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High Throughput Manufacturing of Thin-Film CdTe Photovoltaic Modules

Annual Subcontract Report
16 November 1993 - 15 November 1994

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Solar Cells, Inc.
Toledo, Ohio

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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Table of Contents

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Karl Bihn	James Brown	Steve Cox
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Matt Flis	Jim Foote	Rick Harju
Steve Kaake	John Kern	George Khouri
Sabrina Maynard	Harold McMaster	Kevin Miller
Bob Nicholson	Rick Powell	Nick Reiter
Geoff Rich	Rick Sasala	Mike Steele
Rick Yocum	Teddy Zhou	
Peter Meyers	Jim Spillson	Joe Hanak
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INTRODUCTION

Solar Cells, Inc. (SCI) was founded in 1987 with a dual business objective: 1) to develop, build and operate continuous, automated manufacturing systems capable of producing photovoltaic modules at a cost sufficiently low to generate high sales volume and 2) to install these modules into grid-connected solar fields. Initially, SCI intended to utilize thin-film amorphous silicon to meet these objectives. However, after additional research of other thin-film technologies, CdS/CdTe was selected due to its superior deposition rate, stability, and process flexibility.

In late 1990, a systematic evaluation of CdS/CdTe deposition techniques by SCI resulted in the selection of the close-spaced sublimation process. This technique demonstrated very high deposition rates (>5 µm/min). This deposition rate results in total deposition cycles which are five to ten times faster than those demonstrated by typical thin-film a-Si by plasma enhanced vapor deposition. In 1991, Solar Cells, Inc. (SCI) began a PV module manufacturing development program to demonstrate the technology's many advantages on large areas. SCI designed and built a deposition system for 60cm x 120cm modules. By mid-1992 this system along with other line equipment had produced a 6.5% 60cm x 120cm submodule. This system has produced over 1500 CdS/CdTe substrates as part of the module optimization process.

Due to the success of these efforts SCI began a manufacturing initiative in late 1993 in conjunction with support from The Department of Energy's PVMaT program. Phase I program activities included product definition, process definition, equipment engineering and support programs development. This program will result in high-volume manufacturing of thin-film CdTe modules capable of achieving installed costs (including balance of systems components and labor) of less than $3.00/Watt.

EXECUTIVE SUMMARY

Cadmium telluride (CdTe) is recognized as one of the leading materials for low-cost photovoltaic modules. Solar Cells, Inc. has developed this technology and is preparing to scale its pilot production capabilities to a multi-megawatt level. The three phase PVMaT subcontract supports these efforts.

Phase I of the subcontract consisted of nine tasks related to product definition, process definition, equipment engineering, and support programs development. The following provides a brief summary of the results of each task.

Task 1 Product Definition and Demonstration

Two products have been specified and demonstrated. The grid-connected high voltage product is frameless and incorporates a pigtail potting design. The remote low voltage product may be framed and may incorporate a junction box if market conditions warrant. These products have been demonstrated in several arrays.

SCI has produced a 60.3 watt thin-film CdTe module with total area efficiency of 8.4%. The average total area efficiency of 60cm x 120cm modules manufactured on a developmental pilot line has been demonstrated at greater than 7.0% while the relative standard deviation has decreased to less than 10%.

Modules routinely pass extensive stress testing. SCI has improved its IQT pass rate from less than 20% to greater than 80% as a result of work related to the subcontract.

Task 2 Modification/Elimination of $CdCl_2$ Treatment

An alternative $CdCl_2$ treatment has been demonstrated on 60cm x 120cm modules. This treatment reduces process time by 50%, eliminates four of six process steps, and significantly mitigates the environmental impact of the process.

Task 3 Encapsulant and Pottant Evaluation

Several encapsulation and pottant materials were evaluated. EVA/Glass encapsulation and a urethane molded pigtail demonstrated superior performance during stress testing. The final design reduced module finalization costs by more than 40% compared to previous designs.

Task 4 Manufacturing Process Definition

The 20MW manufacturing process was completely defined and demonstrated. The process was refined and proven on a 100kW pilot line.

Task 5 20MW Manufacturing Line Conceptual Design Review

SCI completed a conceptual layout of the 20MW line. The layout was used to model the manufacturing line and predict manufacturing costs including raw materials, direct labor and factory overhead. An optimized capacity (two shift/day operation) of greater than 20MW at a manufacturing cost of below $1.00/W was projected.

Task 6 20MW Manufacturing Line Equipment Design

Design activities focused on the semiconductor deposition system, laser scribing systems, and miscellaneous custom equipment. The deposition system was designed, procured and installed. Laser systems were specified with the assistance of several vendors. The post deposition process equipment was also identified.

Task 7 20MW Manufacturing Line Utilities Design

General utilities were sized for the plant. Utility requirements are within normal expectations.

Task 8 Quality Assurance Development

SCI initiated a quality assurance program. This program is tested and refined daily on the pilot production line as well as the general plant. The program is concentrated on process control. Efforts resulted in significant improvement in average module efficiency to greater than 6.5% and decreased variation to less than 10%.

Task 9 ES&H Program Development

Several compliance programs were updated and implemented. External independent program auditors were utilized to delineate needed adjustments. An EHS Committee including the President of SCI met regularly to formulate company policy and to supervise implementation of recommended changes. An EHS handbook was provided to all personnel as guidance on the compliance programs. Biological cadmium testing showed normal levels for all personnel as compared to the general population.

PVMaT SUBCONTRACT OBJECTIVE

The objective of this subcontract over its three year duration is to advance SCI's PV manufacturing technologies, reduce module production costs, increase module performance, and provide the groundwork for SCI to expand it's commercial production capacities. SCI shall meet these objectives by designing, debugging, and operating a 20MW/year automated, continuous PV manufacturing line that produces 60cm x 120cm thin-film CdTe PV modules.

The Statement of Work for the duration of the contract is outlined below. Efforts commenced on November 16, 1993.

Phase I

- Product Definition and Demonstration
- Manufacturing Process Definition
- 20MW Line Design
- Quality Assurance and ES&H Programs

Phase II

- 20MW Line Design and Test
- Efficiency Improvement
- Quality Assurance and ES&H Programs

Phase III

- 20MW Line Demonstration
- Efficiency Improvement
- Quality Assurance and ES&H Programs

List of Figures

List of Tables

TASK PROGRESS

Task 1 Product Definition And Demonstration

Objective

- Define a 60cm x 120cm module to be produced on a 20MW manufacturing line
- Demonstrate 7% efficient 60cm x 120cm modules

Progress

- Product definition finalized
- Demonstrated 17V and 65V products
- Demonstrated 55.3 watt, 8.1% efficient modules

Product Definition

SCI modules are 60cm wide by 120cm long. The construction consists of glass/EVA/glass and is approximately 0.9cm thick. The substrates are 5mm soda lime float glass coated with a transparent conducting oxide (TCO). The TCO is comprised of two main layers, SiO_2 and SnO_2:F. Active layers are comprised of the TCO, 0.3µm of CdS, 4.0 µm of CdTe, 0.02 µm of nickel and 0.3 µm of aluminum (see Fig. 1). SCI utilizes a three-scribe interconnect to complete a monolithic module with 116 series-connected cells. The result of this design is a module which produces nominally 50 watts at 65V. The power is collected at each end of the module through a bus bar and a ribbon conductor. The ribbon conductors are threaded through a hole in a 3mm cover glass. The cover glass is laminated to the module with ethylene vinyl acetate (EVA) to protect the module from weathering. An insulated wire is attached to each ribbon and potted with two-part urethane in a pigtail mold. The urethane is also used to mold four mounting pads onto the back of the module. The mounting pads include a threaded insert for easy panelization of individual module installation (see Fig. 2).

Utilizing this design, SCI has developed products to address grid-connected and off-grid applications. Table 1 describes the attributes of these two products. Alternative potting and mounting designs are offered to address market installation requirements. The grid-connected product utilizes the molded pigtail and mounting pads to reduce module and panelization costs. The remote product provides more installation flexibility by offering a junction box and framing. The remote product will also be available in a half-size (30 watts) if market conditions warrant.

Figure 1.

SCI CELL AND MODULE STRUCTURE

(FILM THICKNESS AND LASER SCRIBE DETAIL NOT TO SCALE)

