August 1999 • NREL/SR-520-26435

Subcontractor Report

High Throughput Manufacturing of Thin-Film CdTe Photovoltaic Modules

Final Subcontract Report
16 November 1993—31 December 1998

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

National Renewable Energy Laboratory

1617 Cole Boulevard
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Table of Contents

Table of Contents
(continued)

Table of Contents
(continued)

List of Figures

List of Tables

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1.0 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 (>5μm/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 sub-module. By the end of Phase I this system has produced over 10,000 CdS/CdTe substrates as part of the modules optimization process.

Based on 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. The goal of this program was to develop high-volume manufacturing techniques leading to thin-film CdTe modules capable of achieving installed costs (including balance of systems components and labor) of less than $3.00/watt.

2.0 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 four-phase PVMaT subcontract supports these efforts.

The program consisted of 15 areas of focus divided into four phases. The developmental effort for several of the focus areas was to extend over more than one phase; hence the total number was 27. The effort was related to product definition, process definition, equipment engineering, and support programs development. The following provides a brief summary of the results of the effort.

2.1 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 60.3watt 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. For example, SCI has improved module pass rate on the Interim Qualification Test (IQT) protocol from less than 20% to 100% as a result of work related to the subcontract. However, passing of the damp-heat test (85°C, 85% relative humidity, for 1000 hours) is yet to be achieved.

2.2 Manufacturing Process Definition

The multi-megawatt manufacturing process has been defined. Several of the key processes have been demonstrated. The process was refined and proven on a 100kW pilot line, which now operates as a 250kW line.

2.3 Multi-Megawatt Manufacturing Line Conceptual Design Review

SCI completed a conceptual layout of the multi-megawatt lines. 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 25MW at a manufacturing cost of below $1.00/W was projected.

2.4 Multi-Megawatt Manufacturing Line Utilities Design

General utilities were sized for the plant. The requirements are within the standard range for a manufacturing plant of this size. The utilities at the N. Westwood, Toledo site have been evaluated. Although it was initially estimated that with nominal upgrading the utilities would be adequate for the line, recently an alternate site has been chosen.

2.5 Development of Multi-Megawatt Manufacturing Line Equipment

The multi-megawatt 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. Efforts were focused especially on the high capital cost and custom designed items. Over 70% of the capital cost is attributed to only 4 of the 40 process steps. Two of these systems, metallization and lamination, are off-the-shelf and present relatively low operational risk. The third system, laser scribing, needs to be designed and built by a qualified manufacturer and integrator, using SCI specifications developed during the program. The fourth system, the high-throughput production semiconductor deposition coater, has been designed, based on extensive testing of the LDS systems, using an iterative approach.

2.6 Semiconductor Deposition Systems

In 1991, SCI designed and installed a developmental Large Deposition System (LDS) for depositing CdS and CdTe from source compounds, CdS and CdTe, onto 60cm x 120cm substrates. The process in the first system utilized close-spaced sublimation (CSS) under low-pressure environment.

The success of this equipment has led to two modifications, the LDS-2 and LDS-3, featuring on-demand, continuous, source material feed and entrance and exit load locks, respectively. The LDS-3 has demonstrated semiconductor-coating capability on a multi-megawatt scale. Based on the success of the LDS-3, a Large-Scale Deposition System, featuring high-speed, two-foot wide load locks, and eight-foot per minute linear speed coating was designed and is under construction.

Two other deposition systems have been designed, constructed and tested, the High-Throughput Deposition System (HTDS) and the Advanced High-Throughput Deposition System (AHTDS). Both of these systems also use the on-demand, continuous source feed. Most importantly, they use slit seals or roller seals for moving glass substrates in a continuous manner and without gaps from the atmosphere to the vacuum chamber and after the deposition back to the atmosphere. The ultimate purpose of these designs is to allow a continuous ribbon of glass from a production float line to enter the coating chamber. The AHTDS has been chosen for further development because of its short vacuum chamber, one-meter wide, compared with the 10-meter design of the HTDS.

2.7 100kW Pilot Production

SCI operates a 100kW pilot production line (now upgraded to 250kW) on which the production process was defined and demonstrated. Approximately 6,000 modules have been processed on this line as part of the development efforts.

Some of the process steps have been demonstrated at throughput levels of 100 units/day, which represents approximately 1MW of annualized output. They include semiconductor deposition, glass seamer, and glass washer. The most basic component of this line, the semiconductor deposition, has amply demonstrated a multi-megawatt-annualized capacity.

2.8 Continuous Production Line Run

In Phases III and IV SCI reorganized its pilot production activities, The production team was expanded from four to six members. Its task was to increase production capacity and to upgrade production equipment. During a five-month period the team produced a total of 2,912 coated plates (23,296 sq. ft.) of which 70% were good quality. The highest monthly production was 866 coated plates (7,747 sq. ft.). Over the course of six months, the production rate for completed modules has risen stepwise by 320%, from 5 to 16 finished modules per day, with no increase in labor content.

SCI also formed a Process Team consisting of four individuals with degrees in industrial engineering, chemistry, and EHS affairs. The team was assigned to focus on observing, documenting, analyzing, and statistically improving the pilot process to reduce risk during the scaling period. The team completed its objective of documenting the additional increases in daily production rates for each process step. The SOP has been documented in the IS09000 format that provides the necessary base line on the process.

A cross-functional technical group was set up to determine the cause of an intermittent problems experienced with the yield. The problems were narrowed down to air leaks, causing oxidation, dust formation, and pinholes in the CdS material and to variation in laser scribing. In order to address the second problem, recommendation was made to purchase the laser scribing system, planned for the multi-megawatt module conversion plant, and to begin using it in the Pilot Plant Operation.

2.9 Average Efficiency Improvements

The average module efficiency for the period from early 1994 to the end of Phase III was 6.44%, while for modules made by the standard process the average efficiency was 7.0% (see Fig. 21).

During the accelerated pilot production in Phase IV, over the course of seven months, the monthly average efficiency ranged from 5.34% to 6.50%, with best daily average efficiency of 7.0%.

The net decrease in the average module efficiency during Phase IV is related to expected problems with ramping up of pilot production. It should be noted that the best modules produced are on par with the best devices produced before the ramp-up.

2.10 Quality Assurance Development

SCI has initiated a quality assurance program focused ultimately on the development of the multi-megawatt manufacturing line. This program has undergone periodic evaluation and refinement on a pilot production line. Most of the efforts were 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.

Extensive testing has been implemented to examine and demonstrate module durability. 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). SCI also continued monitoring modules installed at diverse outdoor sites. The data show excellent performance with flat (no aging problem) output curves.

A Product Quality Reporting System was developed to track defects and analyze root cause issues. The product quality reports are used in conjunction with process control measures to facilitate understanding of process variation and to define objectives for performance improvement for operators. Information from the system is evaluated daily in order to provide timely feedback. The system formed the basis for process control activities that included a variety of line processes, such as the semiconductor deposition, the post-deposition treatment and the laser scribing processes.

2.11 ES&H Program Development

Production of CdTe PV modules involves regulated materials including cadmium. An important part of the PVMaT effort was to establish programs for effective handling of environmental health and safety issues stemming from the development, production, deployment and disposal of these modules. SCI 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 training.

Environmental development has focused on process-waste minimization and product recycling [4,5]. SCI has demonstrated feasibility on a waste-treatment process that removes greater than 95% of the cadmium at low concentrations from liquid wastes. This process reduces the disposal volume by over 99%. SCI has also demonstrated recycling and materials reclamation for in-plant scrap by over 99%.

3.0 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. These objectives were to be met by designing, debugging, and operating a multi-megawatt manufacturing line that produces 60cm x 120cm thin-film CdTe PV modules.

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

- Product Definition and Demonstration
- Manufacturing Process Definition
- Review of the Conceptual Multi-Megawatt Manufacturing Line Design
- Development of Multi-Megawatt Manufacturing Line
- Design and Construction of Semiconductor Deposition Systems
- Multi-Megawatt Semiconductor Coater Demonstration
- Manufacturing Line Testing and Modification
- Manufacturing Line Demonstration
- Efficiency Improvement
- Quality Assurance
- Employee Safety and Health (ES&H) Programs

4.0 PVMAT PROGRAM ACCOMPLISHMENTS

4.1 Product Definition and Demonstration

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, 4.0µm of CdTe, 0.02µm of nickel and 0.3µm 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 that produces nominally maximum power of 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.

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
Lamination	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, targeted at grid-connected applications, is the 60cm x 120cm high-voltage module. 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 60.3watt 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).

4.2 Manufacturing Process Definition

SCI operates a 100kW pilot production line (now upgraded to 250kW) on which the process is defined and demonstrated. About 6,000 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 2.)

Table 2. Process steps needed to manufacture CdTe photovoltaic modules.

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

The initial processing step is the preparation of the substrate for the deposition of the various materials that 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, LDS deposition system. 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 defined for Multi-Megawatt Line Production.

4.2.1 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 loaded onto an inspection table, inspected for physical defects, rejected or accepted, and labeled.

4.2.2 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 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 rinse with de-ionized (DI) water, 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.

4.2.3 Semiconductor Deposition

The substrate is now ready for the deposition of the semiconductor layers, CdS and CdTe. The deposition step utilizes a Vapor Transport Deposition (VTD) process that utilizes compound semiconductor materials as feed sources. All depositions take place at reduced background pressures and substrate temperatures between 400°C and 600°C.

The deposition system 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. Then it passes into a second chamber where a layer of CdS is deposited. The substrate then passes into a third chamber where a 4μm thick layer of CdTe is deposited. A fourth section is used to stabilize the temperature substrate before it enters the exit load lock. So called "gas curtain" of a stream of carrier gas may be used in between neighboring chambers to minimize cross-contamination. 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 durability in the field. The substrate is then cooled.

4.2.4 Scribe 1

The first step in the formation of interconnected cells is to scribe a series of cell-isolation channels. A laser system is used to scribe 116 parallel channels, separated by 1cm from each other. These channels are 25μm-50μm wide in which all the layers, including the TCO are ablated, thereby creating 116 individual cells that are electrically isolated from each other. (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 re-scribing.

4.2.5 Film Thickness Test

After exiting from the cooling conveyor also referred to as 'lehr', the semiconductor films are tested for film-thickness uniformity, by means of a semi-automated, proprietary testing procedure. Each measurement is performed in less than 10 seconds, totaling 2 minutes per module.

4.2.6 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 and moved into an atmosphere containing a low concentration of HCl gas.

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.

4.2.7 Scribe 2

The second step in the formation of interconnected cells is to scribe a series of channels for interconnecting the TCO of one cell to the metal electrode of an adjacent cell. A laser system is used to scribe a second series of 117 channels spaced 1cm apart. These channels are offset by a close spacing from Scribe 1 and are similar in width to those of Scribe 1 but only penetrate through the semiconductor layers leaving the TCO bare. Four additional Scribe 2 channels are scribed at each end of the module to facilitate electrical connection to the bus bars. All laser-scribed channels are subjected to an inspection of ablation to ascertain the completeness of the scribe, utilizing electrical measurements and visual inspection.

4.2.8 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 constitutes one of several critical bottlenecks 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 multi-megawatt-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.

4.2.9 Edge Deletion

The "edge deletion" process removes all deposited materials (including metals, semiconductors and TCO) around the perimeter of the substrate extending to within 1cm of all edges. This step is necessary to prevent any shorting between the cells at the edges, as well as to provide for proper lamination. A sand-ablation procedure is used for the removal of these materials. The substrate is automatically fed into the edge-deletion chamber. A series of sand-ablation 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.

4.2.10 Scribe 3

The third and final step in the formation of interconnected cells is to scribe a series of channels for metal isolation. A laser system is used to scribe a third series of 117 channels spaced 1cm apart and offset by a close spacing from the Scribe 2 channels. The Scribe 3 channels are usually narrower than those of Scribe 1 and 2, and only ablate the metal layer along with a small portion of the CdTe layer.

4.2.11 Current-Voltage (I-V) Test

The substrate now referred to as sub-module moves into an automated test station where both the temperature and standard photovoltaic I-V measurements are recorded. Sub-modules which pass the I-V test proceed to the lamination area. Rejected modules are routed to a rework station.

4.2.12 Lamination

The sub-modules that have passed the I-V tests are moved via conveyer to a lamination assembly table where they are placed into set-up racks. Each rack holds three sub-modules. The sub-modules 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 sub-modules 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 sub-module electrodes and the outer surface of the cover glass.

The cover glass is 60cm x 120cm x 3mm with a hole, 2cm in diameter, to accommodate electrical feedthroughs. The glass plate is inspected for physical defects, and placed on a conveyor which moves the glass through a washer. Two sections of metal tape having conductive adhesive on one side, each approximately 1.5 meters long, are positioned to match with the sub-module 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 3-ft length of 12-gauge copper wire is later soldered to the end of the metal conductor after lamination is complete. A by-pass diode is also connected between the two electrodes, if required.

4.2.13 Module Finalization

The next step in the module assembly process involves the application of four mounting pads to the back cover glass. These pads are used to mount the module to the panelization members. The process also involves the application of a potting pigtail that encapsulates the area around the exit hole where the 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 moves to the application station where a mold is pressed against the cover glass surface. Urethane is injected into the mold forming both the mounting pads and potting pads. The mixing and metering equipment are standard. The tooling for the molds is straightforward and has been demonstrated on pilot production.

SCI procured automatic metering equipment to replace hand mixing and measuring on the pilot line (see Fig. 5). A superior resultant mix with a substantial reduction in labor (i.e. potential of 90% decrease) is expected from its use.

The completed module moves next 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 photovoltaic current-voltage (I-V) testing is performed at AM1.5 illumination and a label is attached.

4.2.14 Scaling Issues

Two processes require more evaluation because of scaling issues: substrate 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 with a manual/automated hybrid that meets manufacturing requirements without significantly impacting capital costs.

4.3 Conceptual Design Review of a Multi-Megawatt Manufacturing Line

4.3.1 Conceptual Layout of the Multi-Megawatt Line

SCI has completed a conceptual layout of the multi-megawatt 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. In this case, parallel processing is required because of the long duration of the lamination cycle and the lack of availability of in-line equipment that meets the manufacturing requirements.

4.3.2 Manufacturing Database and Model

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

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 multi-megawatt 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 to 12% by 2005 (see Fig. 9).

4.4 Multi-Megawatt Manufacturing Line Utilities Design

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 3, below, outlines the plant requirements.

The design for the chiller water system and electrical supply for the laser systems was completed.

Scribe 1-laser system utilities were modified to improve performance and capacity of chilled water and system ventilation and exhaust.

The molded support pads with threaded inserts on the module will provide for frameless panelization. A framed panel has also been demonstrated but SCI has adopted the frameless design due to cost and manufacturing benefits.

This panel design has been tested routinely with 30psf loading with no negative results. The support pads have also been individually tested to failure and have demonstrated a factor of safety of approximately ten for a 30psf load. This test is conducted by pulling a bolt which is threaded into the support pad insert. Two modes of failure have been observed: 1) cohesive failure within the urethane and 2) glass failure with the pad and attached glass breaking away from the module. This testing has proven that the four-pad design and materials are more than adequate for outdoor application.

Table 3. Utility and facility requirements for SCI multi-megawatt plant

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

Building
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 - 3,500KVA, 480V connected
Security System - All areas
Rest rooms - Access from all areas
Overhead Doors - Three, 12 ft. minimum
Truck Well - Three with levelers
Utilities - Plant compressed air
    N2 supply (plant or liquid boil)
    Trash compactor
    Numerous exhaust stacks
    Floor drains

4.5 Development of Multi-Megawatt Manufacturing Line Equipment

The multi-megawatt 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 4 shows that over 70% of the capital cost is attributed to only 4 of the 40 process steps. .

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 will design and install the deposition system. Additional information on these and several other systems is provided below.

Table 4. 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%

4.5.1 Substrate Preparation

During the later stages 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, including glass seamer and washer were installed, brought on-line, and demonstrated multi-megawatt capability (see Sections 4.2.1 and 4.2.2). Figure 10 shows the glass washer and an earlier version of the seamer.

4.5.2 Semiconductor Deposition Equipment

The most extensive activity of the project was devoted to the development of manufacturing semiconductor deposition equipment, as it is the most essential component of multi-megawatt, high-throughput manufacture of PV modules. Five different semiconductor deposition systems including the LDS, HTDS, AHTDS, Large-Scale Deposition System (AHTDS) and Multi-Megawatt Deposition System are discussed in subsequent sections.

4.5.3 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 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. A photograph of the HCl treatment system is shown in Figure 11. This process significantly increases material utilization and process control. It also 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 5 compares the vapor process to the wet dip process. During Phase III a full-scale prototype system was tested. 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 multi-megawatt 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.

A conceptual design for a high-throughput, post-deposition treatment system was completed. This system allows for a throughput rate of one substrate per minute. The system uses a continuous conveyance system which increases the "packing factor" of the substrates and, thereby, reduces the floor space required for this relatively long process step.

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

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

An effluent treatment system was designed for the post-deposition treatment system. The effluent treatment system neutralizes emissions from the system. This design is scaleable to the multi-megawatt level.

4.5.4 Laser Scribing Systems

The basic interconnection approach for the multi-megawatt line 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 system is a single-beam laser, which 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 laser scribing, 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. 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 12 and further description in Section 4.10.4). Both systems are identical, each having two lasers, split into two beams. Otherwise they generally match the new specifications for the production line. Installation and debugging activities are underway.

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 laser scribing program begins. Eight high-power laser beams cut channels in the semiconductor simultaneously down through the SnO_2 in a single pass. With only 16 indexed passes the entire substrate is cut into 116 cells measuring 1cm x 60cm. 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. (See also Section 4.2.4).

