NREL/TP-411-7497 • UC Category: 1280 • DE95004065

Cast Polycrystalline Silicon Photovoltaic Module Manufacturing Technology Improvements

Semiannual Subcontract Report
8 December 1993 – 30 June 1994

J. Wohlgemuth
Solarex Corporation
Frederick, Maryland

NREL technical monitor: R. Mitchell

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of the U.S. Department of Energy
Managed by Midwest Research Institute
for the U.S. Department of Energy
under contract No. DE-AC36-83CH10093

Prepared under Subcontract No. ZAI-4-11294-01

March 1995

NOTICE

Available to DOE and DOE contractors from:
Office of Scientific and Technical Information (OSTI)
P.O. Box 62
Oak Ridge, TN 37831
Prices available by calling (615) 576-8401

Available to the public from:
National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4650

PREFACE

This Semi-Annual Technical Progress Report covers the work performed by Solarex Corporation for the period December 8, 1993 to June 30, 1994 under DOE/NREL Subcontract # ZAI-4-11294-01 entitled "Cast Polycrystalline Silicon Photovoltaic Module Manufacturing Technology Improvements". This is the first Semi-Annual Technical Report for this subcontract. The subcontract is scheduled to run from December 8, 1993 to December 7, 1996.

The following personnel at Solarex have contributed to the technical efforts covered in this report.

Fiore Artigliere
Mark Brisson
James Cliber
Mark Conway
Joseph Creager
Thomas Duquaine
Jason Ellis
Daniel Heck
George Kelly
Timothy Koval
Charles Lamport
Jean Posbic
William Poulin
David Ramsey
Madhumita Roy
Jay Shaner
Steven Shea
Timothy Tomlinson
Donald Warfield
Daniel Whitehouse
John Wohlgemuth

In addition, Solarex has been supported by the staff at the Automation and Robotics Research Institute at the University of Texas at Arlington (ARRI). ARRI staff working on the subcontract include:

Brian Huff
Mike Diver
David Vanecek

SUMMARY

The objective of this three-year program is to advance Solarex's cast polycrystalline silicon manufacturing technology, reduce module production cost, increase module performance and expand Solarex's commercial production capacities. Two specific objectives of this program are to reduce the manufacturing cost for polycrystalline silicon PV modules to less than $1.20/watt and to increase the manufacturing capacity by a factor of three. To achieve these objectives, Solarex is working in the following technical areas:

CASTING

The goal of the casting task is to develop the ability to cast ingots that yield four bricks with a cross-section of 15 cm by 15 cm with at least equivalent material quality as now achieved for 11.4 cm by 11.4 cm bricks. This represents a 73% increase in the useable silicon obtained from each casting.

WIRE SAWS

The goal of the wire saw task is to develop the wire saw technology for cutting 15 cm by 15 cm polycrystalline wafers on 400 μm centers at lower cost per cut than achieved today on the ID saws. This represents a 50% increase in the useable silicon obtained from each cast and a 50% increase in the yield of wafers per purchased kilogram of Si feedstock.

CELL PROCESS

The goal of the cell task is to increase cell efficiencies to 15%, while decreasing the cost per watt at the module level. The developed process must be compatible with automated manufacturing at large volumes.

MODULE ASSEMBLY

The goal of the module assembly task is to modify Solarex's present module assembly system to increase throughput by 100% and decrease the labor requirement by 50%. The Automation and Robotics Research Institute at the University of Texas at Arlington (ARRI) is to work with Solarex to model the present automated module assembly system and to recommend modifications to increase throughput and reduce labor.

FRAMELESS MODULE DEVELOPMENT

The goal of the frameless module task is to develop and qualify a frameless module design incorporating a lower cost back sheet material (less than $0.05/square foot) and user friendly, low cost electrical termination (less than $1.00/module). Since PVMaT is designed for large systems, modules can be designed to mount directly onto the support structure without integral frames.

AUTOMATED CELL HANDLING

The goal of the automated cell handling task is to develop automated handling equipment for 200 µm thick 15cm by 15cm polycrystalline silicon wafers and cells with a high yield (less than 0.1% breakage per process handling step) at a throughput rate of at least 12 cells or wafers per minute.

ACCOMPLISHMENTS

Accomplishments during the first six months of the program include:

- Designed modifications to casting stations, ceramic molds and sizing saws to allow for casting and sizing of larger ingots.
- Demonstrated casting of ingots with 17% larger volume.
- Selected and purchased a new wire saw from HCT Shaping Systems. The saw was delivered and made operational.
- Demonstrated wafering of 8 bricks (2400 wafers or ~4.4 kilowatts at the cell level) in a 6.5 hour run.
- Demonstrated 14% average cell efficiency in the laboratory using an aluminum paste back surface field.
- ARRI completed a modeling study of the Solarex module assembly process. A plan has been prepared to increase throughput by 47%.
- Identified and qualified through accelerated environmental tests three (3) new lower cost backsheet materials.
- Designed and built a test structure for mounting frameless modules and selected two (2) adhesives and began testing their ability to hold modules to the structure.

TABLE OF CONTENTS

Section **Page**

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

The goal of Solarex's Crystalline PVMaT program is to improve the present Polycrystalline Silicon manufacturing facility to reduce cost, improve efficiency and increase production capacity. Key components of the program are:

- Casting of larger ingots.
- Use of wire saws to cut thinner, larger size wafers with less kerf loss.
- Transfer of higher efficiency cell processes to manufacturing.
- Increased automation in module assembly.
- High reliability mounting techniques for frameless modules.
- Automated handling of large, thin wafers.

The results of these efforts will be to reduce the module cost per watt to less than $1.20/watt, to increase the production capacity of Solarex's Frederick plant by a factor of 3 and to provide larger, higher efficiency modules that reduce the customer's balance of systems cost. All of this is to be achieved without sacrificing the high reliability already achieved with the crystalline modules in use today.

Solarex is a recognized leader in polycrystalline silicon PV technology, one of the largest commercial PV technologies in the world today. Solarex was one of the pioneers in this technology and has been a commercial leader in polycrystalline silicon PV for more than ten years.

The rationale behind the Solarex program is to use as much as possible of the present equipment and processes, making improvements that lead to larger sizes, better utilization of materials, higher efficiencies and reduced labor requirements. In this way the maximum increase in capacity and reduction in cost can be achieved with justifiable capital investments in equipment modifications. Specific areas to be addressed in the program are discussed briefly below.

Today Solarex casting stations are used to produce ingots from which 4 bricks, each 11.4 cm by 11.4 cm in cross section are cut. The stations themselves are physically capable of holding an ingot that would be large enough to cut 4 bricks 15 cm by 15 cm in cross-section. The first task involves making the modifications necessary to cast these larger ingots. This effort will increase the production capacity of Solarex's casting stations by 73% and reduce the labor content by an equivalent percentage.

Wire saws can be used to cut thinner wafers with less kerf, than is possible on the Internal Diameter (ID) saws now in use at Solarex. The program goal is to reduce the center to center cut distance from 600 microns on the ID saw to 400 microns on the wire saw. This will result in a 50% increase in solar cell and module output from the same silicon feedstock purchased and cast. That is, with the same amount of feedstock material and the same casting capacity Solarex will be able to increase its output of PV modules by 50% (on top of the 73% increase achieved by casting larger ingots). In addition, wire saws can also be utilized to cut larger wafers, something ID saws can not do.

Finally, wire saws have a much higher production capacity. One wire saw may produce as many wafers as 20 ID saws. To increase capacity with wire saws requires a much smaller capital investment than would be required to achieve the same increase with ID saws. The major issue with wire saws is the ability to reduce the variable cost to cut a wafer. The technical effort in this program involves the use of the latest available wire saws, purchased by Solarex. Efforts to reduce the cost of grit, oil, wire, spare parts and labor make up the major part of Task 2.

In this program, Solarex is working on the transfer of high efficiency cell technologies from the laboratory to production. Issues involved in the successful transfer include process cost, ability to scale to large volume, adaptability to automation and the degree to which each step integrates into the overall cell process sequence. Therefore, it is necessary as a part of this program to evaluate each component of the sequence that has proven effective at increasing cell efficiency to determine the most cost effective cell process sequence. Specific areas being evaluated include:

- Optical Coupling
    - double layer AR coating
    - mechanical texturing
    - porous silicon etching

- Passivation/Gettering
    - hydrogen passivation
    - phosphorous gettering

- Back Surface Field (BSF) Formation
    - Al paste BSF
    - back surface diffusion

- Interaction of metallization with emitter
    - screen printed Ag paste
    - plated buried contact system

The goal of the Task 3 cell effort is to increase average cell efficiency (as obtained from a production line, not just from the laboratory) to 15% as measured at STC (Standard Test Conditions - 1000 W/m^2, AM1.5, 25° C). This must be achieved with a process sequence that lowers the module $/Watt manufacturing cost.

Solarex has a first generation automation system in use at the Frederick facility for tabbing, matrixing and lay-up of the PV modules. This system has been highly successful at reducing manual labor in the assembly process. During Task 4 the present system will be evaluated to determine how this system can be modified to handle the larger wafers for this program, to improve throughput, yield and process control and to minimize production labor and cost. To assist with this effort, the Automation and Robotics Research Institute (AARI) at the University of Texas at Arlington is serving as a subcontractor. AARI is assisting Solarex in analysis, modeling and development of handling concepts to improve the operation of the module assembly area.

Solarex modules use low iron tempered glass as a superstrate and Ethylene Vinyl Acetate (EVA) as the encapsulation system. No change is proposed in this encapsulation system to maintain the module reliability. However, a reduction in the cost of the backsheet is possible, although it is extremely important that this change does not negatively impact the module reliability and is compatible with frameless mounting techniques developed in Task 5.

Today most PV modules are sold with a frame to provide means for mounting the module and a junction box for electrical connection. This frame is the largest single contributor to module cost. In large systems, the support provided by the system structure is adequate making the module frame redundant. Eliminating this frame can reduce the module selling price by more than $0.50/Watt. During Task 5, mounting requirements have been evaluated and analyszed. Testing of candidate frameless module mounting schemes has begun.

Similarly, the junction box adds appreciable cost to the module, while requiring addition labor for system assembly. In Task 5, simpler electrical termination schemes are being evaluated and tested. These approaches must be consistent with automated manufacturing as well as with systems design requirements, like the incorporation of by-pass and blocking diodes.

Task 5 also includes the design of a 122 watt module using 36- 15 cm by 15 cm solar cells. This task will include qualification of the design through accelerated environmental tests (Block V, CEC-503, IEC-1215, U.L., and IEEE-1262 now under development) and design of the automated equipment necessary to finish the module.

An important issue for many crystalline silicon PV manufacturers is the ability to handle thinner and larger wafers through the production line. Task 6 will address this issue. Once again, Solarex will be supported in this effort by AARI, whose background and experience is ideally matched to the task of developing handling methods for parts such as the large thin wafers to be used in this program. AARI will perform detailed analysis and modeling of the requirements and then build prototype stations to evaluate various approaches to handling such wafers. Once the concepts have been verified at AARI, Solarex will design and have built a production unit to verify its capability.

