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

Annual Subcontract Report, 16 November 1994 - 15 November 1995

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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 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, 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 preparing to scale its pilot production capabilities to a multi-megawatt level. The PVMaT subcontract supports these efforts.

Activities during the second year of the program concentrated on process development; equipment design and testing; quality assurance; and ES&H programs. 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 2500 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 second year 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 will be 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 product recycling by shipping modules to a raw material supplier for reintroduction into the smelting process.

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 it's 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

- 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

PVMaT PROGRAM PROGRESS - YEAR 2

The focus of the activities in the second year of SCI's PVMaT program were directed at process development; equipment design and testing; quality assurance; and ES&H programs. 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 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 $65V_{max}$. 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.

	Baseline Product	Secondary Product
Application	Large-Scale	Small-Scale
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

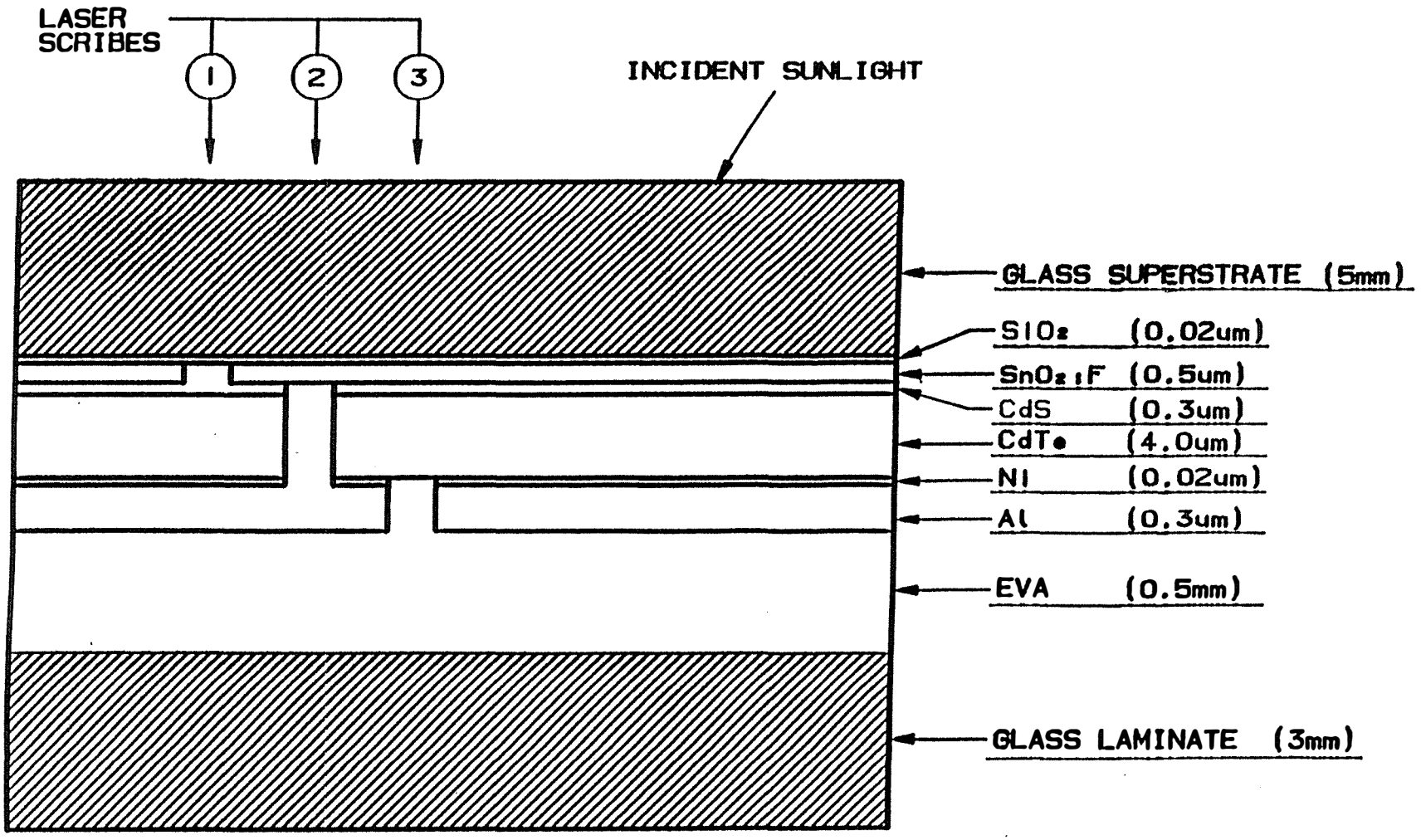
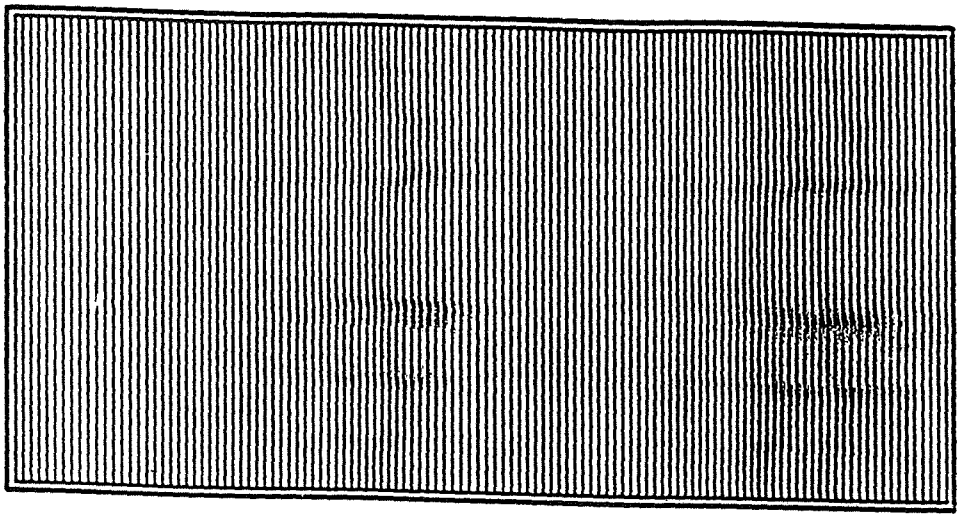
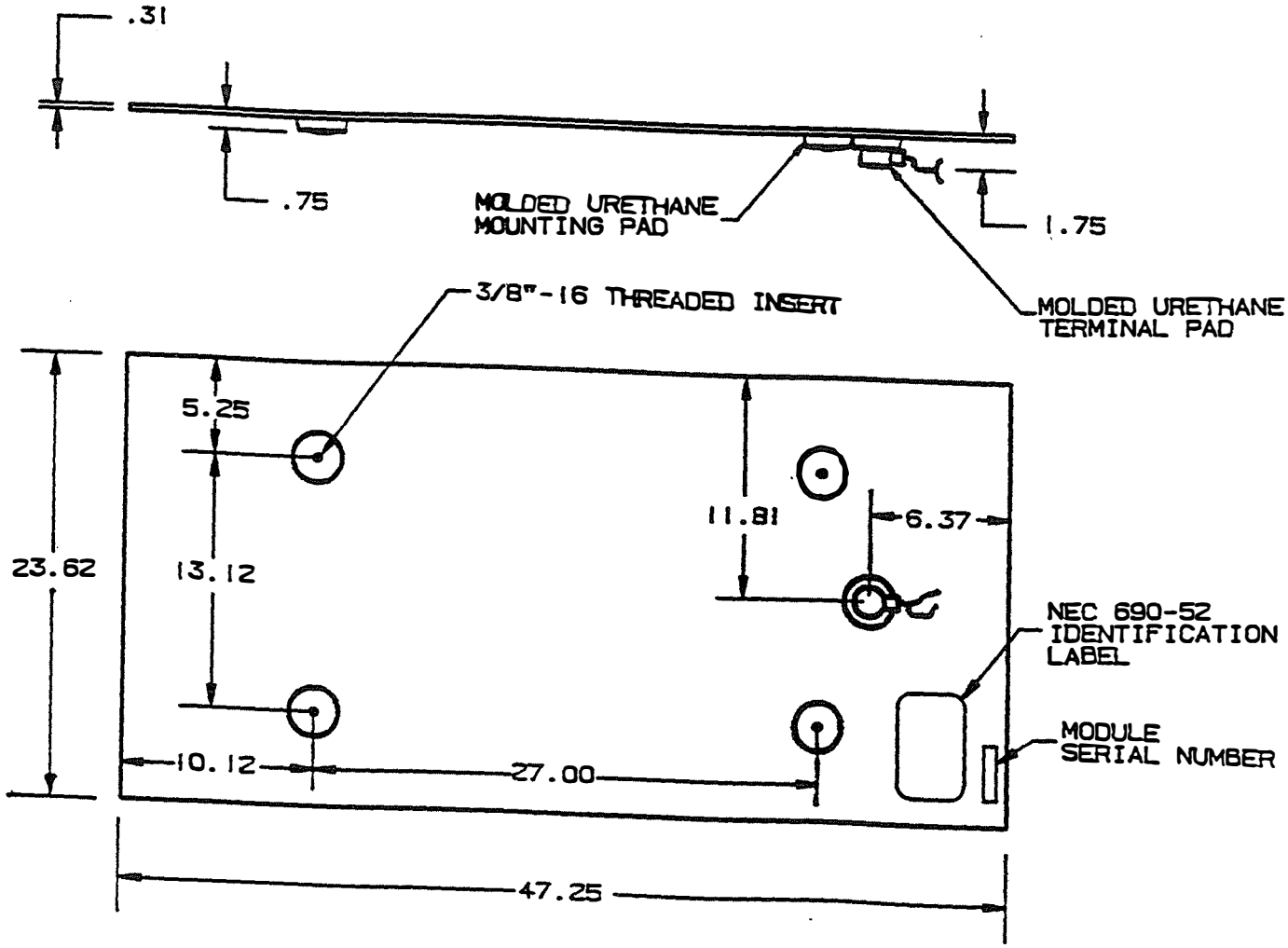