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 laser beams cut channels simultaneously through the semiconductor in a single pass, leaving the SnO_2 exposed and intact. Scribe 2 is offset from Scribe 1 by a close spacing. 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. (See also Section 4.2.7).

Scribe 3 System

A substrate metalized with a back electrode, consisting of two or more metal layers, and having the first two scribes, is conveyed to the laser loading station. The substrate is positioned as in Scribe 1. The entire substrate is completely scribed with 116 channels to form 116 interconnected cells. After the scribing is completed the substrate is automatically unloaded and transferred to a line conveyor. (Also see Section 4.2. 10).

4.5.5 Metallization

(See Section 4.2.8)

4.5.6 Edge-Deletion Equipment

Discussions with the edge-deletion equipment vendor identified minor upgrades required on their basic system to handle regulated materials used in the SCI process. The vendor is pursuing several alternatives. Quotes have also been received on an edge deletion system.

4.5.7 Lamination and Module Finalization

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 6 outlines the main advantages and disadvantages of the materials under investigation.

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 that has led to a significant decrease of the overall finalization costs and, more specifically, panelization and potting costs. Development efforts on this product have resulted in greater than a 40% reduction in product finalization costs including lamination, potting, connections and panelization (see Fig. 13).

Table 6. Lamination Overview

	Advantages	Disadvantages
EVA/glass	Proven Reliable	Weight Cost Manufacturing
Laminated Films UV Curable	Manufacturing Very low cost Fast process time	Cost Durability Toughness Manufacturing
Coatings	Manufacturing Low cost	Early stage of development Multi-functional limitations

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 100% at the end of Phase II. The improvement is attributed to the pigtail durability, reduced glass curvature, and better process control during lamination preparation.

This design has proven to be very effective in providing reliable and safe modules (see also Section 4.2.13). Since beginning the PVMaT program, Interim Qualification Test [4] pass rates have increased from below 10% to 100% (see Fig. 14).

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].

4.5.8 Interconnection Systems

Two vendors for interconnect process systems were identified and samples were sent to confirm process performance. Discussions with experts in the field have indicated that the SCI process may not require standard high-grade equipment. In other words, the equipment may have to be custom built but will require much less sophistication and expense than off-the-shelf equipment.

Additional scalability tests were undertaken so that a firm quote can be delivered. Vendor trials for the interconnect processes were completed successfully. Process variables such as substrate temperature, rinse temperature, and process time were evaluated for optimization. Results of the trials have provided information required to select the equipment.

4.5.9 Panelization

SCI has focused on optimizing a process for frameless panelization (see Fig. 15). Four modules are mounted to two steel members with four self-locking bolts each. The location of the threaded inserts is at the critical points of the module to reduce load-induced stress and deflection. The steel members also serve as wire raceways. SCI is evaluating two wire connection methods: 1) crimped butt-splice and 2) ultrasonic welding. Crimping with a butt-splice has been demonstrated but it is felt that the welding connection is more durable and cost effective. Multiple suppliers of ultrasonic welding equipment have been identified. Samples were sent to the supplier for evaluation and specification of the equipment. An on-site demonstration showed positive results.

This panel design has been tested routinely with 30psf loading with no negative results. The mounting pads have also been individually tested to failure and have demonstrated a factor of safety of approximately ten for a 30psf load. This test is conducted by pulling a bolt which is threaded into the mounting pad insert. Two modes of failure have been observed: 1) cohesive failure within the urethane and 2) glass failure with the pad and attached glass breaking away from the module. This testing has proven that the four-pad design and materials are more than adequate for outdoor application.

Over 60kW of product were panelized and installed in demonstration arrays at various sites listed below. Panelization labor costs were reduced by 60% through training, procedure optimization, fixture modification, and wire connection equipment implementation. Further improvement is expected with setup modifications and panel runner re-design which will allow improved access to mounting bolts.

The frameless panelization design has proven to be very durable and scaleable. The process has been optimized through construction of about 250 panels, each containing 4 modules. These panels have been installed in the following arrays as part of the continued evaluation efforts:

Edwards AFB	25.0 kW
Davis, CA	10.8 kW
Toledo, Ohio	25.0 kW
Golden, CO	1.2 kW
Tunisia	1.0 kW
Las Cruces, NM	0.3 kW

Information provided through a demonstration array indicated that 10% of module-to-module wire splices were not sufficiently processed (i.e., insufficient cure of the splice materials). After an investigation of the problem, a procedural revision was made to working instructions. The problem does not indicate a need for a design change. The defects were field-repaired with minimal effort and no additional materials. The vendor for the panelization ultrasonic lead connector was identified. A unit was installed for testing on the 100kW pilot line. A fixture was designed to improve panelization setup and overall quality.

In Phase I, SCI developed a glass/EVA/glass lamination process with pigtails and four mounting pads for module installation (see Fig. 2). This module design coupled with frameless panelization reduced panel costs by over 40% (see Fig. 13). 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. For example, in the construction of the 25kW array at the Edwards AFB, SCI labor on-site was 30% of competitor's labor.

The panelization process was demonstrated at a multi-megawatt level in producing over 50kW 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.

4.5.10 Multi-Megawatt Line Layout

The multi-megawatt line layout was evaluated to determine optimal layout, space utilization, and operational clearances. The current site in Toledo Ohio is not sufficiently large to accommodate the line, warehouse, and other offices. Other options are being pursued.

4.5.11 Wastewater Pre-Treatment System

A quote was obtained from Trionetics Co. for an ion-exchange wastewater pre-treatment system. The recommended pre-treatment is precipitation of cadmium with lime. A 500-gallon per day treatment system has been installed for $8,000.

4.5.12 Ventilation Systems

Four prototype ventilation systems were designed and installed. 1) A ventilation system was established at the exit of the deposition system as a precaution against unintentional releases of cadmium compounds from the system. 2) A hood with filtered exhaust and negative pressure was upgraded to provide engineering controls related to dust generation during various activities. 3) A negative down draft table was designed and built to control debris and dust caused by the buffing operation. 4) A negative down draft table was designed and built to control debris and dust caused by the edge deletion process. The multi-megawatt line will most likely have a central dust-collection system.

4.6 Semiconductor Deposition - The LDS Systems

4.6.1 The LDS-1 — The Initial Semiconductor Coater

In 1991, SCI designed and installed a developmental Large Deposition System (LDS) for depositing CdS and CdTe from source compounds, CdS and CdTe, onto 60cm x 120cm substrates. The process in the first system utilized 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 had two main drawbacks regarding high throughput production: 1) non-steady state conditions and 2) low capacity. The root cause for these drawbacks is 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.

4.6.2 The LDS-2 — Modified Coater Utilizing On-Demand Feed

During Phase II of the subcontract the system was modified by replacing the batch-feed components of source materials with on-demand feed components. Considerable time was expended in the task of optimizing the operation of the equipment. However, the resulting improvement proved to be rewarding. The benefits that were achieved were 1) a steady-state conditions for the deposition, 2) capability of continuous operation, without the need of opening the system to replenish the feed 3) a four-fold increase in deposition rate and 4) a three-fold increase in material utilization from 30% to over 90%.

The LDS-2 deposition system served as a testing system for subsequent development of multi-megawatt production coating machines, the HTDS and the AHTDS, that are described in Sections 4.7 and 4.8, respectively.

Although the quality of the solar cells and modules produced in the LDS-2 was comparable to those made in LDS-1, this machine was not suitable for high-throughput production. The reason was that the deposition chamber had to be pressurized and opened each time a glass substrate was to be inserted or removed from the system.

4.6.3 The LDS-3 — The Precursor to the Multi-Megawatt Coater

During the second and third phases of the subcontract modifications were made on the LDS to test component designs intended for a multi-megawatt coater. The modifications included the addition of entrance and exit load locks; the use of on-demand, coating components; and the upgrade of the control system. The load locks (see Fig. 16) have resulted in a 75% decrease in cycle time from ten minutes for the LDS-2 to 2.5 minutes for the LDS-3. In addition, the load locks provide a stable pressure in the deposition zone during the introduction and the removal of the substrates. 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 about 1 Torr during an entire run of several hundred substrates.

The LDS-3 coater is designed with the capability of feeding semiconductor raw materials on demand 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.

As in the LDS-2, 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-3 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 several continuous 100-plate runs and have been incorporated into the multi-megawatt coater designs described in the following sections. These features (see Table 7) result in a 100 times greater 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 multi-megawatt manufacturing system is designed for throughput of one module/minute. Table 8 lists the components of the deposition system.

Table 7. Comparison of pilot deposition system with high-throughput deposition system

System:	Prototype	Production
Year Built:	1991	1999
Purpose:	Process Demonstration	Manufacturing
	Process Optimization	
	Limited Production	
Features:	100 kW	10-20 MW
	10 Modules/Day	480 Modules/Shift
	Manual	Automatic
	Batch	Continuous, Steady-State

Table 8. 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 (400°C to 600°C). 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 450°C 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 (optional) — The various zones described above may be separated by isolation curtains. Each curtain would use close-clearance geometry and gas flow to limit cross-over between zones due to diffusion or bulk flow phenomena.

Buffer Zone — extra processing sections downstream of the CdTe zone were added 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.

Detailed Description of the LDS Retrofit

A retrofit of SCI's LDS began in July 1997. The objectives of the retrofit were increased process control, increased capacity, and increased machine reliability. The objectives of the retrofit were to improve process control, increase capacity, increase material utilization, reduce downtime, and increase machine reliability. The results of the improvements will be a four-fold increase in capacity and a three-fold increase in material utilization. One of the improvements is that the batch deposition components will have been permanently replaced with on-demand components representing a major advance in SCI's coating technology.

Disassembly. The disassembly included removing the heaters; quench; insulation; shafts and bearings; chamber-to-chamber seals; intermittent valves; rolls and roll bearings; thermocouples; entrance valve; and the entire fourth chamber section. In addition, the inside of the system was cleaned.

Re-assembly. The installation of new components was divided into functional areas: mechanical; electrical; controls; and deposition. These systems were further tested in October.

Mechanical. The mechanical upgrades focused on providing increased throughput and improved machine availability. The primary upgrade was the addition of load locks onto the entrance and exit of the system. Previously, the system operated with only one gate valve on the entrance and one gate valve on the exit. This arrangement required that the system be pumped down to low deposition pressure during each cycle. Since the load lock volume is much less than that of the entire chamber the pumping time was decreased from over 2.5 minutes to under one minute. Furthermore, the load locks were designed to provide the opportunity to introduce multiple substrates into the system resulting in a decrease in the cycle time from 9.5 minutes to 2.5 minutes. Subsequent testing confirmed system capability for the 2.5-minute cycle. Nominal modifications were identified for the exit cooling station to allow for hot glass unloading. These modifications are consistent with standard glass handling techniques on tempering systems. The modifications will address limited space to improve operator ergonomics and decrease risk of substrate breakage because of impact fracture.

Nominal modifications were identified for the exit cooling station to allow for hot glass unloading. These modifications are consistent with standard glass handling techniques on tempering systems. The modifications will address limited space to improve operator ergonomics and decrease risk of substrate breakage due to impact fracture.

In addition to the capacity improvements, the load locks also significantly improve the process stability by enabling a constant pressure within the deposition zone. Before the upgrade the deposition zone would be cycled between atmospheric pressure and the low operating background pressure. With the load locks in place, the deposition zone is maintained at the target process pressure and does not fluctuate as substrates enter and exit the system. The exit load lock is also used as the cooling chamber for the substrate as it is transferred from the coating zones to the outside cooling conveyor. Pressure control in the exit load lock was adjusted to provide for better uniformity of cooling which was causing glass breakage before the corrections were implemented.

Electrical. Electrical upgrades focused on the heating systems. The original heating design called for exposed heaters throughout the preheat section of the system. These heaters while reliable did pose some problems because of exposed electrical leads in the vacuum system and corrosion of the electrodes. Therefore, the original heaters were replaced with heaters having covered elements to improve lifetime and also to increase power density. The heaters have operated as planned. Additional control capability was indicated during trials and was implemented. Furthermore, a nominal increase in energy density was evaluated for thick substrates (i.e. >5mm), which require more time to heat to deposition temperatures with the current heater configuration. The use of thicker substrates was pursued to meet the requirements of architectural users.

Controls. Significant upgrade of the controls was included during the project. The focus of these activities was to improve tracking of the substrate; provide sequencing for the load locks; increase safety interlocks; and improve conveyor control. The primary improvement was with the replacement of manual controls with a programmable logic controller. Due to these upgrades the system can be run in an automatic mode with no input from the operator except the loading and unloading of substrates. During the 100-plate run during September, one operator was able to handle the operation of the system at a cycle time of three minutes. Before the upgrades one operator was needed to run the system at a ten-minute cycle. Therefore, labor has been reduced by 70% and process variability due to operators has been eliminated. Furthermore, the required skill and training level of the operator is greatly reduced.

Deposition. Perhaps the most significant improvement of the system is related to the design and operation of the deposition components. Prior to the upgrade, raw material (i.e. semiconductor sources) was batch loaded into the deposition system by placing the physical source over the substrate. As a run progressed the source material would deplete and the run would be stopped when the source was depleted to an unacceptable level. Furthermore, the system parameters such as pressure and temperature would need adjustment to maintain the same deposition rate as the source diminished. The new deposition components and design provide on-demand coating and continuous feeding of the raw materials. The on-demand feature allows the heating, vacuum, and conveyance subsystems to be decoupled from the coating subsystem. This was not the case before the upgrades. The on-demand capability allows the operator or control system to turn the coating on at the point when a substrate reaches the deposition zone. This control allows the system to reach steady state temperature and pressure before introducing deposition.

Quality of the Deposited Films

Initial deposition tests of CdS/CdTe films began in September 1997. Small area cells ($1cm^2$) and 60cm x 120cm sub-modules were tested at efficiencies greater than 10% and 7%, respectively.

Cells and sub-modules made with the upgraded coater were installed into SCI's light soaking station to confirm lifetime performance. Preliminary results with approximately 500 hours of light soaking indicate performance comparable with earlier process techniques.

Debugging Tests and Modifications

A series of debugging runs continued over a period of six months. Further enhancements of the control system's flexibility, operator interface, and safety-interlocks were implemented. In addition, data collection of set points and run parameters was expanded to assist in the understanding of process variability.

Glass transportation problems were identified. The problems contributed to film non-uniformity, substrate jamming, and substrate position issues. The cause of the problems was attributed to temperature uniformity, conveyor alignment, and conveyor roll rotation. The last two issues were being addressed with mechanical modifications. The temperature issues were being addressed by control adjustments.

Additional substrate location sensors were added to the system to provide more feedback to the controller. These sensors were also configured into the safety interlock program to assure that the system identified problems and held up the introduction of new substrates until the problem had been corrected.

The deposition components were further tested to assess uniformity of film thickness. The results indicated a uniformity comparable if not better than that from the previous batch process. This result is significant, given that the former batch system required multiple coating passes to "average out non-uniformity" while the on-demand system required only one pass through the deposition zone. Localized uniformity problems were detected and attributed to conveyor stalling and feeder issues. The feeder issues related to consistent flow of raw material into the distribution network.

After exiting the cooling conveyor, the semiconductor films are tested for film-thickness uniformity. A semi-automated thickness-measurement system is used to provide on-line feedback. This non-destructive measurement, performed in less than 10 seconds, totaling 2 minutes per module, allows for area mapping of the 60cm x 120cm substrate.

4.7 High-Throughput Deposition System (HTDS)

In 1994 SCI built and began debugging a high-throughput deposition system (see Fig. 17). This system incorporated several advantages over the initial LDS pilot deposition system including increased throughput and steady state, continuous operation (see Table 7). The main functional advantages of the HTDS are on-demand raw material feed and continuous glass conveyance. These features were expected to lead to a 100-times greater annual capacity than that of the LDS pilot production system, with only a moderate increase in system length (46 feet vs. 36 feet). The testing performed on the HTDS included: 1) tests of entrance and exit "close-clearance slit seal" (CCSS) and 2) initial tests of on-demand feed. This deposition system integrated with approximately 40 other pieces of equipment forms a high-throughput manufacturing line. The system was designed to produce modules at a multi-megawatt annual capacity with a throughput of one module/minute.

4.7.1 Baseline Testing and Modification of Installed Systems on the HTDS

Initial testing of the HTDS revealed the need for several modifications to bring its performance up to design manufacturing levels. The following installed components of the HTDS have been evaluated: glass conveyor, heater controls and capacity, entrance and exit "close-clearance slit seal" (CCSS), and the capacity of the pumping package. It was determined that all of these elements except the pumping package needed to be modified.

Also added were exit enclosure to provide thermal protection for the hot glass substrates and exit cooling sub-system. The latter consists of a "sweep quench" which provides for faster cooling of the substrate through the annealing point.

After successful testing, the deposition components were added to the system. These components have undergone preliminary testing in the LDS developmental deposition system (the LDS system) in a parallel effort.

4.7.2 Semiconductor Deposition Tests

During December 1996 SCI completed its first and second deposition trial on the HTDS, followed by evaluation of the deposited films. Both runs were successful in demonstrating the feasibility of deposition of semiconductor at 120cm/min line speed. Total deposition run time was approximately one hour. Subsequently, runs lasting up to 4 hours were made.

These tests demonstrated that high deposition rates and material utilization can be accomplished with the current vapor distribution design. Material utilization is expected to be up to four times greater (i.e., less waste) that found on the developmental batch coater. Deposition rates have also been demonstrated that exceed those of the batch coater by a factor of at least ten. The higher deposition rates compare with coating rates currently used for on-line TCO by glass manufacturers.