The results of this program will be the modification of today's polycrystalline production facility to:

- Increase production capacity by a factor of three
- Reduce the "profitable" selling price from over $4.00 per peak watt to less than $2.00 per peak watt.

As a worldwide producer of PV products, the world's second largest PV manufacturer and the largest US owned manufacturer of PV modules, Solarex plans to continue an aggressive market development program that would support the increased capacity obtained as a result of this program.

2.0 PRESENT PROCESS AND PRODUCTS

Solarex's Crystalline Silicon Technology is based on use of cast polycrystalline silicon wafers. The process flow is shown in Table 1. The primary product is a module with 36 solar cells each 11.4 cm x 11.4 cm, that produces 60 or 64 Watts under Standard Test Conditions (STC). A data sheet for this module is attached as Figure 1.

Table 1
Cast Polycrystalline Si Process Sequence

Casting

ID Wafering

Cell Process
(Thick Film Print)

Module Assembly

Lamination

Finishing

The various segments of Solarex's module manufacturing process are described below.

Casting

Solarex has developed and patented a directional solidification casting process specifically designed for photovoltaics[1]. In this process, silicon feedstock is melted in a ceramic crucible and solidified into a large grained semicrystalline silicon ingot. In house manufacture of low cost, high purity ceramics is a key to the low cost fabrication of Solarex semicrystalline wafers[2].

The casting process is performed in Solarex designed casting stations. The casting operation is computer controlled. There are no moving parts (except for the loading and unloading) so the growth process proceeds with virtually no operator intervention.

Wafering

Wafering is done with Internal Diameter (ID) saws. These are the same saws that are used in the semiconductor industry to wafer single crystal CZ ingots. At present ID saws are the lowest variable cost wafering option. Solarex has many years of experience with these saws, resulting in low labor and process costs. This is a mature technology with little opportunity for significant increases in productivity or reduction in kerf loss.

Cell Process

The cell process sequence is based on the use of Thick Film Paste (TFP) metallization, where a commercially available screen printed silver paste is applied as the current carrying grid on the front of the solar cell. This process has been designed to be as cost effective as possible. The high temperature process steps including diffusion, firing of the front print paste and Chemical Vapor Deposition (CVD) of a TiO_2 antireflective (AR) coating are all performed in belt furnaces.

Polycrystalline cells processed through this line have an average cell efficiency of 12.5 to 13% at STC. There are many modifications to this process sequence that will increase cell efficiencies. However, many of these modifications would actually increase the total dollar per watt module cost rather than decrease it. Detailed cost analyses indicate what changes in cell processing can lead to both higher cell efficiencies and lower dollar per watt module cost.[3] Implementation of these changes require laboratory verification of the candidate process sequences as well as improvement in the accuracy of the input cost data.

Module Assembly

The first part of the module assembly sequence is to solder two solder plated copper tabs onto the front of the solar cells. Each tab is soldered in 4 places for reliability and redundancy. Solarex uses automated machines to perform the tabbing. Tabbed cells are then laid up into a 36 cell matrix by a robot. The tabs are then soldered to the backs of the solar cells by another robot. Each tab has 2 back solder joints.

Module Lamination

The module construction consists of a low iron, tempered glass superstrate, EVA encapsulant and a 3 part Polyethylene-Mylar-Tedlar backsheet. The lamination process, including the cure, is performed in a vacuum lamination system. Then the modules are trimmed and the leads are attached. Finally, every module is flash tested to determine its STC power output.

Finishing

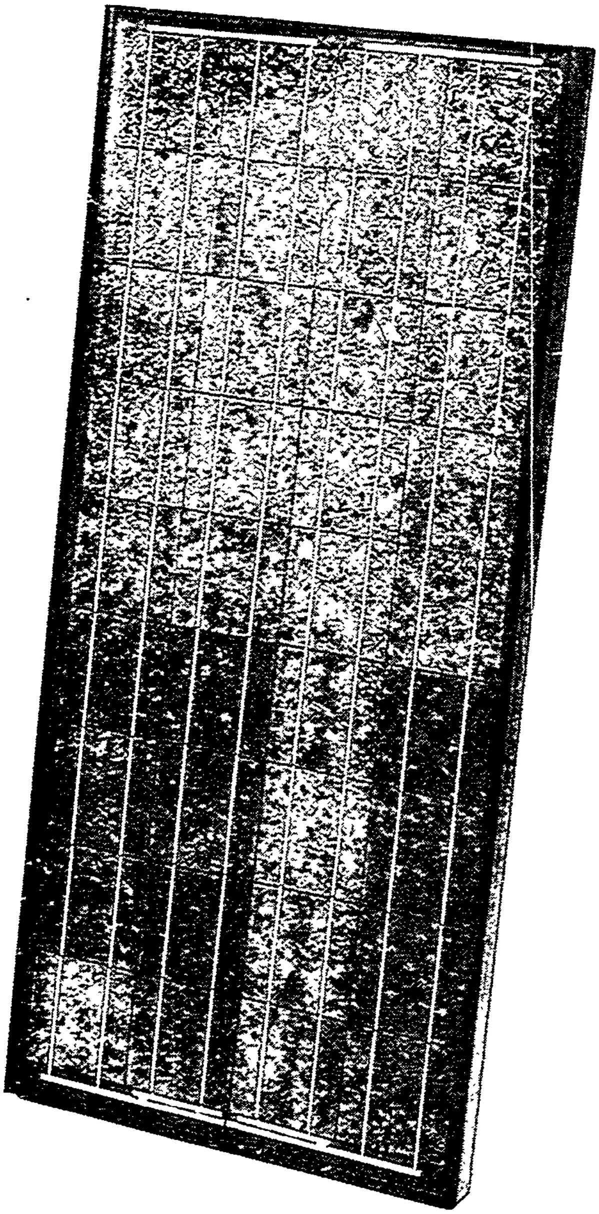
At present most modules are sold with a frame to protect the edges and provide a means of mounting. Solarex uses an extruded aluminum frame that is attached both with a butyl rubber adhesive between frame and glass as well as with 2 screws in each corner of the frame. The framing process is performed by an automatic, robotic framing system.

Most modules are sold with a junction box to protect the output wiring and provide the terminals for electrically connecting the module to the balance of the system. The area where the lead wires are attached to the module is potted to protect the laminate from moisture incursion. The junction box is then attached to the module with adhesive to seal it to the back of the laminate.

MSX-64 and MSX-60 Photovoltaic Modules

SOLAREX
An Amoco Company

The **MEGA**™ SX-64 and -60 are the most powerful of Solarex's **MEGA**™ series of photovoltaic (solar-electric) modules, a product line which is the culmination of 20 years of extensive research in semicrystalline silicon photovoltaics. With over 3 amperes of current at peak power, these are the highest-current commercial PV modules in the world, and generate that current at a voltage high enough to charge batteries efficiently in virtually any climate.



These modules may be used in single-module arrays or deployed in multiple-module arrays, wired in series/parallel combinations as required to meet current and voltage requirements. As single-module arrays, they may be mounted on a variety of surfaces using an optional bracket kit or by means of user-fabricated support hardware. Solarex also offers hardware for supporting multiple-module arrays.

These modules are well-suited for virtually all applications where photovoltaics are a feasible energy source, including telecommunications systems, pumping and irrigation, cathodic protection, remote villages and clinics, aids to navigation—in short, all but the smallest of photovoltaic systems.

HIGH CURRENT POWER AND VOLTAGE

The **MEGA**™ SX-64 and -60 boast the highest peak-power current outputs—3.66A and 3.5A respectively—of any standard modules. They deliver that current at a voltage high enough to charge batteries efficiently, and retain that voltage excellently in hot climates, as shown by the temperature coefficients and I-V curves in this publication.

- Fabricated from large-area (11.4 cm x 11.4 cm) antireflective-coated semicrystalline silicon solar cells;
- Higher current means fewer modules required for given output, less balance-of-system cost.

INDIVIDUALLY TESTED AND LABELED— 20 YEAR WARRANTY

It is inherent in all photovoltaic manufacturing processes that the electrical characteristics of finished modules vary slightly from one unit to another. The electrical characteristics listed in this sheet are those of typical, or production-average, units.

However, unlike any other manufacturer, Solarex tests each finished module in a solar simulator and labels it with its actual output—peak power, and voltage and current at peak power—at STC. In addition to providing a user with exact specifications, this allows Solarex to enforce tighter tolerances on the power output of its modules than any other PV manufacturer.

Furthermore, each module is covered by our industry-leading twenty-year limited warranty, which guarantees:

- that no module will generate less than its guaranteed minimum power when purchased;

- continued power (at least 80% of guaranteed minimum) for twenty years.

Contact Solarex's Marketing Department for full terms and limitations of this unparalleled warranty.

DUAL VOLTAGE CAPABILITY

These modules consist of 36 semicrystalline silicon solar cells electrically configured as two series strings of 18 cells each.

- Strings may be placed in series or in parallel in the field, providing 6V or 12V nominal output, by moving leads in the junction box.
- Allows simple installation of blocking or bypass diodes on 18-cell strings.

LARGE, EASY-TO-USE JUNCTION BOX

Cell strings terminate in a weatherproof junction box mounted on the back of the module.

- Junction box materials: impact-resistant, high-dielectric strength molded thermoplastic resin.
- Large enough for easy connection and manipulation of wiring and diodes. Solarex's Solarstate™ regulator can also be directly attached.
- Terminals accept a wide range of connectors or bare wires.
- Cover screws are captive, not easily lost.
- Industry standard openings accept english 1/2" nominal or metric PG 13.5 cable or conduit fittings.

PROVEN MATERIALS AND CONSTRUCTION

The materials used in these modules reflect Solarex's extensive experience with hundreds of thousands of solar modules and systems installed in virtually every climate on Earth. Founded in 1973, Solarex is the pioneer in terrestrial photovoltaic systems and the use of semicrystalline silicon for solar cells, and has invested the resources necessary to prove its materials, processes, and products.

- Semicrystalline silicon solar cells: efficient, attractive, stable.
- Patented titanium dioxide cell AR (antireflective) coating for optimum optical coupling and maximum efficiency at all light levels.
- Modules are rugged and weatherproof; cell strings are laminated between sheets of ethylene vinyl acetate (EVA) and tempered glass.
- Tempered glass superstrate: self-cleaning, highly transmissive (low iron content), inert, impact-resistant.
- Proven cell interconnection technique and matched thermal coefficient of expansion of glass and cells ensure electrical integrity in severe temperature ranges.
- Framed with corrosion-resistant, bronze-anodized extruded aluminum: strong, attractive framing compatible with Solarex mounting hardware and a broad range of other mounting structures.

SAFETY APPROVED

The MSX-64 and -60 modules are listed by Underwriter's Laboratories for electrical and fire safety (class "C" fire rating) and are approved by Factory Mutual Research for application in NEC Class 1, Division 2, Group D hazardous locations.

