Marianne Walpert, Dan Rodriques, Ed Harris, Shan Daroczi, Dave Doty, Joan Bunch, Juan Amaya, Clayton Briscoe, Laurel Conner, Jean Flores, Steve Higgins, James Kwan

In addition, PVI has been supported by the following non-PVI personnel.

Gorden Armstrong, Dr. Chris Rauwendaal, Scott Unruh, Phil Rockwell, Aram Soghikian, Gerd Bode, Alex Dadiomov, Mike Davis, Phil Argebrite
SUMMARY

PVI is improving the manufacturing of the Powergrid under the PVMaT program in five basic areas.

- Development of an advanced, state-of-the-art lens extrusion system
- Development of an advanced, state-of-the-art module side extrusion system
- Development of a second generation automated receiver assembly station
- Development of low-cost roll-formed steel panel frame members
- Development of a low VOC and Hazmat automated module assembly process

Phase 1 of the PVI PVMaT program is basically a design phase, Phase 2 is basically an implementation phase, and Phase 3 is basically a demonstration phase.

Under Phase 1, the following was accomplished.

- An advanced extrusion system was designed and specified
- Proof-of-concept tests were completed on elements of the extrusion system
- An advanced die for lens extrusion was built and tested
- A unique die concept for module side extrusion was built and tested
- The second generation automated receiver assembly system was designed
- Proof-of-concept tests were completed on elements of the receiver assembly station
- A panel frame utilizing roll-formed members was designed and prototypes built
- A low VOC module was designed and prototypes built
- A process for encapsulating a concentrator receiver with EVA was developed
- Two EVA encapsulation vacuum ovens were built

The Powergrid has the potential to be very low cost in the short term. The PVI PVMaT program should allow PVI to reach the cost goals set by the company. This in turn will allow PVI to become a substantial player in the PV market and will allow the DOE goals of increased application of PV to become a reality.
TABLE OF CONTENTS

1.0 INTRODUCTION ................................................................. 1
2.0 BASELINE MANUFACTURING PROCESS AND RATIONALE FOR THE IMPROVEMENTS ......................................................... 3
  2.1 LENS EXTRUSION .................................................................. 3
  2.2 MODULE SIDE EXTRUSION .................................................. 6
  2.3 RECEIVER ASSEMBLY ......................................................... 6
  2.4 FRAME MANUFACTURING .................................................... 7
  2.5 FINAL TESTING AND SHIPPING .......................................... 7
  2.6 SITE INSTALLATION .......................................................... 7
3.0 PVMAT PROGRAM EFFORTS ................................................ 8
  3.1 TASK 1, LENS EXTRUSION DEVELOPMENT .......................... 8
  3.2 TASK 2, MODULE SIDE EXTRUSION DEVELOPMENT ............ 13
  3.3 TASK 3, AUTOMATED RECEIVER ASSEMBLY STATION DEVELOPMENT .................................................... 14
  3.4 TASK 4, DEVELOPMENT OF ROLL FORMED FRAME MEMBERS ............................................................ 25
  3.5 TASK 5, AUTOMATED LOW VOC AND HAZARDOUS MATERIALS MANUFACTURING .................................................. 27
4.0 CONCLUSIONS ................................................................. 31

LIST OF FIGURES

Figure 1. The PVI Powergrid Concentrator Panel .................................. 1
Figure 2. A Typical Plastic Extrusion System ......................................... 4
Figure 3. PVI Puller ...................................................................... 9
Figure 4. PVI Lens Die .................................................................... 10
Figure 5. PVI Lens Die, Bottom Half of Die Showing "Coathanger" Flow Channel. 10
Figure 6. Vacuum-former / Cold-shoe ............................................... 12
Figure 7, Module Side Extrusion Cross Section ..................................... 14
Figure 8, Automated Receiver Assembly Station .................................. 15
Figure 9. Lead Punch Design .......................................................... 16
Figure 10. Lead Punch Steps ................................................................ 17
Figure 11. Cell Lead Punch Being Tested ............................................ 18
Figure 12. CAD Drawing of Robot .................................................... 18
Figure 13. Cad Drawing of End Effector .......................................... 19
Figure 14. Robot Programming Being Tested ..................................... 20
Figure 15. Rotary Table and Nests ................................................... 20
Figure 16. IR Lamp Soldering Concept .............................................. 22
Figure 17. Laser Soldering Station .................................................... 24
Figure 18. Frame Member Section ................................................... 26
Figure 19. Roll Formed Member Powergrid Frame Design .................. 27
Figure 20. Low VOC module .......................................................... 29
Figure 21. Small EVA Test Oven .................................................... 30
Figure 22. Production EVA Oven .................................................... 30

LIST OF TABLES

Table 1. Lens Die Test Summary ................................................... 13
1.0 INTRODUCTION

The PVI Powergrid is a linear focus concentrator which uses low-cost components and manufacturing techniques that are intended to reduce the price of a photovoltaic system to a level required for broad level deployment of PV. The Powergrid uses a linear-focus Fresnel lens made by a plastic extrusion process, the lowest cost method of manufacturing. The plastic module sides are also extruded. The Powergrid uses solar cells manufactured using the low-cost methods used for one-sun cells. Twelve modules are mounted on a stationary panel frame to move in unison for single-axis tracking, see Fig. 1.

![Figure 1. The PVI Powergrid Concentrator Panel](image)

The components for the Powergrid have been shown to be low cost. Reducing the cost of manufacturing the Powergrid, while increasing the output and reliability, are key to reaching the strategic goals of the company.

During a project sponsored in part under contracts with Sandia National Laboratories and the California Energy Commission, PVI developed a pilot production facility.\(^1\) The company was able to demonstrate 830 KW/yr production capability, but several manufacturing areas were discovered that needed additional development.\(^1\) This resulted in the formulation of PVI's PVMaT program.

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\(^1\) CEC CONTRACT 500-92-055, SANDIA CONTRACT 40 8941 C
The goals for PVI's PVMaT program are to reduce the cost of manufacturing the Powergrid, to demonstrate large volume production, and to reduce the use of volatile organic compounds (VOC) and hazardous materials (Hazmat) in manufacturing. The key components of the program are:

- Development of an advanced, state-of-the-art lens extrusion system
- Development of an advanced, state-of-the-art module side extrusion system
- Development of a second generation automated receiver assembly station
- Development of low-cost roll-formed steel panel frame members
- Development of a low VOC and Hazmat automated module assembly process

Successful completion of PVI's PVMaT program will result in a reduction in the cost of the Powergrid of approximately three dollars per Watt, increase production capacity to 50 megawatts per year, and significantly reduce the emission of VOC and Hazmat during manufacturing. PVI estimates that, during the first five years of large volume production, the savings to the public due to this program will be six hundred million dollars.