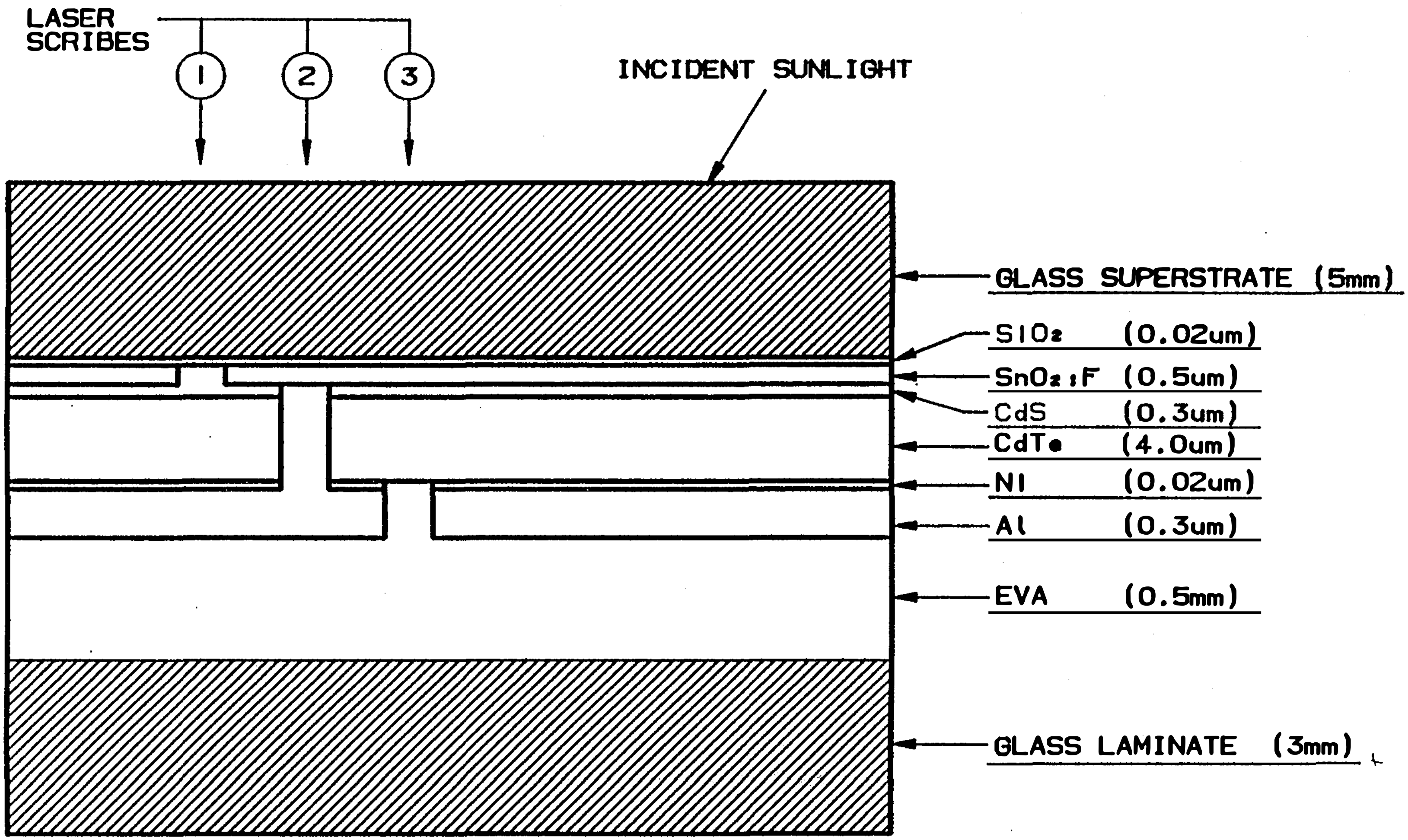
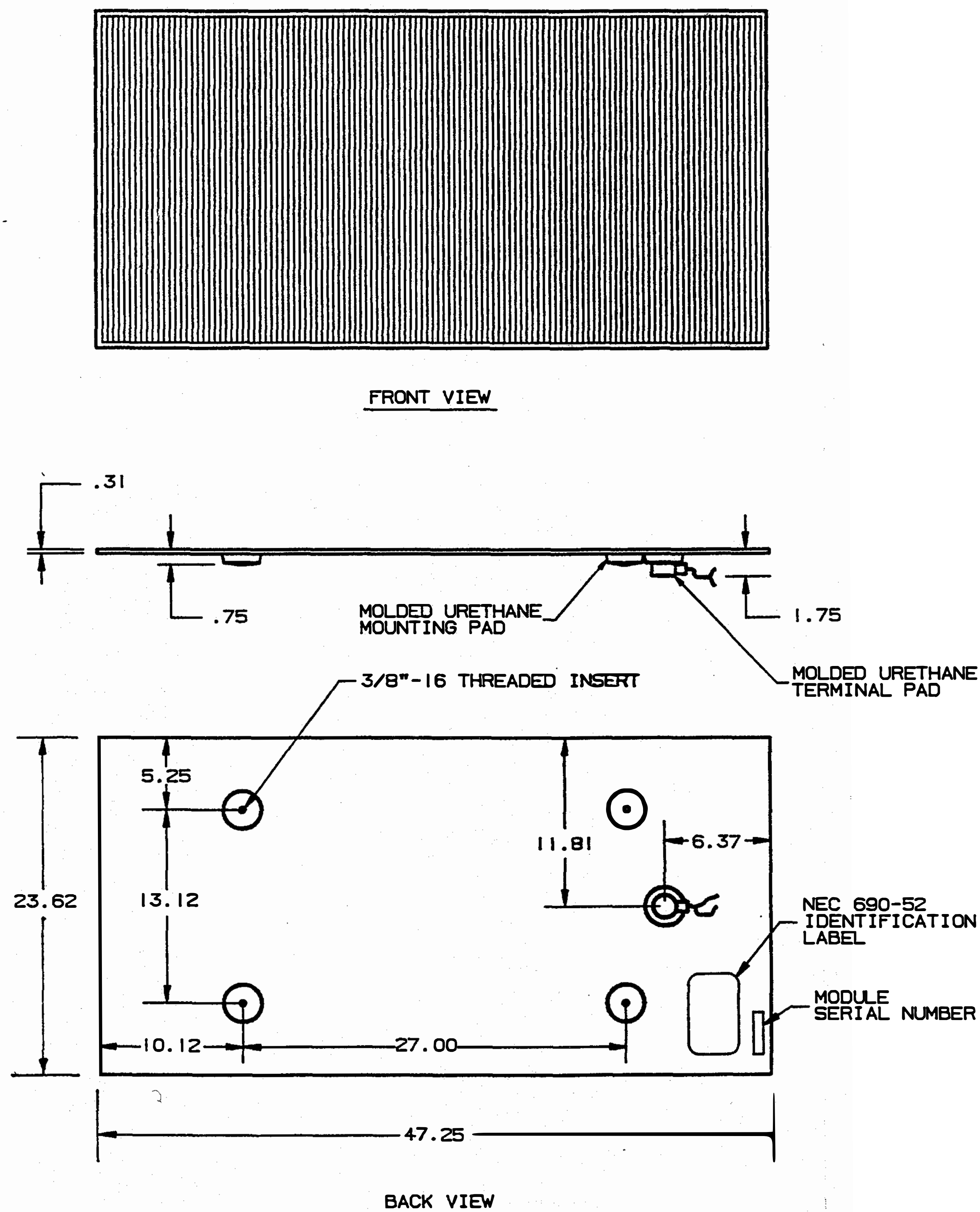


Figure 2.



SOLAR CELLS INC.
STANDARD MODULE

Table 1. Product characteristics for grid-connected and remote applications.

	Baseline Product	Secondary Product
Market	Grid-Connected	Off-Grid/Remote
Nominal Power (8.0%)	58W	58W
Nominal Voltage (Vmax)	65V	17V
Electrical Connection	Pigtail	Pigtail/J-Box
Encapsulation	EVA/Glass/EVA	EVA/Glass/EVA
Panelization	Mounting Pads	Mounting Pads or Frame
Size	60cm x 120cm	60cm x 120cm or 60cm x 60cm

The long-term baseline SCI product is the 60 cm x 120 cm high-voltage module targeted at grid-connected applications. The majority of these reductions resulted from the elimination of module framing and the substitution of pigtails for the junction box. SCI projects that this baseline product along with a patented support structure will reduce the cost of photovoltaic installations to below $3.00 per watt by the year 2001.

SCI has improved the best demonstrated and average module efficiencies during the first phase of the contract by 14% and 30%, respectively (see Fig. 3). SCI has demonstrated a 60.3 watt module with total area efficiency of 8.4%. The average total area efficiency of 60cm x 120cm modules manufactured on a developmental pilot line has increased to greater than 6.5% (see Fig. 4).

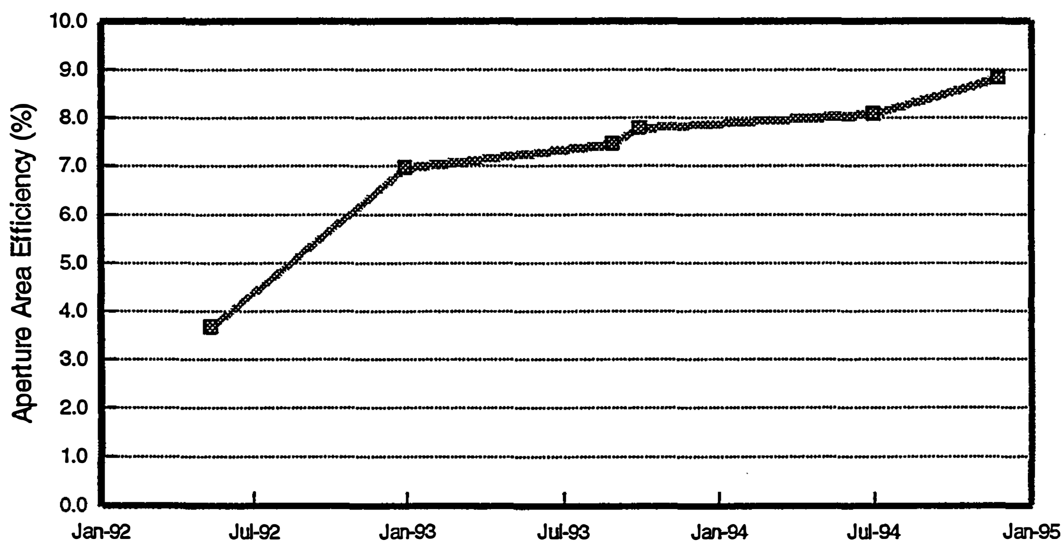


Figure 3. History of best-demonstrated aperture area efficiency on production modules.

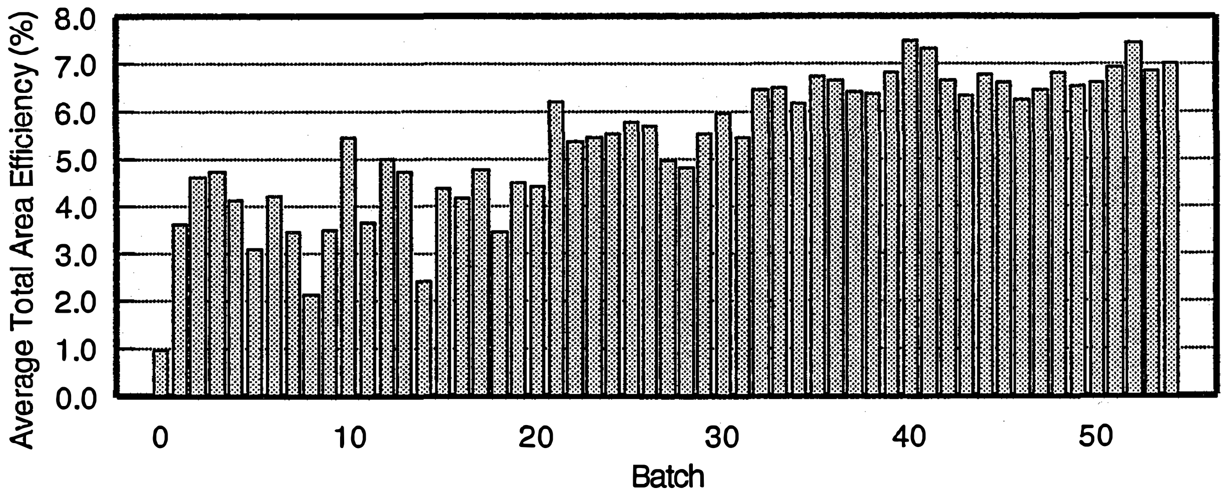


Figure 4. Average module performance by batch. PvMaT efforts during batches 30-54.