OPTIONS

- Protective aluminum backplate
- Mounting hardware kits
- Solarstate™ voltage regulator
- Marine-climate (NEMA-4X) junction box

RELIABILITY AND ENVIRONMENTAL SPECIFICATIONS

These modules are subjected to intense quality control during manufacture and to rigorous testing before shipment. They meet or exceed CEC and JPL Block V test criteria, including the following tests:

- Repetitive cycling between -40°C and 90°C;
- Repetitive cycling between -40°C and 85°C at 85% relative humidity;
- Wind loading exceeding 125 mph;
- Surface withstands impact on one-inch hail at terminal velocity (52 mph) without breakage.

VARIABLES AFFECTING PERFORMANCE

The performance of typical **MEGA** SX-64 and -60 modules is described by the I-V curves and electrical characteristics table on the next page. Each module's actual, tested output characteristics are printed on its label.

The current and power output of photovoltaic modules are approximately proportional to illumination intensity. At a given intensity, a module's output current and operating voltage are determined by the characteristics of the load. If that load is a battery, the battery's internal impedance will dictate the module's operating voltage. An I-V curve is simply all of a module's possible operating points (voltage/current combinations) at a given cell temperature and light intensity. Increases in cell temperature increase current but decrease voltage.

TYPICAL ELECTRICAL CHARACTERISTICS(1)

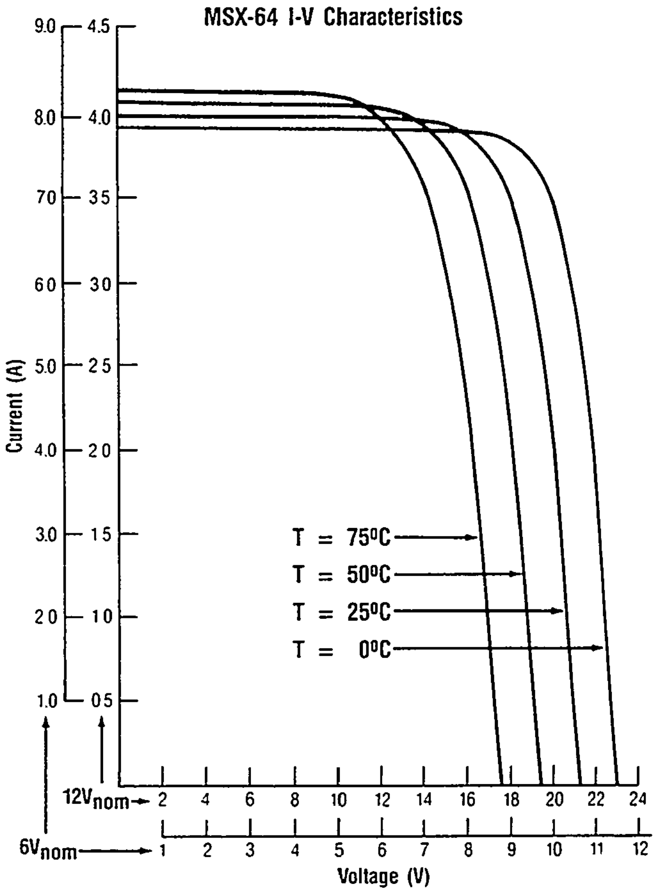
	12 VOLT CONFIGURATION(2) MSX-64	MSX-60
Typical peak power (Pp)	64W	60W
Voltage @ peak power (Vpp)	17.5V	17.1V
Current @ peak power (Ipp)	3.66A	3.5A
Guaranteed minimum peak power	62W	58W
Short-circuit current (Isc)	4.0A	3.8A
Open-circuit voltage (Voc)	21.3V	21.1V
Temperature coefficient of open-circuit voltage	-73 mV/°C	-73 mV/°C
Temperature coefficient of short-circuit current	3 mA/°C	3 mA/°C
Approximate effect of temperature on power	-0.38%/°C	-0.38%/°C
NOCT(3)	49°C	49°C

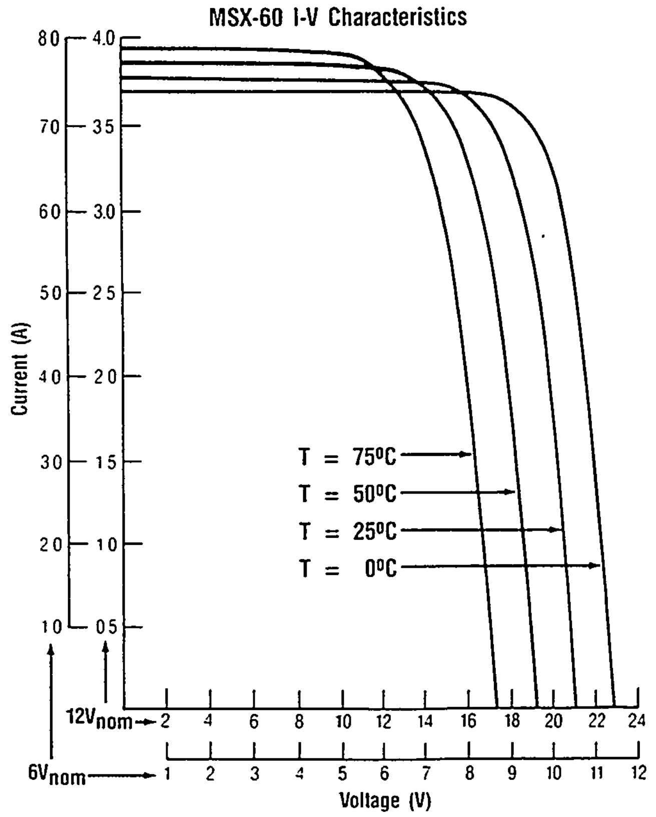
Notes:

(1) These data represent the performance of typical modules as measured at their output terminals, and do not include the effect of such additional equipment as diodes and cabling. The data are based on measurements made at Standard Test Conditions (STC) which are:
- Illumination of 1 kW/m² (1 sun) at spectral distribution of AM 1.5
- Cell temperature of 25°C or as otherwise specified (on curves).

(2) Electrical characteristics of modules wired in the nominal 6V configuration may be found by using the 6V scales on the I-V curves. For more exact values, divide the 12V voltage characteristics in the table by 2 and multiplly the 12V current characteristics by 2. Power values are unchanged.

(3) Under nearly all climatic conditions, the solar cells in an operating module are hotter than the ambient temperature, a fact which must be considered when reading module data. NOCT (Nominal Operating Cell Temperature) is an indication of this temperature rise, and is the cell temperature under Standard Operating Conditions: ambient temperature of 20°C, solar irradiation of 0.8 kW/m², and average wind speed of 1 m/s.

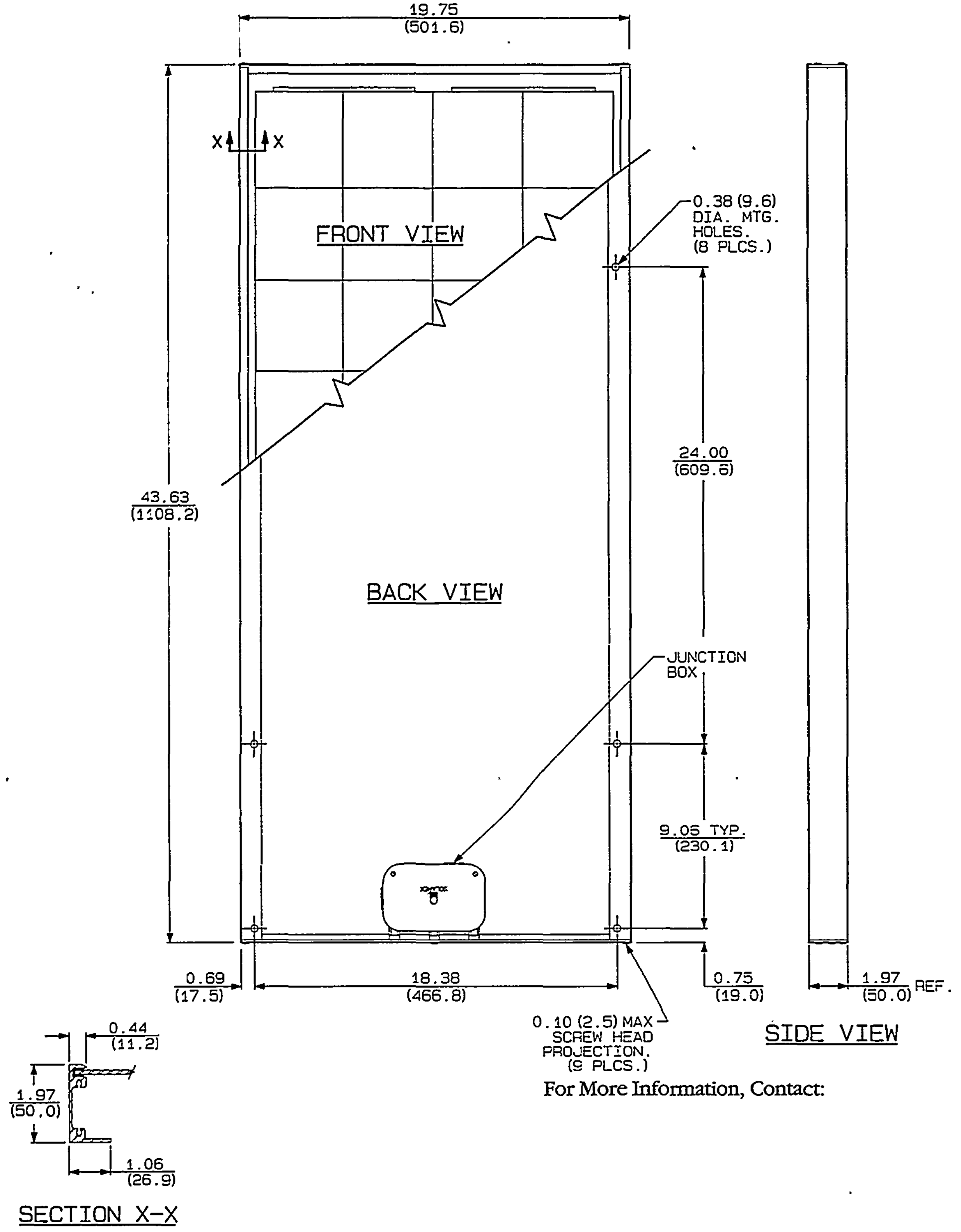

MSX-64 I-V Characteristics


MSX-60 I-V Characteristics

MECHANICAL CHARACTERISTICS

MEGA SX-64 and -60 are mechanically identical, differing only in electrical output.

Weight: 15.9 pounds (7.2 kg)
Dimensions: Dimensions in brackets are in millimeters
Unbracketed dimensions are in inches



For More Information, Contact:

SPECIFICATIONS SUBJECT TO CHANGE WITHOUT NOTICE

3.0 PVMAT PROGRAM EFFORTS

The following sections detail the progress made during the first six months of the program.

3.1 TASK 1 - POLYCRYSTALLINE SILICON CASTING IMPROVEMENTS

The goal of the casting task is to develop the ability to cast ingots that yield four - 15 cm by 15 cm bricks with at least equivalent material quality as now achieved when casting four - 11.4 cm by 11.4 cm bricks. During the first six months of the program Solarex has designed and fabricated new larger ceramic pieces, designed modifications to the casting stations and designed and implemented modifications to the sizing saws in order to be able to cast and size larger ingots.