The PVI PVMaT program attempts to solve the major impediments to low-cost production. The ability to extrude high-quality lenses is key to high output, and thus low cost per Watt, of the Powergrid. Related to this is the ability to extrude accurate module sides. Manual assembly of the receivers is very labor intensive and is a major component to the manufacturing cost. The present manufacturing method for the panel frame members is also expensive. Another labor intensive area is module assembly. The use of VOC and Hazmats are indirect cost components.

A unique part of the PVI Powergrid is the extruded lens. PVI has always depended on custom extrusion companies for the development of the extruded lens. This has proved unsatisfactory because of low performance of production lenses and excessive development time. The low performance has primarily been due to lack of sophisticated controls and equipment available with these traditional commercial extrusion companies. For the PVMaT program, PVI is borrowing heavily from the medical extrusion industry to develop an in-house, state-of-the-art extrusion system. The system uses a computer to monitor and control the extrusion process. It also uses a number of advanced tooling features in the extrusion die and in the post-extrusion tooling. These developments should allow extruded lenses to be produced that approach the optical transmission of lenses produced with other more expensive technologies.

The extrusion of the module side has had similar problems. The accuracy of parts produced from custom extrusion companies has been unsatisfactory. Again, this is primarily due to the lack of sophisticated controls and equipment at these companies. Under the PVI PVMaT program, the company is developing advanced tooling and controls to produce accurate extruded module sides. Much of the effort extended in developing the lens extrusion system can be used for the module side extrusion. In the beginning, one extrusion machine will be used with a different set of tooling installed to produce either lenses or sides. During the later part of the program, the company plans to add a second extruder to manufacture module sides.
Receiver assembly is the major manufacturing cost component. This is due to the high manual labor content now used. Under the Sandia and CEC programs, an pilot-scale automated receiver assembly station was designed, produced, and tested. As explained in section 2.3, the machine was unreliable and taken out of service. The experience gained from this machine will enable PVI, under the PVMaT program, to design and produce a second generation automated receiver assembly station that will be far more reliable and produce high quality receivers.

As explained in section 2.4, the present panel frame members are expensive. PVI is developing the technology for lower cost roll-formed panel frame members. Since the Powergrid is supplied with the panel frame, this should result in a sizable reduction in product cost.

Module assembly is presently labor intensive and involves the emission of VOC's and use of hazardous materials. Grouped under module assembly is receiver encapsulation, which, because of the type of silicone encapsulant used, is presently the greatest contributor by far of VOC emissions and in the use of hazardous materials. The adhesives presently used to bond the plastic parts together also emit VOC. PVI is developing automated EVA receiver encapsulation and improved module assembly process. These developments should eliminate all VOC emissions and the use of hazardous materials in receiver encapsulation and reduce or eliminate VOC emissions in module assembly. Manual labor, and thereby cost, should also be reduced.

2.0 BASELINE MANUFACTURING PROCESS AND RATIONALE FOR THE IMPROVEMENTS

This section describes in detail the manufacturing technologies in place at the start of the PVI PVMaT program and the problems associated with these technologies. It also describes the logic for improvements being done.

2.1 LENS EXTRUSION

At the beginning of the PVI PVMaT program, lens extrusion was done at an outside company that specializes in custom profile extrusion of acrylic parts. They had had experience with lighting diffusers that use a similar profile to the PVI lens. They were contracted to develop tooling and produce sample lenses and limited production quantities of lenses. All aspects of the tooling design and development was handled by this company. PVI did the lens design which was then given to the extrusion company as a computer file.

The extrusion process is very simple in concept, see Fig 2. A hopper of plastic pellets gravity feeds a screw rotating in a barrel. The screw is similar to the type used in pasta makers or meat grinders for home use. The friction in the screw and electric heaters surrounding the barrel melts the plastic which is then fed into a die. The pressure upstream of the die can range from 500 to 5,000 psi, depending on the flow rate and die design. The temperature of the acrylic is at this point approximately 400°F. A critical part of the die is the manifold section that is
designed to evenly distribute the plastic to the profile section of the die. Downstream of the manifold, the profile section is designed to impart the desired cross section to the exiting plastic, called extrudate.

![Diagram of a plastic extrusion system]

**Figure 2. A Typical Plastic Extrusion System**

After the plastic exits the die it starts to cool and solidify. Equipment for after-forming of the part, such as an air rack or vacuum sizer, is used to control the cooling of the plastic and help define the final shape. A puller is used to draw the plastic from the die and through the after-forming equipment. A cutoff saw cuts the lens material to length. The plastic is drawn down (reduced in cross-section area) by the puller. This is a necessary step in the lens extrusion process to properly orient the plastic molecules and control the shape of the final part.

The extrusion process, although simple in concept, is complex in detail. The plastic exhibits non-Newtonian flow which means that the viscosity is not constant but dependent on the shear rate. Viscosity is also dependent on temperature, which is not uniform in the extrudate. The plastic is also elastic, meaning that it will try to regain the shape it had before traveling through the profile section of the die. For these reasons it is very difficult, if not impossible, to completely model the flow of the plastic through the die. Because of the unknown velocity profiles in the die, the final shape of the part is unknown until the die is tried.

From the above paragraph, it would seem that obtaining the desired part is next to impossible. But this is not the case. Dies are developed using sound engineering principles, past experience, and design of experiments methodology. Once a die is developed and the desired shape is obtained, repeatable, consistent parts can be made day after day. That is, as long as the extrusion parameters do not change.

Accurate measurements and control of the extrusion parameters is absolutely necessary to obtain high efficiency extruded lenses. The normal instrumentation
and controls found on commercial extruders are fine for most parts but are not sophisticated enough for the high quality lens we require.