Task 2 Modification/Elimination of $CdCl_2$ Treatment

Objective

- Eliminate post-deposition wet $CdCl_2$ treatment
- Sustain module performance
- Reduce manufacturing steps
- Mitigate environmental impact of the process

Progress

- Eliminated wet treatment
- Optimized/demonstrated "dry" treatment
- Demonstrated comparable performance

Two approaches were used in developing alternative processes to the wet $CdCl_2$ treatment: 1) elimination and 2) modification. Investigations of eliminating the treatment focused on the growth of the CdS/CdTe films. Specifically, semiconductor deposition process changes included various ambient growth conditions and deposition rates. The goal of these efforts is to produce CdS/CdTe films with the correct structure as to eliminate the treatment. Even though SCI was able to demonstrate devices with efficiencies above 5% with this approach, none of the devices performed within 20% of the baseline wet treatment.

The modification approach focused on changing the wet treatment to a process with reduced process time, reduced materials cost, and better uniformity. SCI has developed a post deposition vapor treatment which eliminates the traditional wet dip $CdCl_2$ treatment. The process uses HCl in moderate vacuum with a substrate temperature above 350 degrees Celsius. This process significantly increases material utilization and process control. In addition, SCI feels that this process has the potential to eliminate post treatment rinses, thereby, mitigating the environmental impacts of the traditional process and providing a more efficient process for manufacturing implementation [1]. Table 2 compares the vapor process to the wet dip process.

Table 2. Comparison of the wet dip $CdCl_2$ treatment to an alternative vapor process.

	Wet Treatment	Vapor Treatment
Device Efficiency	11.9%	10.7%
Module Efficiency	8.1%	7.0%
High Voc (mV)	820	800
Process Time (min)	>60	<30
Process Steps	6	2
Materials	Solvents	No Solvents
Material Utilization	Low	High
Post Processing	Rinse	No Rinse

Task 3 Encapsulant and Pottant Evaluation

Objective
- Finalize module packaging
- Reduce package cost
- Maintain reliability and manufacturability

Progress
- Demonstrated EVA/glass encapsulation
- Demonstrated molded potting and panelization
- Reduced Panel costs by 41%
- Significant advances on IQT performance
- Catalogued many future encapsulation options

SCI investigated four groups of materials in the Phase I efforts. The materials were judged on the basis of cost, manufacturability, and durability. EVA/glass was used as the benchmark. Table 3 outlines the main advantages and disadvantages of the materials under investigation.

Table 3. Encapsulation overview.

	Advantages	Disadvantages
EVA/glass	Proven Reliable	Weight Cost Manufacturing
Laminated Films	Manufacturing	Cost
U.V. Curable	Very Low Cost Fast Process Time	Durability Toughness
Coatings	Manufacturing Low Cost	Early Stages of Development Multi-functional limitations

The three material groups other than EVA/glass were put through various tests similar in nature to those of the IQT. None of the materials were found to be promising. Further development of the EVA/glass package resulted in a design which greatly reduced the overall finalization costs and more specifically significantly reduced panelization and potting costs. Development efforts on this product have resulted in greater than a 40% reduction in product finalization costs including encapsulation, potting, connections and panelization (see Fig. 5).

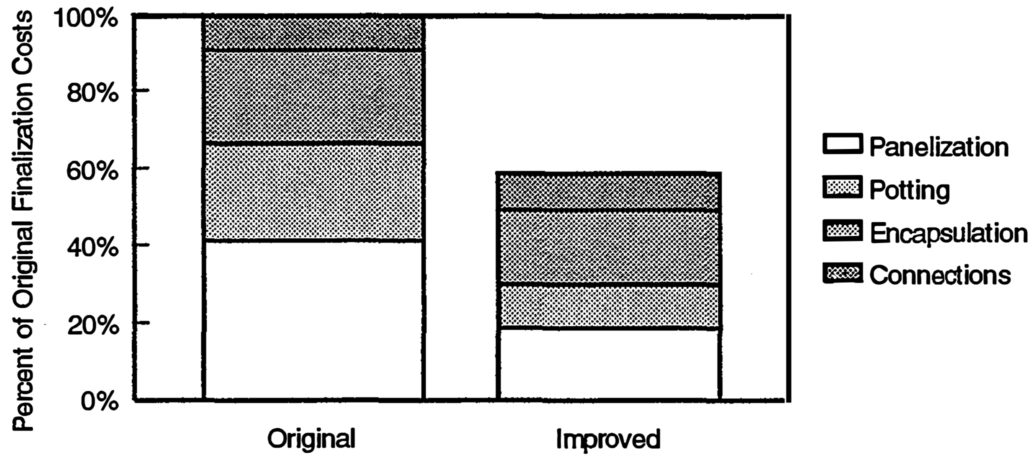


Figure 5. Product finalization cost reductions.

Even though the alternative materials had significantly reduced materials costs (70% reduction), they were not able to withstand the testing called for by the IQT. However, the EVA/glass modules routinely pass extensive stress testing. The majority of these stress tests are based on the protocols established in the "Interim Qualification Tests and Procedures for Terrestrial Photovoltaic Thin-Film Flat-Plate Modules" (IQT) [2]. SCI conducted one IQT series per month during Phase I activities. This testing demonstrated significant improvement in overall pass rates from below 10% in early 1993 to well over 80% at the end of Phase I. The improvement is attributed to the pigtail durability, reduced glass curvature, and better process control during lamination preparation.

SCI also extends certain elements of the IQT to evaluate module lifetime. For instance, three modules have undergone over 650 thermal cycles and demonstrated less than a 10% decrease in performance. This result is one indication that the current module design has a 30-year lifetime [3].

Task 4 Manufacturing Process Definition

Objective

- Evaluate process for 20MW Implementation
- Define process

Progress

- Baseline process definition and demonstration complete
- Positive evaluation for 20MW implementation

Process Definition

SCI has defined the process for the 20MW manufacturing line. Table 4 outlines the major processes used to manufacture the thin-film cadmium telluride modules. These processes are demonstrated daily on a 100kW pilot production line.

Table 4. Major manufacturing processes.

Substrate Inspection	Scribe 3
Substrate Preparation	Bus Bar Application
Scribe 1	Encapsulation
Semiconductor Deposition	Potting
Film Thickness Check	Safety Checks
Post Deposition Treatment	Pmax Test
Scribe 2	Final Inspection/Label
Metal Deposition	

The initial processing step is the preparation of the substrate for the deposition of the various materials which constitute the photovoltaic module. The substrate is a glass sheet measuring 60cm x 120cm x 5mm with a transparent conducting oxide (TCO) coating. This process is followed by the deposition of the semiconductor layers, CdS and CdTe, which takes place in the "High throughput Deposition System" (HTDS). After some post deposition treatments, the module is ready for cell interconnecting and the deposition of the top metal contact. Cell interconnecting divides the large area device (measuring 58cm x 118cm) into smaller cells by scribing through the various layers using a laser. The device is then encapsulated to protect against environmental effects. Electrical connectors are attached to allow modules to be electrically connected to form a panel. The following provides a more detailed description of the process.

Substrate (TCO) Inspection

The glass substrate is transported from the warehouse to the staging area where it is unpacked and made ready for processing. The glass substrate is then hand loaded onto an inspection table, inspected for physical defects, rejected or accepted and labeled.

Substrate Preparation

The glass enters an edge seamer where the edges are ground to increase strength and reduce handling hazards caused by the sharp edges of the raw glass. This operation utilizes commercially available equipment with automatic load and unload capabilities. This step is essential because of the high temperatures in the deposition process. After exiting the edge seamer the substrate moves through a wash cycle where it is given a detergent wash and a DI water rinse followed by air drying. A commercial washer with automatic load and unload capability is used for this step. This is necessary for pinhole free films and good film adhesion.

Scribe 1

The first step in the formation of interconnected cells is to scribe a series of cell isolation channels. A Nd:YAG laser system is used to scribe 117 parallel channels, separated by 1cm, across the module. These channels are 25µm-50µm wide and ablate the TCO layers thus creating 116 individual cells which are electrically isolated. (Two cells are used for bus bar attachment and two cells are lost in edge deletion.) The laser system has automatic load, unload and indexing features. Before exiting the Scribe 1 station, all cells are tested for electrical isolation. Substrates which exhibit incomplete isolation are routed to a rework station for rescribing.

Semiconductor Deposition

The substrate is now ready for the deposition of the semiconductor layers, CdS and CdTe. The deposition step utilizes a chemical vapor deposition (CVD) process in which elemental vapors are introduced into the chamber, where they are mixed and allowed to condense and react on the substrate to form the compounds. All depositions take place at pressures in the 1 Torr range and substrate temperatures between 400 °C and 600 °C.

The deposition system (HTDS) is a four chamber system which utilizes indexing load locks. This system allows for steady-state conditions in the deposition zones as the substrates are conveyed within close proximity of each other.

After passing through the entrance load lock, the glass enters a preheat chamber where it is heated to above 300 degrees Celsius. It then passes under a nitrogen gas curtain into a second chamber where a layer of CdS is deposited. The substrate then passes under another curtain into a third chamber where a 3µm thick layer of CdTe is deposited. A fourth section is used to stabilize the temperature substrate before it enters the exit load lock. The exit load lock serves two functions: 1) allows transition from vacuum to atmosphere and 2) quenches (quickly cools) the substrate. The quenching of the substrate increases the glass strength for better field durability. The substrate is then cooled.

Film Thickness Test

After exiting from the cooling conveyor or lehr, the semiconductor films are tested for film thickness uniformity. This is a totally automated testing procedure which utilizes beta back scattering from a radioactive source for measurements in less than 10 seconds.

Post Deposition Treatments

Normally, an essential step in the formation of high efficiency CdTe photovoltaic devices is exposure of the CdTe to $CdCl_2$ at elevated temperatures. However, SCI has developed a vapor treatment to replace the standard wet dip $CdCl_2$ process. The substrate is heated to approximately 400°C and moved into a low concentration atmosphere of HCl (see Task 3.)

The second post deposition treatment consists of removing any CdTe and/or CdS that was coated on the glass side of the module. The module is automatically loaded into a fixture that holds the module on the sides exposing the glass underside to a cylindrical buffer. The buffer removes the film and cleans the glass.

Scribe 2

The second step in the formation of interconnected cells is to scribe a series of interconnect channels. A Nd:YAG laser system is used to scribe a second series of 117 channels spaced 1cm apart. These channels are offset from Scribe 1 by 200µm-400µm and are similar in width to those of scribe 1 but only penetrate through the semiconductor layers leaving the TCO. Four additional scribe 2 channels are scribed at each end of the module to facilitate electrical connection to the bus bars.

All channels are subjected to an ablation completion inspection to evaluate the effectiveness of the scribe in clearing the semiconductor.

Metal Deposition

Metallization takes place in a three zone sputtering system with provisions for future improvements such as surface treatments and interfacial layers. The process is standard Ni and Al sputtering. Metallization of 200Å Ni, 3,000Å Al and 200Å Ni is accomplished in one pass under the targets. The module then exits the chamber through the exit load lock.