Two possible modifications to enlarge the casting stations were evaluated in detail. The first proposal retained all of the present chamber with the addition of a height extension. The second proposal involved replacing the pour chamber with a new larger chamber. The height extension option required less capital investment and time to implement, as well as requiring less input power to melt the silicon charge. Therefore, chamber modification was selected for the program. All of the necessary modifications have now been designed, drawings sent to vendors, quotes received and the parts ordered.

Solarex manufactures its own ceramic vessels. Casting of larger ingots requires producing larger pour vessels and larger receivers. The size and shape of the receivers into which the silicon pours are dictated by the shape of the ingot desired. For the PVMaT program the ingot cross-section increases from approximately 24 cm by 24 cm to 32 cm by 32 cm, so the receiver must increase in size accordingly. Patterns for the molds were designed, built and used to produce the molds. Sample receivers are ready for use, but have not yet been used to cast ingots.

The largest ceramic piece is the crucible in which the silicon feedstock is melted. A potential problem was the ability to fire larger pieces of ceramic, while maintaining yield and physical properties. Just extending the height of the crucible to hold the additional silicon feedstock would likely result in a ceramic piece that is difficult to produce and hard to load with feedstock. The cross-section of the crucible was modified from cylindrical to elliptical to fit around the heating elements. This change increases the volume of the crucible by approximately 20%. An elliptical crucible mold pattern has been designed, built and used to make an elliptical mold. The mold was used to cast elliptical crucibles. These crucibles were fired and successfully used to pour an extra 20% silicon, producing an ingot with a larger cross-section.

To achieve the remainder of the 75% increase in volume, an extender will be placed onto the top of the crucible. This extender can be mounted on top of the elliptical crucible after it has been loaded with silicon. The extender mold pattern has been designed, built and used to produce a mold.

3.2 TASK 2 - WIRE SAW IMPROVEMENTS

The goal of this task is to develop the wire saw technology for cutting 15 cm by 15 cm polycrystalline wafers on 400 μm centers at lower cost per cut than achieved today on the ID saws.

This represents a 50% increase in the useable silicon obtained from each cast and a 50% increase in the yield of wafers per purchased kilogram of Si feedstock.

The first step in this task was to identify what wire saws are available commercially. Solarex identified four vendors of wire saws and visited each vendor to see their wire saws. Three of the vendors were able to wafer a Solarex brick and provide the resultant wafers for evaluation. A detailed comparison of the characteristics of the four available saws appears in Table 2.

Table 2
Comparison of Wire Saws

Company	Type of Business	Wire saw Experience	Solarex Material	Capacity 11.4x11.4	Capacity 15x15	Cost
Meyer-Berger	Semiconductor Equipment	> 10	good	4	2	mod
HCT	Wire saws	> 60	excellent	8	4	mod
M. Setek	Crystal growing & wafering	10 to 20	good	2 or 3	1	mod
Nippei Toyama	Machine tool manufacturer	~ 36	NA	2 or 3	2 or 3	high

HCT Shaping Systems has the most experience building wire saws. A test run on the HCT saw provided the best uniformity of surface texture and wafer thickness. Probably the most important factor, however, was the ability of the HCT machine to cut 8-11.4 cm by 11.4 cm bricks or 4-15 cm by 15 cm bricks at the same time. Preliminary cost analysis indicated that the throughput rate, that is the number of wafers cut in a given amount of time, was the single most important factor in determining the cost payback of the investment in the wire saw. Solarex selected and ordered an HCT wire saw.

The HCT wire saw was delivered to Solarex late in the reporting period. The saw has been installed and a demonstration run successfully completed.

3.3 TASK 3 - HIGH EFFICIENCY CELL DEVELOPMENT

The goal of this task is to increase cell efficiencies to 15%, while decreasing the cost per watt at the module level. While a number of approaches to achieving high efficiency have been reported, many of these utilize processes and material that are not likely to be cost effective when applied to cast polycrystalline silicon in a manufacturing environment. The key to achieving the goal of this task is to select modifications to the present process that increase efficiency while lowering the cost per watt. That is, the increased cost of the process is less than the value of the increased power produced by the improvement.[4] During the first 6 months of the program Solarex has worked in the areas of optical coupling, back surface fields (BSF), hydrogen passivation and gettering. Each of these areas is discussed below:

3.3.1 Optical Coupling

The highest silicon cell efficiencies have been achieved using textured surfaces to increase the amount of incident sunlight that is coupled into the solar cell. Our first program efforts were to determine how to evaluate the effectiveness of the various optical coupling techniques. The usual approach to evaluating optical coupling techniques is to fabricate solar cells and then to measure their performance under Standard Test Conditions, using the short circuit current as the figure of merit. There are several problems with this approach.

1. Cell measurements are usually taken using a solar simulator, for example with a xenon light source. The light intensity should be set using a reference cell with a matched spectral response. However, since the test cell has an experimental optical coupling surface, it is impossible to have a matched reference cell. Often the new process turns out to be optimized for the simulator spectrum rather than for the solar spectrum.

2. The optimum cell processing parameters are likely to be a function of the geometry of the emitter surface. Therefore, the structure of the optical coupling surface and the process to turn it into a cell must be optimized concurrently. Typically a new optical coupling process does not produce the expected current gain because the subsequent cell process has not been optimized, even if it is actually better optically.

An improved method for evaluating the performance of an optical coupling surface has been developed that does not require the fabrication of solar cells. This method only requires fabrication of samples of the optical surface under study. The reflectance of the surface is then measured as a function of wavelength as shown in the bottom curve of Figure 2 for a chemically textured 100 CZ silicon surface. If the reflectance is then multiplied by the solar spectrum, it yields the energy or the number of photons entering the material at every wavelength. Integrating this value over the entire wavelength yields a value for total energy entering the material. This value has been used as a figure of merit for optical coupling, but since it does not take the spectral response of the cell into account, it is not a good predictor of solar cell performance.

At this point a cell technology (for example Solarex cast polycrystalline silicon or a high efficiency buried contact cell on float zone silicon) is selected to test with the optical coupling surface under study. For the cell technology selected, determine the internal quantum efficiency as a function of wavelength. The top curve in Figure 2 is the internal quantum efficiency as measured for a typical Solarex cast polycrystalline cell with a conversion efficiency of approximately 13% when covered with a single layer TiO_2 antireflective coating. Multiplying the internal quantum efficiency by the energy entering the cell calculated from the reflectance curve, yields a predicted (external) quantum efficiency curve for the selected cell with the new optical coupling surface.

The external quantum efficiency at each wavelength can then be multiplied by the energy in the solar spectrum at each wavelength and integrated over the entire wavelength range of interest. A percentage of the active area can be removed to take the shadowing of grid lines into effect. The result is an estimate of the short circuit current of the selected cell technology with the experimental optical coupling surface. Various surface treatments can now be compared to determine which is best suited for the particular cell technology of interest. Figure 2 shows the calculation for a cast polycrystalline cell with a chemically textured surface. The analysis then predicts that if you could chemically texture cast polycrystalline material (like you can CZ) the cell efficiency would increase from 13% to 14%.

Figure 2
Optical Coupling for Textured Polycrystalline Silicon

First-Cut Current Integration Model

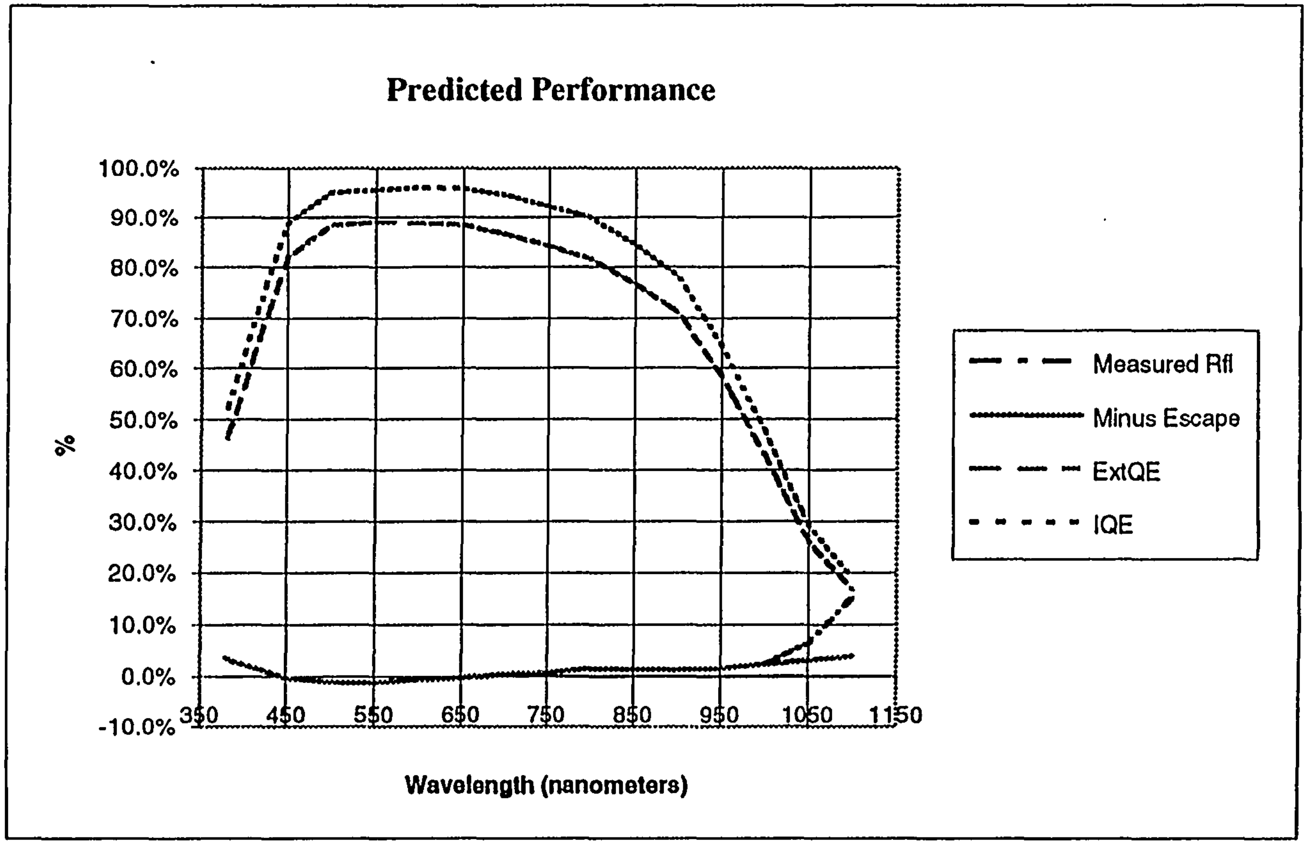
Solarex Corporation

International Electrotechnical Commission AM1.5 Spectrum
Integrates from 380 to 1100 nanometers
Assumes reflectance values represent oxide-on-silicon (no metal present)
TDK:3/31/94

Reflectance ID: **Chemtex CZ TiO2 M95**
IQE ID: **YYCell**
Collected Current: **31.0** *mA/cm^2*
Jsc: **33.6** *mA/cm^2*
Device Isc: **4.024** *Amps*
Simulated Efficiency: **14.00** *(%)*
(Assumes 595 Voc, 76% FF)

CellSize (cm): 130
Coverage (%): 8.0%
IQE Selection: 3
Reflectance Selection: 7

Wavelength	Reflectance
400	0.022
450	-0.003
500	-0.011
550	-0.012
600	-0.006
650	-0.003
700	0.004
750	0.006
800	0.014
850	0.013
900	0.012
950	0.015
1000	0.023
1050	0.064
1100	0.150



Chemical texturing is used by most manufacturers of single crystal silicon solar cells. In this process an alkaline etch is used to etch the 100 silicon surface leaving the exposed 111 planes that etch at a slower rate, resulting in a surface covered with small pyramids. This technology has not worked well on polycrystalline silicon because this material contains crystal grains of different orientations. A large fraction of the grains are typically oriented close enough to the 111 plane that they etch slowly and do not produce pyramids.