The extrusion company that we used for most of our lens development made very good diffusers for lamp fixtures, but did not have the equipment necessary to extrude accurate lenses. (Diffusers need not be very accurate.) The extrusion company did not have a pressure sensor for the die or barrel head. Temperature controls for the die were inaccurate. Puller speed was not measured. Extrudate temperature was unknown. Temperature of the vacuum sizer was not measured. Many of the controls, such as puller speed and screw speed, were not capable of fine adjustment. All of these problems lead to inconsistent results and non-repeatability. For instance, during one test, we were able to extrude 10-inch wide lenses with mid-80's optical transmission, but we were not able to repeat the optical transmission during a subsequent production run.

Because of pressure to complete their regular production, our lens development was given low priority at the extrusion company. This added significantly to the development time. For instance, the development time for the 15-inch lens was in excess of one year, and was never truly carried to completion.

The lens die used at the custom extrusion house consisted of an adapter, a number of manifold plates and a die plate. All of these parts are solid plates of steel, sometimes several inches thick, that have channels or profiles cut in use using wire electric discharge machining (wire EDM). The profile section itself is approximately one inch thick, 20 inches wide, and 8 inches high. The lens profile in the die was curved to approximately the final radius. The profile is approximately 10% larger than the final part (10% draw-down). All of these plates are heated while in use using electric heaters to approximately 400°F.

A major problem with the previous die design was that changes took too long. Modifications to the lens die required cooling down the entire assembly, disassembly, and machining. The parts then have to be re-assembled and heated. The entire process takes at least 48 hours. Deburring the profile section of the die after machining was difficult because it was one piece and could not be split for access to the facets. Major changes, such as a new profile, required at least one month because an entire new profile plate had to be made.

The after-forming tooling consisted of a vacuum-sizer/cold-shoe and an air rack. The lens was substantially cooled as it slid through a curved slot in the cold-shoe. The top section of the cold-shoe was removable for starting-up the line. The air rack completed the cooling. This part of the tooling worked well after some initial problems were solved.

The problems experienced in the past could only really be solved by bringing the extrusion process in house. PVI has only one product to develop and can thus give this product full attention. PVI has acquired the expertise, through years of experience with the former suppliers, and through hiring expert consultants, to design an extrusion system capable of making the needed accurate lenses. An in-
2.2 MODULE SIDE EXTRUSION

The development of the extruded module side was also done through a custom extrusion house. Similar problems to the extruded lens development were encountered. Although optical transmission is not one of the required properties for the module sides, accurate forming of the sides does influence the module output. Varying width from part to part, or even in the same part, have affected the lens focus and thus module output. Also, internal stresses, due to unequal cooling, have caused oil-canning (local buckling in the material) which also has affected output. Because of all the reasons described above, the only real solution to inaccurate module sides is to bring the extrusion process in house.

2.3 RECEIVER ASSEMBLY

The first version of the automated receiver assembly station attempted to assemble the cells in-situ on the heat sink. A PVI developed pressure-sensitive adhesive (PSA) was first placed on the heat sink. Leads and cells were then placed on the heat sink in the proper sequence. The leads were then soldered to the cells on the heat sink using a hot-block. Solder was supplied via solder coating the leads. Flux was obtained from application of liquid no-clean flux that evaporated after soldering. Leads were punched from ribbon in two stages, one done on the station, and one done on a separate machine.

The major problem with this machine was the soldering. For one thing, soldering on a heat sink is difficult because of the heat dissipating properties. Also, the rate of heat dissipation depended on the bond in the PSA, which was variable depending on a number of factors. The heat transfer from the hot-block was also variable depending on contract pressure, flatness, and cleanliness. All of these uncontrolled variables resulted in unreliable solder joints.

The mechanics of the station itself was unreliable. Many material jams occurred during the final punching of the leads. The operator frequently had to interrupt the process to adjust cell leads that were not placed correctly by the machine. Cells were also often misplaced or broken by the machine. Most of the receivers made using the first generation automated receiver assembly station had to be reworked, adding considerable cost. Although all of these mechanical problems could have been fixed, the basic concept of in-situ soldering was flawed.

An additional problem with the first generation automated receiver assembly station was that it was slow. Although it was designed to assemble a receiver within three minutes, the actual time was 30 minutes. One reason for this was that an insulation tape had to manually placed between the top and bottom leads. The original concept was to interleave the top and bottom lead fingers and have insulation already on the solid section. There were two problems with this concept. The interleaving proved impossible with the accuracy obtainable, and the insulation placed on the copper ribbon feed stock caused the off-line punch to jam.
Manual soldering and receiver assembly was adopted and is being used now. This adds extensive labor in receiver assembly and makes this part of the Powergrid manufacturing the most expensive part. The second generation automated receiver assembly station being developed by PVI is needed for PVI to meet the cost goals.

2.4 FRAME MANUFACTURING

The PVI Powergrid is sold as a complete DC system, including the frame. The present manufacturing method for the frame members is expensive. The frame members are manufactured from extruded square aluminum tubes. The holes where the wires exit the tube, and the holes for the other hardware used for mounting the modules, tracker, mounting feet and legs, etc., all have to be added after the channel is extruded. The holes and hardware are added using fixtures and manual labor. This adds cost to the already expensive channels.

The roll-formed steel frame members will be much less costly. All the holes and other features can be punched into the steel, using automated machinery, before it is rolled into a section. The steel is far less expensive than the aluminum. A lock seam is produced in the steel that allows the section to resist torsion as well as the extruded section. The closed steel section can also be used as an electrical conduit as the extruded section is. This improvement should significantly reduce the product cost.

2.5 FINAL TESTING AND SHIPPING

Final testing is done outdoors. The modules are then placed in wooden shipping containers to be trucked to the installation site. The frame members and miscellaneous parts are shipped in a separate container. Final testing is presently limited to sunny days.

PVI is planning to develop an indoor module test facility, not part of this PVI PVMaT program. Prototypical indoor module test facilities have already been built. Collimated light is needed to accurately test the concentrator indoors.

2.6 SITE INSTALLATION

The panels are erected on site. The frames are assembled on the ground or saw horses and then tilted to the proper angle. The frames are shipped with most of the internal wiring installed. A minor amount of field hookup is required for the wiring inside the frames, which is done when the frame are assembled. A variety of foundations have been used depending on the circumstances. For roofs, penetrations that connect to the building frame are used. For ground, either screw anchors or poured concrete foundations have been used. After the frame is in place, the module are added and connected. The tracker is then installed and the system is ready to be used. Any wiring from the panel to the use point is installed after the panels are in place.
No improvements to the panel installation procedure is planned under the PVI PVMaT program.