Figure 1 Cross Section Schematic

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 year of the subcontract work the process was demonstrated at a 150kW level. This level is a ten-fold increase over the previous year's production. Even though throughput was increased substantially the yield and average efficiency increased (see Figure 3). Information from this effort allowed for activities to proceed on equipment design and manufacturing layout. 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, 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. A more detailed description of the process is provided below.

The manufacturing line is composed of about 40 pieces of equipment plus various conveyors (see Figure 3). 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 4 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.

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

Figure 3. Production Distribution.

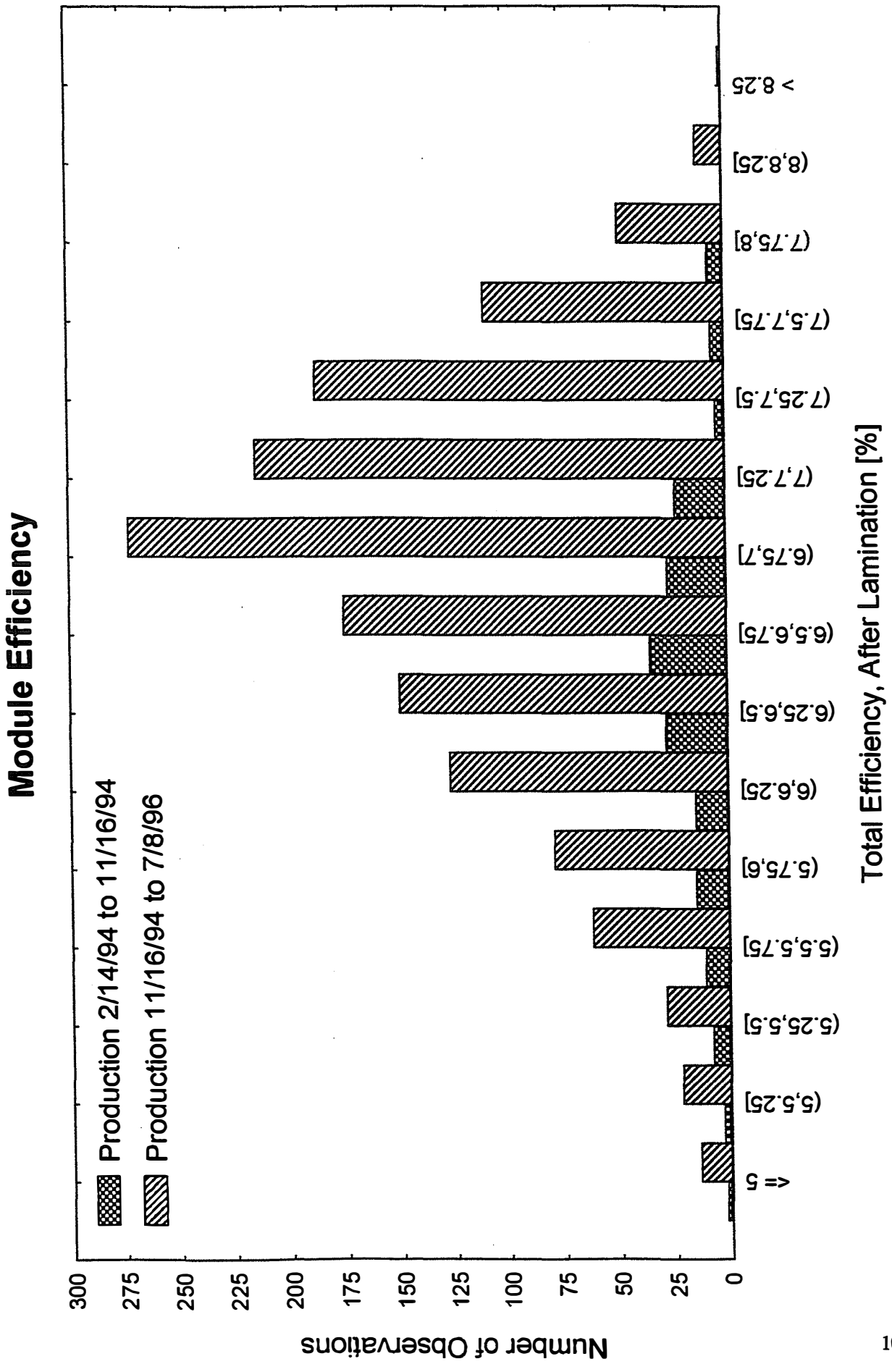
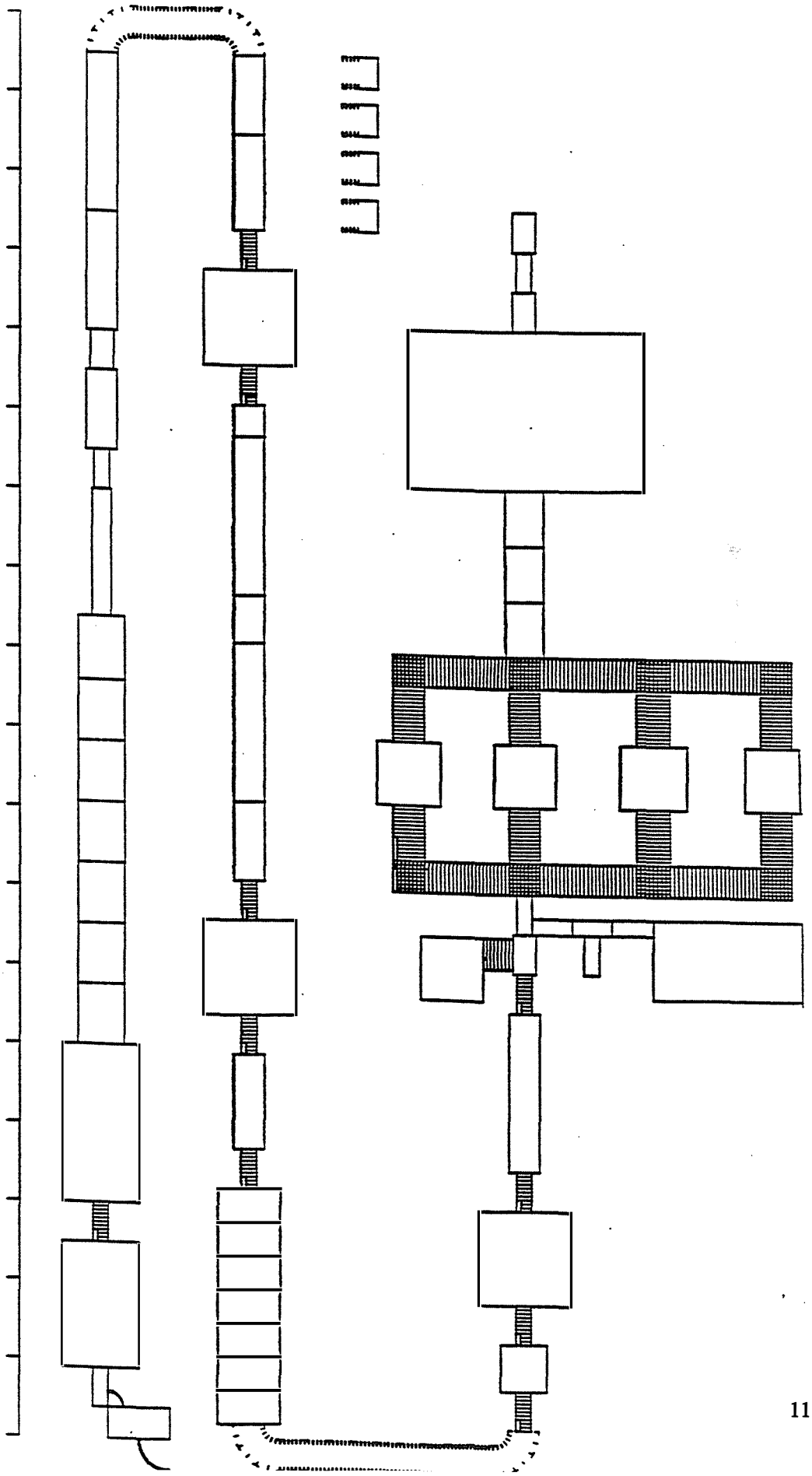


Figure 4. Unannotated line schematic.



Substrate Preparation

SCI currently purchases TCO-coated glass from an outside supplier this glass is received in raw cut form. 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 equipment for these processes are on-line (see Fig. 5) and have demonstrated multimegawatt capability.

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.

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.

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 and transferred its focus to the development of its production system.

