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High-Throughput Manufacturing of Thin-Film CdS/CdTe Photovoltaic Modules

**Annual Subcontract Report
16 September 1996–15 January 1998**

D.W. Sandwisch
Solar Cells, Inc.
Toledo, Ohio

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1617 Cole Boulevard
Golden, Colorado 80401-3393
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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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NREL technical monitor: R. Mitchell

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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 large-scale, energy 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 ($>5 \mu\text{m}/\text{min}$). 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, 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 2500 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. Program activities include 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 scaling its pilot production capabilities to a multi-megawatt level. The PVMaT subcontract supports these efforts.

Activities during the third phase of the program concentrated on process development; equipment design and testing; quality assurance; ES&H programs; and large-scale next generation coating system prototype development. These efforts broadly addressed the issues of the manufacturing process for producing thin-film, monolithic CdS/CdTe photovoltaic modules.

Equipment Design and Testing

SCI operates a 100kW pilot production line on which the process is defined and demonstrated. Over 5000 Modules have been processed on this line as part of the development efforts. The process can be described by eight basic process steps (see Table 1.)

Table 1. Process steps needed to manufacture CdTe photovoltaic modules.

Substrate Preparation	Metallization
Semiconductor Deposition	Lamination
Post-Deposition Treatment	Module Finalization
Laser Scribing	Panelization

During the third phase of the subcontract work the process was demonstrated at a 150kW level. Information from this effort allowed for activities to proceed on equipment design and manufacturing layout.

Prototype processing systems have been designed, built and tested to demonstrate process viability. The effort focused on establishing workable standard operating procedures and quantifying process variability. This variability was reduced through equipment modification, process refinement, and operator training. Most of the equipment for the 20MW manufacturing line is available from outside vendors with minimal customization. The semiconductor deposition system is of SCI's design and specification.

Quality Assurance

Quality systems have been established to control the flow of the product and to evaluate its functional dependence on process variables. Over 40 product and process inspections are incorporated to build an information database which drives process

optimization. Some of the processes are manual in nature and require extensive operator training. These processes are automated on the manufacturing line.

Product testing includes but is not limited to power performance, durability performance, and safety-related benchmarks. Over 20kW of modules were produced with an average efficiency of 6.7%.

ES&H Program Development

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 [1,2]. 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 recycling and materials reclamation for in plant scrap and end-of-life products.

Advanced High-Throughput Deposition System

Much of the effort during the third phase of this subcontract was focused on the development and specification of a high-speed, continuous semiconductor coater. The coater design was completed and assembly has begun. The result of these tasks is expected to be the demonstration of a full-scale prototype coater capable of accepting a ribbon of glass at the rate of eight feet per minute.

PVMaT SUBCONTRACT OBJECTIVE

The objectives of this subcontract are 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 shall meet these objectives by designing, debugging, and operating an multi-megawatt 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

- Manufacturing Line Design
- Efficiency Improvement
- Quality Assurance
- ES&H Programs

Phase III

- Manufacturing Line Design and Test
- Efficiency Improvement
- Quality Assurance
- ES&H Programs
- Advanced High-Throughput Semiconductor Coater Design

Phase IV

- Manufacturing Line Demonstration
- Efficiency Improvement
- Quality Assurance
- ES&H Programs
- Advanced High-Throughput Semiconductor Coater Demonstration

PVMat PROGRAM PROGRESS – Phase III

The focus of the activities in the third phase of SCI's PVMat program were directed at process development; equipment design and testing; quality assurance; ES&H programs; and large-scale next generation coating system prototype development. These efforts broadly addressed the issues of the manufacturing process for producing thin-film, monolithic CdS/CdTe photovoltaic modules.

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 $\text{SnO}_2\text{:F}$. Active layers are comprised of the TCO, $0.3\mu\text{m}$ of CdS, $4.0\mu\text{m}$ of CdTe, $0.02\mu\text{m}$ of nickel and $0.3\mu\text{m}$ 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 $65V_{\text{max}}$. The power is collected at each end of the module through a bus bar and ribbon conductor. The ribbon conductors are threaded through a hole in a 3mm thick 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 urethane in a pigtail mold. The urethane is also used to mold four mounting pads onto the back of the module (see Fig. 2). The mounting pads include a threaded insert for easy panelization of individual module installation.