3.0 PVMAT PROGRAM EFFORTS

This section describes the different tasks covered in this reporting period, the work done under those tasks, and the results of the effort.

3.1 TASK 1, LENS EXTRUSION DEVELOPMENT

The goal of this task was to design an advanced state-of-the-art extrusion system including the tooling. The system was planned to be computer controlled with feedback supplied from sensors that measure such things as optical transmission and part size. Advanced tooling was to be designed including the die and after-forming equipment, including a flying cut-off saw and stacker. The extrusion system is designed for a lens extrusion rate of four feet per minute which equates to approximately 25 MW/yr production from each extruder.

In addition, during Phase 1, the die was to be built and developed. Die development involves a series of testing and changes to the die. The changes include trying different profiles and machining the back side of the profile section to modify the flow of the plastic.

This task was successfully completed with the design of the extrusion system finished and fabrication of the extrusion system started. The equipment is scheduled to be installed by January 1997. Also, the die was built and developed at an extrusion company. PVI leased the equipment at the extrusion company by the day to perform tests on the die.

The extrusion system will be one of the most advanced systems in the world. It is custom designed for the PVI products. Components were chosen from different sources to provide a system tailored to PVI requirements. When components were not available that met PVI requirements, they were designed and built from scratch. For instance, the puller is a custom designed piece of equipment, see Fig. 3. A commercial puller was not available that fit the lens profile, provided the required control, and was capable of computer control.

A PC will sense and control all aspects of the system and will store data for instantaneous and later analysis. The software will be capable of establishing trends and of adjusting the parameters based on these trends. For instance, the extrudate temperature might be adjusted based on maximizing optical transmission. The interaction of the different parameters is very complex and only a computer can analyze the multidimensional control function.

PVI retained Dr. Chris Rauwendaal to help design our new die. Dr. Rauwendaal is a recognized expert in die and extrusion screw design. He has written several books on these subjects. Dr. Rauwendaal was able to do a finite element analysis on the flow of plastic through the profile section of the die and recommend changes that could improve the extrudate flow and make die development easier.
The new die, see Fig. 4, represents a radical departure from previous effort. It is a larger lens, 20 inches wide as opposed to 15 inches wide. We borrowed from sheet die technology to produce a flat die and manifold.

The manifold is designed to provide uniform extrudate flow at the profile section of the die. It uses the "coathanger" design, so called because the distribution flow
channel is in the shape of a coat hanger, see Fig 5. This shape is determined by a standard formula which has been proven out over many years of making sheet dies. Before reaching the profile section, the extrudate is directed over a raised section that has a varying land length. This varying land length is what gives the uniform flow.

Figure 4. PVI Lens Die

Figure 5. PVI Lens Die, Bottom Half of Die Showing "Coathanger" Flow Channel
The profile section of the die is designed for easy and fast changes. It is a removable die plate. This allows rapid changes of the die plate and easy modification to correct flow problems. Because the facets are accessible, they can be highly polished, which increases lens transmission. The die plate is mounted opposite a flexible lip that allows changes to be made to the profile opening while the lens is being run. This is a great advantage over our previous die design which could only be changed by making a new die plate, which required at least one month. Using a flat die allows all these features which in turn allow rapid and easy development, leading to high optical transmission.

We were able to proceed with the die development by leasing an extruder and supplying our own controls and pieces of equipment. We developed the die over several sessions. A number of die plates and modifications to the die plates were tested. This resulted in a lens with sharp, accurate facets. We plan to continue development of the die by leasing an extruder while our equipment is installed. We anticipate that the quality of the lens will improve once we are using our own extruder.

We found that the advanced features we designed into the die worked well. We were able to remove the die plate and make changes quite easily. We were able to have the die polished which added to the quality of the lens. We were also able to change the thickness of the lens by adjusting the die lip.

PVI also developed after-forming tooling. This consisted of various pieces of hardware to support the soft extrudate, including a vacuum-former / cold-shoe. The cold-shoe was designed and built to have better control over the cooling of the lens and to maintain the proper shape during solidification. It consists of three hemicylindrical aluminum blocks that the outside (smooth side) of the lens slides on, see Fig. 6. The blocks have a series of slots with alternating vacuum and water connections. The lens rides on a film of water supplied by the slots that are connected to water. The slots connected to vacuum suck away the water and keep the lens in contact with the cold-shoe. The water is very effective in carrying away the heat in the lens.

Uniform cooling of the lens is very important. If it is cooled more rapidly on one side, it will curve away from that side. In effect, the cooling freezes that portion while the remaining part continues to shrink as it cools. Cooling rates can be changed by changing the thickness. If one section of the lens is thicker, it will cool slower and consequently shrink more. Under these conditions, internal stresses are built in that later manifest themselves as warps as the plastic relaxes. The lens must be extruded with uniform thickness and cooled uniformly.

The cold-shoe was too effective in its cooling, causing the lens to curl away from the shoe and consequently have a very small radius. We reduced the water and vacuum flow in the cold-shoe, decreasing the cooling rate on the outside. We also added forced air cooling to the inside (facet side) of the lens. By varying the cooling on the outside and inside of the lens, we were able to produce a lens with the proper radius.
During Phase 1, PVI performed a series of tests on the die and after-forming tooling. Table 1 summarizes these tests and the results.

By the end of Phase 1, we were able to extrude a lens with minimum radii and flat facets. The surface finish of the lens was rough due to a non-polished die. We were able to repeat our experiments and control the geometry of the lens. We were able to obtain facets in the part that reflected the facets in the die.

