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Subcontractor Report

Specific PVMaT R&D in CdTe Product Manufacturing

Phase II Annual Subcontract Technical Report May 1999—September 2000

Alan McMaster
First Solar, LLC – Technology Center
Perrysburg, Ohio

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NREL Technical Monitor: R.L. Mitchell

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Contents

Section I – Personnel

Greg Nelson	Executive Vice President
Alan McMaster	Principal Investigator
Contributors:	John Bohland, Process Area/EHS Manager Frank Borgeson, Manager Laser Technology Wayne Monie, Vice President of Projects and Systems Integration; Ken Smigielski, EHS Engineer Chris Zarecki, Process Area Leader Mike Ross, Electrical Engineer Jim Poddany, Senior Designer Dr. Joseph Hanak, Consultant Product Search, Inc., Sub-contractors

Section II – Phase II Tasks Overview

Task 4. Manufacturing Line Improvements – Laser Scribing and Potting

First Solar, LLC (First Solar) shall develop and implement an improved potting procedure and design associated equipment. First Solar shall conduct a thorough review and analysis of the current process to identify throughput, labor, and equipment drawbacks. First Solar shall formulate an improved process through adaptation of well-proven glass manufacturing methods and automation. First Solar shall engage industrial experts and vendors such as the ARRI as needed in the development, design and testing of alternative potting solutions which are directly scalable to 60 modules per hour with potential of exceeding that capacity with nominal upgrades. First Solar shall complete off-line development of the individual potting processes such as diode connection, mold positioning, and urethane injection. First Solar shall carry out the prototyping of material handling steps for the potting process such as: handling large sheets of glass in and out of buffers; feeding glass in and out of the potting work station; flash tests; and parts-feeding. First Solar shall test a prototype potting station to demonstrate the improvement elements and provide functional information for the high-throughput design. First Solar shall complete testing of the improved high-throughput potting system, including process and material handling components, on its module production line. The task is expected to result in high-throughput, low-cost potting by increasing throughput per potting line by a factor of at least four; reducing labor costs by at least a factor of ten; and increasing overall quality.

First Solar shall also implement an improved scribing technique and design associated equipment. First Solar shall conduct a thorough a review of the current process to identify throughput, labor, and equipment drawbacks. First Solar shall formulate an improved process through adaptation of state-of-the-art techniques and automation. First Solar shall engage industrial experts and vendors such as the ARRI as needed in the design, and testing of the new scribing technique to expedite task progress. The task is expected to result in high-throughput, low-cost scribing by increasing throughput by a factor of two; reducing downtime by a factor of three; and reducing equipment capital requirements by at least a factor of two.

Task 5. Product Readiness

First solar, LLC shall initiate and complete qualification testing of a modified module. Modifications may include one or more of the following depending on the market interest: 1) junction box instead of pigtails; 2) sizes other than 60cm x 120cm; 3) alternative voltage; 4) encapsulation materials or process; and 5) other product changes influenced by market demand. First Solar shall obtain UL1703 certification for its modified module. Experts from the field including Underwriters Laboratory and the Photovoltaic Testing Laboratory at the Arizona State University will be utilized as needed to expedite the successful completion of the task. The task is expected to improve acceptance into existing and new markets.

Task 6. Environmental, Safety and Health Programs

First Solar, LLC shall continue to refine and improve its Environmental, Safety, and Health, (ES&H) programs throughout its facilities. First Solar shall conduct an extensive review of its current programs and highlight areas that need improvement. First Solar shall employ industry experts such as OSHA On-Site Consultation of the Ohio Bureau of Employer Services to expedite progress on improvements and provide guidance for plan implementation. First Solar shall initiate improvements through a series of training and educational seminars for its employees affected by the targeted issues. First Solar shall complete the implementation of refinements and improvements in critical areas and establish a plan for continuous improvements in its entire program. This task is expected to result in an Environmental, Safety and Health program which ultimately will place First Solar in a leadership position relative to comparable businesses both within and outside of the photovoltaic industry.

Section III - Results for Phase II by Task and Milestone

Foreword

Just prior to the beginning of Phase II of the PVMaT project major changes occurred in the company's corporate structure. Beginning February 1, 1999 Solar Cell, Inc. (SCI) formed a joint venture partnership with True North Partners of Scottsdale, AZ. The new company was named First Solar, LLC. This event, anticipated for some time, resulted in an infusion of new financial resources and manpower toward the immediate start of construction of a new major manufacturing facility for photovoltaic modules, based on cadmium telluride. The site of the new plant is at Cedar Park Boulevard in Perrysburg, a suburb of Toledo, Ohio. Most of the engineering plans for this facility had been completed by SCI just prior to the formation of joint venture. These plans included the design of the new, large, semiconductor coating equipment that was developed in the course of the preceding PVMaT Subcontract ZAI-4-11295-02. This equipment was designed to be capable of producing PV modules at a rate of 100 MW per year.

This turn of events resulted in a dramatic change of emphasis on the goals of the PVMaT project. Not only were the project goals to be met, to comply with the wording of the Subcontract, but their achievement had to be realized and implemented in time to coincide with the startup of the manufacturing activity in the new facility. The schedule of the construction of the new 75,000 square-foot facility was rather aggressive as outlined below:

- Building site cleared in April 1999
- Building slab poured in June
- Roof on the building completed by the end of July
- Installation of manufacturing equipment began in August
- First deposition of the semiconductor film on the new large coater in January 2000

A photo of the new First Solar PV module manufacturing facility appears in Figure 1. Consequently, the effort on the PVMaT project has been expanded to include the former SCI team in Toledo, Ohio, and a new, additional team of engineering subcontractor, Product Search, Inc. in Scottsdale, Arizona. These two teams joined in a collaborative effort on Tasks 4: Manufacturing Line Improvements and on Task 5: Product Readiness.

Because of the impending start of manufacturing activities scheduled for early 2000, the objectives were expanded as a result of continual reviews of the equipment and product design, to remove any potential bottlenecks in the overall manufacturing process.

<u>Activities Assigned to the Product Search, Inc. Team</u>

The effort by Product Search team began on March 26, '99. In the "First Solar Finalization Project Statement" there were three goals to be met:

Figure 1. A photograph of the new First Solar 100 MW/year PV module manufacturing plant in Perrysburg, Ohio

- Increase the module throughput from 60 to 400 units/day (at 100 % yield)
- Reduce the material costs from \$27/unit to \$20 per unit and
- Reduce direct labor costs from \$20/unit to \$4/unit.

The activity through the end of April consisted in site visits to First Solar, to gather information, to lay ground for beginning research on the process from start to finish, and to start focusing on the finishing line. The team started developing a baseline and conceptualizing the process to address the three tasks , which resulted in a report "Conceptual Semi- Automated Solar EVA Finishing Line (SoFL)." Thus began the collaborative effort with the PVMaT team at First Solar, which nearly coincided with the start of Phase II of the project on May 1. The "new high-throughput potting system" in Phase II was the main project of Task 4.

Task 4. Manufacturing Line Improvements – Laser Scribing and Potting

In anticipation that the potting process would be excluded, it was suggested that the name of the project should be changed from "Potting" to "Contact Termination and Mounting," that was to be used henceforth.

Alternative methods of mounting of PV modules into arrays

With the abandonment of potting with polyurethane, a different method of mounting of the modules into arrays was required, to replace the potted "mounting pucks" or pads, shown in Figs. 2a and 2b. During the R&D phases of the project it was established that a wide range of customer roof-mounting methods would be required; hence, the company chose to provide modules with the option left to the customer and integrator to determine the mounting method, based on site application.

Milestone	Description
m-2.1.1	Complete thorough review of potting preparation and potting processes including time studies, equipment utilization, materials flow, and yield.

As a result of combined team activities of First Solar and Product Search, Inc., this milestone was completed successfully. An account of these activities follows. The objectives of the potting task in Phase II were to:

- increase manufacturing throughput by a factor of four,
- reduce labor costs by a factor of ten,
- increase overall quality.

In May 1999, at the Solar Finishing Line Concept Design Review the results of the module qualification task for Phase I PVMaT were reviewed. A round of modules had been submitted for qualification to Arizona State Photovoltaic Testing Laboratory for IEEE 1262 Testing. Those modules failed two of the four sequences, the humidity-freeze test and the damp-heat test. From this report it became apparent that the polyurethane potting method for the electrical contact termination and for the molding of mounting pads may have to be replaced, in order to achieve the goals of environmentally durable device, a high-throughput manufacturing process and a cost-effective product.

In response to that, from the beginning of Phase II several alternative module finalization schemes have been evaluated toward achieving the Phase II qualification objective. Three possible solutions have been investigated simultaneously or in close sequence starting in June 1999.