The HTDS (see Fig. 6) incorporated several advantages over the pilot deposition system including increased throughput and steady-state, continuous operation (see Table 4). The main functional advantages of the production deposition system are on-demand raw material feed and 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.

Figure 5. Photograph of substrate seamer and washer

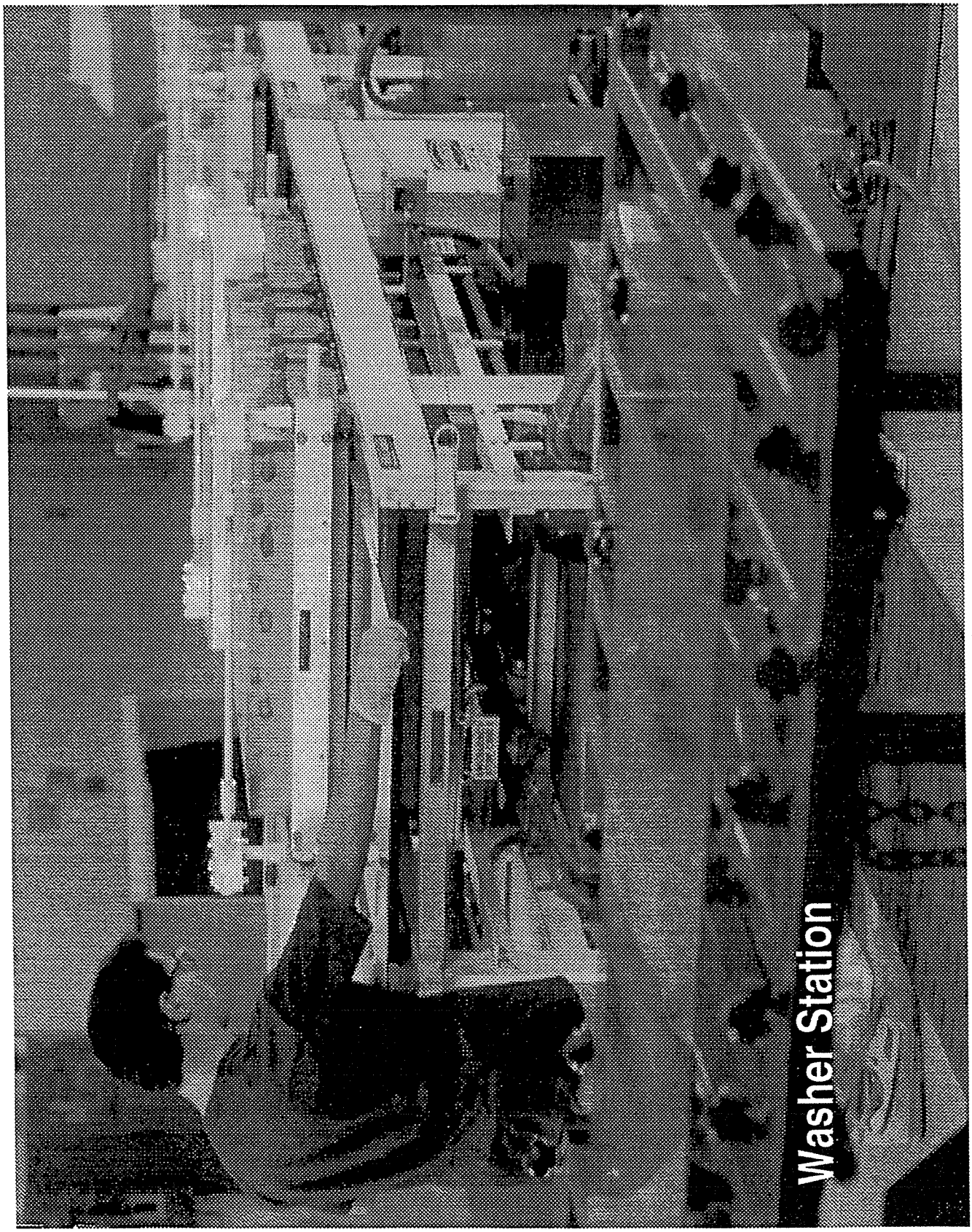


Table 4. Comparison of pilot deposition system to high-throughput deposition system.

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 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. 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.

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 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.