However, the initial deposited films did not meet quality standards because of large amounts of material condensed as powder on the surface. Consequently, deposition trial runs in the HTDS continued through April 1997 with intermittent modifications on the HTDS system.

4.7.3 System Modifications and Film Deposition

System pressure exceeded normal operating pressure during the semiconductor deposition tests because of variable sealing at the exit seal. Hence, modifications were made by replacing sealing materials and improving pumping capacity.

Modifications to the entrance drive were also needed and implemented. The drive proved to be much more reliable than the replaced unit. Alignment of the substrates was greatly improved and no drive related problems occurred during the run.

In order to promote deposition of well-adherent films, the team focused on bringing the system temperature to above a target of 5000°C. Because of consequent glass breakage caused by excessive thermal shock, SCI turned to pre-stressing (tempering) the substrates before introducing them into the HTDS. This stopgap activity allowed SCI to proceed on the development of the temperature control program for start-up without the limitation of thermal shock problems. Consequently, the startup ramp was reduced from 12-16 hours to less than eight hours. This allowed the process and development teams to conduct a 1000-substrate run in 16 hours.

SCI procured a tempering furnace to strengthen its own glass and reduce the costs and lead-time of purchased substrates.

4.7.4 Quality of the Deposited Films

In spite of the preceding modifications, the films deposited in the HTDS from December '96 through April '97 did not meet quality standards because of large amounts of material condensed as powder on the surface. This characteristic has been tracked to the combination of lower substrate temperature and higher background pressure than those established in the LDS.

4.7.5 Termination of HTDS Testing

The results of the testing on the HTDS through June 1997 indicated that the length of the vacuum section of the Advanced High-Throughput Deposition System (AHTDS) can be reduced by as much as 90%, thereby minimizing the problems with the system pressure. This experience has led to the termination of the tests on the HTDS and to the design and construction of the "Advanced High-Throughput Deposition System" (AHTDS), described in the next section.

4.8 Advanced High-Throughput Deposition System (AHTDS)

Testing on the HTDS has provided data that length of the vacuum section of the coating system can be reduced by as much as 90%. This result led to a decision to design and construct an Advanced High-Throughput Deposition System (AHTDS), that is also designated as the "C24 system." Figure 18 shows the comparison between the relative sizes of vacuum chambers for the LDS and the AHTDS coating systems. The latter utilizes slit seals that are operated at elevated temperatures.

Design activities on the AHTDS proceeded with a focus on simplifying the deposition section of the coater so that the required low pressure in the vacuum chamber could be routinely maintained. Design, procurement, and assembly of parts for the AHTDS have been completed. As shown in the design schematic in Fig. 19, the system uses heating and cooling sections outside of the vacuum chamber.

A cross-section of the deposition chamber of the AHTDS is attached for reference (see Fig. 20). The schematic shows a cylindrical, vacuum-coating chamber, one-meter diameter, equipped with roller seals up and downstream of the chamber. This design replaces a 10-meter long design of the HTDS that was used to test the slit-seal concepts. As in the case of the HTDS this system is designed to be a pre-cursor of coating equipment that will be capable of coating a continuous hot ribbon of glass issuing from a glass float line. Ceramic components are used to test the four-foot wide, close-clearance, roller seals at elevated temperatures.

An up-stream roller hearth heating system, operating at atmospheric pressure, is used to pre-heat the glass substrates in air to deposition temperature prior to entry into the short (1m), vacuum deposition chamber.

Existing vacuum pumping systems were relocated to the basement under the site of the new process to minimize noise and vibration.

4.8.1 Cold-Testing of the AHTDS System

After the construction and installation of the C24 machine, it was tested in the cold mode. Cold glass was moved continuously through the system, at background pressure in the vacuum chamber at acceptable operating levels.

Preparation of the glass substrate is a critical step in the operation of the C24 system. The width dimension and squareness of the substrates must consistently maintain their proper tolerances. The edge profile is another important consideration in that it affects how well the glass can withstand the thermal and mechanical stresses of the process. For this purpose an edge-grinding machine was installed, adjusted and used for the preparation of the substrates.

Several additional cold tests of up to two hours were completed. Acceptable background pressures have been maintained, albeit with fluctuations. Several instances of glass breakage have occurred that terminated the tests, prompting the team to concentrate on glass conveyance and pressure control.

The system was baked out at operating temperatures for the first time. In the first hot run, without vacuum, temperature imbalances were observed that resulted in the glass warping and moving out of position. A new set of seals was fitted to the chamber.

4.8.2 Vacuum-Hot-Testing of the AHTDS System

Several additional hot runs were made without vacuum, while attempting to balance the temperatures in the system. In this mode the moving glass remained flat and stable. These tests made it possible to perform the first hot run under vacuum. Operating temperature and pressure in the normal operating range were achieved for the first time and a line speed of 120cm/minute. Eventually, glass breakage ended the run. Glass breakage will be the main obstacle to overcome to achieve reliable operation. Another hot run under vacuum was performed during this period with similar results.

The problems with glass breakage during hot runs under vacuum continued for two months. Various edge configurations were tried with mixed results. The machine was operated under heat and vacuum to determine the best conditions. Varying temperature showed promise, as it was possible to flatten the glass and feed the blanks continuously into and through the vacuum chamber.

4.8.3 Miscellaneous

At the conclusion of Phase IV the AHTDS C24 system was moved to a new SCI R&D Center in Perrysburg, Ohio (a suburb of Toledo) where its development will be continued.

4.9 Multi-Megawatt Production Deposition System

4.9.1 Design of a New Production Machine

After having demonstrated multi-megawatt semiconductor coating capability with the LDS-3 system (see Section 4.6), the manufacturing group has set up a Task Force to design a new, multi-megawatt production semiconductor coating machine (PLL2000). This equipment will employ high-throughput entrance and exit load locks, for quasi-continuous feed, to match the coating speed. The design was completed midway through Phase IV.

The detailed drawings of the new production machine were reviewed with a number of fabricators to determine the ability to manufacture this design. Positive reactions were received with a number of sources available in the local market. Detailed quotations were received in the third quarter of Phase IV, allowing time for contracts to be let before the year-end.

The materials and planning department has implemented a computer tracking system for all materials and labor that is used to produce coated plates and finished modules. This data allows development focus to be placed on the process/materials that have the highest impact on the final cost/watt of the SCI modules,

The Manufacturing/Engineering Department continued to work on the line layout confirming and updating quotations and delivery schedules for all suppliers.

The computer tracking system implemented in July by the Material and Planning Department was used throughout August to supply management data.

The Manufacturing/Engineering Department continued to work on the projected line layout and sources of individual pieces of line equipment. Two members of the Manufacturing Engineering Department visited the Glasstech Trade Show in Düsseldorf, Germany, where new sources of processing equipment were identified. These companies have been requested to quote on the multi-megawatt finishing line.

4.10 Manufacturing Line Testing and Modification

4.10.1 Substrate Preparation

The edging and washing systems currently used on the pilot line have been evaluated for use on the multi-megawatt line. Time studies show that both systems are capable of providing the required throughput with nominal upgrades. The effluent handling system is needed on both systems and an expanded drying section is required on the washing system.

4.10.2 Semiconductor Deposition

The 100kW pilot semiconductor deposition system (LDS) underwent testing to increase batch throughput and material utilization. These tests included system materials, insulation materials and raw material loading designs as well as process variable variance. Results demonstrated continued improvement over Phase I activities. Throughput has increased three to four-fold to more than 100 substrates per day. Furthermore, raw material utilization has more than doubled. These efforts have provided input for the design of the multi-megawatt deposition system.

A new semiconductor deposition feed system was installed and tested. This loading system utilized different component materials in order to improve the thermodynamic design. Results showed significant improvement in raw material utilization and nearly doubled the length of a single run.

Testing continued on the high-throughput deposition system. Design modifications have been outlined to address some of the system's drawbacks. Modifications include active drive integration, gate valve evaluation, and material feed refinements.

Prototype ventilation systems installed in Phase II proved very effective in handling dust and particles and reducing exposure potential. Area and personnel air samples showed sufficient control with the appropriate protective equipment.

4.10.3 Post-Deposition Treatment

A prototype treatment system was installed and process optimization was started.

Modifications were made to reduce defects related to contamination and gas absorption. These process modifications included time, temperature and system purge parameters. The system processed substrates at a demonstrated rate of sixty per week.

4.10.4 Laser Scribing Systems

SCI purchased two used industrial laser systems in the first quarter of 1995. Each laser system consists of two laser heads each of which are split to provide a total of four beams on the laser scribing table. One of the systems has been installed for testing and debugging. After completion, this system was slated to be incorporated into 100kW line production activities for debugging.

The work on the laser system included programming, optical optimization, and scribing variance tests. The system was tested for initial capability of scribing 30 substrates per hour in the first year of operation. Capacity will be increased, as needed, to meet production schedules.

Numerous electrical, mechanical and optical malfunctions were identified and corrected, including computer booting problem; optics alignment; laser cooling controller; laser readiness; control cabinet cooling; various interlock and safety protocols; and vacuum table readiness.

The major subsystems of the laser were brought on-line in June 1996. The laser controller, position controller, optical rail, and support systems passed startup testing. This allowed for the first scribing of glass substrates coated with CdTe. Initial results were encouraging. Specifically, the power and speed of the laser system provide for at least a ten-fold increase in capacity over the pilot production laser system. In addition, the width and the variability of the lines has been reduced which may allow for closer scribe spacing than the pilot laser. The system scribed a 60cm x 120cm substrate in less than 90 seconds which is a reduction of greater than 90% from the pilot system. The tests have indicated feasibility of using this laser in the multi-megawatt line.

Following the initial testing, the effort was directed on matching the industrial laser with SCI's R&D laser in terms of performance. These tests included laser power stability, power fluctuation, mechanical registration, and ablation completeness. The optical registration system on the laser was also under evaluation to facilitate setup and reduce load time and registration variation.

The industrial laser system has been cleared for pilot production on two of the three scribes required in the interconnection process. The laser system has routinely laser-scribed 60cm x 120cm substrates in less than 90 seconds, which is a reduction of greater than 90% from the pilot system. It is expected that the system will reduce scribing time for each module by 94%. Operating tests continued on the third scribe.

Subsequently, the second scribe continued to present some challenges because of the selective process of ablating the semiconductor without affecting the TCO. The objective was to increase scribing speed while reducing lost active area. Furthermore, tests were underway to optimize power and other laser characteristics for manufacturing use.

The reliability of the laser source (i.e. the laser lamp and associated optics) continued to be a subject of activity. Some of the components have a lifetime of only one hundred hours as specified by the current system. SCI has identified alternatives to these components which will increase the lifetime and energy efficiency of the system significantly. SCI has reviewed these components for procurement.

4.10.5 Interconnection Systems

Vendor site testing was performed to evaluate the effectiveness of standard industrial equipment.

4.10.6 Metallization

The metallization is off-the-shelf that presents lower operational risk than the laser and semiconductor deposition systems. Specification of equipment for metallization was done with vendors' assistance. The equipment will be acquired when needed to for high-throughput manufacture.

4.10.7 Edge Deletion

Edge deletion equipment was tested at the vendor's site. Samples were received and analyzed. The vendor has high confidence that the system is adequate for removing the TCO, CdS and CdTe with no detrimental effects to the rest of the module.

Quotes have also been received on an edge deletion system. Discussions with the equipment vendor identified minor upgrades required on their basic system to handle regulated materials used in the SCI process.

In order to reduce raw material costs, SCI has procured a prototype glass edge grinder. This grinder, currently in a test mode, is capable of grinding the edges of sixty substrates per hour. The substrate size can range from 60cm to 240cm in width. The equipment was purchased used, and some maintenance was needed on spindles and motors to bring it on line. The grinding capability allows SCI to accept glass directly from the glass manufacturer and, thereby, save significant processing and shipping costs associated with intermediate suppliers. These extra costs contribute over $0.50/Watt to the module cost. By installing the grinder, these costs will be minimized.

4.10.8 Lamination

A fixture for preparation of lamination was constructed and demonstrated in pilot production. This fixture will be used to determine the cycle time of manual assembly of the bus bars, cover glass, and EVA. This process was demonstrated on over 50 panels which were slated to be installed at PVUSA. Process cycle time was reduced from 12 minutes to 3 minutes. More reduction is predicted from nominal automation and additional fixtures. At 3 man-minutes per module the process is ready for the first year of the multi-megawatt manufacturing scale-up.

The prototype laminator was tested further with a modified process. The new process significantly reduces defects in the EVA as a result of vacuum lamination. Modules produced with this process are undergoing the IQT protocol to assure comparable durability with the original process. Scaling the new process will reduce the requirements on the vacuum laminators and, therefore, reduce capital requirements and some bottlenecking.

The lamination system was installed. The system will provide for at least a ten-fold increase in lamination capacity. The new system is operated as a batch process similar to that used by the automotive industry to construct windshields. The system was released for start-up and debugging.

4.10.9 Urethane Application

Equipment testing at the vendor's site was conducted to evaluate the effectiveness of standard industrial equipment.

4.10.10 Panelization

The ultrasonic welder for panelization wiring connections was tested on the pilot line and resulted in reduced labor, materials cost, and significantly better control over the ruggedness of the connection.

New techniques for applying the bus bars and cover glass were specified and tested. These activities should reduce the process time by over 90% and should be directly scaleable to the multi-megawatt line.

4.10.11 Testing of the HTDS and the AHTDS Systems

A detailed description of the design, construction and testing of the HTDS and AHTDS systems is given in Sections 4.7 and 4.8.

4.10.12 Multi-Megawaft Production

Upgrading of the LDS Semiconductor Coater

During the first half of Phase III, SCI began work on the retrofit of its developmental LDS semiconductor coater. The objectives of the retrofit were to improve process control, increase capacity, increase material utilization, reduce downtime, and increase machine reliability. These retrofits, resulting in an upgraded system LDS-3, included the deposition apparatus, first developed on the LDS-2 and utilized on the HTDS, and installation of entrance and exit load locks. These improvements were forecast to result in an increase of production capacity from 100kW to over 1MW, reduction of cycle time by 70% and a three-fold increase in up-time. In addition, material utilization was expected to increase from 30% to better than 90% and labor costs drop by as much as 70%.

In the second half of Phase III SCI met or exceeded all of these objectives with a continuous 100-plate run. Small area cells (1 cm^2) and 60cm x 120cm sub-modules were tested at efficiencies greater than 10% and 7%, respectively. Cells and sub-modules made with the LDS-3 were installed into SCI's light soaking station to confirm lifetime performance. Preliminary results after approximately 1,000 hours of light soaking indicated performance comparable with earlier process techniques.

During subsequent deposition activity, problems with glass substrate transportation were identified. The problems contributed to film non-uniformity, substrate jamming, and substrate position issues. The cause of the problems was attributed to temperature uniformity, conveyor alignment, and conveyor roll rotation. The problems were addressed with mechanical modifications and by adjustments in temperature controls.

Further tests were made with a focus on the uniformity of film thickness. The results indicated that uniformity was comparable if not superior to that from the previous batch process. This result is significant given that the former batch system required multiple coating passes to "average out non-uniformity" while the on-demand system required only one pass through the deposition zone. Localized uniformity problems were detected and attributed to conveyor stall and feeder issues that were subsequently resolved.

By February 1998 the LDS-3 machine was routinely operated in both a research and manufacturing mode to advance the deposition process and to identify weak points in the design. In March a formal schedule was set up in which the production and research operators were in charge on their respective days. This procedure allowed the important research program to move forward while allowing production to train new operators and to stabilize the process on a set production cycle.

The results of the manufacturing activities of the LDS-3 are described in Section 4.12.2 entitled 'Production in the LDS-3'.

4.10.13 Modeling of Manufacturing Processes for Multi-Megawatt Production

Solar Cells completed the evaluation of manufacturing simulation and animation software directed at providing better information on operational costs including materials, labor, and indirect costs. Modeling was done on the processes required to produce plates (CdS/CdTe coated substrates) for the purpose of reducing errors in planning and highlighting critical operational elements of the manufacturing system. The software was tested with simplified processes and proved very flexible in animating and costing operations. The simulation of SCI's 10MW plate manufacturing process was also completed.

Results of the study indicated manufacturing costs of 30% to 40% of those incurred on the pilot production line. Most of these savings are due to increased volume, increased yield, and lower labor. At the modeled costs the plates will be very competitive with other "PV cell raw materials."

The software was utilized to analyze used equipment for the $CdCl_2$ process. Because of the flexibility of the software SCI was able to analyze several different capacities in the flow and determine the optimal size of the equipment. This equipment was specified and was under procurement with a savings of over $15,000.

4.10.14 Miscellaneous

Design and specification activities have resulted in the procurement of processing equipment for glass cutting, substrate edging, substrate washing, preheat, semiconductor deposition, $CdCl_2$, and lamination.

The glass cutter will reduce glass costs attributed to a current customer and has a payback of less than six months. The cutter provides SCI the internal flexibility to match customer size specifications for small orders while a product trial period is completed.

Tests on the substrate edger, and washer were completed with acceptable preliminary results. Efforts continued on the timing sequence in the preheat system. Efforts focused on developing a "sweep quench" cycle which increases the throughput of the system and provides valuable information for the coating systems regarding quench pressure, flow, and pattern. After the completion of the tests, these three systems have prepared an ample supply of substrates for debugging activities on the HTDS.

In order to reduce capital requirements, SCI has selectively purchased used equipment when available. The edger and washer were purchased for a fraction of the off-the-shelf price, but do require nominal upgrading and maintenance for start-up.

Design and specification of equipment for potting, metallization, and labeling were completed. Vendors and outside engineering have been consulted to specify designs and preferred equipment for these steps. Used equipment has been identified and is under evaluation to determine its remaining lifetime and adaptability to the SCI module process.

