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OVERVIEW OF THE PHOTOVOLTAIC MANUFACTURING TECHNOLOGY (PVMaT) PROJECT

C. Edwin Witt, Richard L. Mitchell, G. David Mooney

The Photovoltaic Manufacturing Technology (PVMaT) project is a historic government/industry photovoltaic (PV) manufacturing R&D partnership composed of joint efforts between the federal government (through the U.S. Department of Energy) and members of the U.S. PV industry. The project's ultimate goal is to ensure that the U.S. industry retains and extends its world leadership role in the manufacture and commercial development of PV components and systems. PVMaT is designed to do this by helping the U.S. PV industry improve manufacturing processes, accelerate manufacturing cost reductions for PV modules, improve commercial product performance, and lay the groundwork for a substantial scale-up of U.S.-based PV manufacturing plant capacities.

The project is being carried out in three separate phases, each focused on a specific approach to solving the problems identified by the industrial participants. These participants are selected through competitive procurements. Each associated subcontract under any phase of this project is, and will continue to be, selected for funding on its own technical and cost merits. The PVMaT project is specifically structured to ensure that these PV manufacturing R&D subcontract awards are selected with no intention of either directing funding toward specific PV technologies (e.g., amorphous silicon, polycrystalline thin films, etc.), or spreading the awards among a number of technologies (e.g., one subcontract in each area).

Phase 1 of this project, the ***problem identification phase***, was completed in early 1991. Phase 1 competitive bidding was open to any U.S. firm with existing PV manufacturing capabilities, regardless of material or module design. Responses identified problems in the manufacture of flat-plate crystalline-silicon modules, flat-plate thin-film modules, concentrator modules, and manufacturing equipment.

Phase 2, the ***problem solution phase***, which addresses process-specific problems of specific manufacturers, is now underway with an expected duration of 5 years. The first solicitation under this phase (PVMaT 2A) was open only to those organizations that received awards in the Phase 1 solicitation, and seven resulting subcontracts were implemented in early 1992. The subcontracts are cost-shared between the U.S. government and U.S. industrial participants. Proposals were due in September of 1992 for a second, overlapping, and similar process-specific solicitation (PVMaT 2B). This second Phase 2 solicitation is in the evaluation stage, with awards planned for later this year (1993). PVMaT 2B was open to all U.S. PV industrial firms, thus giving organizations that were not ready for the first Phase 2 procurement cycle another chance to "ramp-on" and participate in the solution phase of the program.

Phase 3 addresses R&D problems that are relatively common to a number of PV companies or the PV industry as a whole. These "generic" problem areas are being addressed through a teamed research approach. A solicitation on this type of generic manufacturing technology was released in October 1991. Two subcontracts for Phase 3 were recently awarded. These research organizations are focusing on module-related R&D problems found to be common to a significant set of PV manufacturers.

PHASE 1

The Phase 1 portion of the PVMaT project, the ***problem identification phase***, was completed in early 1991. This work involved competitive bidding that was open to any U.S. firm with existing PV manufacturing capabilities, regardless of material or module design. Early in 1991, the competitive selection process for this phase was completed with 22 subcontracts awarded (see Table 1). Each of these subcontracts was funded at a level of up to $50,000 for a duration of 3 months. The problems identified by the research in this phase represented opportunities for individual industrial participants to improve manufacturing processes, reduce manufacturing costs, increase product performance, and support a scale-up of U.S.-based manufacturing plant capabilities. These opportunities have since been detailed in the approaches suggested by these organizations for Phase 2 research. It is not anticipated that another Phase 1-type solicitation will occur. The procurement under this phase was only meant to precede and support the first Phase 2 solicitation.

Phase 1-subcontracted research included five subcontractors working on flat-plate crystalline silicon technology, ten on flat-plate thin-film modules (one on thin-film crystalline silicon, five on amorphous silicon, and four on polycrystalline thin films), six on concentrator systems, and two working on general equipment/production issues.

Table 1. PVMaT Phase 1 Subcontractors

Subcontractor	Location
Spire Corporation	Bedford, MA
AstroPower, Inc.	Newark, DE
Solarex Corporation	Rockville, MD
Siemens Solar Industries	Camarillo, CA
Westinghouse Electric Corp.	Pittsburgh, PA
Silicon Energy Corporation	Chatsworth, CA
Glasstech Solar, Inc.	Golden, CO
Global Photovoltaic Specialists	Canoga Park, CA
Alpha Solarco, Inc.	Cincinnati, OH
Photon Energy, Inc.	El Paso, TX
Energy Conversion Devices	Troy, MI
Mobil Solar Energy Corporation	Billerica, MA
ENTECH, Inc.	Dallas, TX
Boeing Aerospace	Seattle, WA
Solar Kinetics, Inc.	Dallas, TX
Chronar Corporation	Lawrenceville, NJ
Crystal Systems, Inc.	Salem, MA
Iowa Thin Films Technology	Ames, IA
Solar Cells, Inc.	Toledo, OH
Kopin Corporation	Taunton, MA
Solar Engineering Applications	San Jose, CA
Spectrolab, Inc.	Sylmar, CA