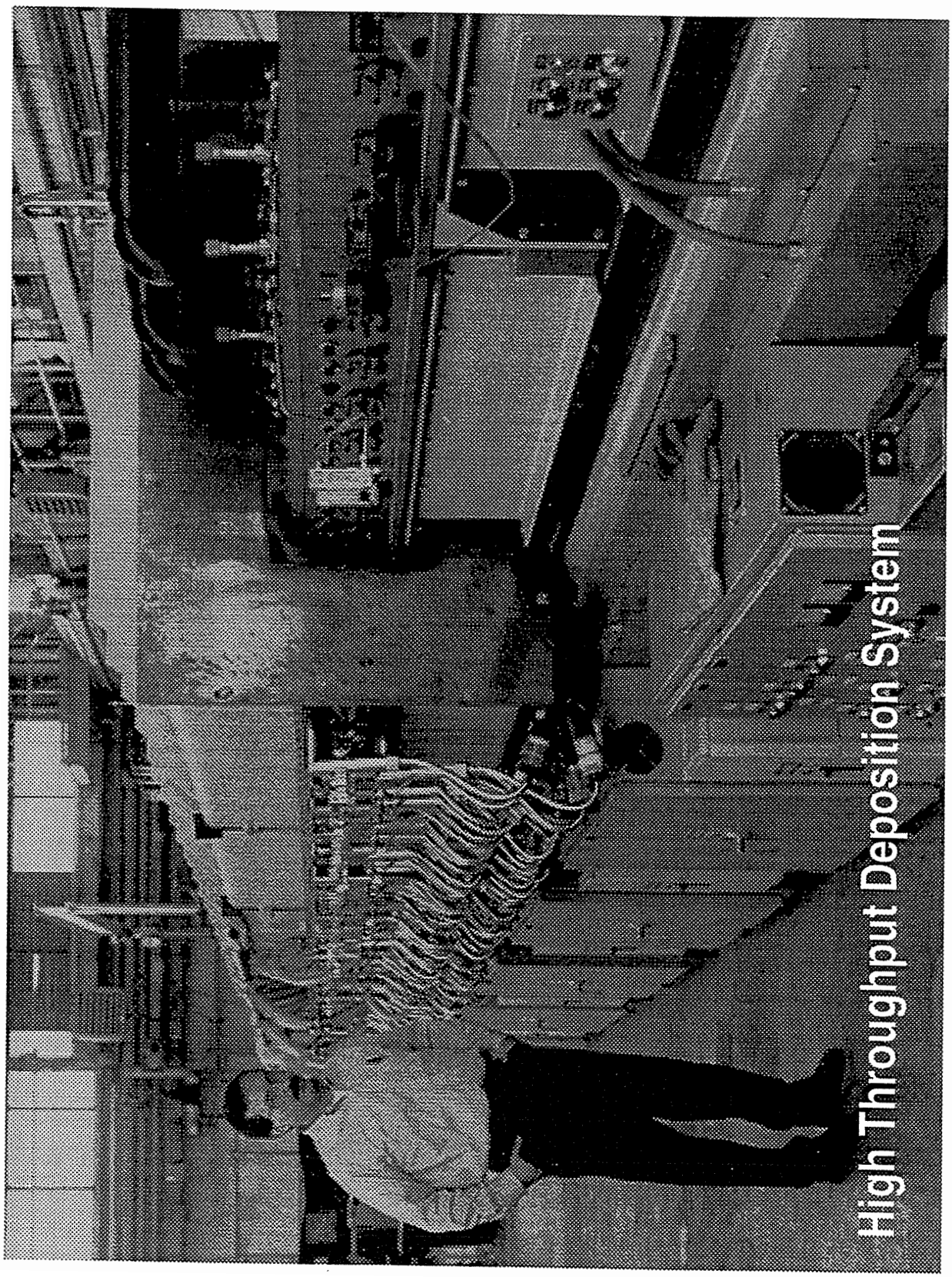


Figure 6. Photograph of high-throughput deposition system.

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.

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 $CdCl_2$ 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 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.

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 [3]. 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. Table 5 compares the vapor process to the wet dip process. During the second year efforts a full-scale prototype system was designed and built (see Fig. 7).

Figure 7. Photograph of full-scale prototype HCl treatment system.

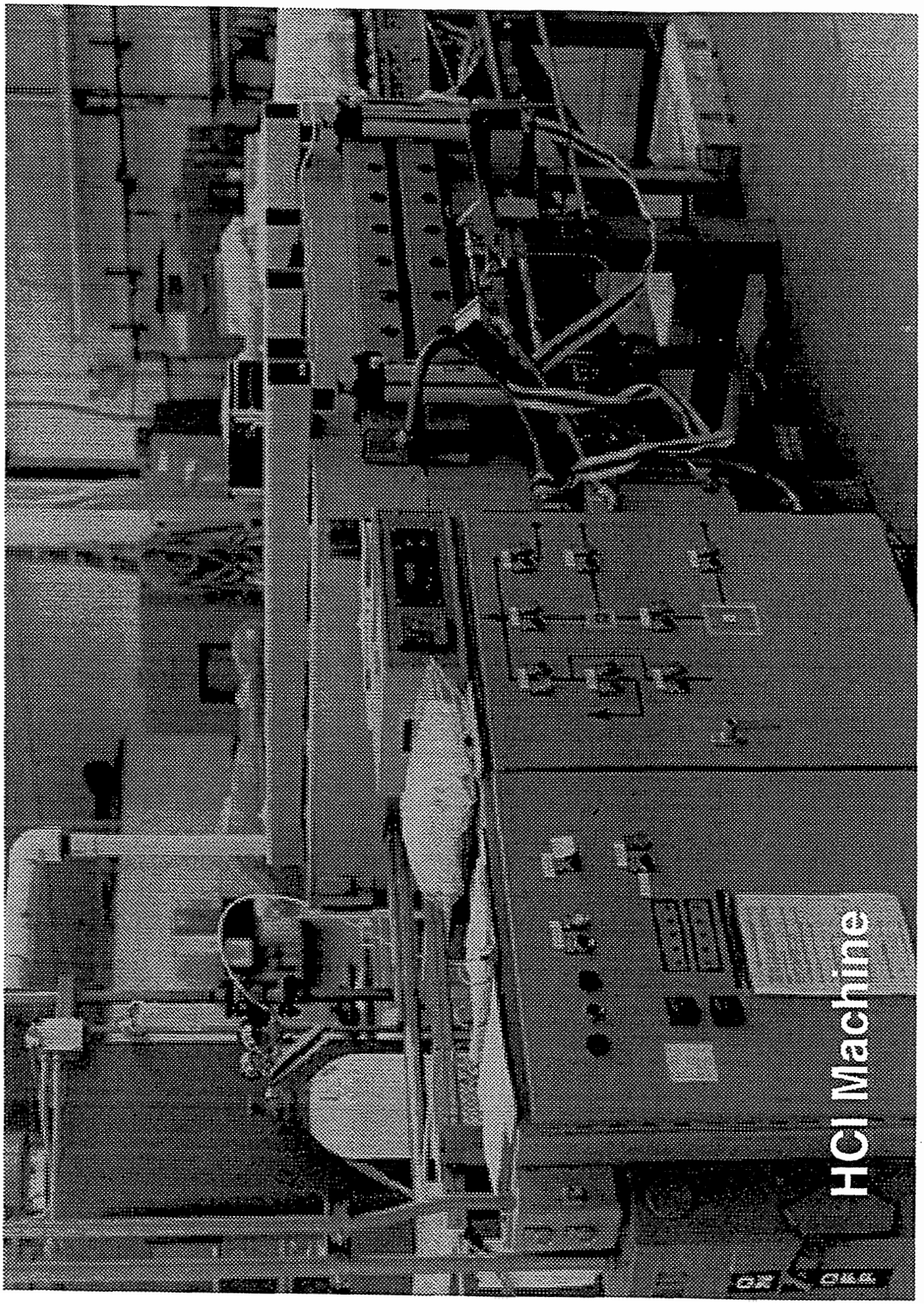


Table 5. Comparison of the wet dip $CdCl_2$ treatment to an alternative vapor process.

	Wet Treatment	Vapor Treatment
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 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.

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.

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-1000µm. 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.