A vendor for the buffing system has been identified and a budgetary verbal quote has been received; however, testing is required to confirm that the equipment can perform to specifications. The system is required to clean residual coating off of the glass side of the substrate.

4.11 100kW Pilot Production

4.11.1 Pilot Production Results

The pilot production efforts were accelerated in early November 1994 to increase throughput and better demonstrate the process and quality systems. Over the Phase II period a total of over 725 modules were produced; production was active for eight months. Thus on average, 91 modules per month were produced at an average conversion efficiency ranging monthly from 6.7% to 7.3% (7.0% average) and at a yield ranging from 60% to 81% (70% average). The variation in the efficiency was due to optimization of the new raw material loading components in the 100kW deposition system. Defects in the films were traced in part to the material used for holding the source material in the deposition zone. This material was substituted by a more stable material that eliminated some of the problems. Over 32kW of product was produced and shipped.

During the third phase of the subcontract SCI reduced its production activities to focus on the equipment design and debugging activities. However, towards the end of the phase, activities were ramping up with the goal of completing a 100kW array in Toledo, Ohio by the end of 1998. Figure 21 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 debugging 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%.

Some of the process steps have been demonstrated at throughput levels of 100 units/day, which represents approximately 1MW of annualized output. They include semiconductor deposition, glass seamer, and glass washer. The most basic component of this line, the semiconductor deposition, has amply demonstrated a multi-megawatt-annualized capacity.

By the end of the program, approximately 6,000 modules have been processed on the 100kW line (now upgraded to 250kW) as part of the development efforts.

4.11.2 Related Information

Figure 22 shows the power output of a 1.0kW array installed at NREL, corrected for temperature. This array has been in operation for over three and one-half years and has demonstrated solid performance. The design and process used for the panels and modules was supported by this subcontract.

4.11.3 Miscellaneous

Improvements were made in the buffing process to reduce process time, maintenance and rework. The new process reduces waste by-products and reduces CdTe film contamination due to over-spray of the buffing compound.

The edging and washing systems currently used on the pilot line have been evaluated for use on the multi-megawatt line. Time studies show that both systems are capable of providing the required throughput with nominal upgrades. An effluent-handling system is needed on both systems and an expanded drying section is required on the washing system.

4.12 Continuous Production Line Run

After concluding the HTDS operations, SCI reorganized its production activities. The pilot production team consisting of experienced operators and technicians from past production activities as well as new members with technical and manufacturing backgrounds was assigned to concentrate on upgrading production equipment. SCI resumed production with a team of four operators and expanded the team to six members.

SCI also formed a Process Team consisting of four individuals with degrees in industrial engineering, chemistry, and EHS affairs. This team was assigned to focus on observing, documenting, analyzing, and statistically improving the pilot process to reduce risk during the scaling period. Specifically, their function is to reduce variation in the processes that limit progress in achieving significant improvements in the production process.

4.12.1 Documentation of the Standard Operating Procedure (SOP)

The Technical Process Team completed its objective of documenting the additional increases in daily production rates for each process step. The SOP has been documented in the IS09000 format that provides the necessary base line on the process. This team is now in the position of being able to prepare changes in the SOP to increase output and lower manufacturing costs. These procedures are planned to be in full operation by January 1, 1999.

4.12.2 Production in the LDS-3

Following the retrofitting of the LDS system in Phase III, the Pilot Production Team engaged in the improvement of production procedures and in converting coated plates to modules that stood at an average rate of 5 modules per day.

In Phase IV the modified LDS process continued to be operated in a production mode developing not only plates for further conversion into working modules, but also yielding valuable insight helpful to the task force designing the new production machine.

During a five-month period a total of 2,912 coated plates were produced (23,296 sq. ft.) of which 70% were good quality. The highest monthly production was 866 coated plates (7,747 sq. ft.). This increase in operation was needed to supply coated plates for internal (7,747 sq. ft.). This increase in operation was needed to supply coated plates for internal use.

Problems were experienced in the coating quality of the CdS material. A decrease in the average conversion efficiency was experienced which was traced, in part, to dust particles formed during the film deposition. This dusting leads to pinholes that, in turn, affect finished conversion efficiency. Most of the off-specification plates were caused by feeder/distributor problems.

A cross-functional technical group was set up to determine the cause of this intermittent problem. A matrix of possible causes were developed and thoroughly studied. The problem was narrowed down to air leaks in the feeder, giving rise to the formation of dust particles.

Over the course of six months, the production rate for modules has risen stepwise by 320%, from 5 to 16 finished modules per day, with no increase in labor content. Additional production workers were hired and received their initial training during this period, to achieve additional increases in daily production rates.

Another cause for the decrease in the average conversion efficiency for the modules was traced to problems with laser scribing. The latter has prompted a plan to accelerate the procurement and testing of new laser technology in the Pilot Plant. In order to address this problem, recommendation was made to purchase the laser scribe system, planned for the multi-megawatt module conversion plant, and to begin using it in the Pilot Plant Operation. Quotations have been received and evaluated for a potential order. As of October 1998 a laser system integrator has been identified, however, the type of laser to be used is still undecided.

4.13 Average Efficiency Improvements

From Dec. '94 to Oct. '95 the monthly average efficiency of pilot production modules ranged from 6.7% to 7.3%, with a variance of less than 10%. Best demonstrated modules were measured at greater than 60watts. Both of these results show an increase of approximately 8% compared with previous levels. Improvement efforts were focused on reducing the variance further so that well-designed experiments can be run in a highly controlled manner. Over this period the key processes examined for device improvement were the deposition of CdS/CdTe, $CdCl_2$ heat treatment, lamination and urethane application (potting and mounts).

Subsequently, SCI continued pursuing process improvements leading to increased efficiency. Most of these efforts have been undertaken by SCI's R&D team. The manufacturing team took the approach of first pursuing line issues related to variation in the efficiency to be followed by implementation of identified potential efficiency improvements as they become available. The variation is caused primarily by the variation of across-web film uniformity of the new on-demand coating system in the developmental coater. The film characteristics have been thoroughly tested with 1 cm^2 cells. These results have indicated that the film's potential efficiency is on par with films deposited with the batch process.

4.13.1 Thickness Uniformity

The Manufacturing Team has concentrated on resolving machine variables that may have direct effect on the uniformity of coating thickness. The temperature uniformity of the glass as it is presented to the deposition system is suspected to be the variable with the major effect on coating uniformity and resulting average output efficiency. Plans and equipment were placed on order to be able to map the temperature of the glass as it is transported in the vacuum/heating chamber. This information is critical to the design of the heater/conveyor sub-system of the production deposition system.

4.13.2 Conversion Efficiency of PV Modules

During the 7-month period March and September of Phase IV the Pilot Production Team produced 950 completed modules. The largest output of 277 modules was in July. It should be noted that less than one half of the 'good' coated plates were used for finished modules.

The highest average efficiency of 6.50% was obtained in April, followed by a downward trend during the summer months down to 5.34% in July and a partial recovery in September with an average of 6.05%. The causes of the problems with efficiency are discussed in Section 4.12.2 entitled 'Production in the LDS-3.'

4.14 Quality Assurance Development

4.14.1 Process Control and Product Improvements

SCI has initiated a quality assurance program specifically focused on the multi-megawatt manufacturing line. This program has undergone periodic evaluation and refinement on a pilot production line. Most of the efforts were 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 the first two and one-half year period with significant increases in the past twelve months covering production batches 30-50 (see Fig. 23). Concurrently, the relative standard deviation of the performance decreased substantially to below 10% (see Fig. 24). The average module performance over the course of the first three phases is shown in Fig. 21.

These improvements are the result of several quality programs, already implemented or in progress, including standard operating procedures (SOP), 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. 25). 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.

4.14.2 Product Durability

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 Phases I and II of the subcontract. IQT pass rates have increased from below 20% to 100% on a module basis (see Fig. 14). Most of the improvement was a result of better potting designs and lamination 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. Lamination process improvements including cleaning of the sealing surface on the module improved pass rates for the humidity-freeze test from approximately 50% to 100%.

An IQT series was conducted. Six modules were randomly selected from the pilot line inventory for each test. The average overall change in efficiency for the six modules was less than a 10% decrease. In addition, three modules were tested for over 650 thermal cycles to determine module lifetime. Performance of the modules decreased by less than 5%. This result indicates a module life of 20-30 years. Subsequently, these modules were subjected to further damp-heat stress testing.

4.14.3 Process Control

Process control activities were focused on the semiconductor deposition process. Significant improvement was made on total batch throughput and thickness uniformity. As part of this effort on-line process variable charting is used to track critical processes. Semiconductor thickness has been identified as a key process indicator. SCI now measures the thickness of each substrate as it is produced so that system adjustments can be made for subsequent substrates. This activity has increased semiconductor deposition yields by 100%. The goal was to increase the output of the pilot deposition system by a factor of four so that significant quantities of modules can be produced for process optimization and demonstration.

Inspection measures were added to check the performance of the three scribing processes. For Scribe 1 and Scribe 3 this measurement is the resistance across the scribe. For Scribe 2 a visual inspection is made to subjectively rate the completeness of CdS/CdTe ablation. Efforts are underway to develop a quantitative measurement for the Scribe 2 process. The primary technique under evaluation is image recognition with spectral differentiation capabilities.

A Product Quality Reporting System was developed to track defects and analyze root cause issues. The product quality reports are used in conjunction with process control measures to facilitate understanding of process variation and to define objectives for performance improvement for operators. The system identified the post-deposition treatment as an area for improvement, Process revisions were incorporated and the yield of the process increased to a level comparable with other processes. Information from the system is evaluated daily in order to provide timely feedback.

4.14.4 Monitoring of Modules Installed in the Field

In Phase IV SCI continued monitoring modules located at several sites. The data show excellent performance with flat (no aging problem) output curves. Performance of the 1kW array installed at NREL is shown in Figure 22. Environmental module testing continued to show no failures.

SCI has installed several modules into weathering chambers to assure results are consistent with expected values. The primary test is humidity-freeze in combination with the wet hi-pot. These tests have proven to be the most difficult to pass in the past, however, since 1995 these tests are passed routinely.

4.14.5 Total Q.C. Plan

In July 1998 Quality Control Department has been set up within the Pilot Production Team for the purpose of establishing a total Q.C. Plan. The plan will contain of a full set of testing procedures that will be used in production. In September the Q.C. Plan was ready for revision. Analysis of inspection points has resulted in the removal of some non-value-added measurements. ANSI and ISO9000 information was monitored for future system improvements.

During March 1998 a thermal IR scanner, ScanIR, was tested from Ircon Inc. A viewing window was mounted to allow the glass to be scanned as it transferred in the heat and vacuum between the heating and deposition chamber. This device allows the full surface to be measured for thermal variation during processing. Temperature variations of more than 50°C were observed from glass center line to edge. This information will allow the design of improved glass heating systems. A direct correlation between glass temperature uniformity and deposition coating uniformity is expected.

4.15 ES&H Program Development

Production of CdTe PV modules involves regulated materials including cadmium. An important part of the PVMaT effort was to establish programs for effective handling of environmental health and safety issues stemming from the development, production, deployment and disposal of these modules. SCI 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 testing.

4.15.1 Major EH&S Programs Addressed in Phase I

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 9 outlines the major EH&S programs addressed in Phase I.

Table 9. 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

4.15.2 SCI Employee Handbook

The EHS Committee finalized the SCI Employee Handbook. The handbook is a guide to the program development phase of the EHS activities. The handbook addresses:

- General Safety Policy
- SCI Safety Mission Statement
- SCI Safety Process Objectives
- Safety Principles/Philosophies
- EHS Committee Responsibilities
- Employee Responsibilities
- General Safety Rules
- Disciplinary Action
- First Aid Policy
- Personal Protective Equipment
- Safety and Environmental Training Policy
- Employee Training Requirements
- Employee Medical Examination Requirements
- Chemical Spill and Release Policy
- Fire Response Procedures
- Evacuation Procedures

4.15.3 EHS Compliance Plan

The EHS Committee developed a plan to surround all EHS compliance and administrative responsibilities. This plan has four central elements:

- The Employee Handbook
- Compliance programs and training documented in one or more EHS procedure manuals
- Incorporation of EHS issues and procedure into existing production standard operating procedures based on principles of hazard recognition and analysis
- A central indexed EHS file system

Most of the compliance issues and programs have been implemented. Frequent and periodic training of employees is continuing.

4.15.4 Monitoring Employees for Cadmium Exposure

During Phase SCI completed an upgrade of its biological monitoring program. This upgrade includes two urine and one blood test for cadmium. All new employees receive a baseline test and thereafter receive follow-up testing depending on job duties. All of the test results showed were within the normal range of the general population. Periodic biological testing for production personnel is slated about one year apart.

SCI has successfully managed the work place health risk from cadmium exposure by meeting or exceeding the requirements of the OSHA Cadmium Standard. Throughout the program, the annual cadmium biological monitoring results continued showing no values above the expected norm.

During January and February of 1998, eighteen employees were monitored at the Medical College of Ohio for cadmium blood, urine and beta 2 microglobulin levels—all employees passed.

Subsequently, eight additional employees were hired to assist in developing additional module processing rates. These new employees were tested at the Medical College of Ohio to establish base line data to assure compliance with all federal CdTe exposure requirements. SCI continues to manage the health risk of all employees to cadmium exposure and monitoring of employees continues to assure compliance.

4.15.5 Cleaning Procedures for Cadmium and Cadmium Compounds

SCI instituted cleaning procedures to assure that cadmium and cadmium compounds remain in controlled areas. These procedures include cleaning techniques, hazard communication, schedules, and monitoring activities. These improvements were suggested by the Bureau of Workers' Compensation through an industrial safety survey conducted by SCI request in March 1994. These procedures were used subsequently to clean the areas where cadmium compounds are handled in the process—specifically semiconductor deposition, edge deletion, and substrate cleaning.

4.15.6 Hiring of EHS Manager

At the start of Phase II, SCI hired an EHS manager, who brings extended industrial experience with manufacturing processes. In this capacity, the manager also serves on the EHS Committee.

4.15.7 Related EHS Activities

Lockout/tagout, an important compliance program, was completed. The program includes the training of in-house instructors, training of all operational personnel, and identification of lockout/tagout procedures for all critical equipment. This program will be expanded to include electrical line tracing and labeling.

Engineering controls were specified for two processing areas. These controls restrict and reduce the opportunity for contamination outside the specified process area. These controls include improved ventilation handling techniques. The complexity and cost of these controls is low and the designs are scaleable to the multi-megawatt line.

Results from an industrial noise level test conducted in May 1995 showed no areas exhibiting over the OSHA permissible exposure level in the plant.

Activities related to OSHA Cadmium Standard compliance including employee training were completed.

Activities related to OSHA Hazard Communication Standard compliance including employee training were completed.

Activities related to Resource Conservation and Recovery Act compliance including employee training were completed.

4.15.8 Hazard Recognition and Analysis Plan

A pro-active hazard recognition and analysis plan was put into place. Under this plan area inspections will be conducted by the EHS Committee eventually on a monthly basis. A hazard recognition form containing prompts (hazard hints) provides added confidence that the inspection identifies hazards beyond simple housekeeping issues. Identified deficiencies are assigned a risk value based on the estimated frequency and severity of the potential hazard. Corrective measures are determined and resources assigned based on priority and overall ranking of the hazards.

This hazard recognition program has been very effective in identifying and correcting current and potential hazard issues. Employee involvement has also increased due to point of interest interaction with the EHS Committee.

4.15.9 New SCI Process for Separating Hazardous Waste

SCI's ESH team through the assistance of PVMaT and SBIR programs has demonstrated and implemented a self-contained process which strips the semiconductor films off of the substrates. This process has been used to eliminate scrap produced during debugging activities. Unbroken substrates were tested for possible recycling. Some of the substrates showed that the process did not impact the performance of the TCO. However, a recent test with TEC-15 showed damage to the TCO. Thus, recovered substrates may be usable for architectural applications but not as solar cell substrates. Broken glass is ground into small pieces before stripping. This process has already eliminated tons of potentially hazardous scrap thereby saving thousands of dollars in raw materials and disposal costs. This process is now automated.

A simple cadmium precipitation treatment was started on the pilot production line liquid effluent. This treatment reduced liquid effluent by over 95% on several process steps.

5.0 REFERENCES

[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.