Edge Deletion

The ‘edge delete’ process removes all deposited materials (including metals, semiconductors and TCO) from the perimeter of the substrate extending from within 1cm of each edge. This is necessary to prevent any shorting between the cells as well as to provide for proper encapsulation. A sand blasting procedure is used for the removal of these materials. The substrate is automatically fed into the edge delete chamber. A series of sand blasting nozzles automatically scans along substrate perimeter, removing all materials on the glass. The module then moves under an air jet to remove excess debris before entering the scribe 3 station.

Scribe 3

The third and final step in the formation of interconnected cells is to scribe a series of metal isolation channels. A Nd:YAG laser system is used to scribe a third series of 117 channels spaced 1cm apart and offset from the Scribe 1 channels by 500µm-1000 µm. The scribe 3 channels are identical in width to those of Scribe 1 but only ablate the metal layer.

IV test (rework /reject)

The submodule moves into an automated test station where both the temperature and standard photovoltaic I-V measurements are recorded. Submodules which pass the I-V test proceed to the lamination area. Rejected modules are routed to a rework station.

Encapsulate

The submodules which have passed the IV tests are moved via conveyer to a lamination assembly table where they are automatically placed into lamination racks. Each lamination rack holds three submodules. The submodules will remain in these racks throughout the lamination process. An operator places a preassembled cover glass, with an encapsulant layer (EVA) and bus bar connections already in place, over each of the submodules in the lamination rack. The lamination rack is then conveyed to the laminator where it goes through an 8-12 minute lamination cycle.

The preparation of the cover glass assembly is a semi-automatic process. The completed cover glass plate contains both an EVA layer for the subsequent lamination process and all of the electrical connectors (including bus bars) between the submodule electrodes and the outer surface of the cover glass.

The cover glass is 60cm x 120cm x 3mm with a 2cm diameter hole for electrical feedthroughs. It is inspected for physical defects, and placed on a conveyer which moves the glass through a washer. Two sections of metal tape with conductive adhesive on one side, each approximately 1.5 meters long, are positioned to match with the submodule bus bars and threaded through the center hole of the cover glass. Polyester insulation tape is placed over that section of the metal tape which is positioned over active cells. A 3ft length of 12 gauge copper wire is later soldered to the end of the metal conductor after lamination is complete. A bypass diode is also connected between the two electrodes if required.

Potting and Mounts

The next step in the module assembly process involves the application of four mounting pads (used to connect the module to the panelization members) to the back cover glass and a potting pigtail that encapsulates the area around the exit hole where the bypass diode as well as electrical connections are located. This is accomplished by a "Reaction Injection Molding" (R.I.M.) process using a fast-cure, two-part urethane.

The module first moves under a spray applicator where a layer of primer is applied. The module then moves to the RIM application station where an injection mold is pressed against to the cover glass surface. Urethane is injected into the mold forming both the mounting pads and potting pads. This completes the assembly of the module.

Inspection, Testing and Labeling

The completed module next moves to a testing station where a standard “Hi-Pot” test is performed. The purpose of this test is to determine the effectiveness of the encapsulant as it applies to electrical safety. The module then moves through an inspection station. Finally, the module moves to an automated test station where standard photovoltaic I-V testing is performed and a label attached.

SCALING ISSUES

Two processes are undergoing more evaluation because of scaling issues: superstrate cleaning (buffing) and lamination assembly. Currently, substrates are buffed manually. This process is not applicable to the multi-megawatt manufacturing line. A vendor for automated equipment has been identified but no testing has been completed. The system would also need a waste handling system which minimizes process byproducts.

The lamination assembly process is labor intensive. SCI is evaluating the tradeoffs of an automated system compared to a manual/automated hybrid that meets manufacturing requirements without significantly impacting capital costs.

Task 5 20MW Manufacturing Line Conceptual Design Review

Objective
- Review and Revise 20MW Conceptual Line Layout

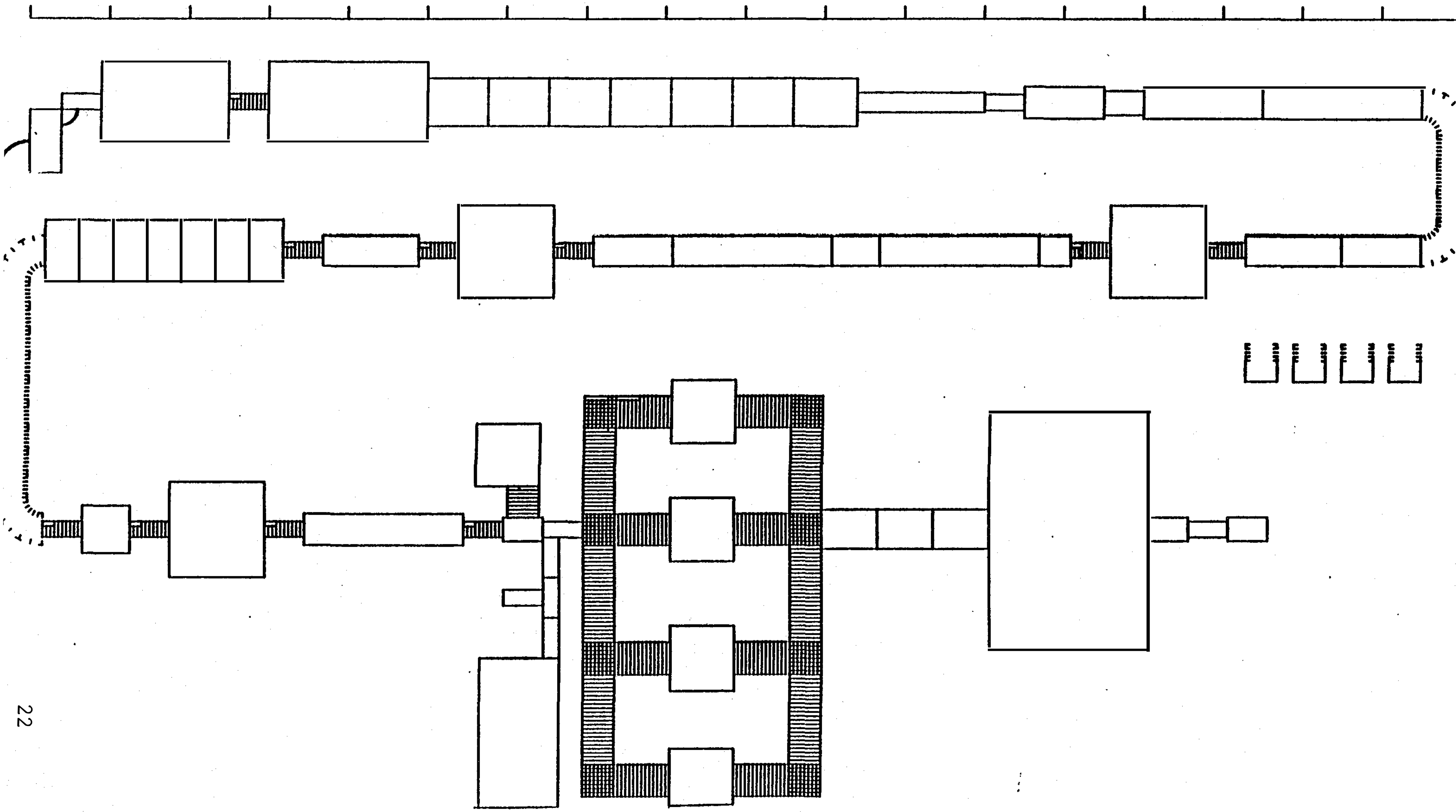
Progress
- Completed integrated layout of 20MW line
- Developed manufacturing model
- Completed identification of all key equipment

SCI has completed a conceptual layout of the 20MW line (see Fig. 6). This layout includes all of the primary processes. The layout utilizes the advantages of the thin film technology through continuous in-line manufacturing. Several test stations are included to check the process performance throughout the complete cycle. Every process can be accomplished with a single in-line machine except lamination. Due to the lamination cycle time and lack of available in-line equipment that meets the manufacturing requirements parallel processing is required.

A manufacturing database and model have been developed. The database acts as supporting evidence for cost projections as well as a vehicle to identify high cost processes in the production line. The database holds details on each process including:

- Process Efficiencies
  - Uptime
  - Yield
  - Material Utilization
  - Line Speed
- Materials
  - Description
  - Part Number
  - Supplier
  - Unit Cost
- Equipment
  - Description
  - Part Number
  - Supplier
  - Unit Cost
  - Space Requirements
  - Utility Requirements
- Labor
  - Direct/Indirect Allocation
  - Wage rates

Figure 6. Unannotated 20 MW line layout. Flow is from top-left to bottom-right.



SCI utilizes the manufacturing model to generate prediction of manufacturing output, direct and indirect costs, and process specifics. An example of the model output is displayed in Figure 7. In general the model takes assumptions and matches them with information in the database to calculate overall manufacturing costs for the 20MW line. This model has assisted SCI in projecting capacity and manufacturing costs for the first ten years of line life. These predictions show that the line is capable of greater than 25MW in the year 2005. In addition, the cost of modules is projected to decrease by over 60% over the same period (see Fig. 8). The steady improvement in cost and capacity is driven by manufacturing improvements related to uptime, yield, and materials utilization as well as volume discounts on raw materials. However, the primary factor in attaining these goals is meeting efficiency targets. Module efficiency should increase steadily to 12% in 2005 (see Fig. 9)

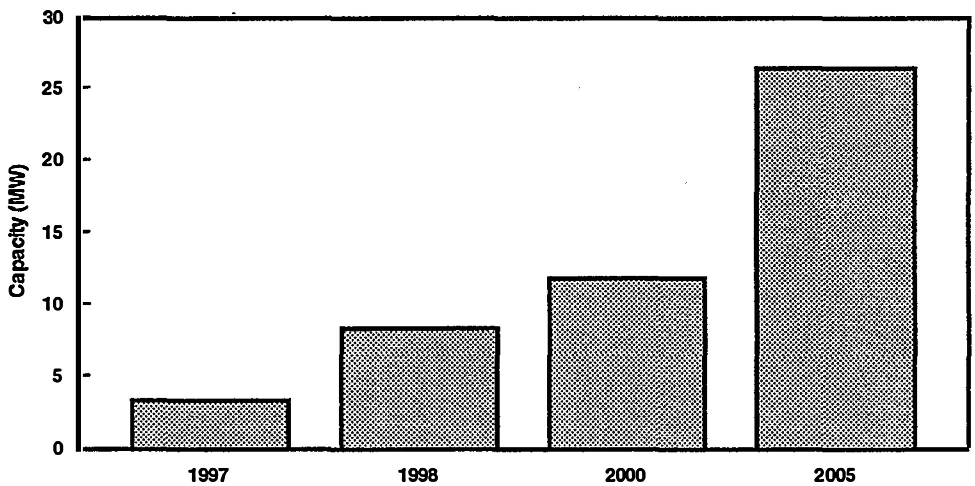


Figure 7. Projected plant capacity of 20MW line. Assumes 1 shift operation for 1997 and two shift operation for all other years.