Utilizing this design, SCI has developed products to address both large-scale and small-scale applications. Table 2 describes the attributes of these two products. Alternative potting and mounting designs are offered to address installation requirements. The product for large-scale applications utilizes the molded pigtail and mounting pads to reduce module and panelization costs. The product for small-scale applications provides more installation flexibility by offering a junction box and framing. This product will also be available in a half-size if market conditions warrant.

Table 2. Product characteristics.

	<u>Baseline Product</u>	<u>Secondary Product</u>
Application	Large-Scale	Small-Scale
Nominal Power (8.0%)	58W	58W
Nominal Voltage (V_{max})	65V	17V
Electrical Connection	Pigtail	Pigtail/J-Box
Encapsulation	EVA/Glass/EVA	EVA/Glass/EVA
Panelization	Mounting Pads	Mounting Pads or Frame

Figure 1. Cross Section Schematic

SCI CELL AND MODULE STRUCTURE

(FILM THICKNESS AND LASER SCRIBE DETAIL NOT TO SCALE)

Figure 2. Module Diagram

FRONT VIEW

BACK VIEW

In the long-term, the baseline SCI product will be the 60cm x 120cm high-voltage module targeted at grid-connected applications. 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. The majority of these cost reductions have resulted from the elimination of module framing and the substitution of pigtails for the junction box.

During the second and third phase of the subcontract work the process was demonstrated at a 150kW level. Even though throughput was increased substantially during that period the yield and average efficiency increased from previous performance (see Figure 3). Information from this effort allowed for activities to proceed on equipment design and manufacturing layout. Due to resource limitations pilot production activities were reduced so that greater effort could be employed towards the design and debug of full-scale manufacturing equipment.

Task 17a Manufacturing Line Equipment Design

Task 17b Manufacturing Equipment Testing and Debugging

The process can be described by eight basic process steps (see Table 1). 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. 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. A more detailed description of the process and associated equipment is provided below

The manufacturing line is composed of about 40 pieces of equipment plus various conveyors (see Figure 4). 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 3 shows that over 70% of the capital cost is attributed to only 4 of the 40 process steps. Additional information about these systems is provided below.

Table 3. Capital cost of major process equipment with number of vendor quotes available for review.

<u>Equipment</u>	<u>Suppliers</u>	<u>% of Capital</u>
Laser Systems	4	25%
Deposition System	custom	20%
Metallization System	4	14%
Laminators	3	12%

Figure 3. Production Distribution.

Figure 4. Unannotated line schematic.

Substrate Preparation

SCI currently purchases TCO-coated glass from an outside supplier. This glass is received in raw cut form. 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. In order to eliminate or reduce handling safety issues and to prepare the glass for semiconductor deposition the substrate is edge seamed and washed. 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 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.

During the third phase of this effort, the substrate preparation equipment was upgraded to provide a ten-fold capacity increase over SCI's pilot line equipment. The equipment employed is standard and readily available from multiple suppliers. The two systems (see Fig. 5) were installed; brought on-line; and demonstrated multimewatt capability.

Semiconductor Deposition

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 similar to close-spaced sublimation. 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.

During the third phase of the subcontract modifications were made on the LDS to test component designs intended for a multimewatt coater. The modifications included the addition of load locks; the replacement of batch coating components with on-demand coating components; and the upgrade of the control system. The load locks (see Fig. 6) have resulted in a 75% decrease in cycle time from ten minutes to 2.5 minutes. In addition, the load locks provide a stable pressure in the deposition zone. Before the load locks were employed the entire system would be pumped from atmosphere to roughly 1 Torr for each substrate. With the load locks the deposition zone is maintained at roughly 1 Torr during an entire run of several hundred substrates.

Figure 5. Photograph of substrate washer.