[5] R. Sasala and J Bohland, "Physical and Chemical Pathways for Economic Recycling of Cadmium Telluride Thin-Film Photovoltaic Modules," *25th IEEE PVSC, 1966.*

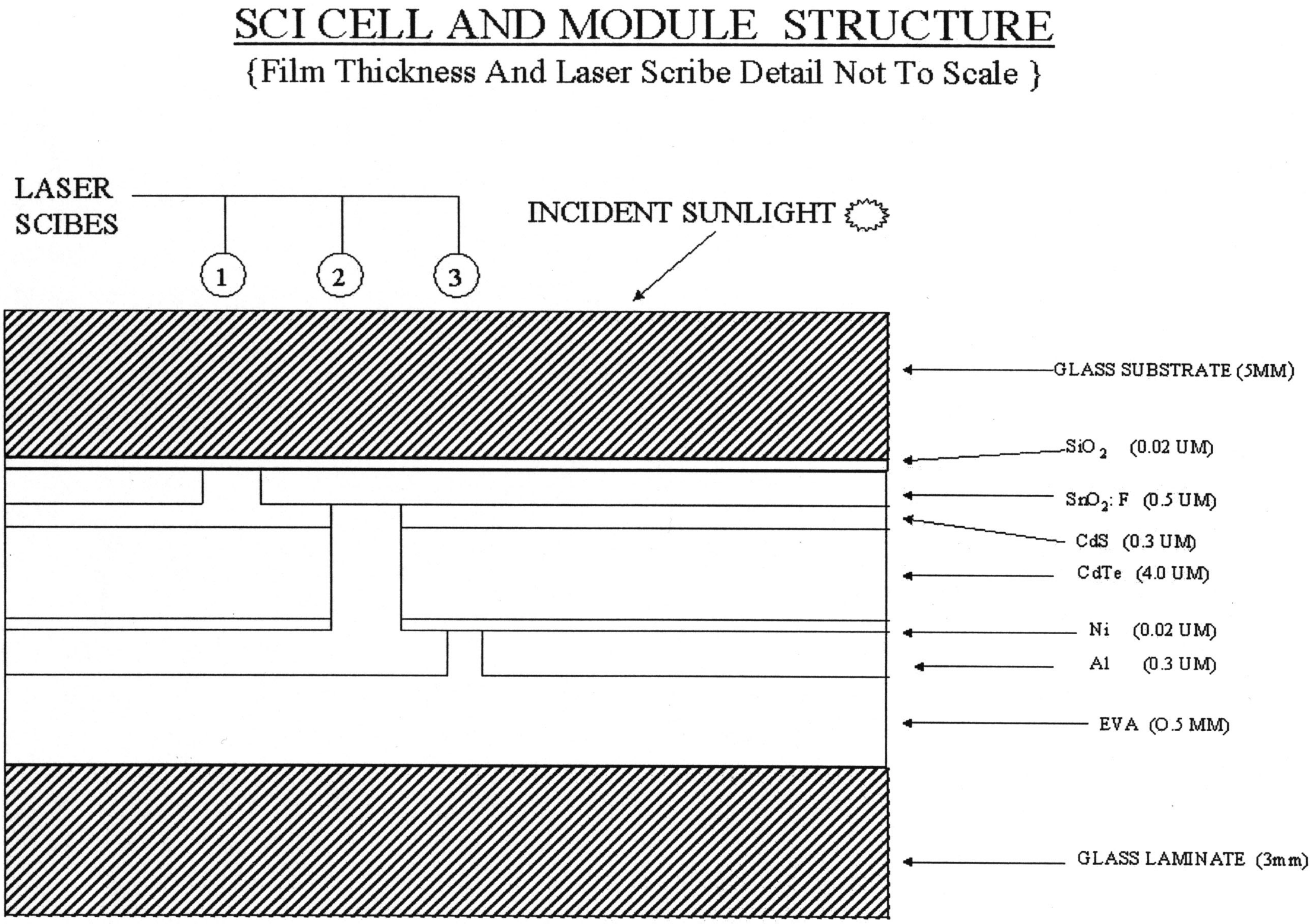


Figure 1. Cell and module structure

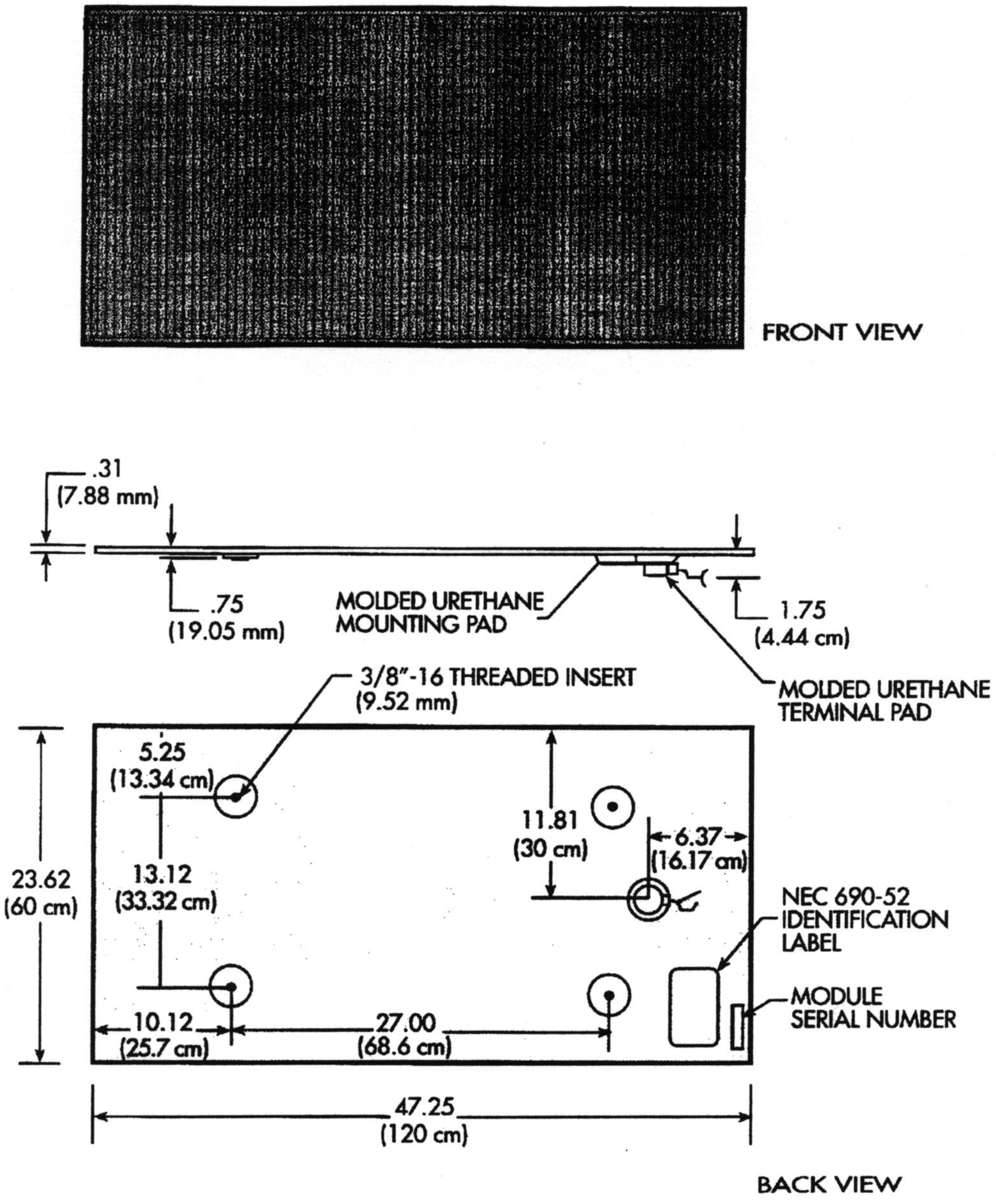


Figure 2. **Module diagram**

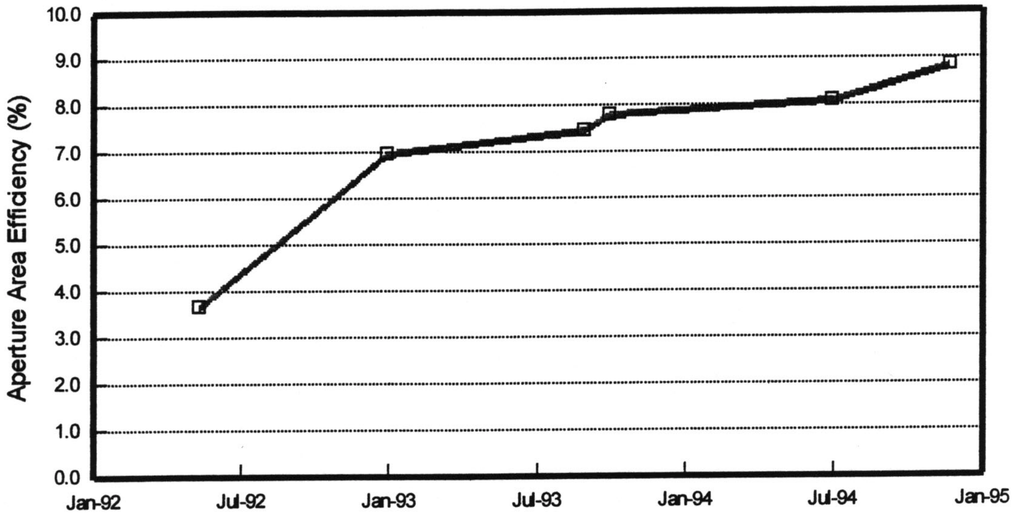


Figure 3. History of best-demonstrated aperture area efficiency for production modules

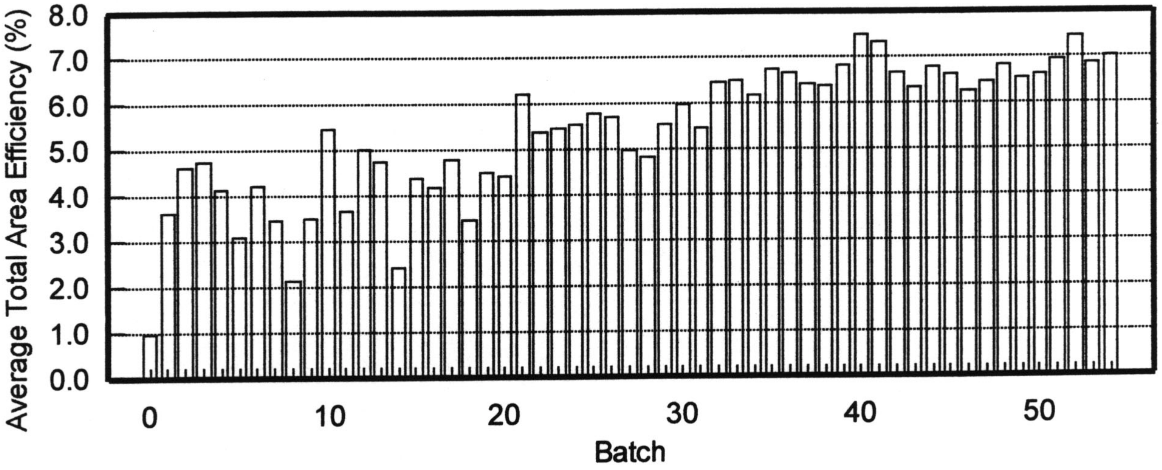
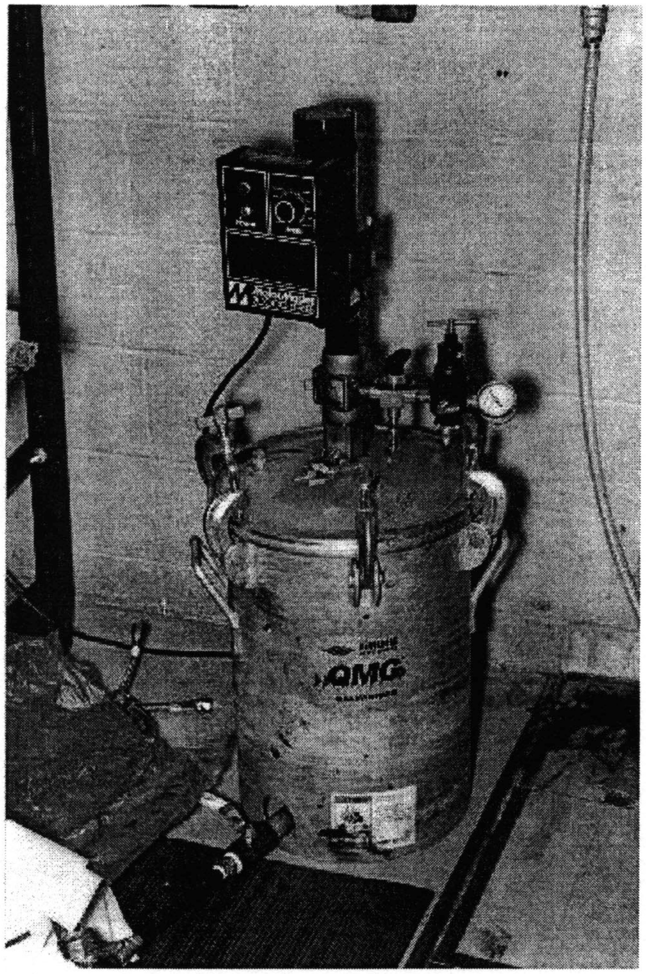


Figure 4. Average module performance by batch for batches 30-54 of PvMaT efforts



Metering Equipment for Potting Process

Figure 5.

Manufacturing Line Layout

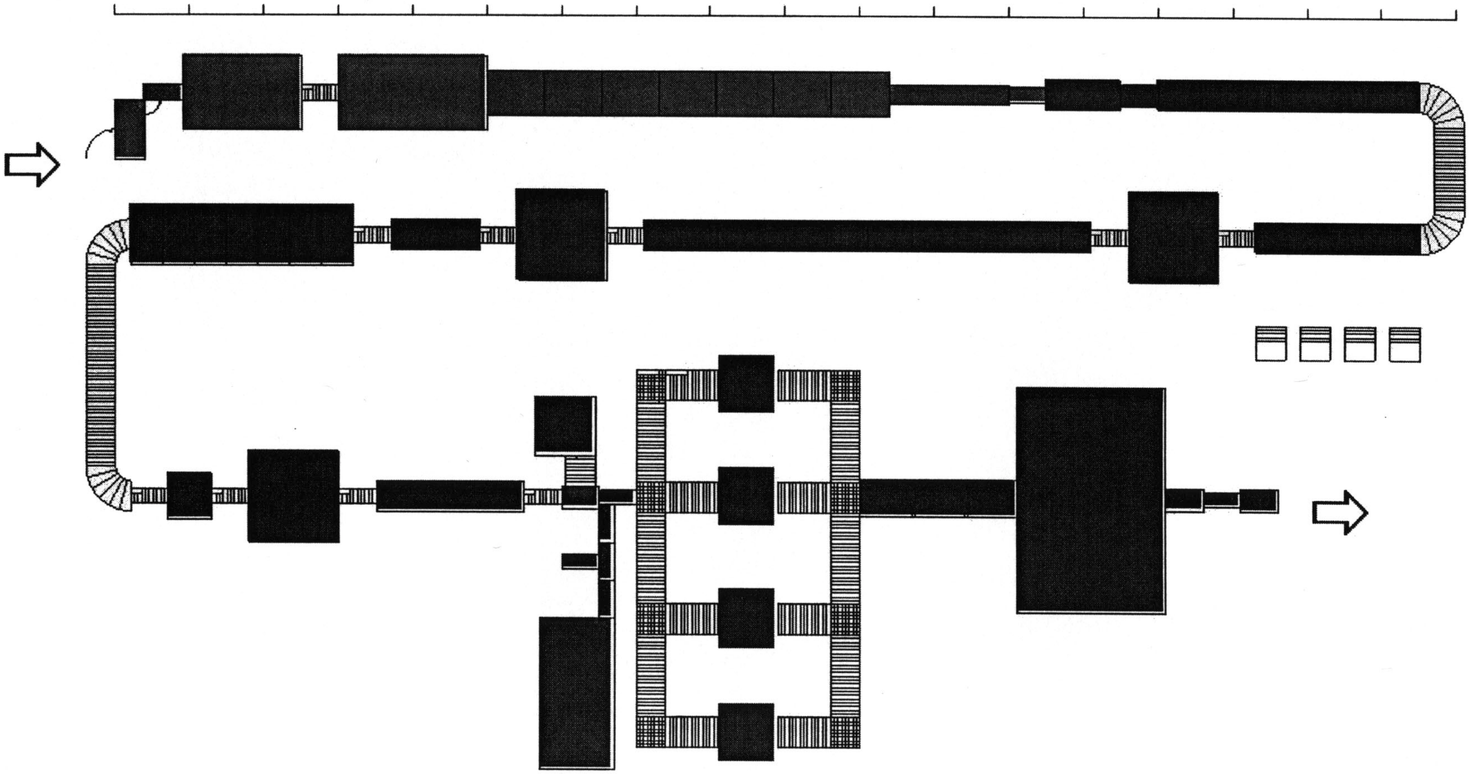


Figure 6. Unannotated layout of the multi-megawatt line

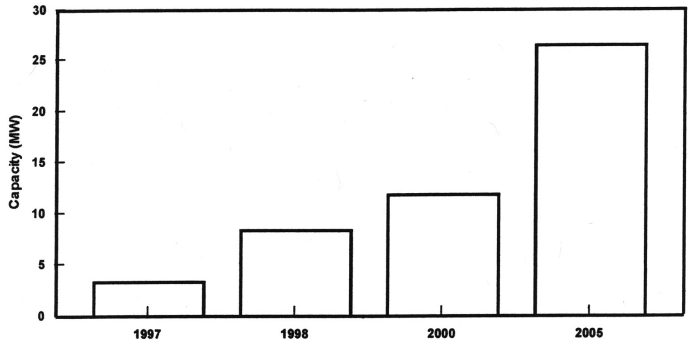


Figure 7. Projected plant capacity of 20MW line assuming 1 shift operation for 1997 and two-shift operation for all other years.