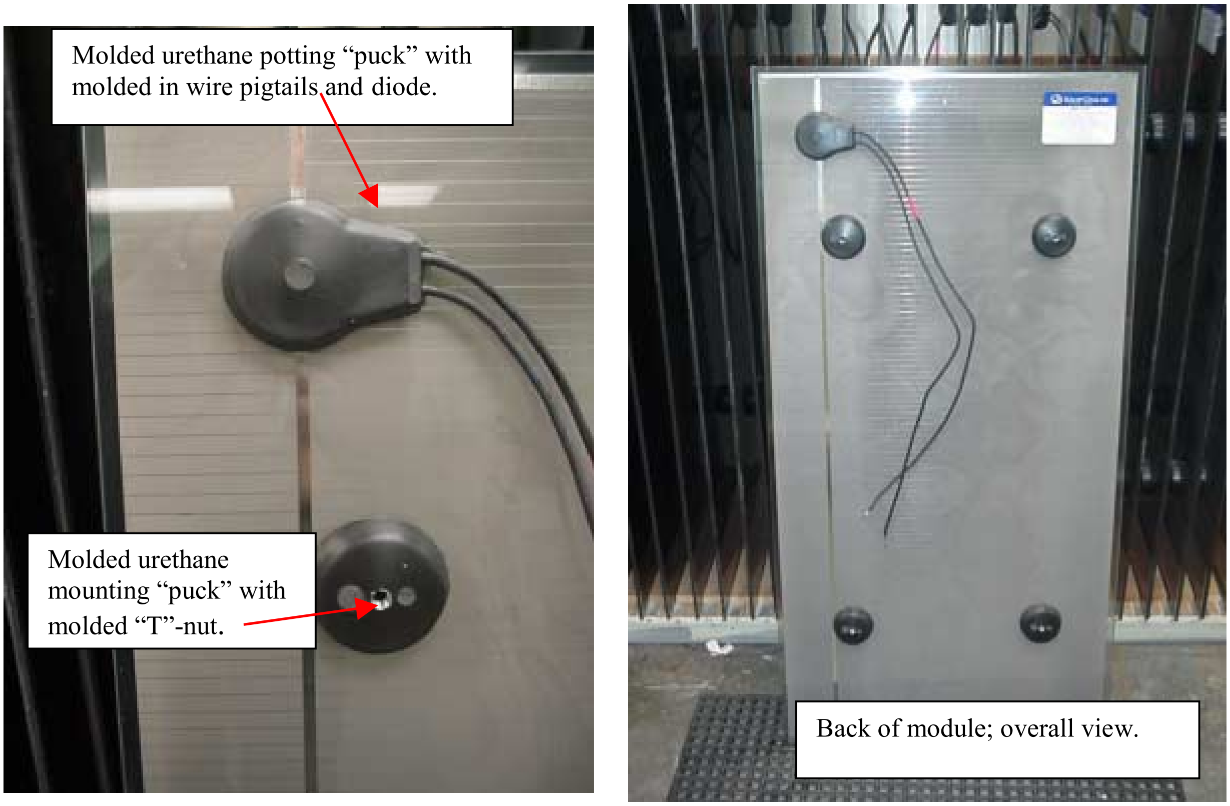

Figure 2. Photographs of potted polyurethane termination "pigtails" and mounting pucks on the rear of PV modules—(a) a closeup of the potted parts and (b) a view of the whole module.

A practical alternative method of mounting has been identified, patented by Powerlight, Inc. This method, developed for a horizontal mounting on rooftops, utilizes the modules bonded to a solid foam material and interlocked together, much like a puzzle, in cushioned frames. This method does not require either mounting pads or fastening of the modules to the frame. Several other sketches have been made for alternative mounting but thus far none have been selected for development, pending successful development of contact termination.

Contact Termination

The Top-Hat design for contact termination

In considering the projected production line improvements, potential cost-reduction measures have been identified in potting, labor and material and increased throughput. The Top-Hat design was one of the items where sizeable cost reductions appeared to be achievable by eliminating the potting process both for the termination and the mounting pads. For the electrical termination a small, injection-molded part called the Top Hat was designed and its development was initiated. The Top Hat is an electrical connector fixture made of polymeric material as shown in a photograph in Fig. 3.

The Top-Hat design was intended to replace the potted polyurethane termination shown in Fig. 2a that uses wire termination, referred to as “pigtails.” It uses metallic “spade” terminals that are soldered to the two metallic strip conductors. In this design, the bottom rim of the Top-Hat fixture would fit underneath the cover glass. The fixture is affixed to the module by means of EVA pressure lamination. The Top-Hat connector and method were designed for high-throughput production of PV modules, low cost, and simplified method of installation of the modules in the field.

Figure 3. A photograph of the “Top-Hat” termination fixture

Milestone	Description
m-2.2.1	Complete potting improvement plan including methodology and resource allocation.

The plan for potting improvement, now called contact termination, was initiated during the preceding quarter and completed during the sixth quarter as described below. For testing of the Top-Hat concept in finished modules, prototypes of the Top-Hat fixtures were NC-machined of phenolic material. In eventual production, the fixtures would be made by injection molding. Testing of assembly fixturing was done first, to facilitate the attachment of the lead wires to the Top-Hat connector and of the resulting assembly to the double-sided tape that's on the module. A total of over 25 modules have been made incorporating the Top-Hat connector. These modules were intended to be submitted for UL testing, following in-house testing.

The second half of the Top-Hat fixture design is a matching connector, which was to be fabricated following the planned testing.

On August 26, 1999 preliminary product specifications, including drawings were submitted to UL for their preliminary review and evaluation. In this process UL conducts an "Engineering Evaluation," of the documentation and attempts to form a visual picture of the product, what the components are and how it's put together. Then UL provides a feedback based of potential problems and issues.

Following the fabrication of the modules using the Top-Hat connector for termination, the devices were subjected to damp-heat tests, which were completed in October. Some problems with the pottant have been identified. The potting that was being used for the Top-Hat insulation, a RTV silicone, was failing under strain relief testing. This problem was due to the size of the termination cavity, being potted to provide the strain relief. It was also too thick and the RTV would require an unacceptable curing time. Otherwise, from the standpoint of moisture-proofing, RTV tested to be satisfactory. Nevertheless, the Top-Hat design was abandoned and replaced by a new termination design, named the "*Cord-Plate"* design, wherein the stress-relief failures were expected to be eliminated. Sketches of the Cord-Plate termination design are shown in Figures 4 and 5 of Milestone m-2.3.1 Section.

UL report on "Results on Preliminary Investigation" for the Top-Hat design

Some memos and documentation has been received from UL throughout October regarding the Engineering Evaluation of the product specification and module mockup submitted in September. A preliminary report was received from UL in mid-November called "Results on Preliminary Investigation," which is included in the monthly reports. It contains extensive evaluation, their comments and the feedback they gave us. The report contained mainly comments related to product materials used in the Top Hat, to passing product flame-retardant tests, other issues about thermal testing, and more on flame retardant materials, and thermal tests to which all the materials and modules were to be subjected.

A major issue that UL raised that the mounting method for the module had not been submitted. Without the mounting method, all that UL could provide was only with "Recognition" of the PV module and not an actual listing. In order to get the listing, the complete package must be submitted, including the mounting method, termination and all aspects of finalization. Reading of the entire report prior to future submission is advised.

As stated above, the initial submission included the Top-Hat termination design. However, in November timeframe some strain-related problems were discovered with the Top-Hat design. On November 11 a memo was sent to UL to have the test postponed. It was anticipated that the submission to UL would be made in January 2000 following the fabrication and in-house testing of modules incorporating the new Cord-Plate design.

Milestone	Description
m-2.3.1	Complete initial testing of potting process improvements.

This milestone was completed with success. Two major accomplishment were achieved, one in successful testing of a new module design with "Cord-Plate" contact termination and the construction, installation and initial testing of the solar finishing line for the production of the new module.

The Cord-Plate termination design

In going over a possible redesign of the Top Hat, a decision was made to pursue a new design, the *Cord-Plate* design to circumvent the problems posed by the Top-Hat design.

Work on the Cord-Plate design began on November 15, 1999. Thus, once again, a new line layout was developed for the termination process. It involved the design of a new electrical connection fixture, shown in Fig. 4, and the use of EVA as the encapsulant for the lamination of the module. Prototypes of the Cord Plate were made by NC machining, using a polymeric material. Incorporation of the Cord Plate in the modules was done by attaching it to the module by means of Very High Bond (VHB) adhesive tape, a 3M product. The VHB tape that is currently used to attach the Cord Plate to the surface of the module is 3M # 4941-F, 0.046-inch thick. The potting material used to pot all of the termination locations is 3M # 3748-VO-Q JET-MELT. The new design utilizes MC (Multi-Contact Corp.) connectors.

Then a potting material 3M # 3748-VO-Q JET-MELT is used to all of the termination locations. The new design utilizes MC (Multi-Contact Corp.) connectors. The new design also made use of the FC connectors. The manner in which the Cord Plate is incorporated on the rear of the PV module is shown in Fig. 5. Following the fabrication of PV modules using the Cord Plate, in-house testing of the product was conducted. The tests included the damp-heat, humidity-freeze tests, followed by the hi-pot tests, and the current leakage tests. The high-pot and the current-leakage tests were the most stringent tests that had to be passed. One of the main concerns was whether the VHB adhesive would withstand the environmental tests.

Prototypes of the Cord Plate were fabricated by NC machining from a suitable polymer. It is planned, that in production, these components will be made by injection molding. The parts were then used as electrical connectors for termination in PV modules. As