The on-demand coating components have resulted in a four-fold increase in deposition rate and a three-fold increase in material utilization from 30% to over 90%. Furthermore, the coating components have eliminated the need to oscillate the substrate in the deposition zone to "average out the thickness" by providing an accurate amount of reacted raw material vapor to the substrate as it passes unidirectionally.

The control system and program for the LDS was also enhanced to decrease process variability and labor. The upgrades resulted in the automation of the conveyance and deposition components and a 75% reduction in labor.

These modifications were demonstrated during a continuous 100-plate run and have been incorporated into the multimewatt coater design. These features (see Table 4) result in 100 times the annual capacity of the pilot system with only a moderate increase in system length (36 feet vs. 46 feet) and a significant decrease in costs related to labor, materials, and process variability. The multimewatt manufacturing system is designed for throughput of one module/minute.

Table 4. Comparison of pilot deposition system to high-throughput deposition system.

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

The multimewatt coater 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. This flexibility results in enhanced film growth control and reduced materials costs. The vapor generators are located within the system close to the deposition zone in order to limit the possibility of premature deposition away from the substrate.

Equipment 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 design uses heaters which can be replaced from the outside of the system or are redundant to facilitate maintenance and greatly reduce downtime due to heater failures.

CdS Deposition—CdS is deposited to a thickness of 3000 Angstroms in approximately 20 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 one minute. Substrate temperatures reach up to 620C 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.

SCI also investigated close clearance slit "seals" as an alternative to load locks. These seals could provide significant opportunities to increase single system capacity to well above 100MW. These efforts are underway in parallel with the more conventional approaches (see Task 22).

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

Post Deposition Treatment

Two approaches were used in developing alternative processes to the wet CdCl₂ 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 was 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.

Figure 6. Photograph of entrance load lock on LDS.

The modification approach focused on changing the wet treatment to a process with reduced process time, reduced materials cost, and better uniformity. During the second phase of the subcontract effort SCI developed a post deposition vapor treatment which eliminated the traditional wet dip CdCl_2 treatment. The process uses HCl in moderate vacuum with a substrate temperature above 350 degrees Celsius [3]. This process significantly increased 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.

Table 5 compares the vapor process to the wet dip process. During phase three a full-scale prototype system was tested (see Fig. 7). The results indicated that the operating window for the vapor process was considerably smaller than that of the wet process. Therefore, SCI specified, purchased and installed a full-scale batch oven to handle multimewatt quantities of substrates for this process. SCI will continue to develop the vapor process and implement it as soon as the operating parameters are within manufacturing specifications.

Table 5. Comparison of the wet dip CdCl_2 treatment to an alternative vapor process.

	<u>Wet Treatment</u>	<u>Vapor Treatment</u>
Avg. Module Efficiency	7.5%	7.0%
High V_{oc} (mV)	820	800
Process Time (min)	>60	<30
Process Steps	6	2
Materials	Solvents	No Solvents
Material Utilization	Low	High
Rinse Needed	Yes	No

Laser Scribing

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 25 μm -50 μm 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.

Figure 7. Photographs of full-scale CdCl_2 treatment oven.

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 200 μ m-400 μ m 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.

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 500 μ m-1000 μ m. The scribe 3 channels are identical in width to those of Scribe 1 but only ablate the metal layer.

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. A preferred vendor has been chosen based on technical abilities, component reliability, and photovoltaic module manufacturing experience. The specified laser systems incorporate laser packages which are known for outstanding stability and reliability. The vendor 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.

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 800 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).

One drawback of the preferred vendor's quote is the lead-time before delivery of the systems. Consequently, SCI took advantage of the opportunity to procure two used systems (see Figure 8). Both systems are identical and generally match the specifications for the new systems. Installation and debug activities are underway.

Metallization

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 sputtering. Metallization is accomplished in one pass under the targets. The module then exits the chamber through the exit load lock. The system is of conventional design. SCI's pilot sputtering unit is a critical bottleneck in its current process. The cycle time of the sputtering unit is 20 minutes/substrate. Even though SCI has identified several well-qualified suppliers for its multimewatt sputtering unit, it has not purchased a unit due to budgetary constraints. SCI has a high level of confidence that this step does not represent a technical risk to scaling to the target levels.