Flat-Plate Crystalline Silicon Modules. Crystalline silicon (c-Si) is the most common semiconductor material for PV devices. With Phase 1 PVMaT support, five companies identified problems of this technology. This group of crystalline silicon research organizations included Mobil Solar Energy Corp. of Billerica, Massachusetts; Crystal Systems, Inc., of Salem, Massachusetts; Westinghouse Electric Corp. of Pittsburgh, Pennsylvania; Solarex Corp. of Rockville, Maryland; and Siemens Solar Industries of Camarillo, California.

Flat-Plate, Thin-Film Modules. Modules made of thin-film materials have inherent cost advantages, including the use of less semiconductor material and integrated manufacturing for cells and modules. However, at present prices for amorphous silicon (a-Si) modules are still comparable to those of crystalline silicon. Other promising thin-film technologies—such as $CuInSe_2$ (CIS), cadmium telluride (CdTe), thin-film silicon, and gallium arsenide (GaAs)—are rapidly approaching commercialization. Ten U.S. companies received Phase 1 support to identify potential cost reductions for thin-film module manufacturing: one working in thin-film crystalline silicon, five concentrating on a-Si, and four focusing on polycrystalline thin films.

AstroPower was the only manufacturer to focus on thin-film crystalline silicon solar cells. The five a-Si research organizations included Glasstech Solar, Inc., of Golden, Colorado; Iowa Thin Films Technologies, Inc., (ITFT) of Ames, Iowa; Energy Conversion Devices (ECD) of Troy, Michigan; Silicon Energy Corp. of Chatsworth, California; and Chronar Corp. of Lawrenceville, New Jersey. Additionally, four organizations focused on polycrystalline thin films. This group of research organizations includes Siemens Solar Industries of Camarillo, California (CIS); Boeing Aerospace & Electronics of Seattle, Washington (CIS); Photon Energy, Inc., of El Paso, Texas (CdTe); and Solar Cells, Inc., of Toledo, Ohio (CdTe).

Concentrators. Concentrator modules use lenses to intensify the sunlight falling on banks of small, high-efficiency cells, which reduces semiconductor material costs per unit of power output. R&D issues include optimum cell packaging and assembly, concentrator optics, and low-cost tracking arrays and support structures. Manufacturing cost reductions would occur primarily through automated assembly.

The six concentrator companies involved in PVMaT included Alpha Solarco, Inc., of Cincinnati, Ohio; Solar Engineering Applications (SEAC) of San Jose, California; Kopin Corporation of Taunton, Massachusetts; ENTECH, Inc., of Dallas, Texas; Spectrolab, Inc., of Sylmar, California; and Solar Kinetics, Inc., of Dallas, Texas.

Other Phase 1 Activities. Two Phase 1 participants are targeting improvements to their commercial lines of PV manufacturing equipment. This diversified group includes Global Photovoltaic Specialists, Inc., (GPS) of Canoga Park, California; and Spire Corporation of Bedford, Massachusetts.

PHASE 2A

The winners in PVMaT 2A are listed in Table 2 below. Following Table 2 is a description of the seven subcontractor projects and FY 1992 PVMaT accomplishments.

Siemens Solar Industries *Photovoltaic Cz Silicon Manufacturing Technology Improvements* Siemens Solar Industries (SSI) researchers are improving Czochralski (Cz) Si-ingot quality; increasing the materials use efficiency for c-Si wafer sawing; investigating improvements in device processing; investigating the introduction of automation to a significant portion of their c-Si module-manufacturing lines; and reducing the amount of hazardous waste generated. This effort will be addressed in three, 1-year phases. Successful implementation of this program will result in decreasing SSI's c-Si module cost by more than half while doubling its U.S. manufacturing capability. Siemens's accomplishments during the first phase of this subcontract include: an increase in wire-saw production capacity by over 30% due to reduced Kerf loss and thinner wafer processing; an increase in crystal growth yields through polysilicon studies; use of freon is being eliminated and replaced by a no-clean solder paste in Siemens module production by April 1993; and incorporation of graphite design changes into the Siemens crystal growers have resulted in a 30% savings of $300K/year.