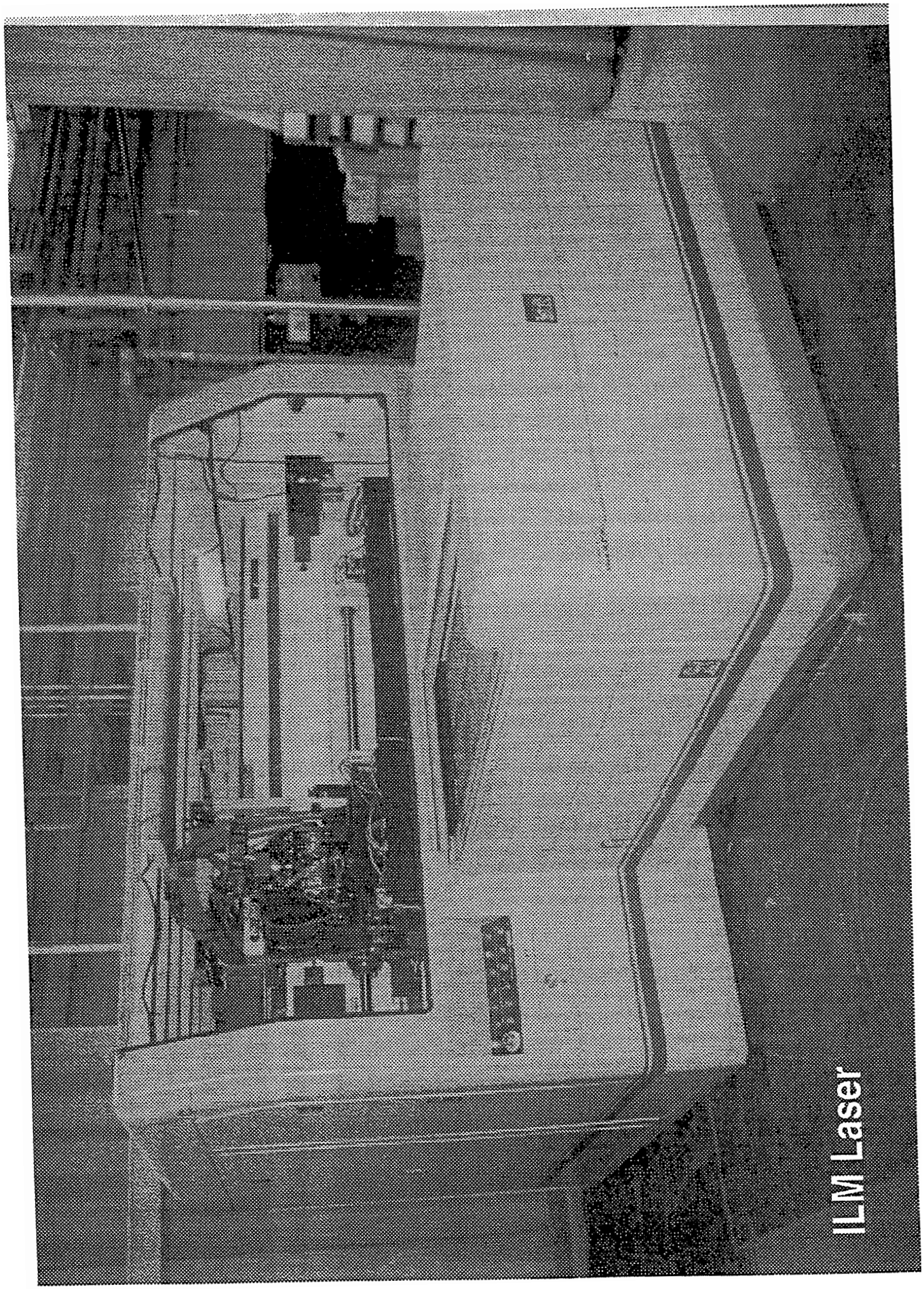
Metallization

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.

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,

Figure 8. Photograph of industrial laser scribing system.



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 conveyer 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.

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 conveyer which moves the glass through a washer. The bus bar, conductors, and wire are attached to provide electrical connection.

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.

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).

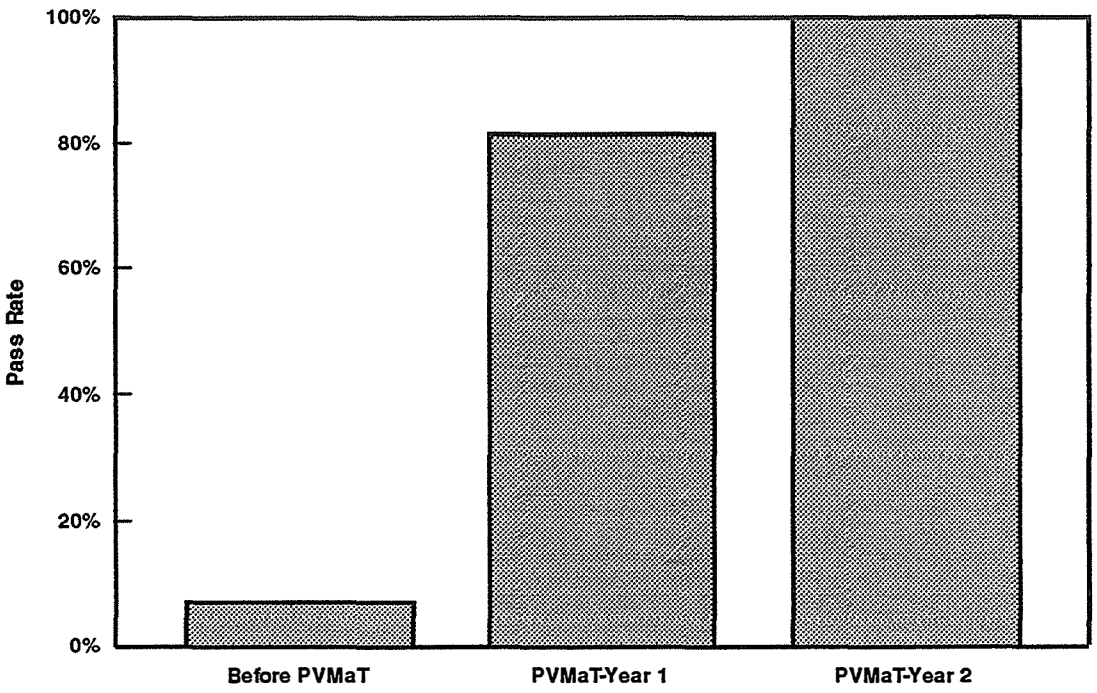


Figure 9. Module pass rate for IQT testing before and since the PVMaT efforts began.