Lamination

Before lamination, an edge deletion 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. After the scribe is complete, 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.

The submodules which have passed the IV tests are moved via conveyor to a lamination assembly table where they are automatically placed into set up racks. Each rack holds three submodules. The submodules will remain in these racks throughout the lamination process. An operator places a pre-assembled 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 a 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.

Figure 8. Photograph of industrial laser scribing system.

The cover glass is 60cm x 120cm x 3mm with a hole for electrical feedthroughs. It is inspected for physical defects, and placed on a conveyor which moves the glass through a washer. The bus bar, conductors, and wire are attached to provide electrical connection.

During this phase, SCI specified, procured, and installed a glass hole drilling station. This station is used to prepare standard float line glass for the lamination process. The hole is positioned on the substrate based on the customers specifications for feedthrough location. This equipment was added to the operation to increase product design flexibility and reduce materials costs. Preliminary results indicate a savings of up to 50% per cover glass or \$0.05/W.

Module Finalization

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 electrical connections are located.

The module first moves under a spray applicator where a layer of primer is applied. The module then moves to the application station where an mold is pressed against the cover glass surface. Urethane is poured into the mold forming both the mounting pads and potting pads. The mixing and metering equipment are standard. The tooling for the molds is straight forward and has been demonstrated on pilot production.

During this phase, SCI procured automatic metering equipment to replace hand mixing and measuring on the pilot line (see Fig. 9). Startup and debug activities are underway and initial results have indicated a superior resultant mix with a substantial reduction in labor (i.e. potential of 90% decrease).

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 is attached.

This design has proven to be very effective in providing reliable and safe modules. Since beginning the PVMaT program, Interim Qualification Test [4] pass rates have increased from below 10% to 100% (see Fig. 9).

Panelization

In Phase I, SCI developed a glass/EVA/glass encapsulation process with pigtails and four mounting pads for module installation (see Fig. 2). This module design coupled with frameless panelization (see Fig. 10) reduced panel costs by over 40% (see Fig. 11).

The panelization materials costs alone were reduced by over 50%. Furthermore, labor associated with panel installation and field wiring has been demonstrated to be as much as 60% less than comparable power systems utilizing framed panels.

The panelization process was demonstrated at a multimewatt level in producing over 25kW of standardized panels. A prototype panelization station with registration table, ultrasonic wire welder, and low-light voltage tester was utilized during these pilot production efforts. Labor costs associated with frameless panelization were reduced by over 90% compared with SCI's previous framed designs.

Figure 9. Metering equipment for the potting process.

Figure 10. Photograph of 25kW array at Edwards Air Force Base demonstration framless panel installation.

Figure 11. Product finalization cost reductions.

Task 18 Continuous Production Line Run
 Task 19 Average Efficiency Improvements
 Task 20 Quality Assurance Development

During the third phase of the subcontract, SCI reduced its production activities to focus on the equipment design and debug activities. However, towards the end of the phase activities were ramping up with the goal to complete a 100kW array in Toledo, Ohio by the end of 1998. Figure 12 shows the history of module performance for the period from early 1994 to the present. The data includes those modules used by the R&D group to test new processes and methods and includes data related to the debug of new equipment. The average efficiency for all modules during this period was 6.44%. However, those produced with the standard process are represented by the upper end of the distribution and approach an average of 7.0%.

Various steps of the process have been demonstrated at throughput levels of 100 units/day which represents approximately 1MW of annualized output. The key remaining bottleneck is the sputtering unit. Capacity improvements will progress through the fourth phase of the effort.

Figure 12. Historical efficiency data for R&D and production modules.

Task 21 ES&H Program Development

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 [1,2]. 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 recycling and materials reclamation for in plant scrap and end-of-life products.