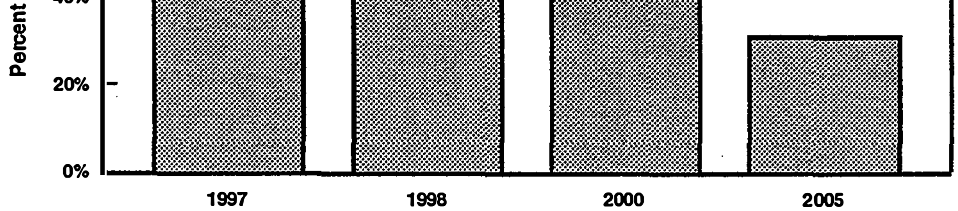


Figure 8. Projected manufacturing costs compared to the first year costs.

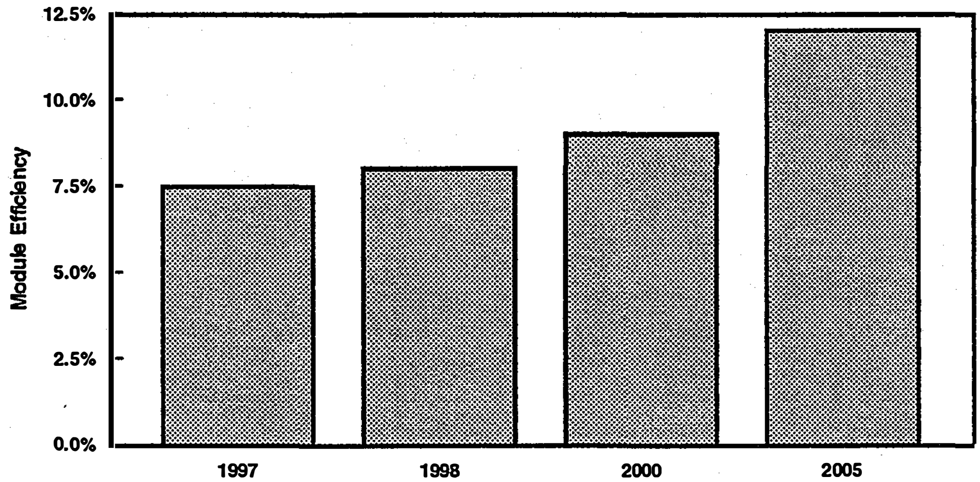


Figure 9. Average module efficiency assumption for manufacturing projections.

Task 6 20MW Manufacturing Line Equipment Design

Objective

- Design/Specify key components
- Identify Suppliers
- Evaluate Custom Equipment Requirements
- Specify In-Line Test Stations

Progress

- Specified all key off-the-shelf equipment
- Contacted suppliers for all key components
- Designed and constructed CdS/CdTe Deposition System
- Described In-Line test Stations

The 10MW production line is composed of about 40 pieces of equipment plus various conveyors. SCI has obtained quotes or budgetary estimates for all major equipment and has made independent estimates on the balance of the equipment. SCI focused its efforts on the high capital cost and custom designed items. Table 5 shows that over 70% of the capital cost is attributed to only 4 of the 40 process steps.

Table 5. Capital cost of major process equipment with number of vendor quotes available for review.

Equipment	Suppliers	% of Capital
Laser Systems	4	25%
Deposition System	custom	20%
Metallization System	4	14%
Laminators	1	12%
		71%

The metallization and lamination systems are off-the-shelf and present lower operational risk than the laser and semiconductor deposition systems. The laser systems have been quoted by multiple suppliers and will be procured after a full investigation of the vendors' capabilities. SCI designed the HTDS and is currently finishing installation. Additional information on these critical systems is provided below.

Laser Systems

The basic interconnection approach for the 20MW follows the established method demonstrated daily on the 100kW pilot production facility. Process parameters are well documented and can be incorporated into the new production line. The present laser is a frequency doubled, Q-switched, Nd:YAG laser made by U.S. Laser in 1990. The system incorporates a computer controlled three-axis table, which accommodates the 60cm x 120cm substrates. Although this laser is capable of making all the required scribes, it is impractical for production. Shortcomings of the current laser system include; single beam lasing, limited table speed (250mm/sec), and manual load/unload.

Through an extensive search, SCI has identified laser companies which could provide us with a state-of-the-art industrial scribing system. Florod is considered to be the lead candidate to supply the laser systems due to their technical abilities, component reliability, and experience with other photovoltaic manufacturing companies. One of Florod's advantages is the incorporation of laser packages which are known for outstanding stability and reliability. Florod also has a good track record for delivering high quality cutting & scribing systems to the photovoltaics and semiconductor industries. Their systems contain excellent optical and mechanical designs as well as competitive pricing and timely delivery.

Each laser scribing system incorporates two lasers split four times. Table motion control and laser parameters are easily set by an integral 486 computer having 80 MB hard drive, a 3.5" disk drive and new application specific software. During the scribing process the cutting by each beam is observable from a video monitor. The intensity of the final beams is displayed on individual monitors. Primary beam and power characteristics are continuously available. The system also utilizes a unique intensity feedback mechanism that insures stable primary beam intensity without any operator assistance. Ablation by-products, namely air-borne particles, dust, and fumes, produced during scribing are continuously removed and are safely collected. Requirements for the systems vary depending on amount of material to be ablated (i.e., Scribe 1, Scribe 2, or Scribe 3).

Scribe 1 System

A substrate is conveyed to the laser loading station. The loader senses the substrate and loads it onto a motion table. The substrate is positioned accurately against three stops and the lasing program begins. Eight high-power infrared beams simultaneously cut scribes in the semiconductor down through the SnO_2 in a single pass. With only 16 indexed passes the entire substrate is cut into 116--1cm x 60cm cells. After the scribing is completed the substrate is automatically unloaded and transferred to a line conveyor. Total cycle time for the handling and scribing is under one minute.

Scribe 2 System

A substrate having Scribe 1 completed is conveyed to the laser loading station. The substrate is positioned as in Scribe 1. Eight high-power green laser beams simultaneously cut scribes through the semiconductor leaving the SnO_2 in a single pass. Scribe 2 is separated from Scribe 1 by 100-200 µm. After 16 indexed passes the entire substrate is scribed. After the scribing is completed the substrate is automatically unloaded and transferred to a line conveyor. Total cycle time for the handling and scribing is under one minute.

Scribe 3 System

A substrate metallized with a back Ni-Al coating and having the first two scribes is conveyed to the laser loading station. The substrate is positioned as in Scribe 1. Eight high-power green laser beams simultaneously cut isolation scribe lines through the Ni-Al metal in a single pass. The scribes are separated from Scribe 2 by 100-200 µm. After 16 indexed passes the entire substrate is completely scribed with 116 interconnecting cells.

After the scribing is completed the substrate is automatically unloaded and transferred to a line conveyor. Total cycle time for the handling and scribing is under one minute.

High-Throughput Deposition System

In 1991, SCI designed and installed a developmental deposition system (LDS) for depositing CdS and CdTe from compounds onto 60cm x 120cm substrates. This process is very similar to close-spaced sublimation (CSS). This system served four main functions: substrate heating, raw material vapor generation, vacuum pumping, and substrate cooling. This system has been utilized successfully for process optimization experiments and small scale pilot production. However, this system has two main drawbacks regarding high throughput production: non-steady state conditions and low capacity. The root cause for these drawbacks are batch operations for introducing substrates and semiconductor raw materials into the system. Nonetheless, SCI proved process feasibility for manufacturing environments with this system and transferred its focus to the development of its production system.

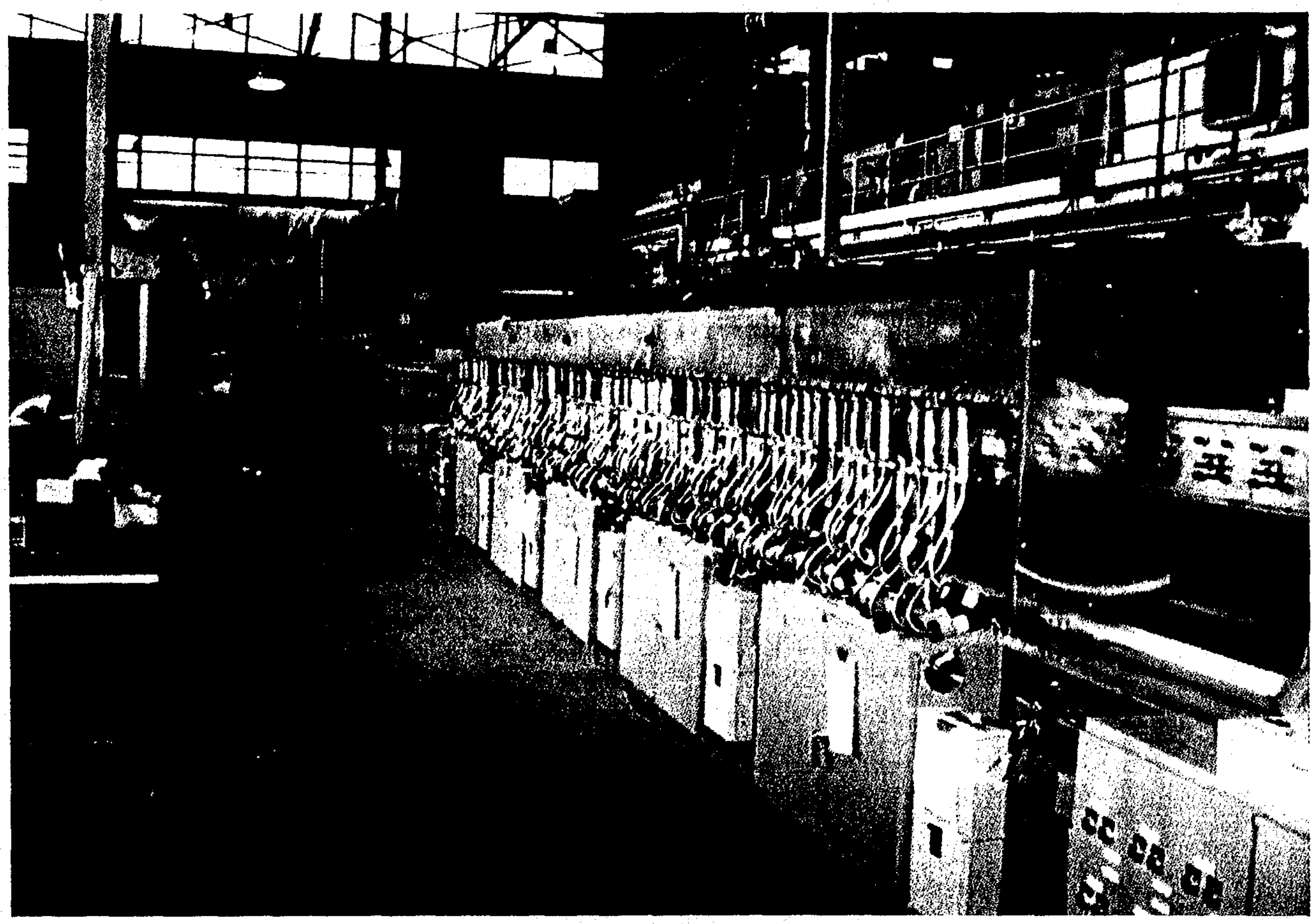
In 1994, SCI built and began to debug a high-throughput deposition system (see Fig. 10) which incorporated several advantages over the pilot deposition system including increased throughput and steady-state, continuous operation (see Table 6). The main functional advantages of the production deposition system are on-demand raw material feed and indexed glass conveyance. These features result in 100 times the annual capacity of the pilot system with only a moderate increase in system length (36 feet vs. 46 feet). The manufacturing system is designed for throughput of one module/minute. This advanced deposition system will be integrated with approximately 40 other pieces of equipment to produce modules at an annual capacity of 10-20MW.