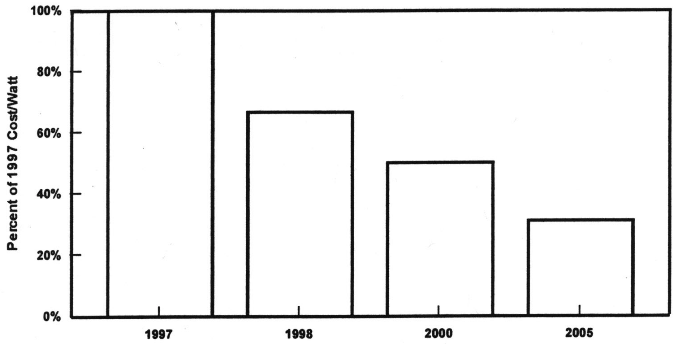


Figure 8. Projected manufacturing costs compared with the first year costs

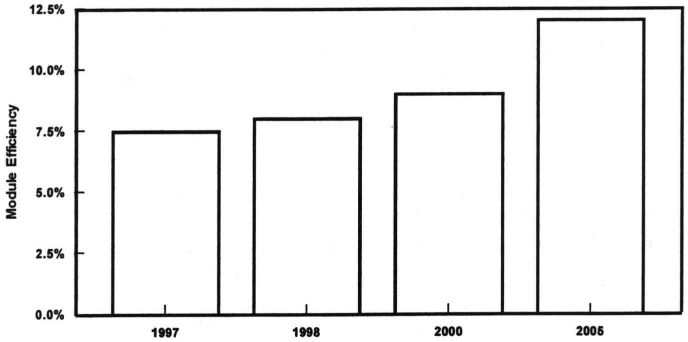


Figure 9. Average module efficiency assumption for manufacturing projections

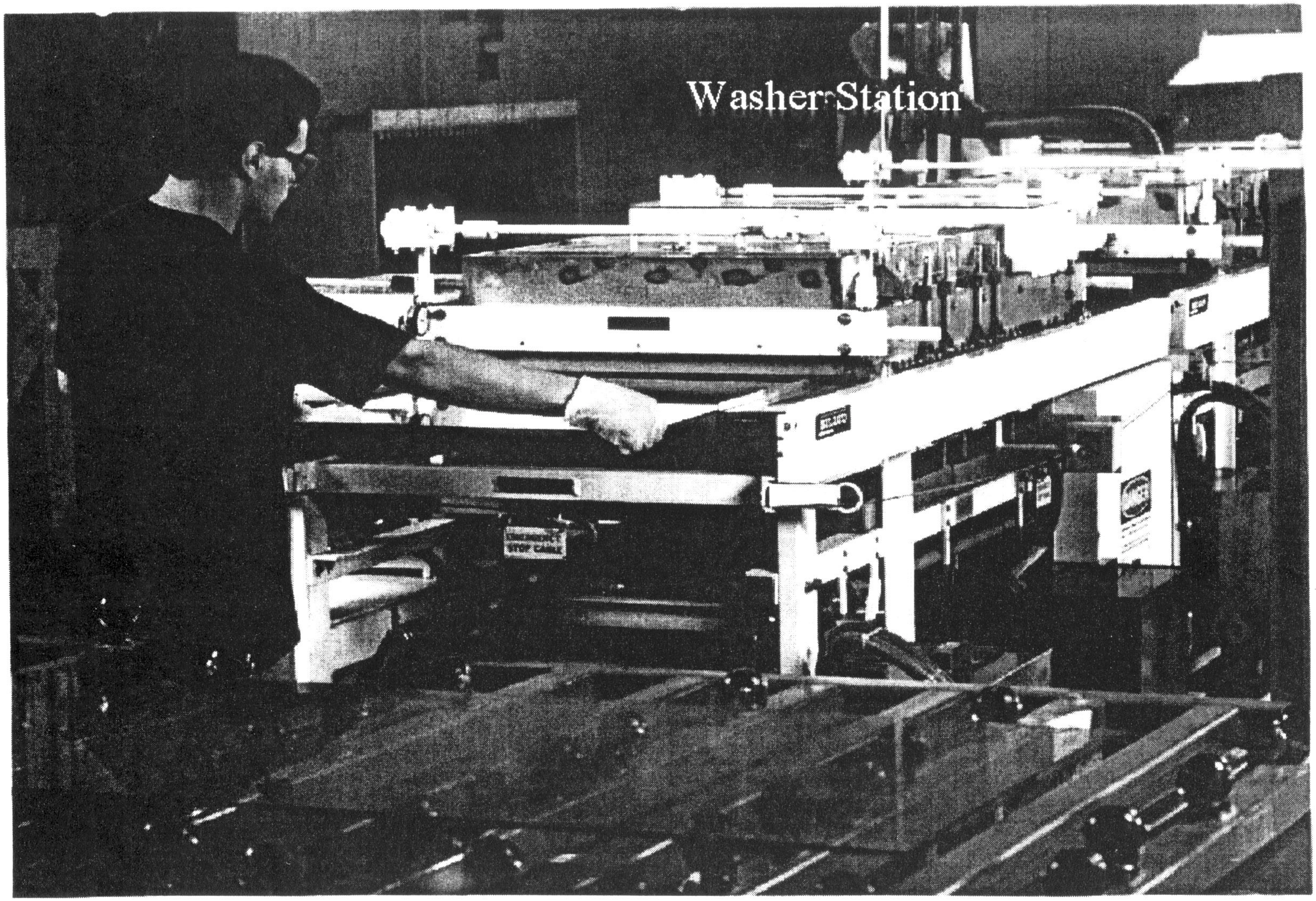


Figure 10. Photograph of glass substrate seamer (foreground) and washer

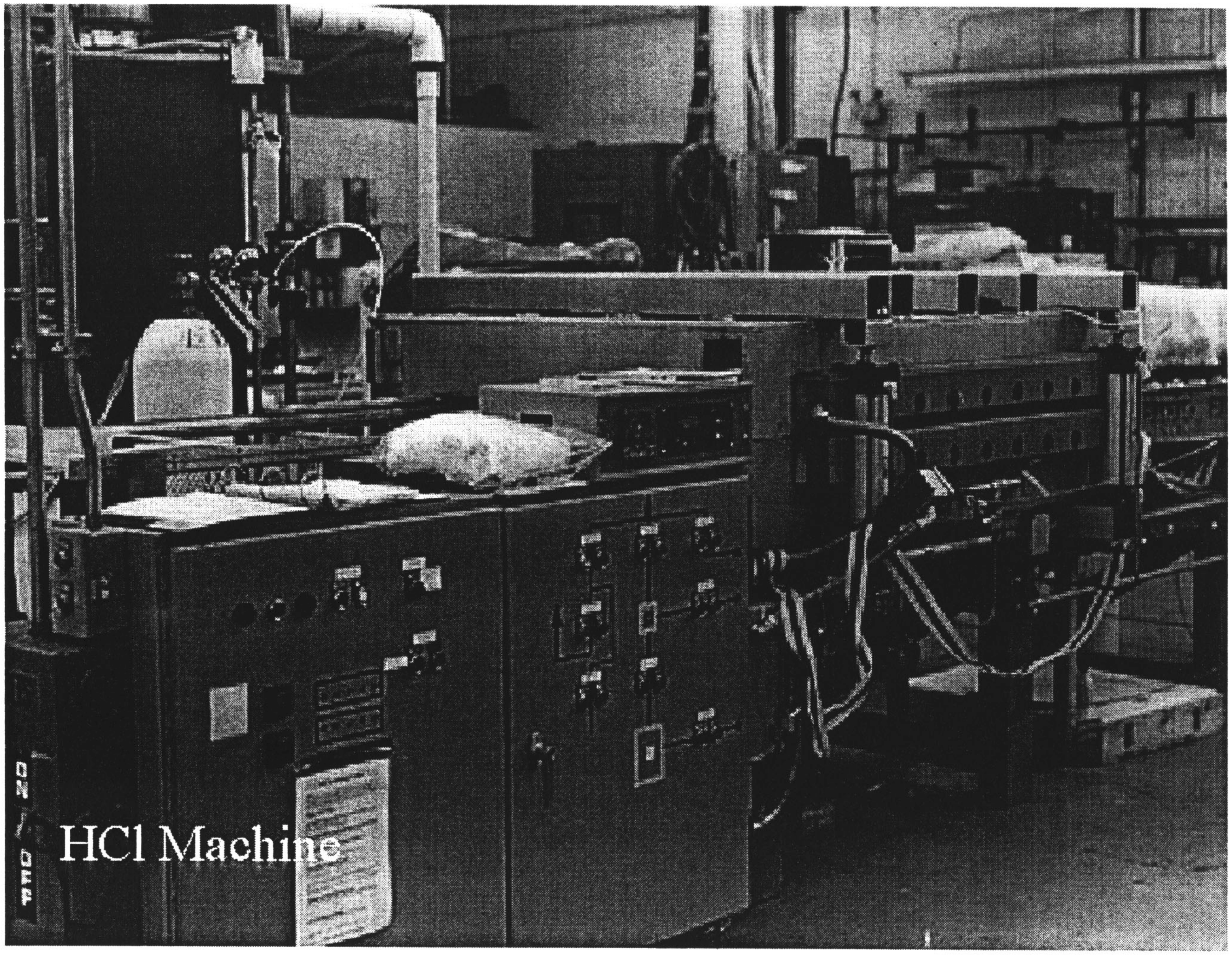
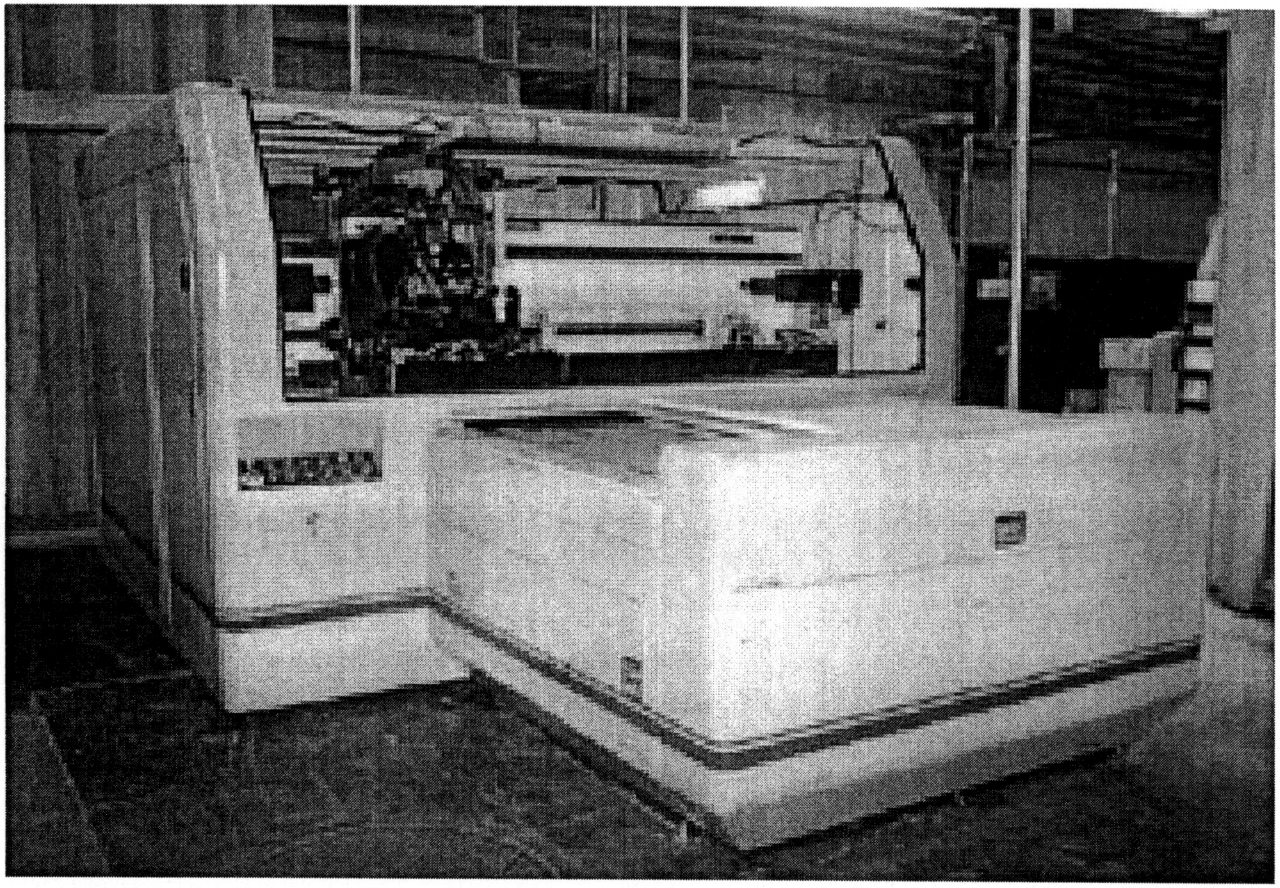


Figure 11. Photograph of HCl post- treatment oven



Industrial Laser Scribing System

Figure 12. Photograph of industrial laser scribing system

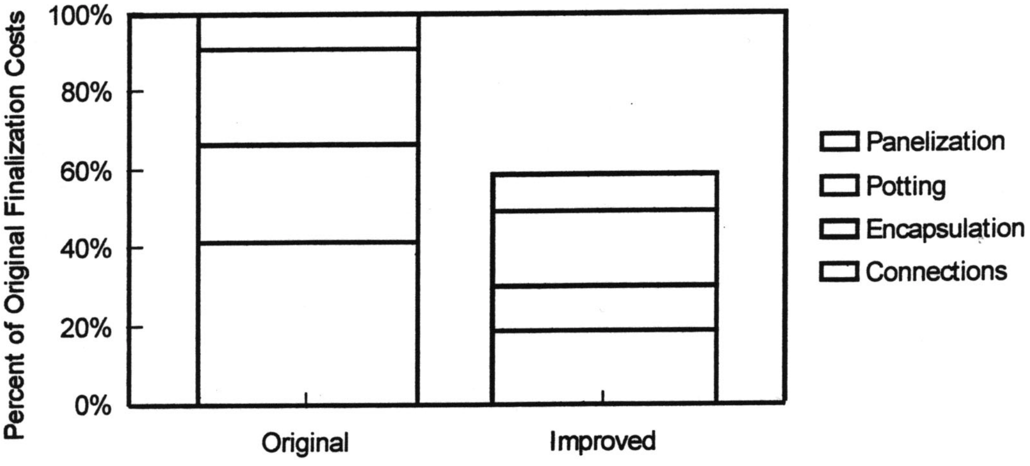


Figure 13. Product finalization cost reductions

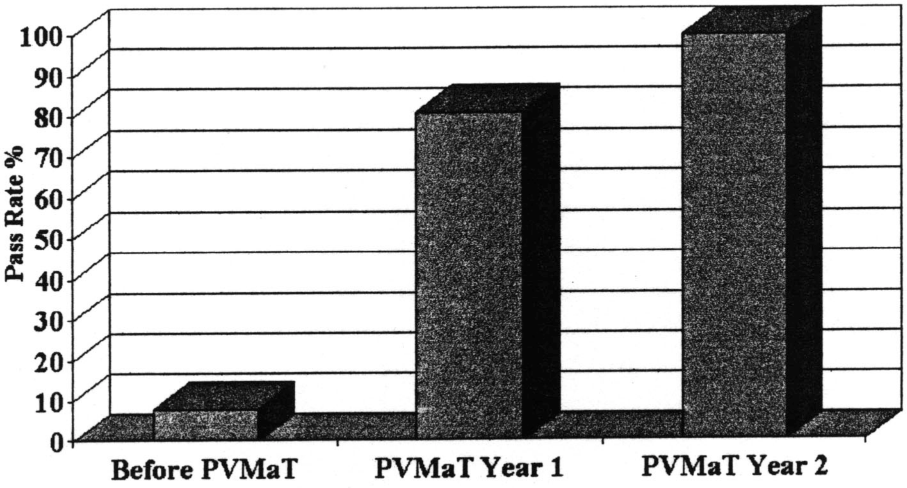


Figure 14. Module pass rate for IQT testing prior to and since the PVMaT efforts began

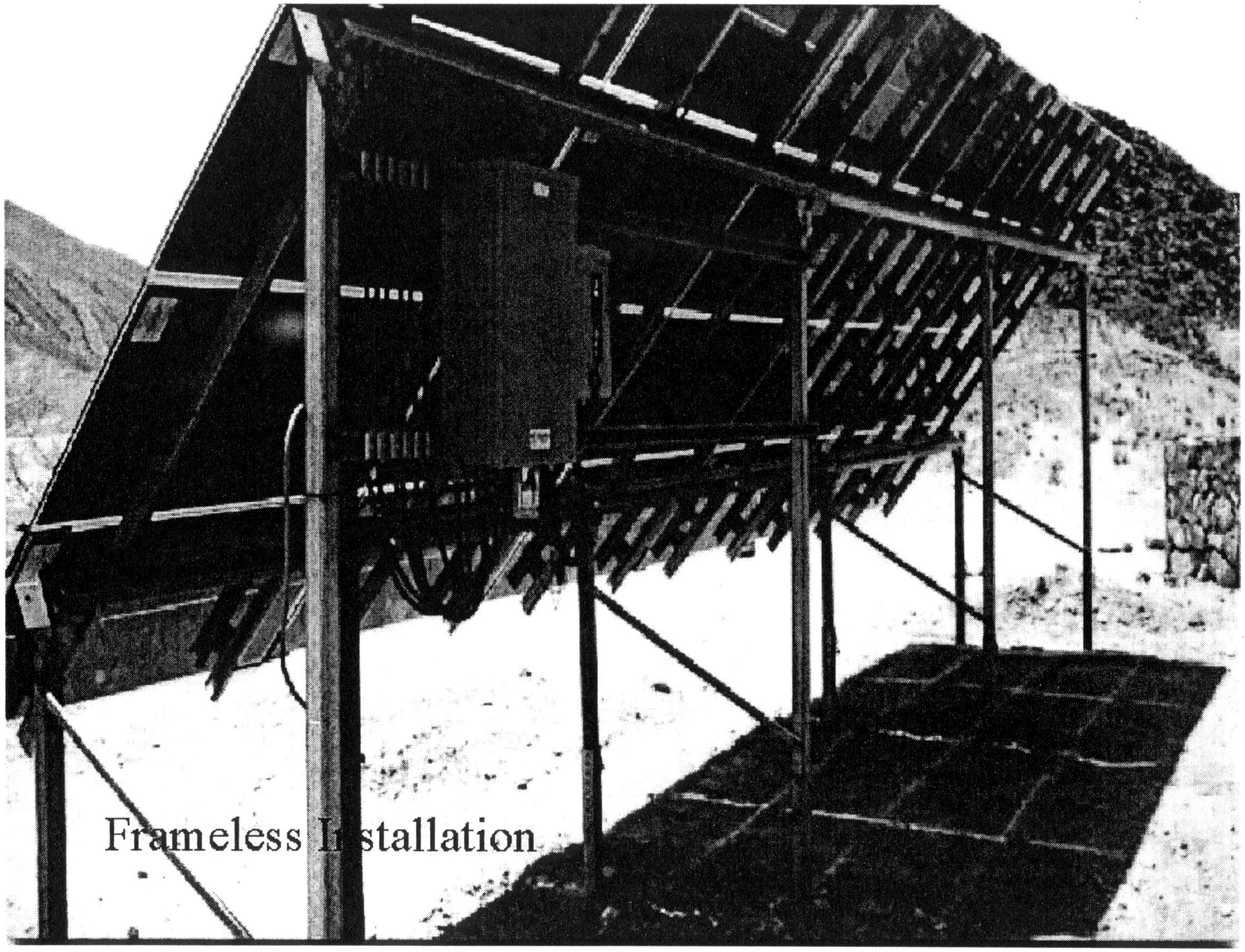


Figure 15. Photograph of 1.2kW array in Tunisia demonstrating frameless panel installation