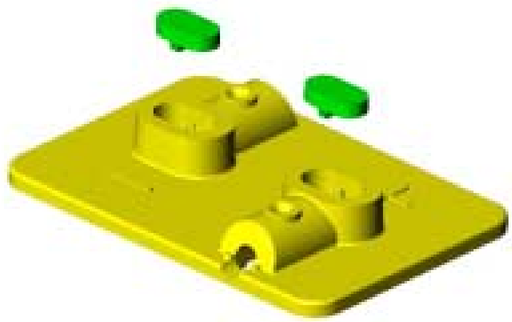

Figure 4. A sketch of the “Cord-Plate” contact termination fixture

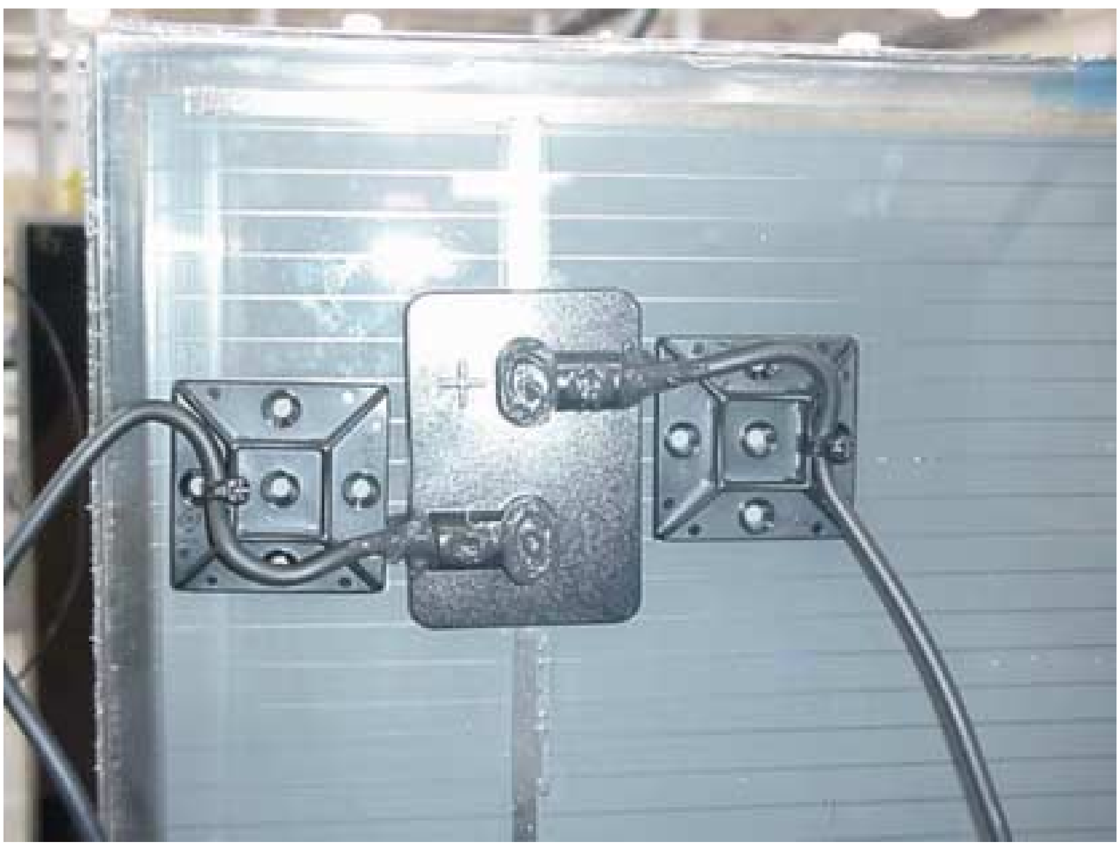

Figure 5. Photograph of the “Cord-Plate” termination fixture, including the power-lead strain relief, incorporated in a module

stated previously, EVA was used as an encapsulant in the lamination of the modules. The modules have been fabricated through a collaborative effort between First Solar in Toledo and Product Search, Inc., in Scottsdale. The finished modules were sent to the Arizona State University (ASU) test lab for UL listing application testing.

Initial test results indicated that all the modules came out of the damp-heat test thermal chambers, with no breakage, and they went into the dry hi-pot, the humidity-freeze cycle test all passed. The modules also performed well in the wet hi-pot test, and with only one failure of a total of 24 modules sent. From previous experience, passing of the wet hi-pot was the biggest concern as indicated. There was only one minor item that required a change for power-lead strain relief, which was accomplished successfully shortly thereafter.

This accomplishment marks the completion of the front half of the finishing-line project, which includes the buss bar application, laying down the EVA, installing the back glass, putting on the silicone rings and getting it to the point where it goes into the oven or autoclave for encapsulating. There was a good indication that this process can be accomplished on the production line.

Design, construction and installation of the Cord Plate and contact termination assembly lines (A report by Product Search, Inc.)

As reported in Task 5, there are positive indications that the latest product design using the *Cord-Plate* termination method was expected to pass the UL testing. This news enabled all line assembly methods and automation design efforts to proceed at full speed. A final installation and start-up date in the new Cedar Park facility was established as April 10 thru April 28 of 2000.

Product Search, Inc. shipped the pre-lamination (buss bar, EVA, back glass and seal ring) assembly line the last week of Feb. 2000 and installed it in the Cedar Park facility the week of March 5th 2000.

All efforts were focused on the completion of the Cord-Plate assembly and contact termination assembly lines. This phase of the project also incorporated automated hi-pot testing and solar simulator testing with a production throughput rate of one module per minute. Coordination efforts with Vortec Industries as manufacturer of the simulator and Product Search as automation integrator were completed.

Product Search has completed the design and construction of the Cord-Plate assembly and hi-pot and solar simulator test equipment in Scottsdale, AZ. The planned shipment, installation and start-up is April 11 through April 28, 2000. Some documentation activity (i. e., manuals, drawings, etc.) was scheduled to continue for a few days in May 2000. This installation will conclude the activity of Product Search, Inc. in Phase II of the project. Quotes have been provided for an additional solar simulator at the submodule line.

Completion and installation of the solar finishing line

Product Search completed the engineering design and build of the SOFL (solar finishing line) project at the Scottsdale, Arizona location. Limited operation of equipment and assembly tables was performed to debug equipment functions and assembly methods. However, a more intense debug test run of equipment operation was planned upon the completion of its installation at First Solar in Toledo. As stated earlier, Product Search shipped the pre-lamination assembly line and installed it in the First Solar facility during the last week of February, 2000. The remaining equipment, identified as the "Cord-Plate assembly", "I-V test station" (solar simulator), and "Hi-Pot station" were shipped and received on April 14th.

Product Search personnel were on site at First Solar on April 17 through April 28, 2000. Installation and initial start-up of the equipment was completed. Photos of various parts of the new solar finishing line are shown in Figures 6, 7, 8, and 9. Because of the late delivery of the Vortec I-V test equipment, time did not allow for adequate operator training and pre-production operation of the equipment. A second trip to First Solar for actual start up and operator training was planned for later May 2000. At that time operator manuals and electronic data-base files were to be transferred.

Upon completion of the training, Product Search Inc. will have completed involvement with this phase of the project with exception of service support or other tasks requested by First Solar. The completed task, which meets the initial goals, was to design and build an effective and safe production process. Baseline production throughput and associated labor cost will need to be monitored to evaluate actual process improvement.

Milestone	Description
m-2.4.1	Complete demonstration of improved potting process

Module Finalization

In May, the activity consisted of preliminary testing of the lamination process, using rejected modules for the purpose of determining yield and cosmetic quality. The yield on 20-plate batches was 95 percent for things like voids, bubbles in EVA and module breakage. In June, the next step was to undertake module production, using good quality submodules. For the past two weeks, good sub-modules were being processed up through lamination, 20 modules per day. The modules were used for test purposes—in preparation for passing the IEEE test. High yield was demonstrated with the processed modules. One of the items of interest was to determine what effect the heat in the lamination process had on the module efficiency. In the Westwood plant, where autoclave was used, the typical decrease in efficiency was 0.4% (absolute) of the module efficiency, equal to a decrease of about 5 W per module.

What has been demonstrated using the new lamination process at the new Cedar Park plant, with relatively few modules, was that the decrease in efficiency was only 0.1 to 0.2 %. This improvement is attributed to a more stable cycle, being run at a slightly lower

Figure 6. EVA sheet application station before lamination – start of solar finalization line

Figure 7. Hi-Pot testing station after lamination

Figure 8. Cord-plate contact termination application line

Figure 9. Current-Voltage (I-V) test station, solar simulator

rate, with no overheating of the modules. There is no temperature uniformity problem that the autoclave had. More tests are needed to establish confidence in this conclusion.

Majority of these modules have not gone through the Cord-Plate processing, because they were consumed in other tests, which did not require the Cord Plate. In this time frame (June 2000) the Cord-Plate process was not in operation because the second half of the line was down on account of the hi-pot tester not performing reliably. These problems were being addressed as well as those of the automated I-V test station. There were also some hardware problems that are being rectified working with the vendor.

In July the status of the solar finishing line has not changed since June. The rate of module lamination has remained constant (100/week). Problems have occurred with the software of the automated I-V testing station, which required sending the modules for testing to the old pilot plant at Westwood. Some problems have also occurred with buffing of the glass side, edge deletion, and delamination of the plates which are being resolved as part of de-bugging of the manufacturing process.

Repair of the test station was completed by mid August. At this point the production rate was increased to 200 modules/week (40-hour week). Thereafter plans are to ramp upproduction on a monthly monthly bases by 200 modules/week up to a goal of 1000 modules/week by the year end. A report on successful UL qualification of the product appears in the Task 5 Section.

Milestone	Description
m-2.4.1b	Complete thorough review of laser scribing process including parameter flexibility, capital costs, and cycle time.

This milestone has been successfully completed. Detailed description of the work during the eighth quarter is next, followed by the summary of the accomplished items at the end.

Laser Scribing

Note: This material is COMPANY CONFIDENTIAL

Review of the laser-scribing process

Cell interconnection by the use of laser scribing is a new task to Phase II. The stated objective is to implement an improved scribing technique and design associated equipment, so as to result in low-cost scribing by increasing the throughput by a factor of two, and reducing the downtime by a factor or three and reducing capital requirements by at least a factor of two.

With the imminent scale-up of PV module manufacturing throughput at First Solar, to anticipated 20 MW within a year and 100 MW within 2 to 3 years, the R&D and

Engineering teams have been facing a major challenge of putting in place appropriate laser facilities to handle this task. Up until recently a Q-switched, lamp-pumped, frequency-doubled, neodymium YAG laser for the scribing, which emits green light at 532 nm. Lamp-pumped lasers operate at a low pulse frequency of up to about 20 kHz and at a long pulse width of up to several hundred nanoseconds (ns) which limit their scribing rate to about 20 cm/s, same as the maximum rate disclosed in several patents [1, 2] and published articles [3, 4]. With the existing systems, a continuously operating single laser system at a 100% yield would theoretically support a throughput of only 30,000 modules per year, equivalent to 1.5 MW/year. In addition, the frequency-doubled, green-light emitting lasers have a limited life of only about 700 hours, imposed by the frequency-doubling crystal, which along with their higher initial cost makes their use for high-rate production prohibitive. It is to be pointed out that while prior art identifies important desirable characteristics of the lasers and a number of preferred methods of operation, there is no recipe given that would teach how to increase the production rate significantly and at the same time to reduce the system and operational costs.