Task 22 Large-Scale Deposition System

The main obstacle to the wide spread use of photovoltaics as a renewable source of energy has been cost. The key to lowering the cost of photovoltaics generated energy to the levels of conventional sources of energy is the manufacturability of the photovoltaics module and more specifically the semiconductor coating. It is necessary to have a technology that is scalable in order to reach the sizes and throughputs needed to make the use of photovoltaics power economically viable. By those well versed in the photovoltaics field, the use of thin films are thought to offer the best chance of obtaining a low cost module. This technology can produce large area monolithic films and is adaptable to high volume manufacturing processes.

The deposition of thin films has been demonstrated in batch type vacuum operations. Standard equipment would employ the use of a vacuum chamber fitted with load locks on each end to increase the throughput. Figure 6 shows the LDS with load locks installed. The use of load locks is well understood and used industry wide. Its implementation is straightforward.

The length of the vacuum system would need to be increased to accommodate higher throughputs. The load locks contain many moving mechanical parts. The capital, manufacturing and maintenance costs associated with a batch type operation cannot economically reach the necessary throughputs for low-cost production. A load lock system cannot operate with a continuous ribbon of glass passing through the vacuum chamber.

The development of the Advanced High Throughput Deposition System (AHTDS) addresses the limitations of a load lock system. With this system, the load locks are replaced with slit seals. Slit seals allow for the transporting of the substrate from atmosphere to vacuum without the use of intermediate gate valves. This will allow the passage of a continuous ribbon substrate material such as that produced by a glass melting operation. The conceptual design of the AHTDS was completed during Phase III, thirteenth quarter. The vacuum system would be built in modules (see Fig. 13). The system can be expanded for higher throughputs by adding more modules. The mechanical design was 95% complete by the end of the fourteenth quarter.

During the fifteenth quarter substantial developments were made in the deposition process where extremely high deposition rates were achieved. Further tests were performed on the HTDS (high throughput deposition system) where a high temperature slit seal was developed. Both of these factors resulted in a reevaluation of the AHTDS design. Since the deposition rates are high, it is only necessary to have a short vacuum chamber. Figure 14 shows the comparison between the relative sizes of vacuum chambers for the current and proposed coating systems. The short vacuum system would require the slit seals to operate at elevated temperatures. Figure 15 shows a cross-section of the vacuum chamber that is approximately 1m long as compared to 13m long for the LDS vacuum system. This greatly simplifies the operation of the system and reduces the costs involved in maintaining a large vacuum system.

By the end of the sixteenth quarter 90% of the mechanical design and 50% of the system design was completed on the short AHTDS (see Fig. 16). The balance of the design will be completed and the fabrication will begin early in Phase IV. The final assembly and testing will begin by mid-Phase IV. By the end Phase IV the project will be on schedule to complete deposition trials and demonstrate a throughput rate of 1000 ft²/hour.

Figure 13. Schematic of AHTDS modular design.

Current Continuous Coating System

indicates vacuum chamber

Proposed Continuous Coating System

Figure 14. Schematic of vacuum length comparisons.

Figure 15. Schematic of AHTDS vacuum section.

Figure 16. AHTDS design schematic.

STATUS OF DEOVERABLES AND MILESTONES

Table 6. Deliverables Status

	Description	Delivered
D-3.1	Representative 60W, fully encapsulated, 60cm x 120cm thin-film CdTe modules produced on the 100kW pilot production line (2 each).	Two best effort modules at 53.5W and 58.8W.
D-3.2	Four-module panel made with fully-encapsulated 7.5% efficient, 60cm x 120cm thin-film CdTe modules produced on equipment for the 20MW production line and 100kW pilot production line where needed (1 each).	Four-module panel with fully encapsulated modules rated at 7.26%, 7.06%, 7.00%, and 7.27%.
D-3.3	Representative 54W, fully-encapsulated 60cm x 120cm thin-film CdTe module produced on the 20MW deposition equipment and 100kW pilot production line where needed (2 each).	Two modules rated at 50W and 53W.
D-3.4	Letter report on the effectiveness of SCI's efforts on average efficiency improvements, quality assurance development, and ES&H programs (1 each).	Complete.
D-3.5	Four-module panel made with fully-encapsulated 8.0% efficient, 60cm x 120cm thin-film CdTe modules produced on the 20MW deposition equipment and 100kW pilot production line where needed (1 each).	Due for delivery March 15, 1998