Table 6. Comparison of pilot deposition system to high-throughput deposition system.

System:	Prototype	Production
Year Built:	1991	1994
Purpose:	Process Demonstration Process Optimization Limited Production	Manufacturing
Features:	100kW 10 Modules/Day Manual Batch	10-20MW 480 Modules/Shift Automatic Continuous, Steady-State

Figure 10.

High-Throughput Deposition System



The HTDS is designed with the capability of continually feeding semiconductor raw materials through a series of feeders and vapor generators. The feeders are replenished without interrupting the process and are controlled individually to provide for flexibility in deposition rates and overall film thickness. The HTDS feeders can use raw material in element or compound form. This flexibility results in enhancing film growth control and reducing materials costs, and achieving deposition at a lower system and substrate temperature. The vapor generators are located close to the deposition zone inside the system to limit the possibility of premature deposition away from the substrate.

Process Specifics

Entrance Load Lock--The entrance load lock indexes the substrate, equalizes pressure with the deposition chambers, and conveys glass into the preheat zone. The substrate is moved into close proximity (< 1 inch) of the upstream substrate. The cycle is less than 60 seconds.

Preheat--The substrate is preheated to the deposition temperature (400C to 600C). The HTDS design uses Watlow heaters which can be replaced from the outside of the system to facilitate maintenance and greatly reduce downtime due to heater failures.

CdS Deposition--CdS is deposited to a thickness of 1000 Angstroms in approximately 40 seconds. Substrate temperatures reach up to 450C at pressures of around 1 Torr.

CdTe Deposition--The CdTe deposition zone follows the CdS zone. CdTe is deposited to a thickness of 3-4 microns in less than 1.5 minutes. Substrate temperatures reach up to 550C at pressures of around 1 Torr.

Isolation Curtain--The various zones described above are separated by isolation curtains. Each curtain uses close-clearance geometry and gas flow to limit cross over between zones due to diffusion or bulk flow phenomena.

Buffer Zone--The HTDS has been designed with extra processing sections downstream of the CdTe zone to incorporate future process developments.

Exit Load Lock--The exit slit is analogous to the entrance load lock. In addition, the purge system is incorporated into a quench for substrate cooling and heat strengthening.

Task 7 20MW Manufacturing Line Utilities Design

Objective

- Specify utility requirements
- Specify support systems requirements

Progress

- Identified Capacities of key systems
- Completed Engineering Evaluation
- Outlined key permit issues

The general utilities and facilities requirements have been identified. A site has not yet been designated. The requirements are within the standard range for a manufacturing plant of this size. Table 7 outlines the plant requirements.

Table 7. Utility and facility requirements for SCI 10MW plant.

<u>**Land**</u>

Acres - 5+ (expansion/demonstration arrays)
Zoning - Light/heavy industry
Parking Places - 90
Transportation Access - Main thoroughfare within 2 miles

<u>**Building**</u>

Total Size - 53,000 sq. ft.
    Manufacturing - 30,000 sq. ft.
    Warehouse - 7,500 sq. ft.
    Offices - 5,000 sq. ft.
    R&D Labs/Offices - 10,500 sq. ft.
Ceiling height (man/warehouse) - 14 ft. minimum
Sprinklers - Wet system throughout
Overhead Cranes - 5 ton minimum
Heat - Full building forced air / gas fired
Air Conditioning - Handle 20,000 sq. ft.
Power Supply - 3,500 KVA, 480V connected
Security System - All areas
Restrooms - Access from all areas
Overhead Doors - Two, 12ft. minimum
Truck Well - 3 with levelers
Utilities - Plant compressed air
    N_2 supply (plant or liquid boil)
    Trash compactor
    Numerous exhaust stacks
    Floor drains

Task 8 Quality Assurance Development

Objective

- Develop Q/A program for 20MW line
- Develop process feedback capabilities
- Demonstrate module performance improvement

Progress

- Outlined quality system based on ISO-9000
- Developed process charting plan
- Identified key process indicators
- Utilized standard operating procedures
- Established module testing laboratory

SCI has initiated a quality assurance program specifically focused on the 20MW manufacturing line. This program is under evaluation and refinement on a pilot production line. Most of the current efforts are focused on process control and module testing. Process control efforts have paid dividends in three basic areas; 1) module performance, 2) module performance variation and 3) process improvements. Module performance has steadily improved over a two and one-half year period with significant increases in the past twelve months covering production batches 30-50 (see Fig. 11). Concurrently, the relative standard deviation of the performance decreased substantially to below 10% (see Fig. 12). The target for the next twelve months is to demonstrate sustained variation of less than 5%.

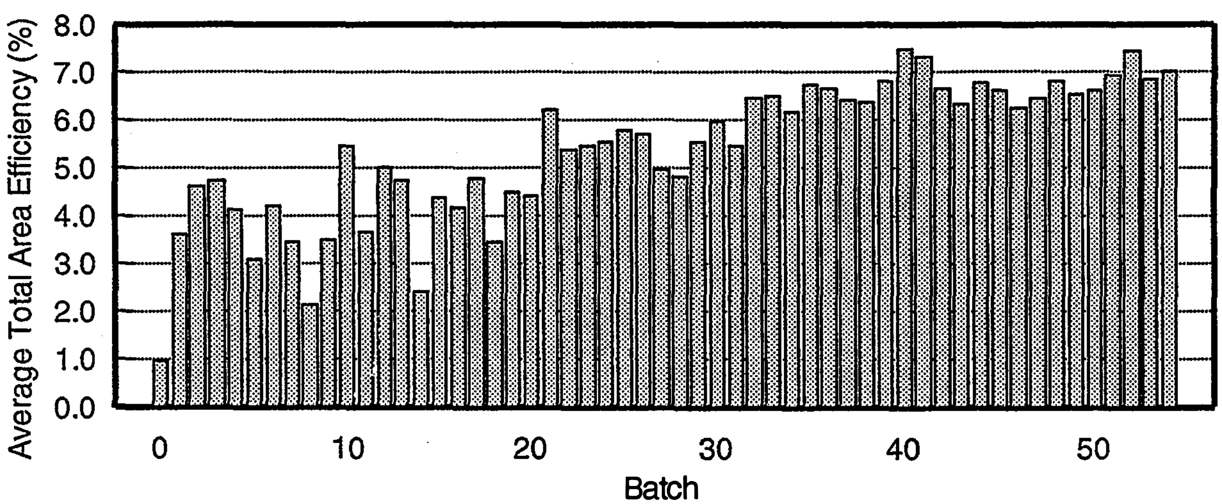


Figure 11. Average total area efficiency vs. production batch. A batch contains an average of 15 modules.

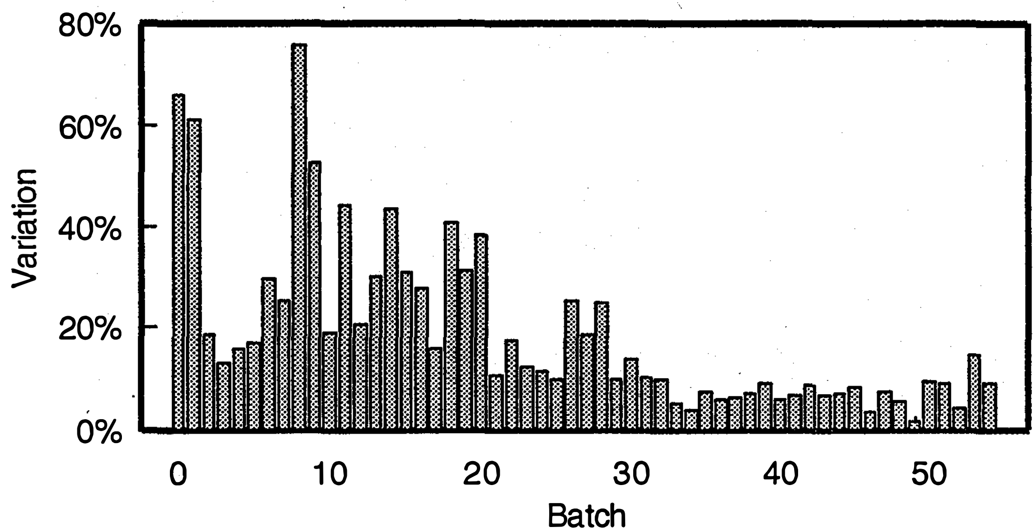


Figure 12. Average relative standard deviation of total area efficiency vs. production batch. A batch contains an average of 15 modules.

These improvements are the result of several quality programs including standard operating procedures, process charting, designed experiments, and process changes. In addition, pilot line operators are involved in capability studies of several processes. One such study on the laser scribing process identified the opportunity to reduce the distance between adjacent scribes. More than 100 modules were utilized in identifying the laser process capability and tracking the results of a reduction in separation distance (see Fig. 13). This change resulted in a 0.5% relative increase in module output due to increased active area. These incremental improvements are important to meeting long term performance objectives.