In order to eliminate this production bottleneck, the main objective of the effort at First Solar is to increase the rate of laser scribing per single laser by a factor of greater than two by taking advantage of newly discovered phenomena, and of ongoing improvements in instrumentation, components and methods. As it turned out, an increase by a factor of ten appears feasible.

The second objective is to develop means for predicting laser specifications and system operating conditions required for increasing the rates of laser scribing.

The third objective is to identify the most suitable lasers from the standpoint of performance, energy efficiency, cost, longevity and serviceability.

The fourth objective is to identify a laser system and method capable of performing all three types of scribe lines needed (S1, S2, and S3) at high speed, good depth and shape control, reproducibility and reliability.

The fifth objective is to achieve all three scribes without significant impairment of the transparent conducting oxide (TCO) electrode and without creating electrical shunts and shorts along the scribe lines.

The sixth objective is to provide a suitable means of scanning the laser beam at required speeds to achieve the required scribing rates. This is the most important objective for developing the production system in the PVMaT program.

Considerable effort has been expended toward these goals during the period of July 1998 to February under Solar Cells and First Solar funding, which is summarized by the way of introduction. As the first step toward achieving said objectives, modeling of the laser-scribing process was performed to facilitate the prediction of the laser scribing parameters. In this modeling the laser scribing speed and the laser wavelength were the only independent parameters. Equations have been identified or developed for predicting laser parameters or process conditions, the most important of which were average laser power, peak pulse power, and pulse frequency. Key input parameters include laser pulse width, pulse energy, scribed area and the material being scribed.

Next, a new laser, heretofore not reported as being used for laser-scribing of solar cells, has been identified as potentially suitable for rapid laser scribing of CdTe-based solar cells of up to 300 cm/s. It is a diode-pumped, Q-switched, neodymium-doped, yttrium vanadate laser, radiating at a near-IR wavelength of 1064 nm, operating at a pulse frequency in the range of 5 to 100 kHz, and with pulse width ranging from 8 to 20 ns. Single-laser units of up to 10 W are now commercially available, which can be combined in a single beam in the multiples of 10 W. Its cost is about 20% less than that of a frequency-doubled laser and its life expectancy is 10,000 hours. It is to be noted that the same near-IR laser delivers approximately twice the average power than the frequency-doubled laser. In addition, replacement of the photodiode assembly at the end of life is a simple task. In some models the replacement requires only about 15 minutes at a replacement cost of only about 20% of the cost of the laser.

At First Solar, experimentation with the vanadate laser began in early 1999 and soon after it was followed by the design of the galvanometer-driven laser scanning system for module production. A description of this effort follows.

Laser scribing experiments – establishing process latitude (parameter flexibility)

A major task was to establish whether the near-IR laser could make scribe lines in the solar-cell layers as good as the green laser, in view of the fact that the reported optical absorption of the near-IR radiation by CdTe is much less than that of the green light at low light power. The performance of the near-IR yttrium vanadate laser was therefore evaluated to determine its limits of practical performance. Very effective laser scribing has been demonstrated by First Solar for all three scribe lines both from the film side and the glass side. Scribing from the glass side was found to be several times more energy efficient and, therefore faster, than scribing from the film side, in agreement with previous reports [3, 4] for the 1064 nm radiation.

In addition, scribing of the S2 and S3 lines from the glass side using the high-pulse frequency at low pulse width, the near-IR yttrium vanadate laser has been found to be more reproducible and better quality, than with the frequency-doubled, green-light laser.

In order to take advantage of the rapid scribing capability of the Nd:yttrium vanadate laser, the “flying optics” normally used on X-Y laser-scribing tables, with a maximum linear speed of 30 cm/s have been substituted by a stationary galvanometer-driven scanning mirror, capable of order-of-magnitude increase in the scanning rate of the laser beam. Development of a module-scribing process using the galvanometer now in progress since the summer of 1999 has become a part of the PVMaT project in the eighth quarter. A summary of the activities toward establishing process latitude is given below.

- A series of bench-top tests was done with a Spectra Physics ND:YVO4, 20W, Model T80-YHP40-106QW laser. The beam was traversed with a General Scanning Z-axis Galvanometer over samples of CdS/CdTe cells on 4-inch square substrates. The beam was focused to provide minimum kerf width of approximately 50 microns, at a given speed. No attempt was made to measure theoretical spot size.
- These tests are being performed to establish the feasibility of scribing the solar cell layers from the glass side. This involves the laser radiation passing through the glass substrate undisturbed, and then selectively removing semiconductor and/or metal coatings based on energy density.
- Earlier tests have shown a window of energy needed to create each scribe. An example of laser-scribing parameters investigated to determine process latitude is given in Table 1.
- Data of this type are used for the determination of window of conditions of average laser power, pulse repetion rate and pulse energy for obtaining the desired scribe. As shown in Table 2, these three conditions are interrelated.

Construction of the laser-scribing equipment

During the seventh quarter, the effort was focused on building of the laser-scribing equipment in Scottsdale, AZ. At the same time, some test runs to determine the cause of what appeared to be erratic pulses from the laser. Scribing was being done to further determine the parameters for optimum ablation. It was noticed that some portion of the scribe lines appeared to have areas where the laser was turning off. These scribes were done at 2000 to 3000 mm/second at repetition rates of 70 to 80 kHz. Subsequent tests showed this pattern changing with different 10 cm x 10 cm panels. Tests were then made on panels from the new 100 kW/year deposition system, called GDS, and the pattern disappeared. When analyzed at the First Solar Technology Center in Perrysburg, these samples did not show any significant film thickness variation. However, here was small difference in grain size.

Delivery and installation of the rapid production laser system to Cedar Park

Through the month of June the laser system from Arizona Manufacturing was shipped to Cedar Park and installed. This system employs a galvanometer-driven, laser-scanning system for rapid laser scribing. The wiring was connected, air supply and nitrogen supply provided (the latter for the lenses) and communications connected to the local network. Currently the software is being completed to control the overall system. The system consists of six major parts: (1) the load station, (2) the scribe station, (3) the unload station, (4) the laser with galvanometer-driven mirrors, (5) the process control (PCs), and (6) the power station. Figures 10 and 11 show photographs taken from the entrance and exit sides of the system.

INPUT	wavelength (nm)	Rep. Rate (khz)	Ave. Power (watts)	Pulse Duration (nsec)	Dot Dia. (microns)	Line Speed (mm/sec)	Pulse stability (%)	OUTPUT	Resistance (ohms)	Dot area (cm2)	Dot Spacing (microns)	Dot Overlap (d-V)/d	Energy/Pulse (uJ)	Energy Density/Pulse (J/cm2)	Power/Pulse (kw)	Power Density/Pulse (MW/cm2)	Results	Note
1331-05		60	12.4	60	75	3000			900	4.E-05	50	33%	207	4.7	3.4	78		Energy/pulse
1332-07		60	12.4	60	75	3000			1000	4.E-05	50	33%	207	4.7	3.4	78		
1331-03		60	13.4	60	75	3000			1200	4.E-05	50	33%	223	5.1	3.7	84		
1331-04		60	13.4	60	75	3000			3000	4.E-05	50	33%	223	5.1	3.7	84		
1331-02		60	14.5	60	75	3000			500	4.E-05	50	33%	242	5.5	4.0	91		
1331-01		60	15.3	60	75	3000			1200	4.E-05	50	33%	255	5.8	4.3	96	poor S2, slight S on sides, large holes to glass, slight Sn bridging across channel	255 (poor)
1333-01		70	8.0	69	75	3000			250	4.E-05	43	43%	114	2.6	1.7	38	good S2, S on sides, continous channel of Sn	114 (good)
1333-02		70	9.2	69	75	3000			220	4.E-05	43	43%	131	3.0	1.9	43	good S2, S on sides, continous channel of Sn	131 (good)
1331-12		70	10.0	69	75	3000			40	4.E-05	43	43%	143	3.2	2.1	47		
1331-14		70	10.0	69	75	3000			35	4.E-05	43	43%	143	3.2	2.1	47	fair S2, slight S on sides,small channel showing glass surrounded with Sn	143 (fair)
1332-02		70	10.0	69	75	3000			35	4.E-05	43	43%	143	3.2	2.1	47		
1333-03		70	10.0	69	75	3000			40	4.E-05	43	43%	143	3.2	2.1	47		
1333-04		70	11.3	69	75	3000			190	4.E-05	43	43%	161	3.7	2.3	53	poor S2, slight S on sides,large holes to glass surrounded by Sn	161 (poor)
1333-05		70	12.5	69	75	3000			120	4.E-05	43	43%	179	4.0	2.6	59		
1333-06		70	12.5	69	75	3000			800	4.E-05	43	43%	179	4.0	2.6	59	poor S2, Channel almost all glass, Sn only along edges, slightl Sn bridges across channel	179 (poor)
1331-13		80	10.4	75	75	3000			30	4.E-05	38	50%	130	2.9	1.7	39	good S2, S on edges, continous Sn strip	130 (good)

Table 1. Example of laser-scribing process parameters for determination of process latitude.