During Phase 2, PVI plans to polish the die developed in Phase 1. The die lip will also be polished. It is felt that there should be an 8 to 12 percentage point gain in lens transmission after this is done. We are also planning to machine a new die plate based upon the developed die. We feel that the true potential of this die will be known after it is run on our own equipment.
Table 1. Lens Die Test Summary

<table>
<thead>
<tr>
<th>Test</th>
<th>Description</th>
<th>Equipment and Procedure</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Initial Die Test</td>
<td>Low-tech temperature controls, air rack cooling, 100% virgin acrylic plastic, modified wheel type puller, attempted stabilized extrusion</td>
<td>Test stopped after loss of temperature control (too hot). Surface poor, large root radii, focal length short, lens transmission 50%</td>
</tr>
<tr>
<td>2</td>
<td>Added equipment, controls, instrumentation.</td>
<td>New puller, new temperature controllers, added extrudate and die TC's, added additional heaters and die TC's, added cold-shoe, new die plates, new transition from flat to round, tried 100% re-grind, ran strategic experiments of extrusion parameters</td>
<td>New plates did not fill, re-grind NG unless dried overnight, re-grind contaminated in grinder, cold-shoe too cold, new puller works well, new heaters indeterminate, surface OK with new (polished) plates, much better control, lens radius very small (unusable lenses)</td>
</tr>
<tr>
<td>3</td>
<td>Cold-shoe spread</td>
<td>Spread cold-shoe into three sections separated by 4 inches, increased temperature of cold-shoe, more strategic experiments</td>
<td>Lenses still have too small of a radius (unusable), sides of lenses have too little flow</td>
</tr>
<tr>
<td>4</td>
<td>Air cooling inside lens</td>
<td>added air cooling to inside (facet side) of lens,</td>
<td>Lens radius OK and adjustable, lenses still unusable due to facet shape</td>
</tr>
<tr>
<td>5</td>
<td>Old die modified</td>
<td>Modified original die for improved flow</td>
<td>Better fill in lens sides and facets, surface rough (die not polished)</td>
</tr>
<tr>
<td>6</td>
<td>Old die modified</td>
<td>Further modifications to original die, ran different line speeds</td>
<td>Good facet form, surface poor, good lens samples, transmission 70%, stopped test due to power supply failure</td>
</tr>
</tbody>
</table>

3.2 TASK 2, MODULE SIDE EXTRUSION DEVELOPMENT

This task is tied closely with the Lens Extrusion Development, Task 1. Initially, the same state-of-the-art extrusion system developed under Task 1 will be used to extrude module sides. The only difference is the tooling. PVI plans to install a separate extruder later in the PVI PVMaT project just to manufacture sides. The extruder can run the sides approximately twice as fast as the lenses, but there are two sides needed for each lens, thus the design side production rate per extruder is approximately equal to the lens production rate of 25 MW/yr.

At the start of the project, we anticipated that we would have to develop entire separate tooling for the sides, including the manifold. We were in the preliminary process of designing this manifold when we completed an experiment that made the separate manifold unnecessary.

This experiment consisted of mounting a die plate designed to make sides on the lens manifold. Although usable parts were not made, the experiment showed us that this was a viable concept. Usually, an extrusion die is designed to eliminate dead spots where the plastic would stay in the die and suffer heat degradation. The
die plate for the sides does not extend to the edges of the manifold and therefore we were concerned that stagnation would be a problem. However it does not seem to be a problem, even after extensive run time. Relative to other plastics, the acrylic plastic that we use can have a long residence time without degradation.

We did not balance the die plate, and therefore, usable parts were not made. We plan to balance this die in the early part of Phase 2. Balancing refers to adjusting the up-stream configuration of the die plate to even out the extrudate flow and is something that is done on almost all extrusion dies.

In order to obtain usable sides to support our production schedule, we developed a module side design using separate pieces. The attachment part (leg) is extruded and bonded to an off-the-shelf flat sheet. PVI developed the die for the leg which is run on a leased extruder. We plan to use the two-piece side while the die for the one-piece side is developed. The one-piece module side configuration is shown in Fig. 7.

Figure 7. Module Side Extrusion Cross Section

PVI has designed the after forming tooling for the one-piece side. We plan to use a vacuum-sizer/cold-shoe similar to the one used on the lens except that it will completely surround the part so that uniform cooling is provided. The cold-shoe will be completely adjustable so that the part can be altered for best fit and function.

During Phase 2 we plan to continue the die development on our own extruder and to fabricate and test the after forming tooling. Accurate sides, that are not warped due to non-uniform cooling, are very important for maximum module output.

3.3 TASK 3, AUTOMATED RECEIVER ASSEMBLY STATION DEVELOPMENT

The purpose of this task is to design a second generation automated receiver assembly station. This new design was to address all of the problems associated with the first generation station. To increase the reliability and quality of the receivers, it was to have the cell soldering of both the top and bottom leads occur off of the heat sink. To reduce hand labor and assembly time, it was to have automated insulating tape insertion between the top and bottom leads. To reduce manufacturing cost, all of the punching of the leads was to be all done on the machine starting with low-cost copper ribbon. To increase the quality of the receivers and eliminate rework, the machine was to provide accurate and reliable placement of the components on the heat sink. To reduce assembly time, it was to be designed to place all the cell assemblies on the heat sink in parallel instead of
one at a time as the first generation station did. All components were to be designed for minimum maintenance, maximum reliability, high throughput, and to produce the highest quality receivers possible.

The design throughput for the automated receiver assembly station is one cell per 15 to 20 second. This equates to 4 to 5 MW/yr for this machine. By parallel processing of cell assemblies, the production of one machine is expected to increase to 50 MW/yr.

A second generation automated receiver assembly station was designed with all of the above features using sound development practices, see Fig. 8. All concepts for the different machine elements were tried in proof-of-concept tests before they were incorporated into the design. The station was designed to be modular so that different elements could be changed out if needed.

Figure 8, Automated Receiver Assembly Station

Many different steps are needed to assemble the receiver. As much as possible, these different steps are performed concurrently. For example, there are two nests for the cells and leads. While one cell assembly is being soldered, the other nest is being unloaded and loaded. In the final version of the automatic assembly station, there will be cell assembly machines, running concurrently, for each of the cells on
the heat sink. This will represent a significant savings in time over the previous automatic assembly station which placed one cell and one lead at a time.

The automated receiver assembly station consists of the following elements:

1. A cell lead punch with de-reeler
2. A robot with custom end effector
3. A two position rotary table with nests for cell assemblies
4. An IR soldering station for the cell leads
5. A solder dispenser for cell soldering
6. A dispenser for the insulating tape
7. A rail transport system for the heat sink
8. A solder dispenser for the lead tabs
9. A laser soldering station for the lead tabs
10. An exhaust system
11. A computer based control system

Cell Lead Punch

The cell lead punch converts rolls of sheet copper to cell leads. It consists of a progressive punch, see Fig. 9, and a de-reeler.