Table 7. Milestones Status

End of the Thirteenth Quarter			
m-3.1.1a	Task 17a	Complete installation of glass seamer, glass washer, CdS/CdTe deposition system.	Installation complete. Startup activities underway. Plan to increase capacity on deposition system in 1998.
m-3.1.1b	Task 17a	Complete operational cost analysis of multi-megawatt plants with optimization of capital, labor,	Interactive animation and simulation software procured. Process fully modeled. System has

		materials, and energy.	already saved \$15,000 in capital costs.
m-3.1.3a	Task 18	Demonstrate 50 modules/week production rate on 100kW pilot production line and some equipment installed for the 20MW manufacturing line under Tasks 10 and 12.	Complete.
m-3.1.3b	Task 19	Demonstrate average efficiency of 7.0% on molds from the 100kW pilot production line and 20MW manufacturing line equipment installed under Tasks 10, 11, and 12.	Produced 120 60cm x 120cm modules with average efficiency of greater than 7.0% and variation of less than 10% on 100kW and 20MW production line equipment.
m-3.1.4	Task 20	Utilize quality assurance program to increase yield to greater than 75% and decrease standard variation to +/-10% on 100kW production line.	Efficiency has improved from below 6.0% to above 7.0% while variation has decreased from approximately 20% to well below 10%.
m-3.1.5	Task 21	Complete conceptual design of the Advanced High-Throughput Deposition	Complete.

End of the Fourteenth Quarter			
m-3.2.1a	Task 17a	Complete installation of glass preheat furnace.	Complete.
m-3.2.1b	Task 17a	Complete installation of auxiliary equipment and quench/tempering system.	Complete.
m-3.2.1c	Task 17a	Complete testing and debugging on a stand alone basis of equipment installed under Tasks 10, 11, 12, and 17a.	Complete.
m-3.2.1d	Task 17a	Complete site selection for multi-megawatt module assembly line.	Complete. Site requirements specified. Current site suitable for up to 1MW of capacity.
m-3.2.2a	Task 19	Demonstrate 70 modules/week production rate on 100kW pilot production line and some equipment installed for the 20MW manufacturing line under tasks 10, 12, and 17a.	Complete.
m-3.2.3a	Task 19	Demonstrate average efficiency of 7.25% on modules from 100kW pilot production line and 20MW manufacturing line equipment installed under Tasks 10, 11, 12, and 17a.	Complete.
m-3.2.4	Task 20	Utilize quality assurance program to increase yield to 90% and decrease standard variance to +/- 7.5% during	SCI has demonstrated an 85% yield with a less than 5% standard variance during a monthly run of

		a one-month run on the 100kW pilot production line.	the pilot line.
m-3.2.4a	Task 20	Begin module testing using "Recommended Practice for Qualification of Photovoltaic (PV) Modules, PAR1262".	SCI modules have undergone and passed 1000-hour damp heat test at an independent laboratory.
m-3.2.5	Task 21	Complete assessment of safety levels relative to industry averages and environmental program effectiveness through reduced waste.	SCI has undergone OSHA reviews and workers' compensation rating reviews and have received favorable assessments. Waste due to module processing has been reduced by up to 90% through the EHS programs.
m-3.2.6	Task 17	Complete mechanical design of the Advanced High-Throughput Deposition System.	SCI has identified a design which reduces the vacuum section of the coater by over 90%. Design is 90% complete.