Average Power (diode current)	Rep Rate (Khz) 40	50	60	70	80	90	100	Average Power (watts) at 70 Khz
28								4.8
29			1408 E=98	1404 E=83	**1402 E=73 poor**	1399 E=64		5.8
30			1407 E=113	1403 E=99	**1401 E=86 poor**	1398 E=77		6.9
31	E=200 poor		**1332-08 E=133 good S2**	**1331-01 E=114 good S2**	1406 E=101	**1397 E=88 poor**		8
32		**1332-10 E=176 poor**	**1331-08 E=152 fair**	**1331-02 E=131 good S2**	1405 E=116	1396 E=102		9.2
33	E=250 poor		**1331-09 E=167 poor**	**1331-14 E=143 fair**	**1331-13 E=130 good S2**	1395 E=113		10
34				**1333-04 E=161 poor**		1400 E=128		11.3
35				**1333-06 E=179 poor**	1410 E=156			12.5
36								13.5
37								14.7
38								15.5
39			E=255 poor					16

Table 1. A chart showing the process latitude of laser-scribing parameters for scribe-2, including average diode current, average laser power at 70 kHz, pulse rate, and pulse energy.

Figure 10. Photograph of First Solar rapid laser-scribing system, showing the loading station, the process control station the scribing station (enclosed in cabinet), and the power-supply station (to the rear)

Figure 11. The laser scribing system - the unloading station and system side view

Shortly after the installation, first glass plates have been successfully moved through the laser scribe station, which is in the center of three stations. After minor adjustments, moving of the glass appears to be working well.

The immediate goal was to finish up the movement of the glass and also to integrate the laser into the system, making it ready to test laser scribing of the modules. Accordingly, during July the following tasks have been completed:

- The mechanical, optical, and electrical alignment of the entire optical train
- Installation of sufficient software to move the glass panel through the machine in proper sequence.
- Installation of sufficient software to scribe the glass accurately and rapidly. The first few tests show that Scribe 1 can be done easily at ~ 1600 mm/s, scribe 2 at ~2500 mm/s, and Scribe 3 at ~ 3300 mm/s compared with ~300 mm/s for the existing scribing system now in use.
- Installation of sufficient software to control the system with both “step and cut” scribing and “continuous motion” scribing. The first timing demonstrations at a scribing speed of ~2500 mm/s resulted in the scribing portion of the machine cycle, yielded times for ~32 seconds for the “continuous motion” method and ~79 seconds for the “step and cut” method per panel.
- Completed some accuracy tests with excellent results. Measuring over 90 scribes with 1-cm spacing, the tests show the system accuracy in the range of ~100 microns cumulative error, or ~ 1 micron per scribe. In comparison with scribing done on the present, production ILM system, the same measurement indicated ~ 1490 microns over 90 cm.

It is expected that within the next few weeks the process parameters will be established for the laser and machine variables, reduce process time, and interface and maintenance software capabilities added. This system will be used for Scribe-1, in which the semiconductor layers and TCO are patterned.

At the First Solar Laser Group in Scottsdale, AZ, the second laser scribing system is nearing completion, which will be used for Scribe-2 and –3, in which the semiconductor layers and the metal electrode layer are patterned, respectively. For all three scribes, scribing is done from the glass side, which is several times faster than scribing from the film side. The scribing procedure will be described in future reports. Wiring of the second system has been completed and checked and mechanical connections finalized. Upon completion, the system will also be moved to the Cedar Park production plant in Perrysburg, OH.

Summary of Milestone m-2.4.1b accomplishments

Description of the laser-scribing process

- A panel is loaded into the Load Station either by an operator or automated equipment. This loading equipment is in-house but has not been integrated as of this date.
- The panel is operator inspected for debris or smudges and cleaned as needed.
- The operator presses the start button and the panel moves to a vertical position and indexes to the bar code read position.
- The panel then moves into the Scribe Station and is automatically transferred to the scribe carriage.
- The scribe carriage moves into the scribe location and fiducials are read and scribe position errors compensated for.
- At this point the vacuum/air pucks are holding the panel at the correct focal point and 3 laser distance gauges have verified the focal plane.
- The panel is then scribed, from the glass side, with 117 scribes as the carriage moves at a constant velocity.
- An alternative scribe process for scribes 2 and 3 is to locate scribe 1 with the vision system, calculate position error, compensate for error, add next scribe, locate next scribe 1 and repeat. This greatly slows down the process but may need to be done until the ILM can place scribes repeatedly in the same location. It may be done on each panel or on a sample basis until confidence is gained.
- After the last scribe has been completed the panel is transferred automatically from the scribe carriage to the exit rollers.
- The panel exits the machine and is placed in the Unload Station.
- The panel is then removed by the operator or by automated equipment (in house).

Parameter flexibility

Initial bench tests described above show the windows for the scribes. Determination of the parametrics on the actual installed production equipment is forthcoming.

Capital costs

The first two systems look like they will be about $320,000 each plus design labor. Additional systems are estimated to cost $300,000 plus $160,000 labor. For comparison, ILT had given us a bid of $720,000 for a four-head system much like the current ILM system.

Cycle time

The systems were designed to meet a one-minute per 120 cm x 60 cm panel cycle time allowing 37 seconds for a scribe. The present speed is two minutes per panel, as we have not yet started to optimize the speed on various functions. If we are required to locate each scribe as described above the time goes to 4 to 5 minutes per panel. This is viewed as temporary but does add flexibility to the system.

References

1. Joseph J. Hanak, "Laser Processing Technique for Fabricating Series-Connected Solar Cells into a Solar Battery," U.S. Patent 4,292,092, September 29, 1981.
2. Robert Dickson, et al., U.S. Patent 4,892,592.
3. A.D. Compaan, I. Matulionis, S. Nakade, U. Jayamaha, "Pulse Duration and Wavelength Effects in Laser Scribing of Thin-Film Polycrystalline PV Materials," *NREL/SNL Photovoltaic Program Review,* edited by C. Edwin Witt, M. Al-Jassim, and J.M. Gee, © 1997 AIP Press, New York, pp. 567-571.
4. I. Matulionis, S. Nakade, A.D. Compaan, "Wavelength and Pulse Duration Effects in Laser Scribing of Thin Films," *Conference Record of the IEEE 26th Photovoltaic Specialists Conference,* Anaheim, CA, Sept. 30-Oct. 3, 1997, p. 491.

Milestone	Description
m-2.4.2	Complete the Phase II portion of the effort under Task 4.

This milestone has been accomplished.

Task 5 Product Readiness

Milestone	Description
m-2.1.2	Initiate contact with the module testing laboratory and complete preliminary module design review

This milestone was accomplished. Periodic communication with UL was maintained both for contact termination and module finalization (Tasks 4 and 5) throughout Phase II.

Preliminary Module Testing Report and Testing Schedule

In Phase I of this work, testing by the Arizona State University Photovoltaic Testing Laboratory according to IEEE 1262 protocol resulted in module failure for the damp-heat test (sequence "C") and the heat-humidity-freeze test (sequence "B"). Based on these results, a plan was developed to identify and correct module design and lamination process issues to allow passage of both IEEE 1262 and UL 1703 qualification tests during this phase of the work. This was not only an important objective for PVMaT, but the PV market demands these certifications and First Solar must achieve them to be commercially successful in the short term.

Specifically, the plan elements to achieve certification were to:

- Evaluate increased edge deletion area as a way to prevent or delay moisture ingress
- Test various edge potting concepts to provide another barrier at the semiconductor/encapsulant interface
- Continue testing of the liquid resin alternative to EVA
- Test insulated glass encapsulation as an alternative to a full contact interlayer
- Verify the thermal uniformity of the autoclave laminating device and confirm appropriate pressure and temperature cycles
- Review the First Solar lamination process with STR (the EVA supplier)
- Test alternative edge preparation techniques
- Investigate different potting techniques
- Develop more rigid cover glass flatness requirements with the cover glass vendor

Solar Finishing Line Concept Design Review

The design review was already discussed in Task 4 in reference to the solar finishing line. At the design review meeting it was also recognized that the issue of the module lamination had not yet been settled. Accordingly, work was to continue at First Solar in Toledo on the cold-cure polyester lamination that had shown promising results to date, and in parallel a new effort was to begin at Product Search. Accordingly, evaluation of other alternatives with two other resin manufacturers was initiated and was well underway by the end of May.

Milestone	Description
m-2.2.2	Complete preliminary testing of First Solar modified modules

Prior to completing preliminary testing of modified modules both the contact termination (see Task 4) and module lamination had to be firmly established. The work on module lamination is summarize next. By the end of the sixth quarter the milestone was completed.

Module Lamination

In response to the failed qualification tests of the modules – from the beginning of Phase II several alternative module finalization schemes have been evaluated toward achieving the Phase II qualification objective. In addition to work on the EVA pressure-lamination process, several possible solutions have been investigated simultaneously or in close sequence starting in June, 1999.

Problems and improvements in the EVA pressure-lamination system

Toward the end of Phase I, two failure modes have been identified. The first one is migration of moisture from the edges of the module along the interface of the front substrate glass and of the EVA laminate to the metal and semiconductor layers, causing their corrosion and failure. Several solutions to this problem have been attempted, including work on three different lamination concepts. These attempts are described in detail in the sixth quarter Deliverable 2.2.2 (November 1999). The following is a summary of this work.

The migration of moisture along the edges is facilitated by a 1-cm wide, “edge-delete” region along the periphery of the coated substrate, which is actually a small step in the glass, formed by grit ablation of the deposited layers. Another cause of failure was found to be the deionized water used to wipe off the dust following the edge deletion. By changing to isopropanol, the modules survived the test, thereby removing the main cause of failures.

In an attempt to find another solution to the moisture-ingress failure mode, development of *an edge-potting technique* was attempted, similar to that used in the crystalline silicon modules. The modules were failing the damp-heat test. The likely reason that edge potting works for the crystalline silicon and not for thin-film modules is that with silicon modules use two layers of EVA, whereas the thin film modules use only one layer.

A secondary mode of failure has to do with incomplete adhesion of the back substrate to the front substrate, which is exacerbated through thermal cycling or thermal stress. Sometimes there would be just a wholesale mechanical failure where the module will delaminate or delaminate in places. Then the electrical contacts get torn off and the module quickly fails.