Figure 9. Lead Punch Design
The copper is 0.007 inch thick and 3.73 inches wide. The copper thickness was determined by cost optimization and represents approximately 0.5% power loss. Thicker copper would have less loss but cost more.

There are four steps in the progressive die. The copper is feed into the die by stationary and moving grippers. All movement, including the punch, is pneumatically operated. The steps can be seen in Fig. 10. First, five rectangular holes plus two round indexing holes are punched. The indexing holes are used, along with indexing pins, to control the placement of the material during subsequent punch strikes. On the second and third strikes, six additional rectangular holes are punched during each strike. On the fourth strike, the lead is cut off, by which time a gripper on the robot end effector has hold of the lead. A tab is produced on one end of the lead that is used to make series connections between the cells.

![Figure 10. Lead Punch Steps](image)

During Phase 1, a progressive die was built and tested, see Fig. 11. We initially experienced problems with jamming of the copper while it was being fed into the punch. The alignment pins would not fit into the alignment holes which caused a burr to be generated that in turn caused the material to jam in the punch. We traced the problem to variations in the width of the copper material. As long as the material was slit properly within the ±0.005 inch tolerance, the punch operated reliably. The variation in the width of the copper was due to startup adjustments in the slitting machine. We do not expect quality control of the copper material to be a problem in production.

During Phase 2, we plan to incorporate the punch and de-reeler in the final automated receiver assembly station.
A commercial robot is being used, see Fig. 12. The robot can move anywhere within the dashed line shown on the figure. The quill can move up and down and rotate. The robot is controlled by the computer through a controller sold with the robot.
The end effector is a custom part designed by PVI, see Fig. 13. It mounts on the robot quill and has grippers for the different parts. There are two sets of pneumatic actuated grippers for the cell leads so that two leads can be transported at one time. Vacuum pickups are used to grip the cells and completed cell assemblies.

During Phase 1, PVI obtained a robot and began learning how it operated and how to program it, see Fig. 14. A temporary end effector was built to test the operation and learn the programming language. The robot is a well developed commercial item and no problems were experienced during the initial testing.

During Phase 2, we plan to build the end effector and incorporate the robot in the final automated receiver assembly station.

**Rotary Table and Nests**

The rotary table has two nests and two positions, see Fig. 15. One position is reserved for soldering the cell assembly, while the other position is used to unload and load a nest and for solder dispensing. The nest consists of a series of grippers that hold the leads and cell in position for soldering.

The rotary table is pneumatically operated. PVI sized the pneumatic rotary actuator to provide the required rotational travel time, given the inertia of the components. The table is required to start rotating, rotate 180°, and stop within 2 seconds.
Figure 14. Robot Programming Being Tested

Figure 15. Rotary Table and Nests
During Phase 1, the rotary table concept was evaluated in a proof-of-concept test. The candidate rotary pneumatic actuator was obtained and a rectangular aluminum plate, that simulated the moment of inertia of the nests and supporting structure, was mounted on it. A pneumatic circuit was built and connected to the actuator. The time to rotate was 1 second with 60 psi air pressure, which is within the specified time limit.

During Phase 2, the nests will be built and tested and incorporated in the automated receiver assembly station.

**IR Soldering**

IR soldering has many advantages. It is a non-contact process which means that variable thermal contact resistance is not a factor. No part of the heating element comes in contact with the molten solder, eliminating corrosion, contamination, and cleaning problems. The IR energy can be switched on and off quickly. There is no massive component to keep hot.

However, the IR soldering must be done correctly to be effective. Timing and intensity of the heating must be controlled. The mirrors on the lamps must be kept clean.

The IR soldering station consists of four line-focus IR lamps arranged to focus on the ends of the lead fingers and cell bus area, see Fig 16. Quartz lamps supply the IR energy that is then focused by first surface elliptical mirrors. The lamp housing and mirrors are water cooled. The vapors generated by the flux is removed by the exhaust system. The exhaust system keeps the vapors from condensing on the mirrors and thereby reducing reflection.

The IR lamps are stationary. The cell assembly nest rotates into position for soldering. This reduces the time required to move the assembly into position and helps to keep the assembly in alignment. Having the lamps stationary also reduces the vibration on the lamp filament, thus extending the life of the lamp.

During Phase 1, PVI completed a series of tests on the IR soldering concept. Different times and light intensities were tried.

The entire soldering cycle takes four seconds. These solder joints were subjected to thermal cycling and freeze-humidity cycling according to the Sandia Qualification Testing. 10% degradation in electrical performance was measured after the tests. Tin-lead-silver eutectic solder paste was used for these tests. The solder paste contained a no-clean flux that eliminated the need to clean the cell after soldering.

During Phase 2, PVI will incorporate the IR soldering into the automated receiver assembly station.
Solder Dispenser

The solder dispenser consists of eight solder reservoirs (syringes) that feed small applicators with solder paste. The applicators dispense eight dots of solder paste. A total of 32 dots are needed for the bottom leads and 32 dots for the top leads. Four placements are needed for the top leads and four placements are needed for the bottom leads. These 32 solder dots need to be placed in 3.5 seconds, including dispenser motion time.

The solder dispenser is located on the load/unload end of the rotating table. Solder is dispensed on the top of the bottom leads before the cell is placed in the nest. Solder is also dispensed on the top of the cell before the top leads are placed. The solder dispenser is on a track to allow the dispenser to be moved out of the way and to position the dispenser for placements.

During Phase 1, PVI conducted tests on a prototype solder dispenser. Different methods of solder dispensing were tested. PVI is confident that the method developed will produce correctly placed and sized solder dots.
During Phase 2, the solder dispenser will be fabricated and added to the automated receiver assembly station.

**Insulating Tape Dispenser**

The insulating tape is supplied with pressure sensitive adhesive (PSA) on both sides with release liner to protect the PSA before use. The release liner has to be stripped off the insulating tape. The tape dispenser applies the insulating tape to the bottom leads as they exit from the punch.

During Phase 1, PVI performed various proof-of-concept tests of tape application methods. A method was developed that produced consistent placement of the insulating tape.

During Phase 2, the tape dispenser designed in Phase 1 will be built and tested and incorporated into the automated receiver assembly station.