Both lasers and/or dicing saws with beveled blades have been used to mechanically texture silicon, resulting in increased absorption and improved cell efficiency. Solarex has demonstrated the use of a beveled blade to increase the efficiency of CZ buried contact solar cells from 15.2% to 17.9% as shown in Table 3. In this experiment mechanical texturing resulted in an 18% increase in short circuit current, more than the 16% achieved using the more traditional chemical texturing. These increases are much larger than ordinarily achieved with texturing because the SiO_2 AR coating used in the buried contact cell process is far from optically ideal. This experiment also showed that mechanical texturing could be utilized without loss of open circuit voltage or fill factor.

Table 3
Comparison of Chemically and Mechanically Textured CZ Cells

Cell Type	Efficiency (%)	Voc (mV)	Jsc (mA/cm^2)	FF (%)
Planar	15.2	619	31.5	78
Chemical Texture	17.2	618	36.6	77
Mechanical Texture	17.9	618	37.4	78

The methodology for evaluating optical coupling approaches has been applied to a number of different surface textures and their expected performance calculated based on their use on Solarex cast polycrystalline silicon. The results are given in Table 4. The planar value is calculated with a single layer TiO_2 AR coating and represents typical production. The calculated value of 3.737 Amperes for a 130 square centimeter cell agrees very well with production cell results. It should also be noted that to date none of the other texturing techniques have proven as effective as chemical texturing.

Table 4
Predicted Current from Integration Model

Surface Texture	Predicted Short Circuit Current (A)
Planar	3.737
Chemically Textured	4.024
70° Blade	3.964
60° Blade	3.976
Texturing Tool	3.828

The challenge of this task is to apply mechanical texturing to the polycrystalline cell thick film paste process and to do it in a cost effective manner. By leaving planar islands for the screen printed metal, mechanically textured cells have been fabricated with beveled blades resulting in current gains of 6 to 7 % over the planar controls (with a single layer TiO_2 AR coating). However, the efficiency only increased by 3 to 4% as both the fill factor and voltage were lower for the textured cells.

3.3.2 Back Surface Field Formation

Aluminum pastes have been used successfully to improve the efficiency of solar cells for years. The issue once again is that of cost. Table 5 compares the results for non-BSF cells with those made using Al paste from two different vendors. Back surface fields usually increase cell efficiency by 5 to 6% on Solarex cast polycrystalline silicon, but at the present cost of these commercial pastes, the process is not economic.

Table 5
Vendor Al Paste Results

Paste	Efficiency (%)	Voc (mV)	Jsc (mA/cm^2)	FF (%)
None	13.13	580.9	29.4	76.8
Vendor 1	13.92	592.2	31.2	74.8
Vendor 2	13.99	589.6	31.6	75.1

The first attempt to reduce the cost was to use less paste by gridding the p+ region. An experiment was conducted comparing a variety of coverage areas. The results are shown in Table 6. The degree of improvement in current and voltage depends upon the area of paste coverage on the back of the cell. The more paste coverage, the better the cell efficiency, so reducing the area of paste coverage does not appear to be a good way to reduce cost.

Table 6
Partial Coverage of BSF

BSF Pattern	Efficiency (%)	Voc (mV)	Jsc (mA/cm^2)	FF (%)
No BSF	12.85	581.7	29.4	75.0
25% BSF	12.94	582.7	29.6	74.9
50% BSF	13.03	583.6	29.9	74.6
100% BSF	13.12	585.9	30.1	74.8

Another method of reducing the cost is to fabricate the Al paste in-house rather than purchasing it from a vendor. The result from the first experiment are given in Table 7. Electrically the in-house paste performed as well as the vendor supplied paste. However, the in-house paste was much more difficult to print. A matrix experiment of 8 paste candidates was run as part of a mixture design trial. All 8 samples were printed and fired at the baseline conditions developed for the vendor paste. All of the in-house pastes printed well. The electrical results are given in Table 8. All 8 candidates performed well, producing an efficiency gain equivalent to that achieved using vendor supplied aluminum pastes. The only problem remaining with the in-house paste is its tendency to produce bumps and/or beads when fired. Changes in formulation and firing parameters are being studied in order to alleviate the bumping/beading.

Table 7
Trial of In-House Paste

Paste	Efficiency (%)	Voc (mV)	Jsc (mA/cm^2)	FF (%)
None	12.69	577.1	29.7	74.1
Vendor	13.56	587.9	31.1	73.7
In-House	13.58	588.6	31.4	73.3

Table 8
In-House Paste Matrix

Paste	Efficiency (%)	Voc (mV)	Jsc (mA/cm^2)	FF (%)
None	13.11	582.3	29.5	76.3
D	14.18	595.8	31.7	75.0
I	14.22	595.5	31.8	75.1
J	14.24	596.7	32.5	73.4
H	14.25	595.3	31.7	75.4
C	14.12	595.5	31.6	75.0
G	14.2	595.4	31.6	75.4
F	14.18	595.6	31.6	75.2
B	14.17	595.5	31.7	75.0

To evaluate the quality of the process being developed the BSF process using 2 different commercial aluminum pastes was applied to chemically textured CZ wafers. The results are shown in Table 9. The cells averaged 15.7%, an excellent efficiency for large area screen printed cells.

Table 9
CZ Cells with BSF

Paste	Efficiency (%)	Isc (A)	Voc (mV)	FF (%)
Paste 1	15.7	4.562	602.1	74.3
Paste 2	15.67	4.522	597.8	75.4

3.3.3 Hydrogen Passivation

A number of PV companies including Kyocera[5] and Mobil[6] report the use of hydrogen passivation to increase cell efficiency. Various approaches including implantation, annealing in forming gas and plasma enhanced CVD of silicon nitride have all been reported to improve cell efficiencies. The effectiveness of a particular method of hydrogen passivation depends upon the substrate material and the balance of the cell process sequence.

Kyocera claims that they use a plasma enhanced chemical vapor deposition (PECVD) of a silicon nitride AR coating. According to the literature, this deposition of silicon nitride in a hydrogen rich plasma not only produces a good AR coating, but also passivates the silicon producing higher cell current and efficiency[6]. Solarex does not have the equipment in which to perform PECVD, so experimentation with this process requires use of outside equipment. Most of our PECVD processing has been done by Pacific Western Systems (PWS).

Table 10 shows the results of an initial experiment with PWS taking their best guess at optimum parameters. As deposited the SiN samples were 2.0% more efficient than the controls with a single layer TiO_2 AR coating.

Table 10
Initial PECVD SiN Trial

	Eff (%)	**Isc** (A)	**Voc** (mV)	**FF** (%)
TiO_2 Control	12.77	3.67	595	76.0
PECVD SiN	13.02	3.75	596	75.7

The literature has a number of references to various heat treatments to SiN cells that improve performance. Following several exploratory trials we selected 500° C as the sinter temperature with sinter times up to 5 minutes. The results are given in Table 11. While the controls got consistently worse, the SiN samples improved 2.5% in efficiency after a 2 minute sinter. The net result is a 4.5% increase in efficiency of the sintered SiN samples over the unsintered controls.

Table 11
500° C Sinter Experiment

AR	**Sinter** (min.)	**Eff** (%)	**Isc** (A)	**Voc** (mV)	**FF** (%)	**Rser** (mΩ)
TiO_2	none	12.86	3.67	597	76.3	7.9
	2	12.37	3.644	591	74.6	8.1
	5	11.29	3.638	591	68.3	20
SiN	none	13.26	3.735	599	77.0	6.6
	2	13.59	3.847	602	76.3	7.0
	5	13.21	3.814	599	75.2	6.9

A large experiment was designed to explore four deposition parameters using Design of Experiment (DOE) techniques. The parameters chosen for study were:

1. Removal of native oxide prior to SiN deposition.
2. The run pressure during the SiN deposition.
3. The use of a post-deposition sinter.
4. The use of a pre-deposition hydrogen drive in.

In addition to exploring the effects of these deposition parameters, we also looked at 2 metallization sequences. One group had the front metallization already fired on the cell, as we would normally deposit our TiO_2 AR coating. In the second group, the depositions were performed after front oxide removal. This second group had metallization applied through vias that were opened in the deposited nitride film as Kyocera reports they do.

Table 12 shows the average electrical results of the various deposition combinations for the pre-metallized samples. Table 13 shows the average electrical results of the various deposition combinations for the via etched samples.

Table 12
Pre-Metallized SiN Experiment

Oxide	Pressure	Sinter	Pre-dep	Eff (%)	Isc (A)	Voc (mV)	FF (%)	Rser (mΩ)
control	control	control	control	12.47	3.72	587	74.2	9.4
removed	low	no	no	12.56	3.89	583	72.0	13.8
present	high	no	no	12.73	3.80	587	74.2	7.8
removed	low	yes	yes	12.22	3.93	578	69.9	12.8
present	low	yes	no	13.12	3.88	590	74.5	7.4
removed	high	no	yes	10.12	3.88	564	60.1	32.9
removed	high	yes	no	12.80	3.94	584	72.2	11.9
present	low	no	yes	13.07	3.85	589	74.9	8.7
present	high	yes	yes	12.52	3.86	585	72.1	7.6

Table 13
Via Etched SiN Experiment

Oxide	Pressure	Sinter	Pre-dep	Eff (%)	Isc (A)	Voc (mV)	FF (%)	Rser (mΩ)
control	control	control	control	12.59	3.69	589	75.3	9.8
removed	low	no	no	3.0	2.26	552	30.5	-
present	high	no	no	13.08	3.84	592	74.8	9.9
removed	low	yes	yes	3.12	2.28	562	30.7	-
present	low	yes	no	13.07	3.87	593	74.0	11.4
removed	high	no	yes	0.2	0.26	519	20.4	-
removed	high	yes	no	3.27	2.35	568	30.6	-
present	low	no	yes	12.95	3.82	592	74.5	10.7
present	high	yes	yes	12.97	3.86	592	73.9	11.2

The results of the trial can be summarized as follows:

- There is no evidence of any benefit in terms of electrical performance from the use of the via-etch technique over the range of parameters investigated.
- There is no evidence that the pre-deposition conditions studied in this trial produce beneficial results.