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 multimegawatt 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 (see Fig. 12). Labor costs associated with frameless panelization were reduced by over 90% compared with SCI's previous framed designs.

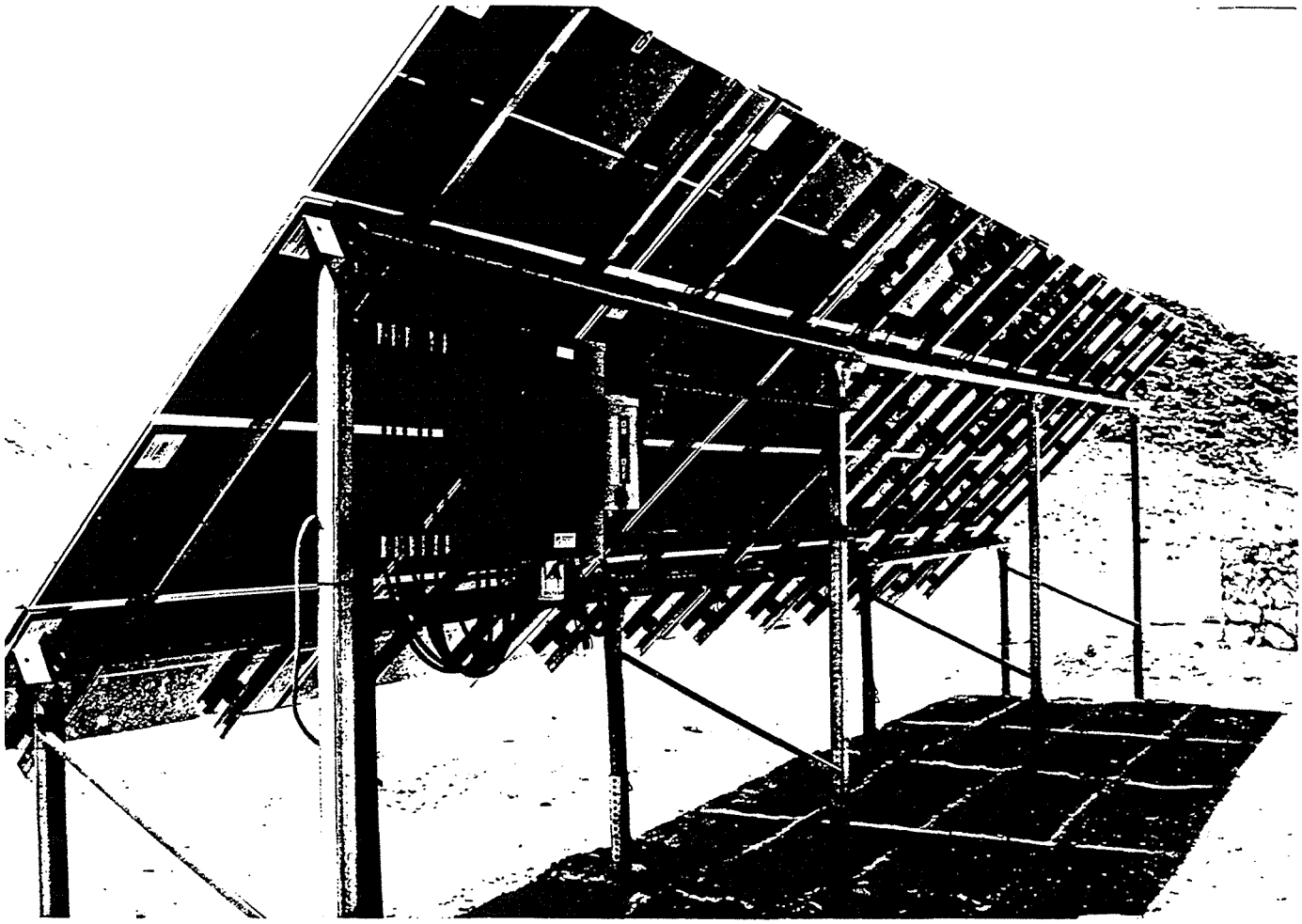


Figure 10. Photograph of 1.2kW array in Tunisia demonstrating frameless panel installation.

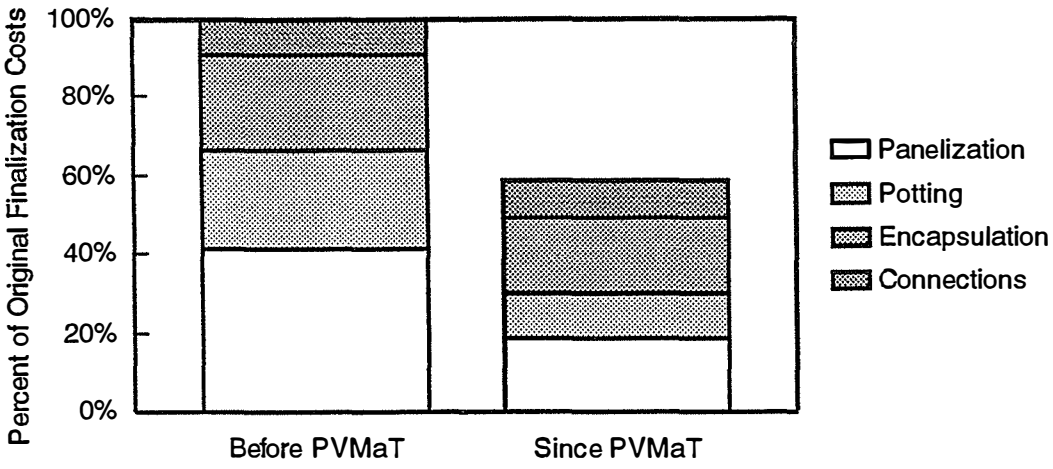


Figure 11. Product finalization cost reductions.