**Rail Transport System**

The rail transport system is designed to move the heat sink through the automated receiver assembly station and to stop at each cell location so that a cell assembly can be placed. It consists of a system of rollers to guide and move the heat sink. The rollers that move the heat sink are driven by stepper motors through a cog belt. The stepper motors will be programmed to uniformly accelerate and decelerate the heat sink while moving the heat sink one cell length (plus clearance).

During Phase 1, PVI calculated the friction and acceleration forces associated with moving the heat sink. The drive system was designed based upon these forces. A generous factor of safety was used in the design. The design transfer time for the heat sink is one second. Based on these calculations, a stepper motor was chosen that has 22 ounce-inches torque. This motor provides a resolution in the heat sink position of less than 0.001 inch. Six stepper motors are used.

During Phase 2, the rail transport system will be built and tested and incorporated into the automated receiver assembly station.

**Lead Tab Solder Dispenser**

After the cell assemblies are mounted on the heat sink, the series electrical connections have to be made. All of the cells on the receiver are connected in series. The cell leads are formed with tabs to make the connections. Two connections have to be made per cell.

Solder paste is used to make the connection between the lead tabs. The solder dispenser for the tabs is very similar to the solder dispenser for the cell leads and uses much of the same parts. The only major difference is that there are two reservoirs and two applicators. The tests used to develop the solder dispenser for the cell leads can be used to on the solder dispenser for the tabs with adjustments made to dispense the larger quantity of solder paste required.
During Phase 2, the tab solder dispenser will be fabricated, tested, and added to the automated receiver assembly station.

**Lead Tab Laser Solder Station**

There are many advantages to using a laser to solder the tabs. It is a concentrated heat source that can be confined to a small spot. It is quick. There are no components that have to be kept hot. It is a non-contact process which means that there are no problems with contamination, corrosion, or cleaning, and the process is reliable.

The laser solder station consists of a 45 Watt diode laser, an optical re-imaging unit for laser spot magnification, and a roller slide to move the laser into position, see Fig. 17. One laser unit is used for the two tabs that need to be soldered. The laser is moved to the two different soldering positions and a stow position with a 3-position pneumatic actuator.

Figure 17. Laser Soldering Station
During Phase 1, proof-of-concept tests were performed. With the tabs off of the heat sink, using a 45 Watt laser, reflow occurred reliably within 2 seconds.

During Phase 2, we plan to complete the laser soldering station and install it on the automated receiver assembly station.

**Exhaust System**

An exhaust system is designed into the system to remove any fumes generated during soldering. Filtered air is used to make up the air that is exhausted. The exhaust system is designed to keep the fumes away from the mirrors of the IR lamps and the laser optics. This system will be installed on the automated receiver assembly station during Phase 2.

**Computer Control System**

The entire automated receiver assembly station is controlled with a PC style computer that operates through a hierarchy of controllers. There are several advantages to using a computer as opposed to a PLC. For one thing, the computer can work as a data acquisition system and diagnose the data. It can also diagnose failures in the system. The computer can show trends such as quality of soldering verses IR lamp current. It can keep track of production. It can interface with other computers in the company to provide up-to-the-minute production information. Also, it is easily programmed and changes are easy.

There are approximately 100 sensors in the system to determine the condition of every element. For instance, there are sensors to determine where the laser is, the position of the solder applicators, if the copper reel is empty, if a cell and leads are in the nests, and many more. The sensors are designed to control the machine and to stop the machine in case of an anomaly. Warning lights will alert the operator and the diagnostic software will tell the operator what is wrong. There is also an emergency stop switch for the operator.

During Phase 1 PVI obtained the computer and several controllers. It was used to familiarize us with its operation and to test various subsystems, such as the punch, the solder dispenser, and robot.

During Phase 2 the remaining controllers will be acquired and the computer system will be hooked up to the automated receiver assembly station and programming software written.

**3.4 TASK 4, DEVELOPMENT OF ROLL FORMED FRAME MEMBERS**

The goal of this task was to design a panel frame using roll formed members and to design the tooling to make these members. The tooling is a sizable investment and so a prototype of the frame was made using our present manufacturing processes.
Roll forming is an established technology. Sheet material is fed into a series of rolls which progressively bend the material to the desired shape. In the case of the Powergrid frame, a closed shape is desired that can transmit torque loads. Our frame section is square with a lock seam, see Fig. 18. This provides the necessary torsional rigidity and strength. The lock seam is produced by progressively rolling the seam together and then running it through crimping rollers to lock the two halves together. Roll forming is very rapid and production rates equivalent to over 100 MW/yr are easily obtainable on one machine.

The roll forming eliminates any post rolling machining. All of the holes and other features are punched and stamped into the metal before it is rolled. The frame members are ready to use after rolling.

During Phase 1 PVI designed a frame intended to use roll formed frame members, see Fig. 19. The frame is 38 feet by 16 feet and has the following features:

- Corrosion resistant
- High strength to weight ratio
- Adjustable for different tilts
- Light weight
- Easy to assemble
- Rodent proof
- Bird resistant

![Lock seam](image)  

Figure 18. Frame Member Section
Several companies that do roll forming were contacted and quotes obtained for the roll form tooling. A prime candidate was selected.

During Phase 2 we plan to build the tooling for the roll formed frame members and introduce them into our production line.

3.5 TASK 5, AUTOMATED LOW VOC AND HAZARDOUS MATERIALS MANUFACTURING

The purpose of this task was to minimize the use of volatile organic compounds (VOC) and hazardous materials (Hazmat) in module manufacturing while increasing the level of automation. This effort was focused in two areas, eliminating silicone encapsulate and minimizing the use of solvent adhesive for the plastic module parts. The silicone encapsulant is being replaced by EVA and the module is being redesigned to minimize the use of solvent adhesive.

Eliminating Solvent Adhesive

During Phase 1 PVI investigated three methods to eliminate the solvent adhesive:

1. Ultrasonic bonding
2. Heat welding
3. Adhesives with 100% solvents

We discovered problems with each of these methods.

Ultrasonic bonding is expensive and problematic for large assemblies such as the Powergrid. Ultrasonic bonding basically uses ultrasonic energy to friction heat the
parts to be bonded and then pressure to weld the parts together. An ultrasonic horn is used to direct the sound waves to the area to be heated. The design of the horn is critical. Also, the sound waves can be reflected off-course when propagating in the part which makes the design of the part critical as well. The entire bond must be made at once to eliminate thermal deflection problems.