- The oxide removal technique attempted prior to SiN deposition results in damage to the pre-metallized samples and an unusable surface on the via-etched samples. The slight positive effect on Isc noted in the pre-metallized samples is more than offset by FF damage resulting a net loss in power.
- The use of a post-deposition sinter enhances both current and efficiency in both the pre-metallized and via-etched samples.
- The lower deposition pressure results in improved performance in both the pre-metallized and via-etched samples.
- The maximum improvement demonstrated in this work (referenced to our standard process) was 5.9% in Isc, 0.5% in Voc, and 5.3% in efficiency. The best Isc and best efficiency improvements did not occur under the same conditions due to FF problems associated with metallization damage.

As a result of this work a baseline SiN deposition sequence was defined. The next step was to compare the baseline process on a number of different materials including:

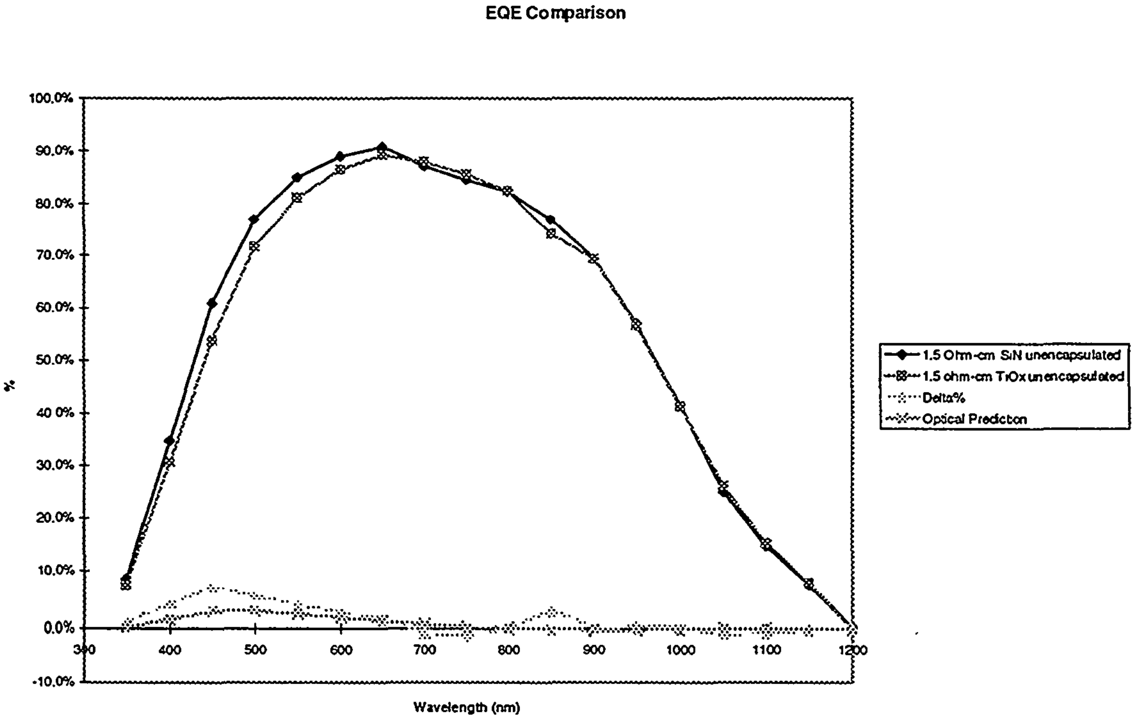
1.5 Ω-cm Solarex poly.
0.7 Ω-Cm Solarex poly.
1 Ω-Cm Kyocera poly.
1.7 Ω-Cm CZ.
0.8 Ω-Cm CZ.

This experiment was designed to provide us with information on the effect of substrate resistivity and on initial material quality as it relates to the performance enhancement obtained through the use of PECVD SiN. The results of this trial, shown in Table 14, indicate that neither the quality of the silicon substrate nor the base resistivity significantly affects the result seen when replacing a standard TiO_2 AR coating with a PECVD SiN coating. While all of the SiN groups are better than their TiO_2 controls, the spectral response data, shown in Figure 3 for Solarex 1.5 Ω-cm poly, indicates that there is no enhancement in the bulk properties of the substrate, supposedly the reason why Kyocera uses this process. There is an enhancement in the shorter wavelength performance, about half of which is due to the optical coupling advantage that SiN has over TiO_2 for cells measured in air. The remaining current improvement (~1.5%), along with a 2-3 mV increase in Voc, suggests that the SiN provides better surface passivation than the standard AR coating. Further work is necessary to determine if a PECVD SiN can improve the bulk properties of the silicon substrate.

Table 14
SiN Substrate Experiment

Cell Type	Eff (%)	Jsc as measured (mA/cm^2)	Jsc Spectrally Corrected (mA/cm^2)	% Change from corrected TiO_2
1.5 Ω-cm TiO_2	13.06	29.9	29.7	
1.5 Ω-cm SiN	13.68	30.7	30.7	3.4
0.7 Ω-cm TiO_2	13.39	29.5	29.4	
0.7 Ω-cm SiN	13.99	30.3	30.3	3.0
Kyocera TiO_2	11.79	27.3	27.1	
Kyocera SiN	12.24	27.6	28.0	3.0
1.5 Ω-cm CZ TiO_2	13.77	30.7	30.2	
1.5 Ω-cm CZ SiN	14.37	31.5	31.5	4.0
0.8 Ω-cm CZ TiO_2	14.09	30.8	30.4	
0.8 Ω-cm CZ SiN	14.61	31.7	31.4	3.3

Figure 3
Quantum Efficiency of SiN and TiO_2 AR Coated Cells



3.3.4 Phosphorus Gettering

Phosphorus gettering has been utilized to improve the minority carrier diffusion length and increase cell efficiency in some polycrystalline material.[7] We have successfully utilized phosphorus gettering as part of a buried contact cell process, resulting in improved cell efficiencies, although the results depend upon the initial quality of the silicon. Material from the bottom of the ingot, that produces 12 to 13% efficient cells without gettering, showed 3.5 to 4.5% improvement in cell efficiency from gettering. The better material from the middle and top of the ingot, that typically produce cells with greater than 13% efficiency without gettering, showed only marginal (0 to 2%) improvement in efficiency. So far attempts to take advantage of phosphorus gettering in the thick film paste process have not given consistent efficiency gains.

3.4 TASK 4 - AUTOMATED MODULE ASSEMBLY

The goal of this task is to modify Solarex's present automated matrix and module lay-up system to increase throughput by 100% and decrease the labor requirement by 50%. Solarex is presently using first generation automated module assembly equipment. This equipment has been very successful at eliminating labor, while producing reliable products. This system, however, still requires appreciable labor and does not have the throughput that Solarex will require as the PV market grows. To assist Solarex in analyzing how this equipment can be improved, the Automation and Robotics Research Institute (ARRI) at the University of Texas at Arlington is serving as a subcontractor. During this program the basic process of lay-up and soldering is not likely to change. The way the material is handled, the order in which the processes are carried out and the specific equipment designs are the variables being optimized.

The first step in this task was the development of a process flow chart detailing all of the module assembly steps. This process flow chart includes information on the process cycle times, labor requirements, product mix and its effect on cycle time and labor, equipment maintenance, process yields and equipment up time. All of this information has been provided to ARRI for modeling and analyzing the manufacturing process.

ARRI has completed a preliminary analysis of the module manufacturing process. The following sections summarize the results of this analysis.

FactoryFlow analysis

FactoryFlow provides an automated method of generating total material handling cost, distance intensity charts, and work center utilization reports to determine the efficiency of a system's operations. This analysis identifies the costs associated with the handling of material throughout the manufacturing process. For the Solarex module assembly process the total calculated cost per year is $28,172. This represents less than 1 cent per watt and so does not offer a significant potential for cost savings.

MPX modeling

The MPX Rapid Modeling software uses queuing theory to evaluate a network model of the proposed designs. This analysis identifies bottlenecks in the production process which limit the potential for increasing output capacity. The bottlenecks identified are cycle times for the Matrix lay-up robot, Framer robot and the Tabbers.

The Tabbers are not being run near their full capacity. The discrepancy between the model and the actual production process in these two areas is probably due to the fact that material shortages occur. This results in interruptions to the manufacturing process flow to the extent that the bottlenecks do not show up. This is an important point since the model itself does not take into account shortages in material. In this case material shortages are an important part of the equation to be taken into account when looking at the potential output of the Solarex factory from the simulation model. A more detailed analysis using stochastic modeling will be used in the future as more analysis is performed on the various processes. This modeling will present a more representative picture of the system behavior.

Resource Capacity analysis

This work was undertaken to support machine loading analysis and bottleneck identification under different product change over strategies and annual production volumes. A secondary benefit of this analysis, is that it provides independent verification for the results obtained from the queuing theory model discussed above. Assuming a steady flow of upstream materials, the overall capacity of the auto-matrix and lay-up system appears to be constrained by the Matrix lay-up robot, Framer station, and to a lesser degree the tabbers. These findings correlate very closely with the findings of the queuing theory analysis discussed above.

Man / Machine Charts were also developed for the lamination area to investigate the impact of resource interaction. These charts indicate that the capacity of the lamination area is constrained by the ability of the operator to service the laminators and the lay-up station. This man-power limitation may potentially result in the blocking of the lay-up station, further limiting the output of this constraining resource.

Based on ARRI modeling results, three specific areas have been selected for further study. These areas are the matrixing lay-up robot, the lamination operator and the framing system. Each of these three areas is being evaluated for possible improvements.

- Matrixing Lay-Up - The robot flow path has been broken down into the individual steps that the robot performs and their cycle times. Two changes (use of an integrated end effector and non-robot removal of the paper between EVA sheets) have been proposed. The modeling predicts that implementation of these 2 changes will result in a 37% reduction in cycle time of the process. The 37% exceeds the targeted goal of a 25% cycle time reduction that was determined necessary by the simulation model in order to achieve the short term goal of 30% increase in production capacity. The necessary changes to software and hardware have been made. The process has been successfully run on an experimental basis with the proposed changes. Production trials are planned.

- Lamination Operator - A discrete event simulation model is being developed for the lamination operations area. To provide input for this model, videotapes of the operation were made covering 4 hours over 2 different days. These tapes will provide a better understanding of the operations performed and their cycle times. Then, using a more accurate simulation model, changes can be defined that will have the greatest impact on improving the lamination operator's process.

- Framer/Finishing - Proposed changes in the framing/finishing area are concerned with reducing the robot travel time. A preliminary layout study resulted in a reduction in the robot angular travel from 1036 degrees per cycle to 630 degrees per cycle, an improvement of 39%. However, discrepancies have been noted between the cycle time from the Solarex flow chart and the cycle times measured from a short videotape made during the last ARRI visit to Solarex. To eliminate these discrepancies, a longer videotape of the framing process was prepared for study by ARRI.

  It should also be noted that a reduction in angular travel will not automatically transfer to a reduction in cycle time. There are accelerations at both ends of a move, and in many cases, some portion of an operation is being performed while the robot is in route to an operation site, causing a slowdown in the angular velocity.