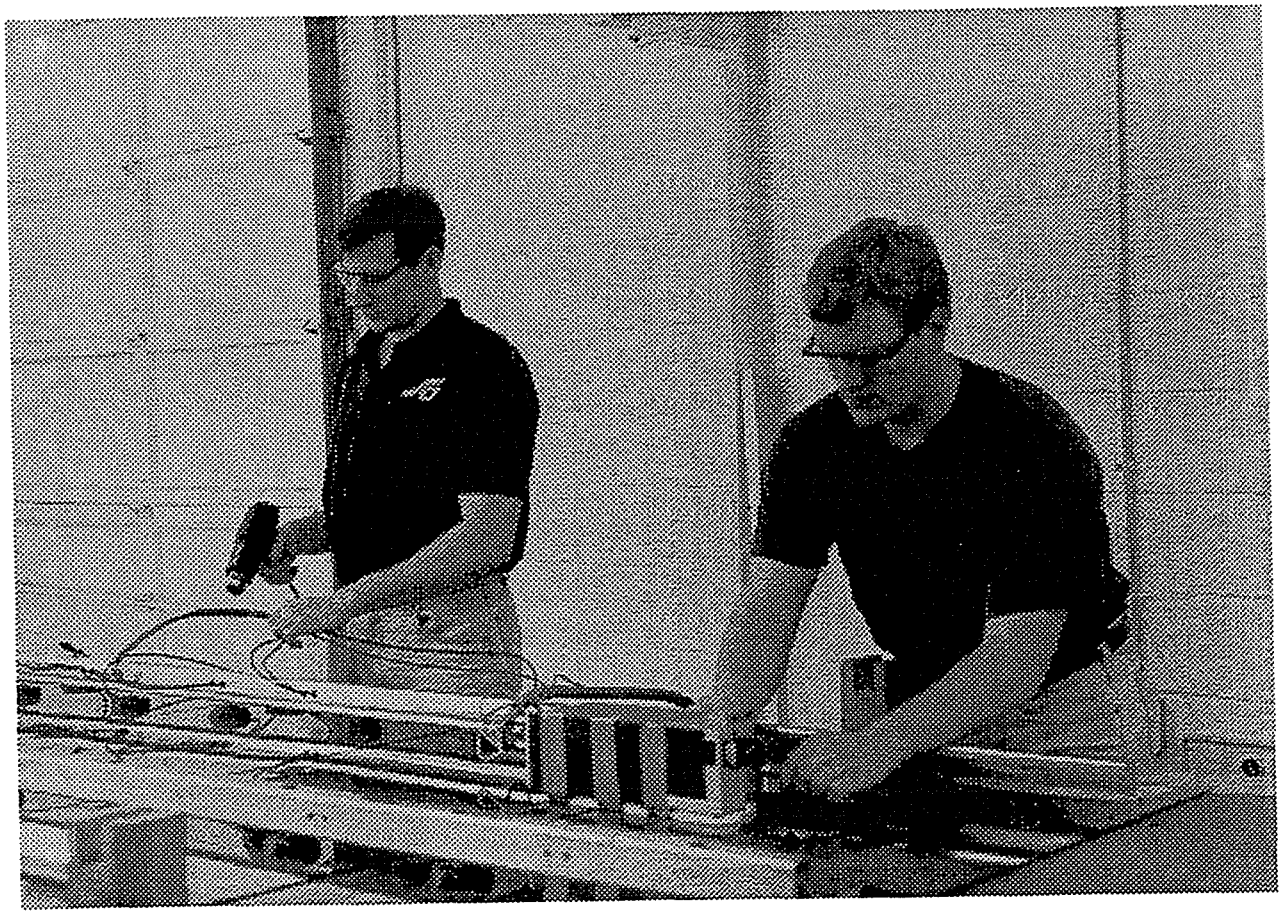


Figure 12. Photograph of panelization station.

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 product recycling by shipping modules to a raw material supplier for reintroduction into the smelting process.

CONCLUSIONS

Activities during the second year of the program concentrated on process development; equipment design and testing; quality assurance; and ES&H programs. These efforts broadly addressed the issues of the manufacturing process for producing thin-film, monolithic CdS/CdTe photovoltaic modules. The following table summarizes the status of program deliverables as of November 1995 for the second year of the subject subcontract. All deliverables were completed within the year at par with or exceeding performance requirements.

Table 6. Deliverables Status

Description		Delivered
Fully encapsulated 8.0% efficient, 60cm x 120cm thin-film CdTe modules produced on the 100kW pilot production line (2 each)		8.1% and 8.0% fully encapsulated modules
Quality Assurance training manual (1 each)		200-page TQM based quality assurance program training manual
4-Module panel, made with fully-encapsulated 6.5% efficient, 60cm x 120cm thin-film CdTe modules produced on 100kW pilot production line (2 each)		Eight modules (i.e. two panels) averaging 6.5% efficiency mounted as part of 1.2kW array in Golden, CO at NREL's outdoor test facility
Total Quality Assurance and Continuous Improvement Program manuals (1 each)		89-page Quality Assurance/Quality Control program manual • Quality system outline • Standard operating procedures • Standard forms and examples • Qualification tests standard forms • Product quality reports

Updated safety and health program manuals (1 each)		102-page EHS programs and procedures reference
		• Compliance Plans
		  • Cadmium Standard
		  • Hazard Recognition and Control
		  • Hazard Communication
		  • Lockout-Tagout
		  • Respiratory Protection
		  • Hazardous Waste
		• Inspection Forms
		• Employee Safety Suggested Operating Procedures
		Employee Safety Packet

Equipment Design and Testing

SCI operated a 100kW pilot production line on which the process was refined and demonstrated. Over 2500 Modules have been processed on this line as part of the development efforts. During the second year 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 will be 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

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 product recycling by shipping modules to a raw material supplier for reintroduction into the smelting process.

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13. ABSTRACT *(Maximum 200 words)*

The objectives of this subcontract are to advance Solar Cells, Inc.'s (SCI's) photovoltaic manufacturing technologies, reduce module production costs, increase module performance, and provide the groundwork for SCI to expand its commercial production capacities. Activities during the second year of the program concentrated on process development, equipment design and testing, quality assurance, and ES&H programs. These efforts broadly addressed the issues of the manufacturing process for producing thin-film monolithic CdS/CdTe photovoltaic modules.

14. SUBJECT TERMS

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