Several test failures in pressure-laminated modules using EVA have been traced recently to the autoclave, the racks on which the modules rest, the means of applying vacuum between the plates, and the non-uniform heating of the modules. A painstaking review of these issues was made, followed by modifications in the laminating system, as described in the monthly reports. Substantial improvements in the module performance and durability have been achieved, as well as increased production capacity. Eventually with continued improvements the EVA pressure lamination process proved to be sufficiently reliable to be adopted for submission of the modules for UL qualification and for production.

Concurrently with the improvements on the pressure lamination process, three alternative lamination methods were under development, as summarized next.

The cold-cure liquid polyester resin laminate system

Work on the cold-cure liquid polyester resin laminate system had been initiated during Phase I. The process involves placing a cover glass over the substrate plate bearing the solar cell layers, placing a double-sided tape on all four sides, leaving a release liner in place on the fourth side, dispensing the resin in it, removing the liner and closing the glass envelope.

Three modules were made with each of three types of cold-cure liquid polyester resin supplied by Zircon, Inc. They were subjected to an in-house environmental testing. In the best cases the modules passed the severe damp-heat test. All three gave indications of exceeding the high temperature/high humidity requirements of the IEEE qualification testing.

The advantages to this system, include process simplicity, low equipment cost, one half the material cost, compared with the EVA process, and the use of flat, annealed back glass. The process also achieved two goals of Phase II, namely, a 25 percent materials cost reduction, and a throughput of 60 modules per hour. Furthermore, there is no degradation in conversion efficiency upon lamination, compared with a relative loss of about 5% in the EVA pressure lamination process. The main disadvantage of the cold-cure process is that it was designed to cure in 24 hours. This lengthy cure would impose a requirement of providing enough space to carry a day's inventory and for allowing the product to cure before it is shipped.

The insulated glass concept for module finalization

Insulated glass technology, originally developed by Pittsburgh Plate Glass, is a concept widely used in commercial building and residential home windows as a means for thermal insulation. A company named Glass Equipment Development uses an improved process called *glass-intercept system,* capable of processing 16,000 square feet of glass in one 8-hour shift. It is a well-proven system, having been put through a very extensive and rigorous environmental testing. Golden Photon used this concept in its PV module finalization; their modules passed both the IEEE 1262 and UL 1703 testing.

Arrangements were made for finalization of three First Solar prototype PV modules to be done by this process. All three modules finalized by the insulated-glass process passed the damp-heat test readily, showing relative decreases in efficiency of 0.1, 4.8 and 9.4%, respectively, thus indicating a viable process for a durable product.

The advantages of the insulated glass product are that it is a proven concept and that the cost of finalization is lower by factors of two and four compared with the polyester resin system, and the EVA system, respectively.

Submissions of product specifications to UL

Product Search submitted the product specifications in September, and received some application forms from UL. Then a preliminary module mockup was completed by the end of September and sent to UL for engineering evaluation by October 1.

Milestone	Description
m-2.2.3	Establish qualification testing schedule.

The qualification testing schedule was established in January, 2000 by submitting modules to UL testing, thereby completing the milestone.

Modification of the manifold on the twenty-module lamination rack

Two changes were made to eliminate the bowing of the modules laminated on the 20-module rack. The spacer, made a silicone caulk, was replaced by accurately machined Teflon spacer, that had a lower coefficient of friction, allowing the module could slide on it. Secondly, center supports have been installed to protect the module from sagging in the middle. Initial tests with this modified rack have shown that the bowing problem has been resolved.

A third change consisted of modifying the manifold on the 20-module rack for the autoclave. It was found that using these two manifolds was that if we had a module that fractured during the evacuation cycle, there was a risk of losing vacuum along with all ten modules being laminated. The modification consisted of providing ten pairs of manifolds, each connected to a pair of modules. That way, if a module cracked, the only other module at risk, namely, its twin. This change resulted in an improved yield and reliability of the process. The change in the manifold design increased the product yield to 90 percent or better through the autoclave cycle. This improvement was specifically with respect to cosmetic failures, such as bubbles and voids that would occur in the EVA.

Submission of PV modules made with the cord plate to UL testing

Efforts to resolve the environmental problems with the cord plate continued into mid-January. Finally, by January 17 the results of internal testing with the humidity-freeze cycles, the environmental chamber, hi-pot testing, current-leakage tests were positive. Internal statistical evaluation indicated that the new cord-plate design had a good chance of passing the UL test and that the company had a good, viable product. Hence, the modules incorporating the Cord Plate have been submitted for UL testing in January.

The major issue then was to get through the UL testing. At this point there was some uncertainty about the material currently used for the cord plate. The intention was to use material called Valox that was used for the top hat. The Valox material was specified because of its dielectric strength and intended use for the top hat design which would have been inside a J box mounted to the module surface. The Lexan # 950 is also a good dielectric material but, in addition, it is also resistant to heat and ultraviolet light. This is required because the cord plate is not intended to be utilized within a J-box enclosure. However, a switch was made to Lexan, or a second alternate material. This switch was made in anticipation of better performance through the destructive testing to which UL subjects it.

It was expected that there would be some detail design changes in the cord plate, to enhance the manufacturability, the moldability, and performance of the cord plate. If the product were to pass the UL test a certain change would be that of going to injection-molded cord plates instead of the NC-machined parts used in these tests.

Manufacturing throughput and costs

Internal evaluation of the progress on the cord-plate termination process to date has made it possible to make projections of the manufacturing throughput and costs. Because of the elimination of potting, which was a time-consuming process, the projected production rate is one finished module per minute, which is about a ten-fold increase over the present rate. With respect to materials costs, First Solar achieved or will achieve the goal, of under $20 per unit, from the present $27 per unit. The materials include all items in the module except the substrate plate containing all of the deposited layers up through the back metal film electrode. It was also estimated that the direct labor cost will drop from the existing $20 to below $5 and conceivably down to $3.75 to $4 per unit. More accurate figures about the costs can be projected following the UL tests and listing.

Following the UL listing, preparations will be made for a new round of IEEE tests in view of fact that the module failed in two of the four tests in Phase I.

The urgency of obtaining the UL listing first is that the customers for First Solar product are demanding it, prior to making any substantial commitments for its purchase. In time, the IEEE approval will also be important for the installation, in obtaining building and construction permits. That is the reason for placing emphasis on UL listing at this time.

Milestone	Description
m-2.3.2	Initiate qualification testing on First Solar's modified module.

This milestone was accomplished on schedule.

UL qualification testing of the Cord-Plate PV module

By the end of March *tests to date have indicated passing with the exception of one minor change that was required for power lead strain relief.* As shown in Figure 5, additional strain relief brackets were subsequently added external to the Cord Plate module (termination connection) to satisfy UL requirements for two levels of strain relief protection. Final documentation of all related components is being prepared to satisfy documentation and routing paper work that the UL Field Engineer will need to see when he visits the First Solar plant.

Additional in-house testing and improvement of the *Cord-Plate* contact termination

The modules that are passing the UL tests utilized machined polymer Cord-Plate fixtures. When it became apparent that the concept was promising, equipment for injection molding of the fixtures was purchased and sufficient quantity of the fixtures for additional in-house testing was produced. The molded parts showed slight irregularities and bending on the bottom side. In order to obtain a flat bottom, the parts were ground on a belt sander. Modules made with the ground parts showed an 80-percent failure rate in the high-pot testing. Apparently the microscopic grooves formed by the grinding contributed to moisture ingress and test failure.

The next attempt to produce a flat, smooth bottom surface was to place the Cord Plate fixtures on a flat surface heated to 150 ^{o}C. This treatment produced the desired characteristics and resulted in a substantial improvement in the high-pot testing.

Milestone	Description
m-2.4.3	Complete qualification testing on First Solar's modified module UL1703.

This milestone was successfully completed on schedule.

Completion of UL qualification testing of the Cord-Plate PV module

Underwriter Laboratories testing was nearing completion in June. First Solar completed UL testing in July and are now certified against UL 1703.

Also in July, First Solar began preparing samples to submit to PTL for IEEE and IEC validation testing. A purchase order was placed with PTL for the testing in July.

Mr. Tim Pruder, site inspector for Undewriter Laboratories (UL) from Novi, Michigan, arrived during July for inspection to the First Solar Cedar Park manufacturing plant. He inspected the documentation and materials listed by First Solar and verified the sources. He found no problems. The First Solar 60 cm x 120 cm PV module based on cadmium telluride is now a "recognized component," approved by UL to be installed in "listed" mounting systems. A copy of the letter from UL in reference to completion of the Initial Production Inspection appears in Attachment A.

On July 10 Underwriter Laboratories issued a Report on COMPONENT – PHOTOVOLTAIC MODULES TO First Solar, LLC, (File E205874, Project 99NK42717). In the Conclusions of this report it is stated that ***the products are judged to be eligible for Component Recognition and Follow up Service.*** This 31 page report and letter will be made a part of the Deliverable D-2.4.5, entitled "Testing report summary and letters of certification for First Solar modified module under UL1703 (Task 5).

Milestone	Description
m-2.4.4	Complete the Phase II portion of the effort under Task 5.

With the successful UL qualification of the First Solar modified module and the building and installation of the equipment for producing it, this milestone has been successfully accomplished. Additional work on encapsulation, using alternative concepts to eliminate back glass cover was undertaken. Description of this work follows.

New module encapsulation projects

Generation-3 (GEN-3) module encapsulation

In March, 2000 a new encapsulation process came under development in which the back glass cover plate is substituted by a combination of a polymer layer as a dielectric and aluminum foil as a moisture barrier, affixed to the front PV plate with adhesives. A confidential full report on this ongoing project is included in the March 2000 report. The main purpose of this project is to reduce the weight, production rate and cost of the PV modules.