PVI initially considered a horn with a roller mounted on it which moved along the length of the bond. After research into this method it was abandoned. The localized heating at the roller does not allow the parts to bond together because the surrounding material keeps the heated area from moving together and fusing. Warpage is also a problem.

To bond the lens to the module sides, a horn or series of horns are needed that would bond both 15 foot joints on either side of the module at once. Although technically feasible, the cost of such a tool, including the driving electronics, would be prohibitively expensive. Also, there probably would be a number of iterations needed to get the horns and parts developed to the point where good bonding was achievable, adding more expense. Another problem with a large ultrasonic welded joint is the generation of microcracking at the edges of the bond, a problem that could not be tolerated with the 30 year life expectancy needed with the PVI Powergrid.

Thermal bonding has the same kind of problems and ultrasonic welding. The entire joint has to be made at once which makes the tooling expensive. Warpage is likely.

Solvent adhesive is difficult to improve upon. Neither ultrasonic nor thermal bonding produce a joint superior to a properly designed solvent adhesive joint. Solvent welding is inexpensive and easy to do. Tooling costs are minimum.

PVI investigated several alternative adhesives that contained 100% solids (no VOC). One adhesive, a urethane based variety, was particularly interesting. It worked like a hot melt adhesive and was applied with a special gun. The adhesive had an initial set that was good enough for normal handling and would cure over 24 hours to provide a strong, flexible joint. The only problem is that it would not stand up under sunlight. All of the alternative adhesives that were investigated during phase 1 would not pass UV tests.

An alternative solution was conceived and that was minimizing the adhesive joints used in the module. Previous to the PVI PVMaT project heavy plastic end caps were used along with heavy plastic side and the lens to provide the structural strength of the module. This meant that the adhesive joints were critical to the structure. In the low VOC module, the plastic parts are reinforced with metal components, see Fig. 20. The plastic end caps are replaced by a metal end caps and light plastic closures. The aluminum heat sink attaches to the metal end caps, becoming an active structural member. The side joint is reinforced with a metal tube. With the modifications to the module, the adhesive joints are not critical and far less adhesive has to be used. The module is also designed to be self jigg ing, eliminating separate fixtures and speeding production. It can also be assembled in
the field, reducing transportation costs. A disassembled version of the module takes far less space to ship.

![Figure 20. Low VOC module](image)

**EVA Encapsulation**

In the past, ethylene vinyl acetate (EVA) encapsulation was not considered for concentrator receivers. The only experience that the PV industry had with EVA encapsulation in concentrators was the Arco Solar Carrisa Plains installation, which was a 2X concentrator using standard flat panels and mirrors. The panels turned brown after several years.

Recent improvements in EVA and synergistic physics of the acrylic lens make the use of EVA in the Powergrid receiver possible. Modern EVA encapsulants have far less propensity to yellow or brown. Also, the acrylic in the PVI lens has a cutoff of UV light in the wavelengths that causes the EVA to turn yellow.

During Phase 1 PVI built two vacuum ovens to test EVA encapsulated receivers. One oven was a small test oven designed to make foot-long samples of the Powergrid receiver, see Fig. 21. The other oven, built later, was designed to make full size receivers for testing and production, see Fig. 22.

Both ovens work on the same principle. The receiver slides into the oven from one end. There is a mechanism that lifts the receiver so that the cells and EVA are touching a diaphragm at the top of the chamber. The door is then shut and the space above the diaphragm and the space below the diaphragm are evacuated. After a preset vacuum is reached, the entire oven is heated according to a prescribed rate. After a set temperature is reached the space above the diaphragm is opened to atmospheric pressure and the diaphragm presses down on the EVA, providing a void free encapsulation. After the maximum temperature is reached, the heaters are turned off and the oven is allowed to cool. The bottom space is open to atmospheric pressure after a certain temperature is reached.
During Phase 1, PVI experimented with various process cycles, varying the temperature rise time, different set temperatures, and different temperatures in the
cycle when vacuum would turned off or on. We have developed a cycle that gives largely void free encapsulations.

During Phase 1, PVI performed UV tests, thermal cycling tests, and freeze-humidity cycling tests on EVA encapsulated samples. The UV tests were conducted with and without an acrylic cover. No problems have been found in these tests that would preclude the use of EVA in the Powergrid.

During Phase 2 we plan to improve the production oven and build a second version. We also plan to introduce the EVA encapsulated receivers into production.

4.0 CONCLUSIONS

PVI has completed the design tasks designated for Phase 1 and is proceeding to implement these designs in Phase 2. This should result in a substantial reduction in production costs and a substantial increase in production capacity. During Phase 3 we plan to demonstrate this increased capacity and reduced cost and to make additional improvements to the manufacturing of the Powergrid.

The Powergrid has the potential to be very low cost in the short term. The PVI PVMaT project should allow PVI to reach the cost goals set by the company. This in turn will allow PVI to become a substantial player in the PV market and will allow the DOE goals of increased application of PV to become a reality.

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13. ABSTRACT (Maximum 200 words)  
Photovoltaics International, LLC (PVI), is improving the manufacturing of the Powergrid™ under the Photovoltaics Manufacturing Technology (PVMaT) program by development in five basic areas: an advanced, state-of-the-art lens extrusion system; an advanced, state-of-the-art module side extrusion system; a second-generation, automated receiver assembly station; low-cost, roll-formed steel panel-frame members; a low volatile organic compound (VOC) and Hazmat automated module assembly process. Phase 1 of the PVI PVMaT program is a design phase, Phase 2 is an implementation phase, and Phase 3 is a demonstration phase. Under Phase 1, PVI researchers accomplished the following: designed and specified an advanced extrusion system; completed proof-of-concept tests on elements of the extrusion system; built and tested an advanced die for lens extrusion; built and tested a unique die concept for module side extrusion; designed the second-generation, automated receiver assembly system; completed proof-of-concept tests on elements of the receiver assembly station; designed a panel frame using roll-formed members and built prototypes; designed a low-VOC module and built prototypes; developed a process for encapsulating a concentrator receiver with ethylene vinyl acetate (EVA); built two EVA encapsulation vacuum ovens. The Powergrid™ has the potential to be very low cost in the short term. The PVI PVMaT program should allow PVI to reach the cost goals set by the company. This, in turn, will allow PVI to become a substantial player in the PV market and will allow the DOE goals of increased application of PV to become a reality.  
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