Table 2: PVMaT Phase 2A Participants

Subcontractor	Subcontract Title	Principal Investigator
Siemens Solar Industries Camarillo, California	*Photovoltaic Cz Silicon Manufacturing Technology Improvements*	T. Jester
Solarex Corporation Newtown, Pennsylvania	*Large-Area, Triple-Junction, a-Si Alloy Production Scale-Up Project*	R. Oswald
Mobil Solar Energy Corporation Billerica, Massachusetts	*Thin Edge-Defined Film-Fed Growth (EFG) Octagons*	J. Kalejs
ENTECH, Inc. Dallas, Texas	*Photovoltaic Manufacturing Technology (PVMaT) Improvements for ENTECH's Concentrator Module*	M. O'Neill
AstroPower, Inc. Newark, Delaware	*Silicon-Film Photovoltaic Manufacturing Technology*	W. Bottenberg
Utility Power Group Chatsworth, California	*a:Si Photovoltaic Manufacturing Technology—Phase 2A*	G. Duran
Energy Conversion Devices Troy, Michigan	*Continuous Roll-to-Roll Amorphous Silicon Photovoltaic Manufacturing Technology*	M. Izu

Solarex Corporation *Large-Area, Triple-Junction, a-Si Alloy Production Scale-Up Project* Solarex Corporation researchers are improving the deposition and quality of the transparent front contact; optimizing the laser patterning process; scaling up the semiconductor deposition process; improving the back contact deposition; and scaling up and improving the encapsulation and testing of a-Si:H modules. Successful implementation of this 3-year program will result in Solarex producing 75 watt a-Si:H modules, ≥0.56-m^2 (≥6-ft^2), 10% stabilized efficiency, with a total overall module yield of ≥75%. At a proposed production capacity of 10 MW/year, this would result in a potential cost reduction from the present price of $11.05/peak watt ($W_p$) to $1.14/$W_p$. Solarex's accomplishments during the first phase of this subcontract include the

design of an ≥0.56-m^2 (≥6-ft^2) PECVD a-Si:H-based deposition system; completion of light soaking tests on Solarex a-Si:H modules; demonstration of a new laser-scribing system that does not cause module failures in the wet hi-pot tests; and the fabrication of a frit dispenser used in Solarex module fabrication.

Mobil Solar Energy Corporation *Thin Edge-Defined Film-Fed Growth (EFG) Octagons*
Mobil Solar Energy Corporation researchers are reducing the cost of solar cell processing through a 50% reduction in EFG Si-wafer thickness; increasing the throughput of the laser-cutting of the wafers; increasing the mechanical strength and, thus, the yield of the wafers; and evaluating integrated computer-aided manufacturing control programs for the Mobil Solar crystal growth manufacturing line to enhance productivity. Successful implementation of this 3-year program will allow Mobil Solar to produce octagonal Si tubes, producing 200-μm-thick Si wafers with a thickness variation of ±50 μm. The previous minimum wafer thickness for this process was 400-μm-thick. Mobil will also develop laser wafer-cutting capabilities resulting in the processing of 12 wafers per min. Mobil's accomplishments during the first phase of this subcontract include testing and analysis that indicate potential materials cost reductions of 15% due to wafer thickness, 10% due to wafer flatness improvement, and 25% due to a growth rate; completing specifications for a factory prototype EFG octagon crystal-growth furnace for 300-μm-thick Si wafers; designing and testing a laser cutting station that will increase pilot production line throughput by a factor of two; and a demonstration of the cutting feasibility of silicon wafers near the low-damage threshold with a 585-nm high-power dye laser.

ENTECH, Incorporated *Photovoltaic Manufacturing Technology Improvements for ENTECH's Concentrator Module*
ENTECH researchers are automating a significant portion of their manufacturing line, helping key ENTECH vendors improve their technologies; scaling up the ENTECH manufacturing line to accommodate large-volume production; and addressing ES&H issues throughout all of the associated manufacturing processes. The effort will be addressed in two, 1-year phases. Successful implementation of this program will result in an initial linear concentrator module manufacturing plant with the capability of producing PV modules at a rate of 10 MW/year. ENTECH's accomplishments during the first phase of this subcontract include the development of laboratory prototype work stations for photovoltaic cell assemblies and receivers; the identification and delivery of process-compatible advanced-cell samples from four separate vendors; the development of an improved prismatic lens cover for cells, which resulted in a 90% reduction in both material and labor costs for that step; the development of a continuous, prelaminated, rolled Fresnel lens that resulted in both a 20% materials cost reduction and the elimination of solvent use in the ENTECH process; and development of ribbon solder techniques that have resulted in an 80% reduction in materials costs with additional savings in labor.

AstroPower, Incorporated *Silicon-Film® Photovoltaic Manufacturing Technology*
AstroPower researchers are enhancing their Silicon-Film® wafer production capabilities, optimizing solar cell processing, and improving the polycrystalline silicon-film module assembly portion of the manufacturing line. Successful implementation of this 3-year program will result in an upgrade to AstroPower's facility that will allow it to reach a production rate of 19 MW/yr of 1.22 m^2 polycrystalline silicon modules with an output of 170 W_p each by the mid-1990s. AstroPower's accomplishments during the first phase of this subcontract include demonstrating an 8.8%-efficient 10-cm x 10-cm Silicon-Film® solar cell; fabricating the first 15-cm x 45-cm Silicon-Film® cell (the largest solar cell ever produced); demonstrating a 0.48-MW/yr Silicon-Film® machine operation rate, and 74% silicon feedstock use efficiency; initial planning for a

2.4-MW/yr wafer fabrication machine; and planning for the introduction of new 225-cm^2 Silicon-Film® solar cell products in 1993.