Several variants of this concept have been fabricated and are undergoing testing. Tests have continued on the concept of using a thin aluminum foil and polymer film laminate at the back surface of semiconductor to seal panels. Problems of differential expansion in tests have caused wrinkles in all films that have had an aluminum foil component in the laminate on the full size modules. All other versions of films with aluminum foil have shown delamination wrinkles after just one full thermal cycle of 20 hours. A double-ply polyester with acrylic adhesive has not shown any delamination in damp heat-cycle tests.

The latest combination tested was a polypropylene film with a vacuum-deposited aluminum coating. The sample was made up as a three-ply construction; it also failed the test. A low bond strength between polymer and the aluminum was suspect. This test is going to be repeated with just a single ply and making sure the aluminum coating is in contact with the adhesive to increase bond strength.

The activities in April continued to focus on solving the wrinkling problems with metal (aluminum) backing materials and the associated differences in thermal expansion.

The tests of thin vacuum-deposited aluminum / polypropylene films bonded to the panel on the aluminum side, seems not to be causing the previous wrinkle problem. This is done with a .002" thickness of a standard Acrylic adhesive system. The next tests was to involve a laminate that is built up of multiple layers and tested for moisture penetration. The test was to be conducted in the damp-heat testing system.

In addition, samples of other materials backed by rubber/EPDM and rubber/vinyl were also undergoing tests. These materials would be relatively inexpensive if moisture migration is low enough not to degrade module performance.

Systems for mounting / backing the module are also being reviewed. At this time the focus was mainly on extruded, vacuum-formed or blow-molded members. The issue was mainly of what type of encapsulation would result in the least material usage and still achieve the desired 20 year life. Materials being considered are: polycarbonate, vinyl, polypropylene and ultra-high molecular weight polyethylene (UHMV).

In May, testing continued with plastic film / foil combinations and pressure sensitive adhesives for bond and lamination strength. All samples have failed so far from wrinkles in the aluminum layer. The two assumptions are that the strength of the bond is not sufficient to prevent the aluminum from delaminating. The other is the issue of the aluminum having over twice the temperature expansion of the glass. With the thermal expansion rates in mind we built samples with a thin galvanized steel backing and bonded it to the panel with a two-part urethane compound. This has survived the 200-hr thermal freeze cycle test with no signs of delamination. It has also shown no signs of delaminating the semiconductor layer. In addition a panel with a layer of polyester film and the urethane / steel was also tested; this resulted in a delamination of the urethane from the polyester. This test will be redone with a plastic film that has a better bond property to the urethane. This construction would allow for a wider range of intermediate bonding agents to the panel and backing metal surface.

A Seaman's panel that uses a composite backing film (ISOVOLTA type) was also run through the thermal cycle and, as expected, it did pass. These films use the intermediate layer of EVA to get a stronger bond, but are also only going against a glass surface and don't need to worry about damaging the semiconductor.

CoralPlast sheets were obtained and tested with the existing films. The results indicated that addition pretreating of the surface would be needed to get a better bond. Also long term effects of the plasticizer leaching form the material would be a concern for weakening the bond to the film or metal surface.

Encapsulation Project

A contact was made with TruSeal about the extruded hot melt. They have not as yet been able to extrude any 4" wide material at this time. They are confident that it can be accomplished; however, their lab equipment has not been able to make satisfactory product. They will be discussing the issue with their engineers to make equipment modifications to their extruder. They were advised about the urgency of the project and informed that First Solar would be willing to apply some "seed" money to expedite the project. They will contact us the first week of June with a timetable. In the meantime, several more mini-modules have been put into damp heat testing using the hot melt. The main focus is the use of primers to improve the bonding between the sealant, glass and foil in an attempt to improve upon last months good test results.

There were several samples in damp-heat testing. One test is a repeat of an earlier failed test with an aluminum foil and a hot-melt edge seal. The only change was to use a primer to improve the adhesion to the foil and glass. Another test was a repeat of a test that passed. This was a glass-to-glass lamination with an edge seal of hot melt. The only change was to use a primer to improve adhesion to the glass. Another test was using a PIB type extrusion, with a vinyl backer, from Plymouth. They will have the ability to extrude a 24-inch wide ribbon by the end of this year. This material is used for insulating electrical cables. No new test results were available this month.

Work was continuing on the aluminum foil buckling problem. One option that is being tested is to bond the foil to a rigid backer, in this case a Coroplast panel. Coroplast is a polypropylene corrugated panel used as a cardboard substitute. It is expected to maintain the foil's planar shape and prevent it from buckling. This panel will be laminated to the sub-module with an adhesive and an edge sealant. This joint will have to be sufficiently flexible to accommodate the thermal expansion differential between the glass and the panel, without losing the hermetic seal. Product Search is making up the panels and performing the thermal cycle tests.

Alternatives are being explored to the aluminum foil for the vapor barrier. The film from Multi-Film Packaging, mentioned in the March report, was shipped at the end of this month and testing began it in June. Some other films have been identified with low MVTRs from ISOVOLTA. They are sending samples for us to evaluate. As reported by the company, these films have been used with success in the production of several MW of PV panerls. They would be flexible enough to correct for thermal expansion and still maintain a good vapor barrier.

In June, TruSeal has obtained a four-inch die for their extruder. The company was attempting to make a .020" x 4" hot-melt ribbon on an aluminum foil backer with a paper liner. They were having difficulty rolling the ribbon into a coil because the paper/hot melt/foil stack-up would kink during the coiling process. A discussion of the problems ensued, including the foil wrinkling problem occurring during the thermal cycle test.

Based upon that discussion First Solar requested to supply a hot-melt ribbon on a paper liner only. This material can be easily rolled into a coil. This ribbon will facilitate testing of mini-modules and also full modules by laying up several strips of the ribbon. Delivery of the hot-melt ribbon was scheduled for July.

After less than 300 hours, none of the damp-heat test mini-modules mentioned in last month's report passed the test. The best results were with the glass-to-glass lamination with a performance drop of 11.04% (relative %). The worst results were with the VM tape with a performance drop of 54%. Most of the decrease was through a drop in Voc.

Work on the back vapor barrier continued. Bonding of aluminum foil with different adhesives to a Coroplast corrugated panel is being tested. Another material on order is honeycomb polypropylene from Nida-Core. This panel has a polyester scrim thermally fused to the face, which should make it easier to bond. Product Search performed a thermal cycle test using 32 GA galvanized steel for the vapor barrier. Steel more closely matches the thermal expansion rate of glass than does aluminum. At First Solar a steel foil was tried in the past, but it also wrinkled. However, the thicker-gauge, galvanized steel has enough stiffness that it was able to resist wrinkling during the test. Although it is not as cost effective as aluminum foil (< \$0.04/ft2 @ 1 mil), the cost is still reasonable (approx. < \$0.30/ft2). It has a significant weight disadvantage of 4.36 lb vs. 0.11 lb for aluminum. It does have some advantages over foil. It is stiff enough to resist the impact tests. It is thick enough to resist the cut test. It may be strong enough to mount directly to it.

The custom film from Flexicon was received. TruSeal performed a MVTR test and found it to be 9.2g/m2/d, which is higher than the hot-melt material. A mini-module will be put through the damp-heat test. Preparations were in progress for this testing, the Thermatron is in the process of being moved from the Westwood Plant in Toledo to the Technology Center in Perrysburg this month. The Thermatron will be operational in July.

We received the ISOVOLTA film laminate. This is a lamination of Tedlar/aluminnum foil/ Tedlar/EVA. The laminate is relatively expensive (\$0.80/ft2). Siemens uses this material for encapsulation with an EVA film. First Solar sent a Siemens module to Product Search for testing in the thermal cycle test.

In the future First Solar is considering alternatives for encapsulation. One alternative is a barrier coating. This would be a metal oxide film such as tin oxide, aluminum oxide or zinc oxide that would use a low-temperature film-deposition process. First Solar personnel is exploring a low-temperature CVD process. Alan McMaster of First Solar is working with Tom McMahon at NREL, who is sputtering barrier layers. His first test used aluminum mirrors on a glass substrate. Initial test with aluminum oxide barriers showed corrosion in less than 24 hours in the damp heat (DH) test. He subsequently ran tests with thicker films ~ 1μ. These film were resisting corrosion after four days. Based upon these results, barrier coatings were planned be deposited on dot cells. Testing was to begin in July.

A “hot-melt” ribbon was delivered from TrueSeal early in July and encapsulation mini-modules for the damp-heat testing was begun. The material is approximately 0.030” thick and 4” wide. It was supplied in a roll with a Kraft back-up paper. Several different types of mini-modules with different back coverings were laminated, using the hot-melt. Some of the mini-modules were covered with 0.003” aluminum foil, others with a glass cover plate, with just the hot-melt alone, and some others with no cover plate. Other coverings used were the Icosolar foil film lamination, Lexan, and the Flexicon film and also the 0.03”-thick galvanized steel; all of them were subjected to damp-heat testing. After two weeks of damp-heat testing the PV performance was again measured. To date, the only one that is still performing to specifications is the mini-module with the glass cover plate on it, which had a performance drop of 5.5 %. All of the other combinations had more than 10 % performance loss after two weeks. The Thermotron, previously located in another building, at Westwood, was moved to the Technology Center, in Perrysburg, early in July and set up in the first two weeks in July. This move facilitated continuing the damp-heat testing at a more convenient location.

Damp-heat testing will be continued with different combinations of encapsulating stack-ups. One that has not been tested up to this point is with alternative edge-delete treatments. Currently we are using sand-blasted edge delete, which leaves a pitted and micro-cracked glass surface, that has been shown to create problems with degradation, as reported recently, because of vapor ingress.