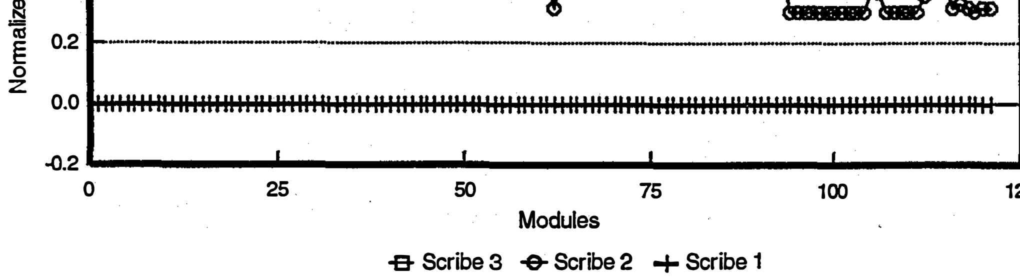


Figure 13. Laser scribing process capability study resulting in a reduction of scribe separation distance. By definition Scribe 1 is at the 0.0 position.

In addition to process control, extensive testing is implemented to examine and demonstrate module durability. Module durability refers to the physical module as opposed to the thin-film photovoltaic device performance (i.e., stability). The stress tests are based on the Solar Energy Research Institute (SERI) protocol Interim Qualification Tests and Procedures for Terrestrial Photovoltaic Thin-Film Flat-Plate Modules (IQT). The intent of these procedures is to provide the minimum tests and inspections required to evaluate photovoltaic modules and to provide a common approach between the producer and purchaser in conducting qualification tests. Ideally, modules that would experience early failures in field operations should fail the qualification tests. The objective of the IQT protocol is

> "Emphasis is placed on testing and evaluating module performance characteristics and design features that will affect possible degradation of module performance and physical properties resulting from solar exposure, environmental weathering, mechanical loading, corrosion, and module shadowing. Because of limited thin-film module field operation experience and the evolutionary nature of new thin-film module material technologies and designs, these tests should not be considered definitive or complete at this time, nor do they provide a basis for assuring 30 year life in the field. Current understanding of failure and degradation mechanisms and the relationship between accelerated tests and field reliability is not sufficient to allow accurate estimation of life-expectancy."

SCI has made significant progress in module durability during Phase I of the subcontract. IQT pass rates have increased from below 20% to above 80% on a module basis (see Fig. 14). SCI tested 34 modules of which 27 passed their respective testing series (see Fig. 15). Most of the improvement was a result of better potting designs and encapsulation process controls. The pigtail potting design with urethane as the potting agent proved to be much more effective in limiting leakage current identified in the wet electrical-isolation test. Pass rates increased from approximately 40% to 100%. Encapsulation process improvements including cleaning of the sealing surface on the module improved pass rates for the humidity-freeze test from approximately 50% to 100%.

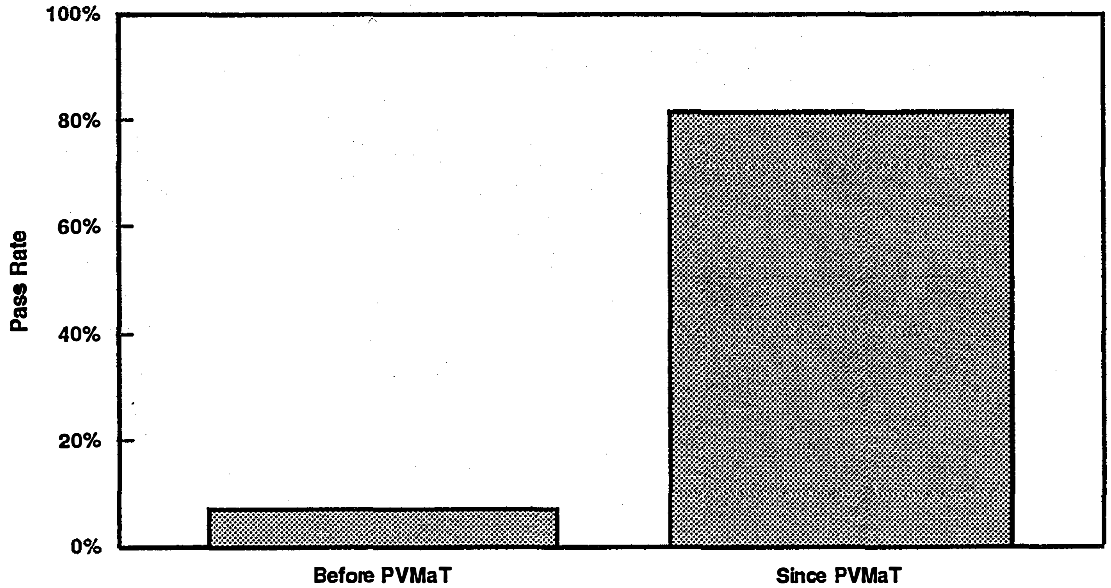


Figure 14. Module pass rate for IQT testing before and since the PVMaT efforts.

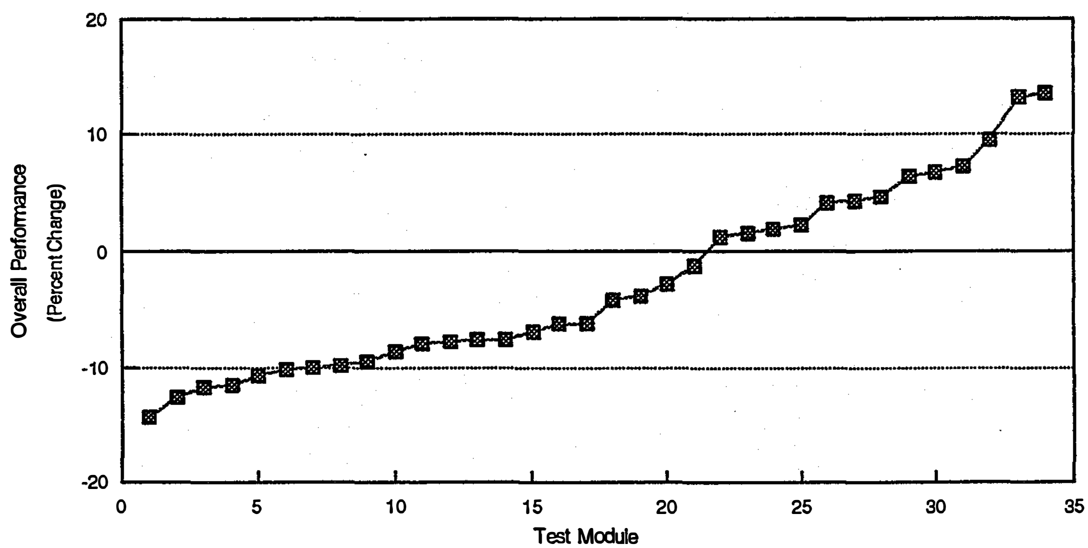


Figure 15. Overall performance in modules tested in IQT protocol.

Task 9 ES&H Program Development

Objective

- Develop program for 20MW plant
- Test program on pilot production line

Progress

- Continued medical monitoring program
- Refined Haz-Com and hygiene action plan programs
- Demonstrated waste reduction process.

Production of CdTe PV modules involves regulated materials including cadmium. An important part of the development effort is to establish programs which effectively handle environmental health, and safety issues that accompany the production, deployment and disposal of these modules. SCI has engaged outside agencies and consultants to conduct safety and health audits of the manufacturing facilities and to formulate appropriate programs and corrective actions. These programs include basic training programs as well as specific operational plans such as industrial hygiene and biological monitoring.

Environmental development has focused on process waste minimization and product recycling [4]. SCI has demonstrated feasibility on a waste treatment process which removes greater than 95% of the cadmium from low concentration liquid wastes. This process reduces the disposal volume by over 99%. SCI has also demonstrated product recycling by shipping modules to a raw material supplier for reintroduction into the smelting process. Table 8 outlines the major EH&S programs addressed in Phase I.

Table 8. EH&S programs in development during Phase I.

Environmental
- Waste Reduction
- Waste Disposal
- Permit Maintenance
- Emissions Monitoring
- 11 Other Areas

Health
- Medical Monitoring
- Hazard Communication
- Field Monitoring
- Hazardous Waste Handling
- 18 Other Areas

Safety

Lock-out/Tag-out
Equipment Inspection and Testing
- -Lead cords
- -Fire extinguishers
- -Chain hoists
- -Other

Employee Training
- -CPR
- -First aid
- -Fire Extinguishers

Fire Response
Over 20 Other Areas

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[1] T. Zhou, et. al., "Vapor Chloride Treatment of Polycrystalline CdTe/CdS Films", *First World Conference on Photovoltaic Energy Conversion* , 1994.

[2] "Interim Qualification Tests and Procedures for Terrestrial Photovoltaic Thin-Film Flat-Plate Modules", SERI/TR-213-3624, 1990.

[3] J.H. Wohlgemuth, "Testing for Module Warranties", *Proceedings of the Photovoltaic Performance and Reliability Workshop*, NREL/CP-410-6033, pp. 200-205, 1993.

[4] R. Sasala, et. al., "Environmentally Responsible Production, Use, and Disposition of Cd Bearing PV Modules", *First World Conference on Photovoltaic Energy Conversion*, 1994.