Utility Power Group *a:Si Photovoltaic Manufacturing Technology—Phase 2A*
Utility Power Group (UPG) researchers are conducting research on encapsulation of a-Si:H modules, with consideration given to approaches that do not require a second glass layer, and automation of module termination. Additionally, UPG's lower-tier subcontractor, Advanced Photovoltaic Systems (APS), is optimizing the automation of its Eureka® manufacturing line; improving the encapsulation of the Eureka® module, and introducing real-time processing and quality control to the Eureka® production line. Successful implementation of this 3-year effort will result in increasing the module manufacturing yield over the current level by 35%, while decreasing the direct cost by about 25%. The accomplishments of the UPG-APS team during the first phase of this subcontract include the completion of POWERGLASS module qualification testing for candidate encapsulation materials; reduced POWERGLASS module termination and encapsulation manufacturing costs by 50%; introducing two new Eureka® module products (a 25W and a 50W product for 12 volt applications); completing the automation of about 60% of the Eureka® production encapsulation line; and completing a design for full-scale enhanced Eureka® modules.

Energy Conversion Devices, Incorporated *Continuous Roll-to-Roll Amorphous Silicon Photovoltaic Manufacturing Technology*
Energy Conversion Devices (ECD) scientist are developing the capacity for the production of 0.31-m x 1.22-m (1-ft x 4-ft) triple-junction a-Si-Ge alloy modules with 11% stable efficiency, reducing their manufacturing costs through utilizing ECD's high-deposition-rate microwave technology to enhance the production throughput, and reducing material and labor costs. The effort will be addressed in three, 1-year phases. Successful implementation of this program will allow ECD to work toward an ultimate goal of building a 100-MW-per-year, roll-to-roll, automated a-Si module manufacturing facility. At this anticipated production capacity, ECD could reduce the cost of PV modules to less than $\$1.00/W_p$. ECD's accomplishments during the first phase of this subcontract include completion of improvements to the ECD a-Si-Ge alloy deposition system establishing the first roll-to-roll a-Si-Ge production line facility; demonstration of 7.2% stabilized efficiency on ≥0.372 m^2 triple-junction a-Si alloy modules; and incorporation of a linear applicator microwave plasma source for multipurpose deposition.

PHASE 3A

The winners in PVMaT 3A are listed in the Table 3 below. Both contracts began in early January, 1993. Following Table 3 is a description of the two subcontractor projects.

Table 3: PVMaT Phase 3A Participants

Subcontractor	Subcontract Title	Principal Investigator
Spire Corporation Bedford, Massachusetts	*Automated Solar Cell Assembly Teamed Process Research*	M. Nowlan
Springborn Laboratories, Inc. Enfield, Connecticut	*Photovoltaic Manufacturing Technology (PVMaT)*	W. Holley

Spire Corporation *Automated Solar Cell Assembly Teamed Process Research*
Spire researchers will conduct manufacturing R&D to improve crystalline and polycrystalline Si PV module manufacturing processes with a goal of substantially reducing module manufacturing costs. Areas to be addressed include processing rates, process control, yield, throughput, material utilization efficiency, and increased use of automation. These issues will be addressed for thin ($\leq$ 200-μm) silicon wafers. To conduct this work, Spire will team with Solec International, Inc., (a PV module manufacturer) and the University of Massachusetts-Lowell/Center for Productivity Enhancement (automation specialists) who will act as lower-tier subcontractors. The effort will be addressed in two, 1-year phases.

Springborn Laboratories *Photovoltaic Manufacturing Technology (PVMaT)*
Springborn researchers will endeavor to solve problems related to the PV-module encapsulant ethylene-vinyl-acetate (EVA) discoloration and/or degradation. Areas to be addressed include a case-history study and problem definition, identification of discoloration and/or degradation mechanisms, development of EVA-stabilization strategies, accelerated testing of new laminates, and pilot-scale production and field-testing of new laminates. To conduct this work, Springborn will team with the Siemens Solar Industries; Photocomm, Inc.; United Solar Systems Corp.; Solarex Corp.; Texas Instruments; Solec International, Inc.; Utility Power Group, Inc.; Advanced Photovoltaic Systems, Inc.; Global Photovoltaic Specialists, Inc.; Arizona State University; Arizona Public Service Company; and the University of Connecticut. The effort will be addressed in three, 1-year phases.