3.5 TASK 5 - FRAMELESS MODULE DEVELOPMENT

In this task Solarex will develop and qualify a frameless module design incorporating a lower cost back sheet material (less than $0.05/square foot) and user friendly, low cost electrical termination (less than $1.00/module).

The key to reducing the finishing cost is to develop frameless system designs. In most larger systems the structural support provided by the frame is duplicated by the support structure. Therefore, frames can be eliminated, significantly reducing the module cost. A number of concepts have been proposed for mounting of modules without frames. Actual deployed systems include the clips used on the Solarex PV USA emerging technology array and a number of Arco Solar systems where the modules are glued directly to the support structure. The selected frameless mounting schemes must provide low cost and be able to withstand the expected mechanical loads, such as wind or snow.

3.5.1 Mounting Structure

The module proposed for this program uses 36 - 15 cm by 15 cm solar cells on a 56.00" by 25.63" piece of glass as shown in Figure 4. In order to utilize these modules in a larger size system, a modular mounting array has been designed for the project. These modules should be mounted with the short dimension parallel to the ground. To allow each row to have approximately 120 volts at peak power, there should be 8 modules in each row. To keep the structure to a reasonable size, the structure will be designed 4 modules high. This structure would be a little more than 19 feet from front to back and 17.5 feet across the front, incorporating 32 modules at a nominal 3.8 kilowatts of peak power as measured at STC. At a 45° tilt, the largest tilt angle typical of US systems, the top of the array would be approximately 13.5 feet above the bottom row or 15 feet off the ground.

A preliminary concept for the mounting structure was developed based on using 2 C-channels behind each module, 2 K-series steel support girders and 2 pipe support legs for each sub-array. The mounting structure concept is shown in Figures 5 and 6. This structure was then analyzed to determine the necessary component specification for the structure to be capable of withstanding 125 mph wind loading with a minimum design safety factor of 1.3.

The wind loading analysis revealed that:

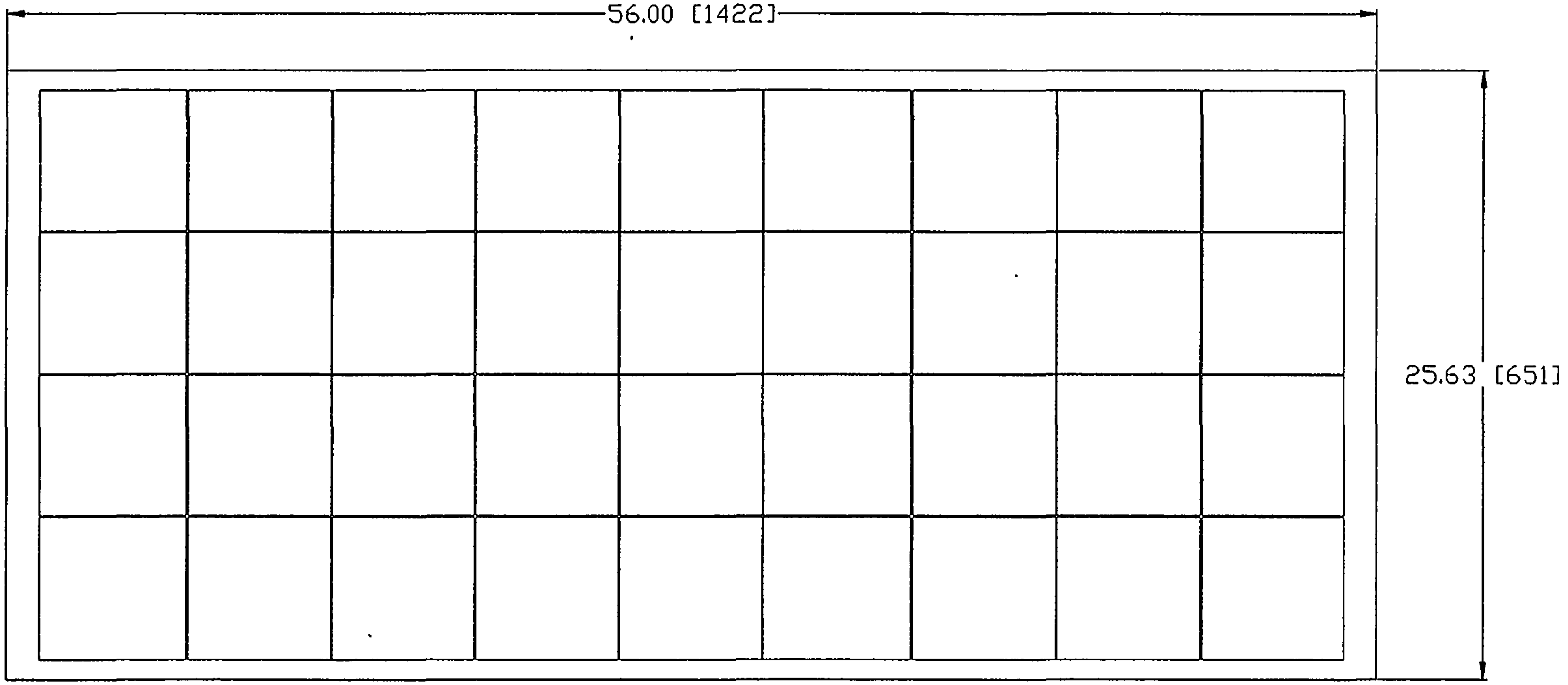
- Solarex's standard 1/8" tempered Solite glass is strong enough when mounted with 2 channels behind the glass, each spaced approximately 12" from the ends of the module.

- A 210" long aluminum C channel can have the smallest cross-section (2" by 1.25") and still be strong enough to support the modules with a safety factor of 3.5 with less than 1/2" deflection, while providing enough surface area for application of an adhesive.

- The K-series steel support girders need to be 17' long and 10" deep.

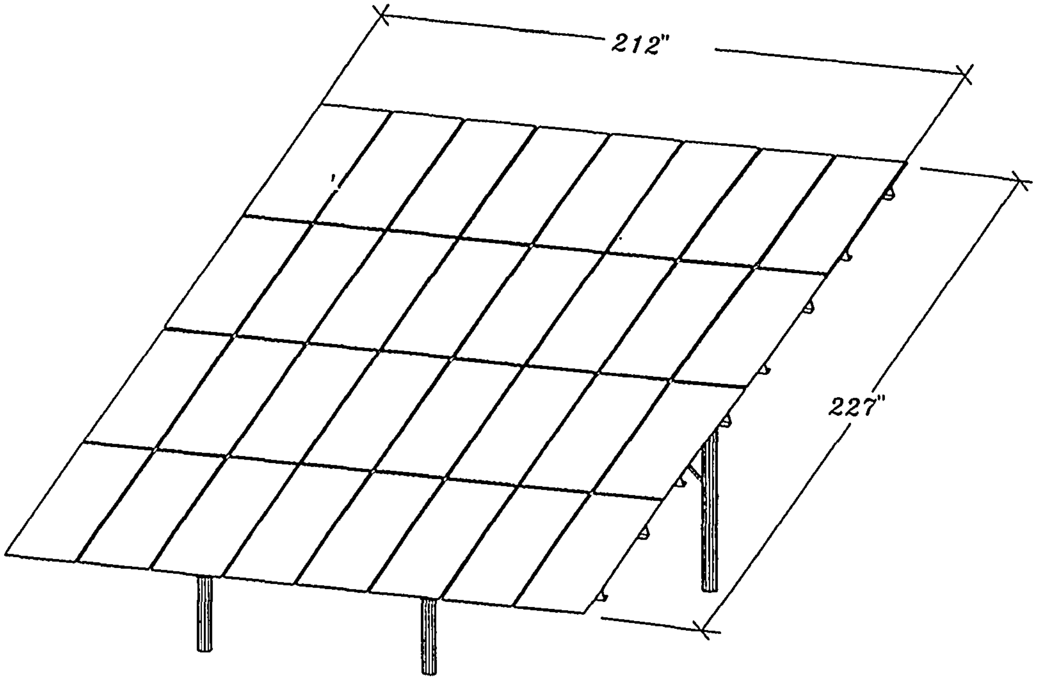
- The rear support legs can be made from 2" sch 40 pipe.

Figure 4
PVMaT Module

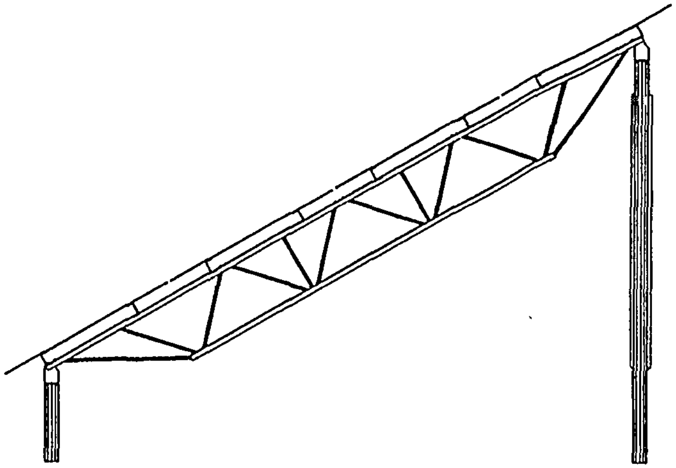


SK-082394-01-A

Figure 5
Mounting Structure
Front and Side View



TYPICAL SUB-ARRAY
FRONTAL VIEW



SIDE VIEW

CONTRACT NO.