End of the Fifteenth Quarter			
m-3.3.1a	Task 17a	Complete design revisions needed on production line equipment.	SCI's large deposition system was upgraded to include improved heater, conveyor, vacuum, and deposition components. Improvements have increased capacity of the machine ten-fold while providing for better quality products.
m-3.3.1d	Task 17b	Complete testing and debugging of 20MW deposition equipment on an operation cell basis.	Deposition system has been demonstrated at the 1MW level. Further capacity enhancements are scheduled during Phase IV.
m-3.3.1e	Task 18	Demonstrate 10 modules/hour production rate on the 20MW deposition system.	Complete.
m-3.3.1f	Task 18	Demonstrate 80 modules/week production rate on 100kW pilot production line and some equipment installed for the 20MW manufacturing line under Tasks 10,12, and 17a.	Complete.
m-3.3.2a	Task 19	Demonstrate average efficiency of 7.25% on modules from 20MW manufacturing line production activities under Task 18.	Produced 120 60cm x 120cm modules with average efficiency of greater than 7.0% and variation of less than 10% on 100kW and 20MW production line equipment.
m-3.3.2b	Task 20	Utilize quality assurance program to increase yield to 50% and decrease standard variation to +/- 10% from production activities under Task 18.	Complete.

m-3.3.3	Task 22	Complete system design of the Advance High-Throughput Deposition System.	Preheat, cooling, and quench sections are 100% complete. Deposition zone is 80% complete.
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End of the Sixteenth Quarter			
m-3.4.1a	Task 17a	Begin installation of first multi-megawatt line.	SCI has already begun to debug some of the multimegawatt equipment at its Westwood Ave. site in Toledo, Ohio. The company is actively searching for a new production site, however, this step is contingent on finding a customer or partner for the multimegawatt production facility.
m-3.4.1b	Task 17a	Complete the Phase III portion of the effort under Task 17a.	85% complete. No change in Phase IV milestones are expected.
m-3.4.1b	Task 17b	Complete testing and debugging on a continuous basis of 20MW deposition equipment.	85% complete with debug of 4MW capacity deposition system.
m-3.4.1c	Task 17b	Complete the Phase III portion of the effort under Task 17b.	85% complete. No change in Phase IV milestones are expected.
m-3.4.2	Task 18	Demonstrate 20 modules/hour production rate on 20MW deposition equipment.	Demonstrated 18 plate/hour production rate.
m-3.4.3	Task 18	Complete the Phase III portion of the effort under Task 18.	95% complete. No change in Phase IV milestones are expected.
m-3.4.5a	Task 19	Demonstrate average efficiency of 7.5% on modules from the 20MW deposition equipment and pilot production line.	Module efficiency has ranged from 5.0% to 7.5%. Cell measurements from the high volume coater have consistently been above 10%. The coating team is focusing on film uniformity to improve the distribution and average efficiency of the modules.
m-3.4.6	Task 19	Complete the Phase III portion of the effort under Task 19.	80% complete. No change in Phase IV milestones are expected.
m-3.4.7	Task 20	Demonstrate that Total Quality Program has led to continuing increases in productivity and module efficiency.	Productivity on two key process steps, deposition and lamination, has increased by 300% and 500%, respectively. Efforts have focused on process control and throughput. Module efficiency has been flat during this phase; however, key diagnostic capability has been installed and significant improvement in efficiency and variation is expected in Phase IV due to these line enhancements.

m-3.4.8	Task 20	Complete the Phase III portion of the effort under Task 20.	Complete. No changes in Phase IV milestones are expected.
m-3.4.9	Task 21	Complete review of fully operational Health, Safety, and Environmental program and assess its effectiveness.	Complete.
m-3.4.10	Task 21	Complete the Phase III portion of the effort under Task 21.	Complete. No changes in Phase IV milestones are expected.
m-3.4.11	Task 22	Complete mechanical assembly of Advanced High-Throughput Deposition System.	Cooling and quenching components are in house and in debug. Preheat and deposition zone components are due in the first quarter of Phase IV.
m-3.4.12	Task 22	Complete the Phase III portion of the effort under Task 22.	The mechanical assembly is not complete however the major section of the system is being procured through a vendor and delivery is scheduled for the first quarter of Phase IV. There is no impact on the Phase IV objectives and milestones. In fact, using the vendor will decrease the length of the debug period. No changes in Phase IV milestones are expected.

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