Edge-deletion techniques are under consideration that are non-ablators, which will leave a pristine glass surface to which the encapsulating films will be bonded. It is felt that the existing edge deletion is the weak link in the encapsulating process. The CdS and CdTe semiconductor materials are relatively easy to remove. The underlying low-emissivity tin oxide layer is very hard and difficult to remove. One method to remove the tin oxide would be a pre-deletion, before the semiconductor layers are deposited. The tin oxide could be removed either chemically or electrolytically, leaving a smooth glass surface.

Another edge deletion treatment under consideration is to isolate electrically the tin oxide film and coat it with another material that lends itself to bonding to tin oxide. Historically, when lamination to the tin oxide surface was attempted, the bond between it and the encapsulant was not good, which allowed water vapor to ingress to the semiconductor, causing a severe drop in performance. By treating the tin oxide with another chemical, so as to increase its surface energy, an improved bond to the encapsulant is expected.

Task 6. Environmental, Safety and Health Programs

Milestone	Description
m-2.1.3	Complete extensive review and survey of current ES&H programs.

Milestone	Description
m-2.2.4	Develop plans for critical areas of ES&H improvement with the assistance of industry experts such as OSHA On-Site Consultation.

Milestone	Description
m-2.3.3	Initiate ES&H improvement projects

Milestone	Description
m-2.4.5	Complete a comprehensive ES&H program assessment including prioritization of improvement areas, established measurement targets, and comparisons with industry historical levels.

Milestone	Description
m-2.4.6	Complete the Phase II portion of the effort under Task 6.

All of the above milestones have been accomplished, with the exception of the external and internal audits, which are now planned for Phase III. The reason for postponing the audits was because all EHS items had to be introduced to the new manufacturing plant

The formation of the First Solar LLC partnership has added a major new responsibility on the EHS activity. It is to prepare environmentally sound and a safe working environment in the new Cedar Park manufacturing facility, and to provide training of new employees in accepted EHS practices. Since its formation, the number of employees has more than doubled.

The goal of the EHS program is to conduct an extensive review of its current programs and address issues that need improvement. Altogether over thirty different activities have been conducted in the EHS program over the period of the Phase II project. Among these activities were: development and implementation of fifteen EHS-related plans and programs; obtaining permits concerning PV manufacture; generating reports to municipal and state agencies; cooperating with said agencies in conducting inspections; environmental sampling of R&D and production equipment and facilities for hazardous substances; installation and monitoring of EHS equipment; conducting safety inspections of all manufacturing equipment; periodic evaluation of employees for baseline cadmium; establishing first aid medical supply station; training of new employees on the EHS Handbook; conducting first aid training; establishing "Safety Council" meeting to address and assign controls to hazards in the start-up of the Cedar Park facility. The ultimate goal of the EHS program is to place First Solar in a leadership position relative to comparable businesses within and outside of the photovoltaic industry. Description of other accomplishments follow in Letter Deliverables D-2.4.6 and D-2.4.7.

NREL PVMat Subcontract No. ZAX-8-17647-06

Specific PVMat R&D in CdTe Product Manufacturing

Phase II Deliverable D-2.4.6
Letter report on results for implementing EHS improvements

Phase II - Second Year
September 7, 2000

First Solar, LLC
1702 N. Westwood Ave.
Toledo, Ohio 43607

Phone: (419) 534-3377 Fax: (419) 534-2794

Distribution:

Two copies to Mr. Richard L. Mitchell, NREL Technical Monitor*

One copy to Ms. Christie Johnson, NREL Subcontract Administrator*

One copy to Mr. Tom McMahon, NREL Technical Monitoring Team Member*

One copy to Mr. Doug Ruby, Sandia National Laboratories Technical Monitoring Team Member**

* National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401

** Sandia National Laboratory
Mail Stop 0752
Albuquerque, NM 87185

The following ES&H improvements have been implemented as outlined in the Phase II Deliverable D-2.2.3:

EHS Accomplishments

May 99 – April 00

General EHS Issues

- Trained 76 new employees: - EHS Handbook Orientation
- Trained current employees: - Laser Safety 19 employees (May 99)
  - Industrial Truck 18 employees (Nov 99, Feb 00)
  - Overhead crane training 10 employees (Mar/00)
  - First aid and CPR 7 employees (Nov99)
  - Respiratory training and fit testing 44 (Nov 00, Mar00)

Environmental Issues

- Completed *Permit to Install* and *Baseline Monitoring Report* for the Ohio EPA and City of Toledo Environmental Services, in regards to our wastewater treatment micro-filtration system.
- Assisted in the specifications and installation of a micro-filtration wastewater treatment system at the Cedar Park manufacturing facility.
- Completed baseline monitoring on effluent discharges for the City of Toledo.
- Continuing in-house analytical evaluation of effluent discharges for the Westwood and Cedar Park facilities on the AA Spectrophotometer.
- Filed EPCRA report for the Westwood and Cedar Park facilities.
- Updated *Hazardous Waste Compliance* plans for the Cedar Park facility.
- Investigated and applied for proper permitting for well construction for the Cedar Park facility.
- Generated emission data for ozone emissions for the Cedar Park facility.

Health Issues

- Investigated and implemented numerous engineering controls (ventilation systems) to reduce cadmium air hazards.
- Generated over 70 air samples to monitor cadmium emissions to the workplace.
- Generated 37 wipe samples to monitor cadmium emissions to the workplace.
- Completed baseline cadmium testing for scheduled employees.
- Evaluated noise exposure for the Cedar Park Facility.
- Developed *Cadmium Compliance* and *Hazard Communication* plans for the Cedar Park facility.

Safety Issues

- Developed and extensive *Hazard Recognition Program* to evaluate mechanical, electrical, and ergonomic issues for the start up of the Cedar Park facility.
- Completed the first phase of the *Hazard Recognition Program* (outlined and corrected level A "high priority safety issues").
- Created MSDS information for the Cedar Park facility.
- Installed fire extinguishers and continuing monthly their monthly inspections.
- Installed motion alarm system for overhead cranes.
- Ordered and installed a cage for the glass handling robots.
- Investigated and implemented several machine guards for the new equipment at the Cedar Park facility.
- Created means of egress maps for the Cedar Park facility.
- Updated the Lockout/Tagout procedures for the Westwood and Eckel Junction facilities.
- Developed a *Contractor Compliance Plan* for the Cedar Park facility.
- Maintained and posted OSHA 200 and 101 accident forms.

NREL PVMat Subcontract No. ZAX-8-17647-06

Specific PVMat R&D in CdTe Product Manufacturing

Deliverable D-2.4.7
Letter report describing First Solar's ES&H historical and expected performance as compared with other comparable industries

Phase II - Second Year
September 7, 2000

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** Sandia National Laboratory
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Albuquerque, NM 87185

Injury case rate and lost workday rate at First Solar compared with the electronics manufacturing sector for Phase II project period of May 1999 – April 2000

Current injury case rate at First Solar is **9.6** and lost workday rate is **17.2** for Phase II project period (May 99 through April 00). This corresponds to an **8.5** injury case rate and a lost workday rate of **13.2** for the Phase I project period and a **6.8** injury case rate and **32** for lost workdays in the electronics - manufacturing sector for the last date available (1996). This data shows that First Solar has experienced a 41% higher accident rate then the electronics-manufacturing sector for this period, however, notably, the severity was *54% lower*.

First Solar experienced a significant accident and lost workday injury during this recording period. During the decommissioning of the Westwood facility (Pilot Manufacturing Plant) an electrician received an electrical exposure, resulting in a burn to his right finger and right arm and a more significant left shoulder impact injury. This employee is currently recovering at home. The accident was thoroughly investigated by the EH&S Department which concluded that the First Solar safety policies and procedures were in place to prevent an accident of this nature and human error was the cause.

First Solar will continue to emphasize safety awareness training to all of its employees in an effort to reduce accidents and to make safety become more routine.

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A. McMaster

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First Solar, LLC-Technology Center
12900 Eckel Junction Road
Perrysburg, OH 43551

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13. ABSTRACT ***(Maximum 200 words)*** Just prior to the beginning of Phase II of the PVMaT project Solar Cells, Inc, (SCI) and True North Partners of Scottsdale, AZ, formed a joint venture partnership name First Solar, LLC. By the end of 1999, this event resulted in the construction of a new major manufacturing plant for photovoltaic modules, based on cadmium telluride, located in Perrysburg, a suburb of Toledo, Ohio. This plant was designed to be capable of producing PV modules at a rate of 100 MW per year within about three years. Significantly, a new semiconductor coating system, the heat of the production line, has already shown the capability of the 100 MW per year rate.

These events have led to the expansion of the effort on the PVMaT project that included the former SCI team in Toledo, Ohio, a new team of engineering subcontractor, Product Search, Inc., and, later, a new laser team from First Solar, both from Scottsdale, Arizona. These three teams joined in a collaborative effort on Tasks 4: Manufacturing Line Improvements, on Task 5: Product Readiness, and on Task Environmental, Health, and Safety Issues.

One Task 4 goal was to address the technical issues of the failed UL 1703 qualification testing in Phase I. Completing this goal, along with module lamination improvement done in Task 5, was instrumental in the design, fabrication, and installation of a high-throughput solar finishing line. The main components of this line, also a Task 4 project, were successfully tested in module finalization on the production line. Developing a novel, single-laser scribing system was another major accomplishment. In Task 5, the major activity was improved module lamination. Progress in Tasks 4 and 5 resulted in improved modules that were submitted for UL 1703 qualification testing.

In March 2000, a new encapsulation process came under development, in which the back glass cover plate is substituted by a combination of a polymer layer as a dielectric and aluminum foil as a moisture barrier. The goal of the Environmental, Health, and Safety program is to conduct an extensive review of its current programs and address issues that need improvement.

14. SUBJECT TERMS
photovoltaics ; laser scribing and potting ; product readiness ; environmental, safety and health ; junction box ; alternative voltage ; semiconductor coating ; contact termination ; module encapsulation ; top-hat design ; cold-cure liquid polyester ; cord plate

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