SOLAREX
An Amoco Company

630 SOLAREX COURT
FREDERICK, MD 21701
301 698 4200

APPROVALS	DATE
DRAVN S.VINPIGLER	4/29/94
CHECKED	
APPROVED	

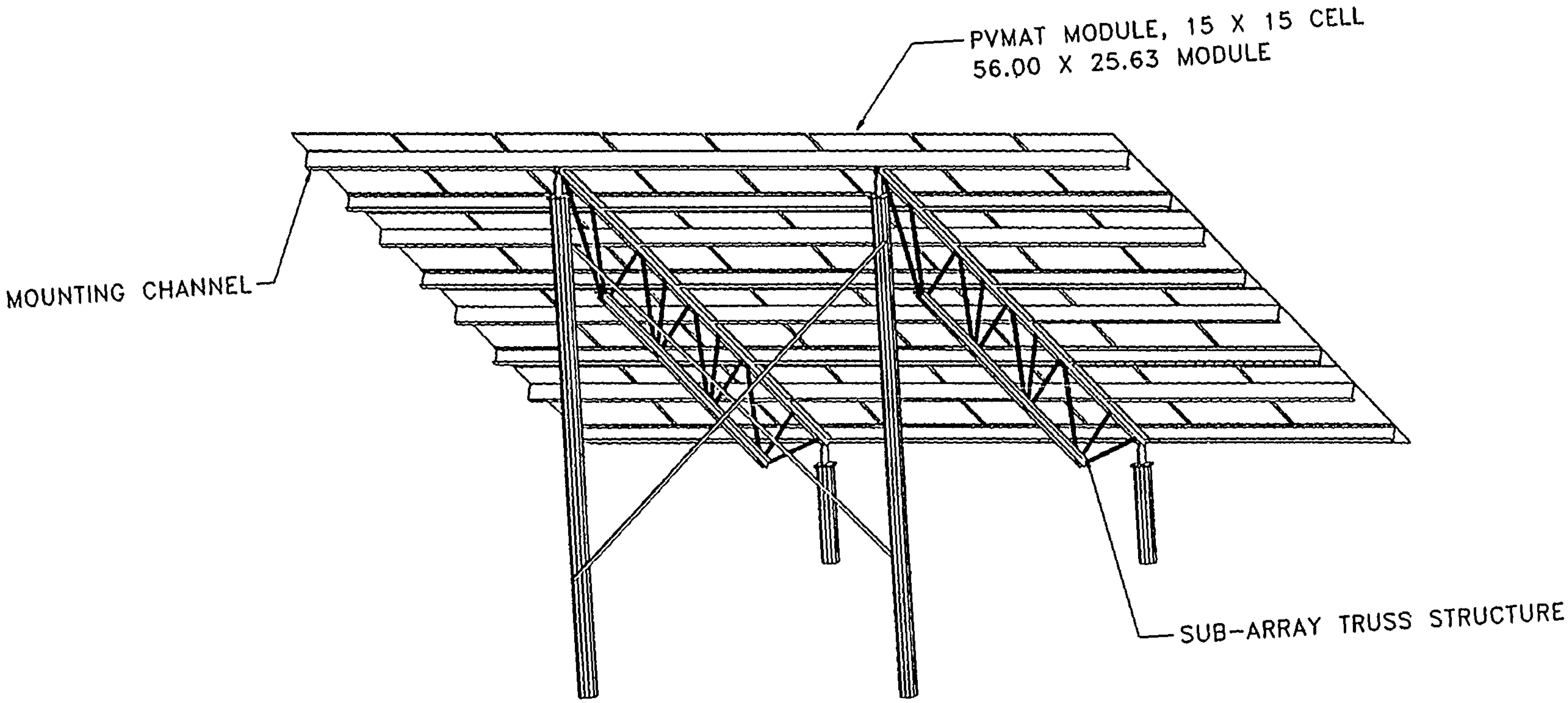
PVMAT TRUSS
CONCEPT

SIZE	DWG. STATUS	SOLAREX STOCK NO	REV.
A		SK-042994-02	A

SCALE NONE

SHEET OF

Figure 6
Mounting Stucture
Rear View



TYPICAL SUB-ARRAY
VIEWED FROM REAR

CONTRACT NO

SOLAREX
An Amoco Company
630 SOLAREX COURT
FREDERICK, MD 21701
301 698 4200

APPROVALS	DATE
DRAWN S.WINPIGLER	4/29/94
CHECKED	
APPROVED	

PVMAT TRUSS
CONCEPT

SIZE A
DWG STATUS
SOLAREX STOCK NO SK-042994-01
REV A
SCALE NONE
SHEET OF

Based on this design the structural cost for one 3.8 kilowatt array was calculated to be $1459 or $0.384 per watt. See Table 15. This is too expensive. The cost is dominated by the high cost of the Al channel.

Table 15
Structural Support Costs - with Al Channel

Item	Quantity	Cost per System	Cost per Watt
Al Channel	8	$1096	$0.288
Steel Girders	2	$ 268	$0.071
Pipe Legs	2	$ 95	$0.025
Total		$1459	$0.384

The structure calculations indicate that B-line steel beams could be used to replace the Al channel at a much lower cost. Using galvanized steel should provide the necessary corrosion protection for a 20 to 30 year lifetime. The structural costs are recalculated in Table 16 using the B-line galvanized steel rather than Al channel. Now the structure for a 3.8 kilowatt array is projected to cost $ 765 or $0.202/watt, a more reasonable value.

Table 16
Structural Support Costs - with Steel

Item	Quantity	Cost per System	Cost per Watt
Galvanized B-line	8	$ 402	$0.106
Steel Girders	2	$ 268	$0.071
Pipe Legs	2	$ 95	$0.025
Total		$ 765	$0.202

3.5.2 Adhesive System

A review of the literature and data on systems performance lead to the decision to use an adhesive system to mount the modules to the support structure. An excellent candidate for bonding PV modules to a support structure is one of 3M's Very High Bond (VHB) Tapes. Scotch VHB tapes are used throughout industry instead of screws, rivets, welds and liquid adhesives to permanently assemble a variety of products. VHB tapes actually have a number of advantages over mechanical fastening.

- The tapes provide continuous contact over the mated surfaces, so they distribute stress over a wider area, eliminating stress points, improving fatigue resistance and providing a better seal against environmental conditions. This allows for lighter, thinner, more flexible and less expensive support materials.
- The tapes conform nicely to contoured surfaces, filling surface irregularities and gaps.
- Use of the tapes eliminates or reduces the number of machining operations to perform, reduces the need to refinish and reclean surfaces, and eliminates the cure times needed for many other adhesive systems.
- The tapes are designed to handle both static and dynamic loads. Dynamic forces such as tension, peel, cleavage and shear are caused by thermal cycling, vibration, wind loading and shifting. The viscoelastic properties of VHB tapes allow it to handle the ever-changing conditions of long term outdoor exposure.

- The tapes resist moisture, solvents and UV light.

VHB tapes are now used for a large number of applications including bonding :

- aluminum panels on vehicles,
- steel strips on airplane wings,
- brass trim to iron on wood burning stoves,
- displays on circuit boards and plastic cases,
- stiffeners onto plastic cabinets, and
- windows to metal cases.

Use of VHB tapes offers an opportunity to improve performance while lowering the material and assembly labor cost for PV systems.

3.5.3 Backsheet

A key component in frameless module design is the backsheet, since the electrical termination and the support system itself must adhere to the backsheet. This offers an additional opportunity to reduce cost since the 3 part backsheet used at Solarex for a number of years has cost as much as $0.71 per square foot.

The first step in developing a new low cost backsheet material is to identify what the requirements are for the backsheet material. The back sheet must:

1. be able to survive the EVA lamination process,
2. be able to survive outdoor exposure for at least 20 years,
3. serve as a mechanical barrier,
4. adhere well to the EVA,
5. be capable of having adhesives bonded to it,
6. pass the UL fire tests with Class C or better rating when used as the backsheet of an EVA module and
7. provide the electrical isolation between the supporting structure and the active circuit elements.

The back sheet material must meet all of these technical requirements, cost less than $0.05/ft^2 when purchased in large quantities (greater than 500,000 ft^2 per year) and be available in widths of at least 27 inches.

Three candidate materials have been selected for evaluation in this program. The three materials are:

- Chlorinated polyethylene (CPE)
- Affinity polyolefin
- Thin Tedlar - polyvinyl fluoride

Small modules were fabricated using the experimental backsheet materials. These small modules were then subjected to a set of environmental qualification tests similar to IEC 1215 - "Crystalline Silicon Terrestrial Photovoltaic (PV) Modules -Design Qualification and Type Approval", but with the addition of a wet high-pot test. The three materials successfully passed all of the environmental tests except CPE samples made without pigmentation. CPE without pigmentation slid more than an inch across the back of the module during each of the high temperature steps (damp heat, thermal cycling and humidity freeze). When pigmented samples were tested, there was no observable movement of the CPE film. Finally, modules made with all three materials have successfully passed the UL fire test.

The major open issue with the candidate backsheet materials is their ability to withstand UV exposure. To evaluate their performance, sample backsheet materials are being tested under accelerated outdoor testing to an equivalent UV exposure of 2 years in Phoenix, Arizona. Two years of direct exposure should represent more UV than the backsheet will normally experience in 20 years of operation on the back of a PV module.

REFERENCES

[1] J.H. Wohlgemuth, "Casting Polycrystalline Silicon for Photovoltaics", Proceedings of International Symposium-Workshop on Silicon Technology Development and Its Role in the Sun-Belt Countries, 14-18, June 1987, Islamabad, p. G-1.
[2] J.H. Wohlgemuth, S.P. Shea, R.K. Brenneman and A.M. Ricaud, "Elimination of Edge Roll-Off In Cast Semicrystalline Silicon", Nineteenth IEEE Photovoltaic Specialist Conference, p. 1524, 1987.
[3] J.H. Wohlgemuth, S. Narayanan and R. Brenneman, "Cost Effectiveness of High Efficiency Cell Processes as Applied to Cast Polycrystalline Silicon", Twenty-first IEEE Photovoltaic Specialist Conference, p. 221, 1990.
[4] S. Narayanan and J. Wohlgemuth, "Cost-benefit Analysis of High-efficiency Cast Polycrystalline Silicon Solar Cell Sequences", *Progress in Photovoltaics*, Vol. **2** No. **2**, p. 121, 1994.
[5] S. Shirasawa, K. Okada, F. Fukai, M. Hirose, H. Yamashita and H. Watanabe, "Technical Digest of Third International Photovoltaic Science and Engineering Conference", p. 97, 1987.
[6] J. Hanoka, *"Hydrogen in Disordered and Amorphous Solids"*, Eds: J. T. Bambakidis and R. C. Bowman Jr., Plenum publishing Corp. P. 81, 1986.
[7] S. Narayanan, S. R. Wenham and M. A. Green, "High Efficiency Polycrystalline Solar Cells", *IEEE Trans. Electron Devices*, Vol. **ED-37**, p. 382, 1990.

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
March 1995

3: REPORT TYPE AND DATES COVERED
Subcontract Report, 8 December 1993 – 30 June 1994

4. TITLE AND SUBTITLE
Cast Polycrystalline Silicon Photovoltaic Module Manufacturing Technology Improvements

5. FUNDING NUMBERS
C: ZAI-4-11294-01
TA: PV550101

6. AUTHOR(S)
J. Wohlgemuth

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Solarex Corporation
630 Solarex Ct.
Frederick, Maryland 21701

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
TP-411-7497
DE95004065

11. SUPPLEMENTARY NOTES
NREL Technical Monitor: R. Mitchell

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE
UC-1280

13. ABSTRACT *(Maximum 200 words)*

This report describes work done under a 3-year program to advance Solarex's cast polycrystalline silicon manufacturing technology, reduce module production cost, increase module performance, and expand Solarex's commercial production capacities. The accomplishments described in this report are as follows: (1) we designed modifications to casting stations, ceramic molds, and sizing saws to allow for casting and sizing of larger ingots; (2) we demonstrated the casting of ingots with 17% larger volume; (3) we selected and purchased a new wire saw from HCT Shaping Systems; (4) we demonstrated wafering of eight bricks (2400 wafers or ~4.4 kilowatts at the cell level) in a 6.5-h run; (5) we demonstrated 14% average cell efficiency in the laboratory using an aluminum paste back surface field; (6) the Automation and Robotics Research Institute (ARRI) completed a modeling study of the Solarex module assembly process; (7) we identified and qualified three new lower-cost back sheet materials through accelerated environmental tests; and (8) we designed and built a test structure for mounting frameless modules, and selected two adhesives and began testing their ability to hold modules to the structure.

14. SUBJECT TERMS
cast polycrystalline ; silicon ; modules ; manufacturing ; photovoltaics ; solar cells

15. NUMBER OF PAGES
38

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT
UL