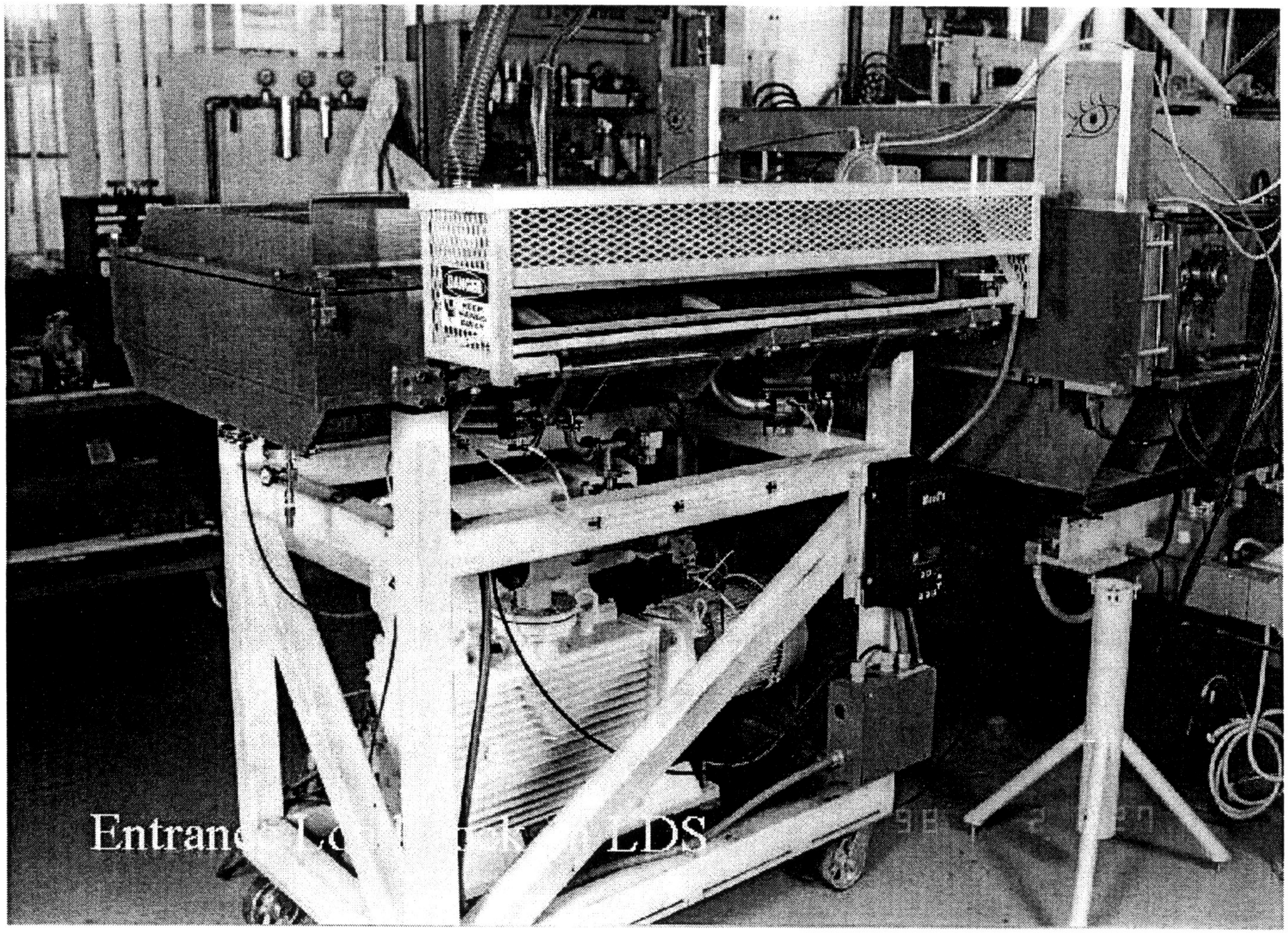
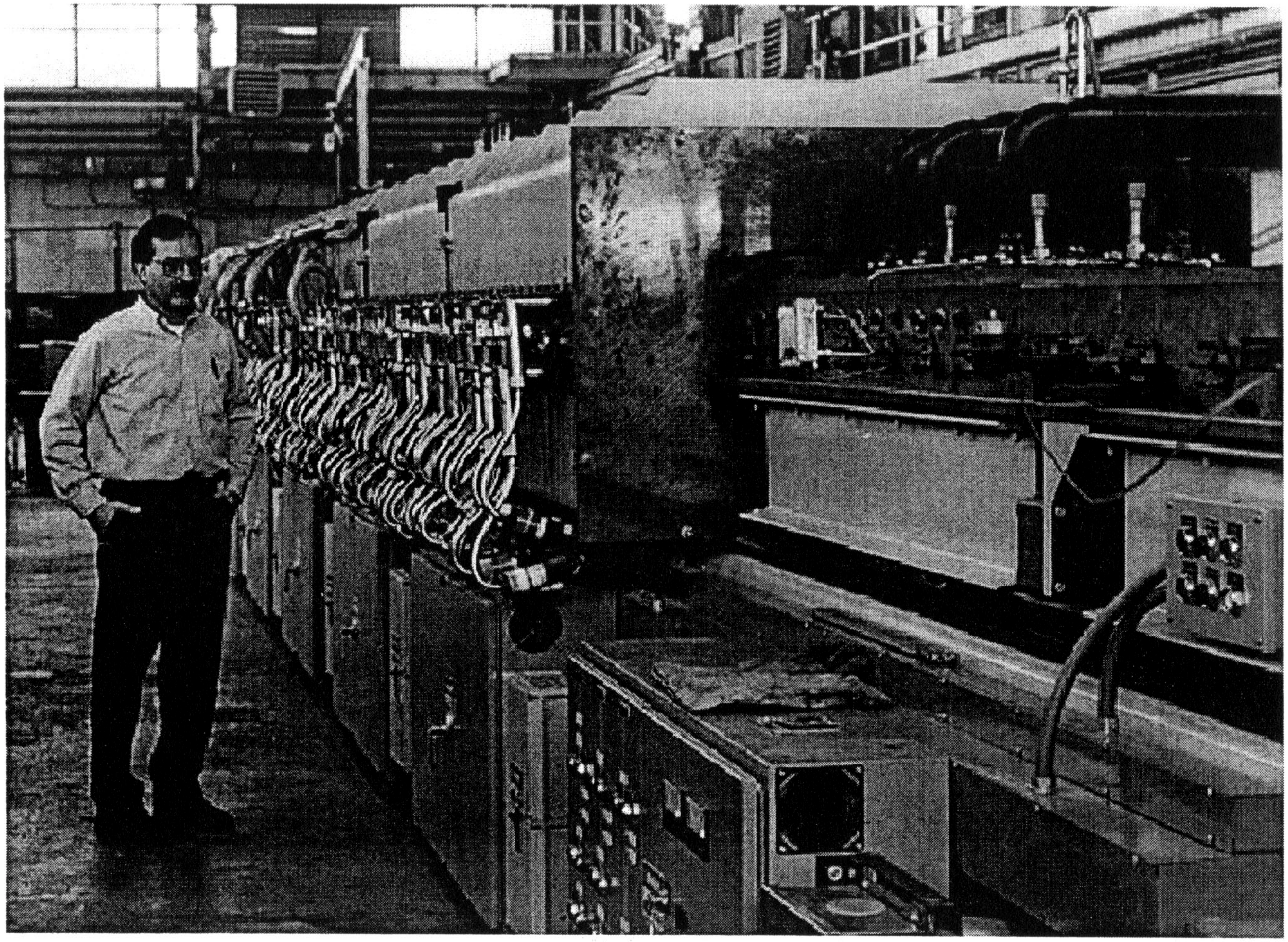
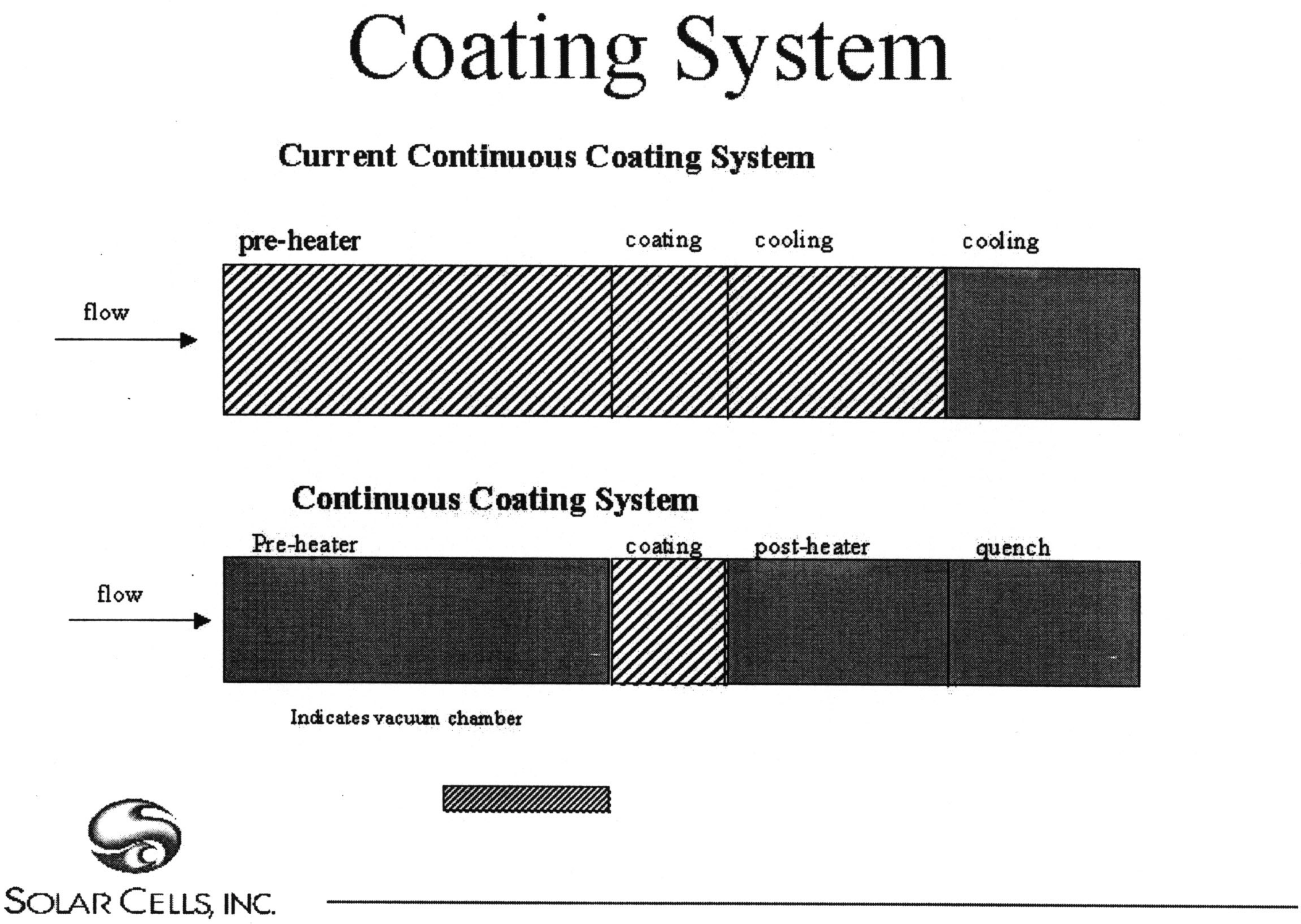


Figure 16. Photograph of entrance load locks on LDS-3



High Throughput Deposition System

Figure 17. Photograph of the high-throughput deposition system (HTDS)



Coating System

Current Continuous Coating System

flow

pre-heater

coating

cooling

cooling

Continuous Coating System

flow

Pre-heater

coating

post-heater

quench

Indicates vacuum chamber

▨

SOLAR CELLS, INC.