APPENDICES

APPENDIX A–DELIVERABLE STATUS

No.	Description	Quantity	Delivered
D-1.1	6.0% efficient 60cm x 120cm module produced on 100 kW line	1 each	5.9% efficient 60cm x 120cm module produced on 100 kW line
D-1.2	Documentation of all SCI employees participating in Medical Monitoring Program	1 each	Cadmium urine test results for all employees
D-1.3	Two 5..0% efficient, 8cm x 8cm submodule processed with modified $CdCl_2$ treatment	2 each	6.10% and 7.12% efficient, 8cm s 8cm submodules processed with modified $CdCl_2$ treatment
D-1.4	6.5% efficient 60cm x 120cm module produced on 100kW line	2 each	6.80% and 6.84% efficient, 60cm x 120 cm modules produced on 100kW line
D-1.5	Two 5.0% efficient, 8cm x 8cm submodule processed with modified $CdCl_2$ treatment	2 each	8.26% and 8.5% efficient, 8cm 8cm submodule processed with modified $CdCl_2$ treatment
D-1.6	6.75% efficient, 60cm x 120cm module produced on 100kW line	1 each	6.9% efficient module
D-1.7	60cm x 120cm module produced on 100 kW line representing the best-to-date encapsulation and potting scheme	1 each	6.2% efficient module with Glass/EVA/Glass encapsulation and molded urethane potting
D-1.8	8.0% efficient, 8cm x 8cm submodule processed with a modified $CdCl_2$ treatment	2 each	Deliverable met by D-1.5 (extra submodules delivered for testing purposes)
D-1.9	7.0% efficient, 60cm x 120 cm module produced on 100 kW line	1 each	7.6% efficient module
D-1.10	60cm x 120cm module processed with the modified $CdCl_2$ treatment	1 each	6.7% efficient module
D-1.11	60cm x 120cm module for IQT series at NREL facilities	6 each	Six modules with an average efficiency of 6.9%

APPENDIX B--MILESTONE STATUS

Reference	Task	Description	Status
End of the First Quarter			
m-1.1.1	1	Demonstrate a 6.0% efficient, 60cm x 120cm thin film CdTe PV module produced on the 100 kW line.	A 5.9% module was delivered. Average module efficiency from 100 kW line demonstrated at greater than 6.0%.
m-1.1.2	1	Complete stress testing on ten 60cm x 120cm modules produced on the 100 kW line. Stress testing may include Interim Qualification Tests (IQT), accelerated life tests, or outdoor testing.	Thirteen modules tested in the IQT protocol. Most of these modules received increased levels of testing including up to 100 humidity-freeze cycles.
m-1.1.3	2	Demonstrate a 5.0% efficient, 8cm x 8cm submodule processed with a modified $CdCl_2$ treatment.	Delivered 7.1% and 6.1% efficient submodules.
m-1.1.4	3	Complete functional and economical evaluation of at least 3 encapsulation and 2 potting schemes.	Four encapsulation concepts and two potting concepts were investigated. Currently, SCI is optimizing EVA/glass for the encapsulation and a molded pigtail for the potting.
m-1.1.5	4	Complete detailed process flow diagram of 100 kW line, and identify all processes under investigation or needing further definition.	A Technical Handbook describing all processes has been written as a reference guide to the pilot line operations and the 10 MW line installation process. A line layout has also been completed (see Fig. 1).
m-1.1.6	8	Introduce work force and management to quality assurance.	Training of the 100 kW work force began with emphasis on process variable tracking and data manipulation and summation.
m-1.1.7	9	Demonstrate that all employees are participating in a Medical Monitoring program.	SCI maintains a urine testing program that includes all operational staff, outside consultants and contracted labor.

m-1.1.8	9	Identify processes that may need off-line waste conditioning to reduce their environmental impact.	SCI engaged the Edison Technology Center to investigate process waste handling related to cadmium bearing materials. Other processes have been identified and discussed with selected vendors.
End of the Second Quarter			
m.1.2.1	1	Demonstrate a 6.5% efficient, 60cm x 120cm thin film CdTe PV module produced on the 100 kW line.	A 6.8% module was delivered. Average module efficiency on the 100 kW line exceeded 6.5%.
m-1.2.2	1	Complete stress testing on ten 60cm x 120cm modules with initial efficiencies greater than 6.0% produced on the 100 kW line.	SCI is introducing at least 10 modules per month into the IQT protocol. All of these modules have greater than 6.0% efficiency.
m-1.2.3	2	Demonstrate a 6.0% efficient, 8cm x 8cm submodule processed with a modified $CdCl_2$ treatment.	Delivered two modules with efficiencies of greater than 8.0%.
m-1.2.4	3	Complete preliminary IQT evaluation of prototypes.	Over 20 modules were tested through the IQT protocol during evaluation of prototypes. Currently, testing is continuing on the EVA/glass/pigtail design.
m-1.2.5	4	Complete definition of tempering system including sequence relative to semiconductor deposition.	SCI has not determined whether or not tempering is a critical or necessary process for making high quality films. With the current encapsulation design, tempering of the superstrate to increase its strength is not necessary. The process will undergo further evaluation.
m-1.2.6	4	Complete definition of CdS and CdTe deposition systems, and TCO coating thickness.	The TCO for the startup of the 10 MW line is a low resistivity (8 ohm/square) product available in sufficient volumes to meet SCI's long term demand. A high-throughput deposition system was designed and built and is currently under startup testing. The deposition components underwent preliminary testing in SCI's research deposition system showing encouraging results.

m-1.2.7	5	Revise conceptual layout of 20 MW per year manufacturing facility to include up to date information from product and process definition work.	A new layout was completed (see Fig. 1).
m-1.2.8	8	Establish quality assurance laboratory for 100 kW line.	Equipment was installed to give SCI the capability to perform complete IQT protocols in-house. Further equipment is available for in-line process control.
m-1.2.9	9	Complete preliminary action plan for waste handling and recycling programs.	SCI is active on three fronts related to SHED issues: 1) an outside consultant has been engaged to develop on-line waste handling processing, 2) a product recycling program is under development, and 3) agreements with raw materials suppliers are underway.
End of Third Quarter			
m-1.3.1	1	Demonstrate a 6.75% efficient, 60cm x 120cm thin film CdTe PV module produced on the 100 kW line.	Demonstrated a 7.7% efficient module. Produced over 50 modules at greater than 6.75%.
m-1.3.2	1	Complete stress testing on 60cm x 120cm modules with initial efficiencies greater than 6.5% produced on the 100 kW line.	SCI has completed four rounds of tests consisting of 39 modules with an average efficiency of 6.3% Round / Modules / Average Efficiency 1 / 10 / 5.8% 2 / 10 / 5.7% 3 / 9 / 6.9% 4 / 10 / 6.9%
m-1.3.3	2	Demonstrate an 8.0% efficient, 8cm x 8cm submodule processed with a modified $CdCl_2$ treatment.	8.5% demonstrated.
m-1.3.4	3	Complete evaluation of prototypes and begin IQT on best encapsulation and potting package candidate.	See m-1.3.2
m-1.3.5	4	Complete definition of patterning and interconnection schemes.	Completed definition of linear interconnect technique utilizing laser scribing. Obtained multiple quotes on industrial systems.
m-1.3.6	6	Complete design of glass preheat station, and utilities for glass preheat station.	Glass preheat station has been designed and built as part of high throughput deposition system currently under testing.

m-1.3.7	6	Complete preliminary estimate of electrical, HVAC, DI washer chiller, drainage, and waste systems demand for 20 MW/year manufacturing line.	Completed with assistance from local engineering/ architectural firm. Efforts continue on detailed analysis of waste systems.
m-1.3.8	8	Complete definition of overall Total Quality Program.	Quality Program outlined based on ISO-9000 standards.
m-1.3.9	9	Complete manual for Hazard Communications Program for production line workers.	Complete. Some workers have finished training.
m-1.3.10	9	Complete manual for Industrial Hygiene Action Plan for Production Facility.	Completed for 100 kW line as part of SCI Safety Packet.
End of Fourth Quarter			
m-1.4.1	1	Demonstrate a 7.0% efficient, 60cm x 120cm thin film CdTe PV module produced on the 100 kW line.	Demonstrated 8.72% efficient module (B14410)
m-1.4.2	1	Complete stress testing on ten 60cm x 120 cm modules with initial efficiencies greater than 6.75% produced on the 100 kW line.	Completed stress testing on 19 modules with average efficiency of 6.9%
m-1.4.3	1	Demonstrate module performance and stability by testing at least three 60cm x 120cm modules for three months in an outdoor test field.	Installed 24 modules on August 29, 1994. As of December 2, 1994 array had improved approximately 4% and average module efficiency was 7.3%.
m-1.4.4	1	Complete the Phase I portion of the effort under Task 1.	Task 1 effort completed.
m-1.4.5	2	Demonstrate a 6.5% efficient, 60cm x 120cm module processed with a modified $CdCl_2$ treatment.	Demonstrated 6.70% efficient module (B9421)
m-1.4.6	2	Complete the Phase I portion of the effort under Task 2.	Task 3 effort completed.
m-1.4.7	3	Demonstrate greater than 80% pass rate for IQT tested modules.	Demonstrated 82% pass rate.
m-1.4.8	3	Complete the Phase I portion of the effort under Task 3.	Task 3 effort completed.
m-1.4.9	4	Complete definition of all process steps including panelization, encapsulation, and interfacial layer.	Completed Standard Operating Procedures and Process Determinations.

m-1.4.10	4	Complete the Phase I portion of the effort under Task 4.	Task 4 effort completed.
m-1.4.11	5	Complete conceptual layout of 20 MW per year manufacturing facility including on-line, off-line, and auxiliary processes.	Layout completed.
m-1.4.12	5	Complete the Phase I portion of the effort under Task 5.	Task 5 effort completed.
m-1.4.13	6	Complete specification of metallization, patterning, lead attachment, automated pinhole repair, encapsulation, and auxiliary glass handling systems, and design of CdS, CdTe, and interfacial layer deposition systems, and quench/tempering system.	Completed specification of all critical systems.
m-1.4.14	6	Complete conceptual design for automated in-line test stations.	completed conceptual design of TCO resistivity, TCO optical transmission, CdTe thickness, Pins, and safety Hi-Pot inspection stations.
m-1.4.15	6	Complete the Phase I portion of the effort under Task 6.	Task 6 effort completed.
m-1.4.16	7	Complete design of utilities for system specified under Task 6.	utility capacities evaluated. Specific utility design not available doe to lack of site.
m-1.4.17	7	Complete the Phase I portion of the effort under Task 7.	Task 7 efforts have been completed except for site specific designs.
m-1.4.18	8	Complete identification of process and product performance indicators.	Over 15 process and product performance indicators have been identified and are being utilized on the 100 kW line.
m-1.4.19	8	Complete definition of training program for production workers.	Current production workers are cross trained on multiple processes to increase overall expertise and awareness of processing activities on product performance.
m-1.4.20	8	Document standard operating procedures for 100 kW line.	Standard Operating Procedures for 100 kW completed but undergo continuous improvement.
m-1.4.21	8	Complete the Phase I portion of the effort under Task 8.	Task 8 effort completed.
m-1.4.22	9	Demonstrate waste management and recycling processes reduce environmental impact of production processes.	Economically and technically feasible waste management and recycling process indicates that cadmium recapture is possible and other wastes can be minimized.
m-1.4.23	9	Complete the Phase I portion of the effort under Task 9.	Task 9 effort complete.

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13. ABSTRACT *(Maximum 200 words)*

This report describes work performed by Solar Cells, Inc. (SCI), under a 3-year subcontract to advance SCI's PV manufacturing technologies, reduce module production costs, increase module performance, and provide the groundwork for SCI to expand its commercial production capacities. SCI will meet these objectives in three phases by designing, debugging, and operating a 20-MW/year, automated, continuous PV manufacturing line that produces 60-cm x 120-cm thin-film CdTe PV modules. This report describes tasks completed under Phase 1 of the U.S. Department of Energy's PV Manufacturing Technology program.

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