Figure 18. Schematic of vacuum length comparison

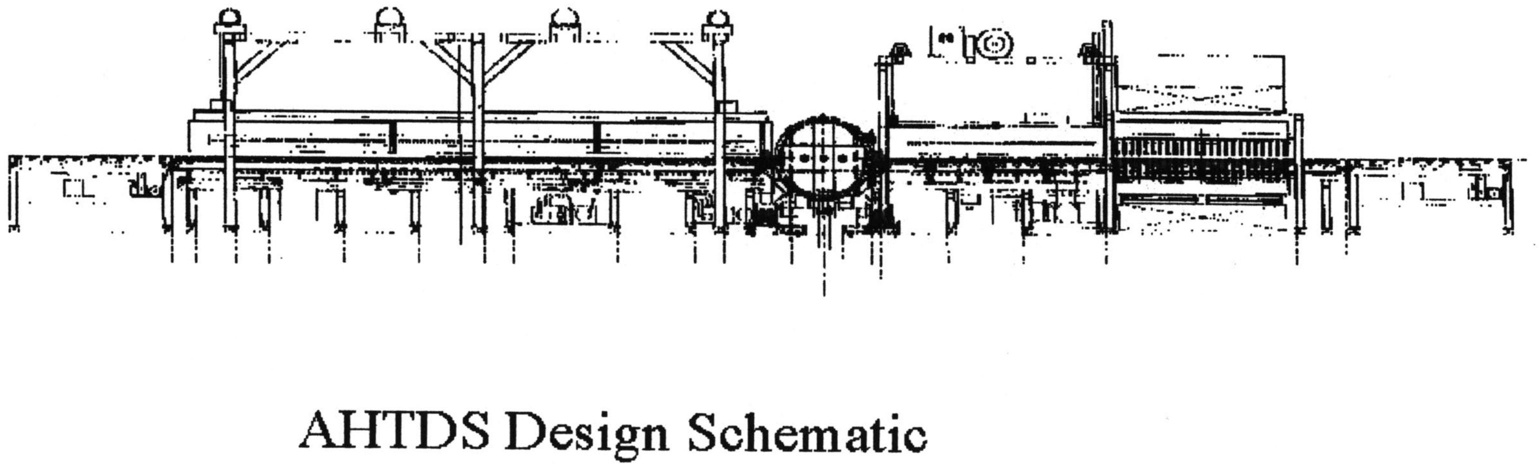


Figure 19. Schematic of AHTDS design

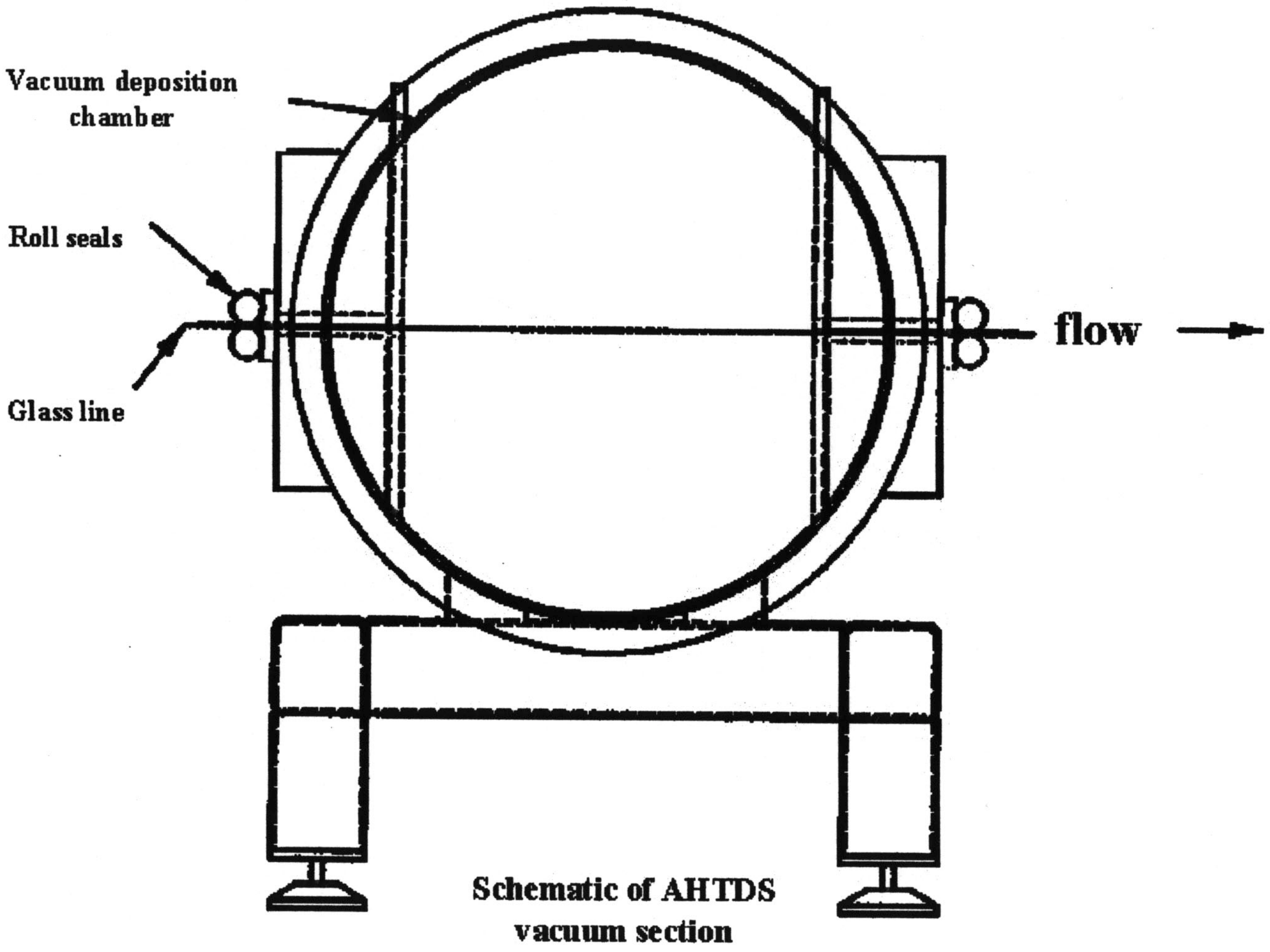
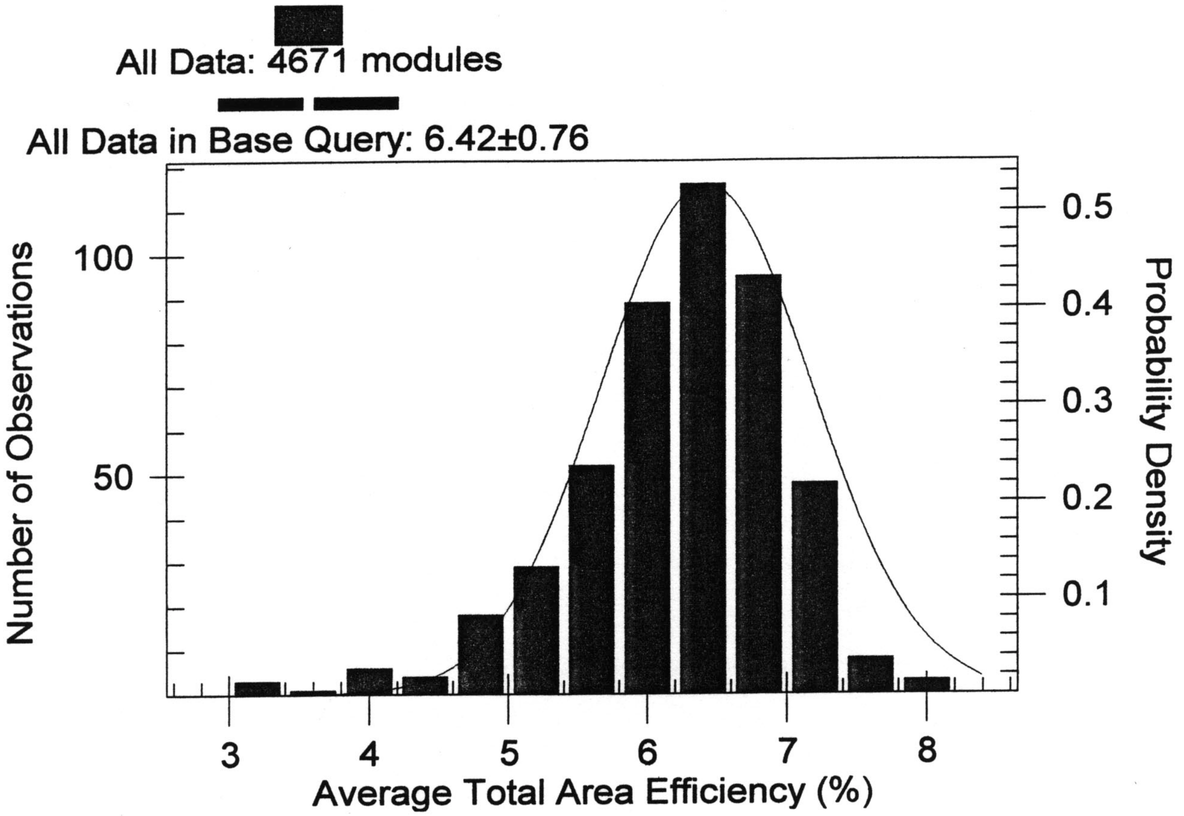


Figure 20. Schematic of AHTDS vacuum deposition chamber cross-section

Figure 21. **Historical efficiency data for R&D and production modules from 1/1/94 to 12/31/98 (data taken following post-metal heat treatment)**



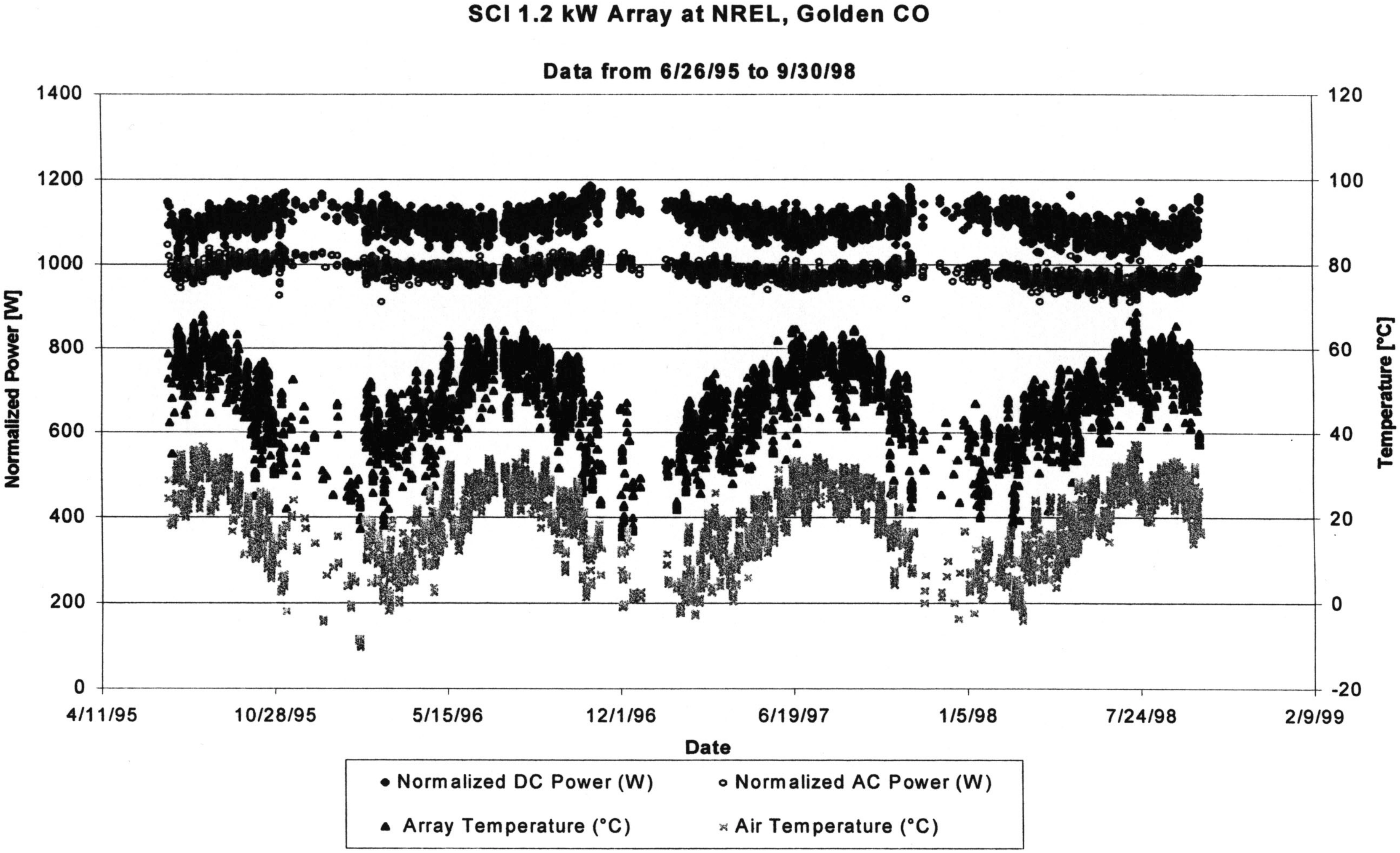


Figure 22. Performance of the 1kW array installed at NREL

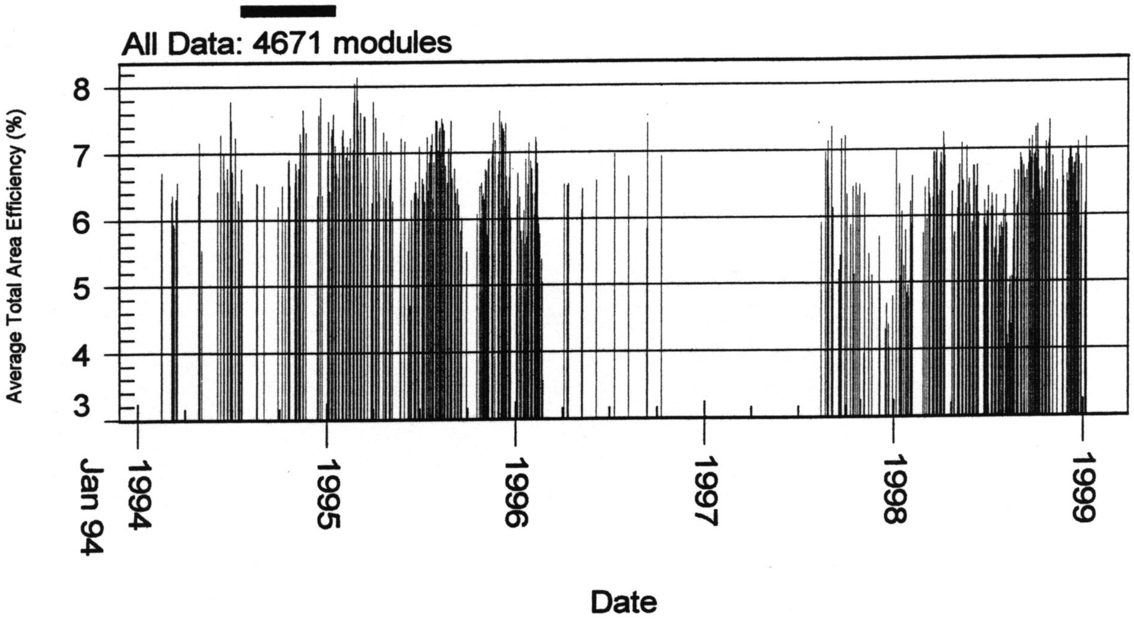


Figure 23. Average total area efficiency vs. production date (data taken following post-metal heat treatment; number of modules per day > 2)

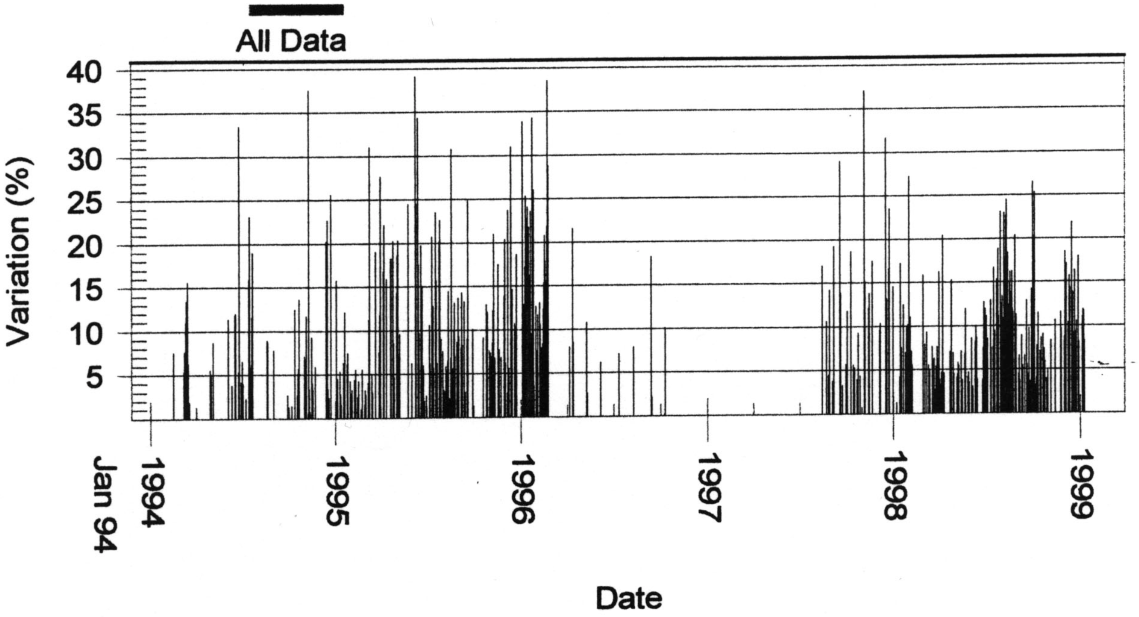


Figure 24. Average relative standard deviation of total area efficiency vs. production date

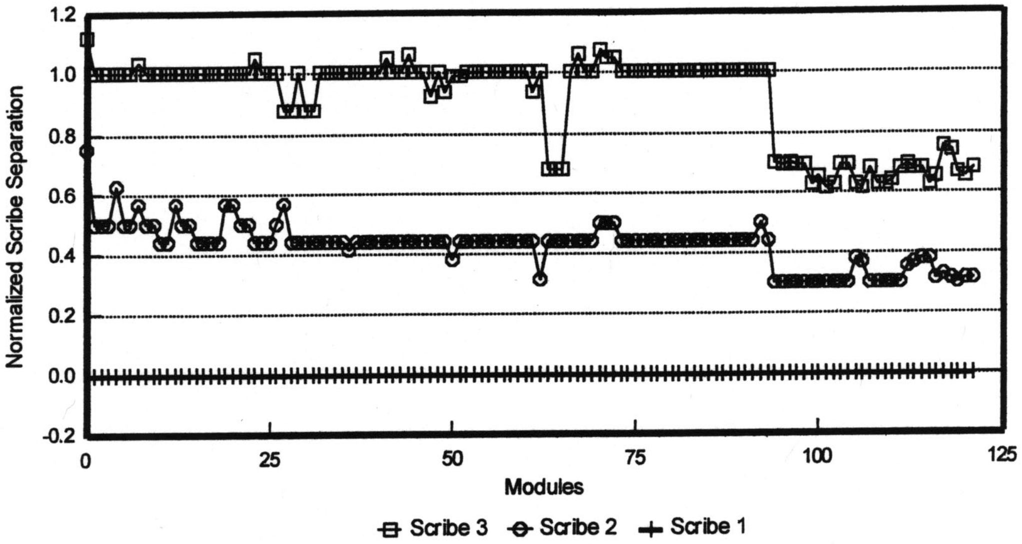


Figure 25. Laser scribing process capability study resulting in a reduction of scribe separation distance. By definition, Scribe 1 is at the 0.0 position.

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13. ABSTRACT *(Maximum 200 words)*

This report describes work performed by Solar Cells, Inc. (SCI), during this Photovoltaic Manufacturing Technology (PVMaT) subcontract. Cadmium telluride (CdTe) is recognized as one of the leading materials for low-cost photovoltaic modules. SCI has developed this technology and is preparing to scale its pilot production capabilities to a multi-megawatt level. This four-phase PVMaT subcontract supports these efforts. The work was related to product definition, process definition, equipment engineering, and support programs development. In the area of product definition and demonstration, two products were specified and demonstrated—a grid-connected, frameless, high-voltage product that incorporates a pigtail potting design and a remote low-voltage product that may be framed and may incorporate a junction box. SCI produced a 60.3-W thin-film CdTe module with total-area efficiency of 8.4%; SCI also improved module pass rate on the interim qualification test protocol from less than 20% to 100% as a result of work related to the subcontract. In the manufacturing process definition area, the multi-megawatt manufacturing process was defined, several of the key processes were demonstrated, and the process was refined and proven on a 100-kW pilot line that now operates as a 250-kW line. In the area of multi-megawatt manufacturing-line conceptual design review, SCI completed a conceptual layout of the multi-megawatt lines. The layout models the manufacturing line and predicts manufacturing costs. SCI projected an optimized capacity, two-shift/day operation of greater than 25 MW at a manufacturing cost of below \$1.00/W.

14. SUBJECT TERMS
photovoltaics ; Photovoltaic Manufacturing Technology ; PVMaT ; CdTe ; product definition ; manufacturing process definition ; multi-megawatt manufacturing line ; thin film ; high throughput

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