A Partnership that Works

Keeping the U.S. PV industry strong. Smoothing out the kinks on the path to PV manufacturing success. One person, one company, one laboratory *alone* is not enough.

But pool the resources of hundreds of talented people from two dozen PV companies and a couple of national laboratories—reinforced by the strength of the U.S. Department of Energy—and you'll find a group that's worthy of the task. That group, the participants in the Photovoltaic Manufacturing Technology (PVMaT) project, is profiled in this issue.

PVMaT is a partnership in every sense of the word. The costs, the work, the rewards are all shared. And we all win, because a strong domestic PV industry gives us homegrown technology jobs and a prized commodity to export to the rest of the world.

Also in this issue, you'll hear from someone many of you know quite well—Larry Kazmerski, the new Director of the National Center for Photovoltaics. Kazmerski was named NCPV Director on December 1. In the University Corner, you'll find news of the nearly $5 million in awards for "University R&D for Future Generation Technologies." Fourteen of the awardees are new to the PV Program. And in the Industry Activity Update section comes word of the many world records achieved lately—a testament to the successful teamwork of industry, university, and NREL researchers.

And speaking of world records, there's another one to boast about right here at NREL. The CIS (copper indium diselenide) Team, led by Rommel Noufi, set a new mark for thin-film solar cell efficiency. The measurement of 18.8% conversion efficiency for the CIS alloy cell topped the previous record, also set at NREL, by more than one percent.

NREL PV

Working With Industry

First Quarter, 1999

Features

Departments

PV... On the Road and Looking Ahead

An Editorial by Larry Kazmerski

NREL/PIX06859

Two new guys. *Fresh from his appointment as Secretary of Energy, Bill Richardson (left) visited NREL last September. Larry Kazmerski, who was later named Director of the National Center for Photovoltaics, was on hand to show him the ropes. "Kaz" is well known in the PV community, for both the excellence of his science and the flamboyance of his ties. He wears badge number seven at the Lab, having been at NREL since its inception 22 years ago.*

Contact Larry Kazmerski at 303-384-6600.

I am struck by our PV industry's accomplishments and gains, which are so eloquently cited in this issue of *PV Working With Industry* that focuses on the successful PV Manufacturing Technology (PVMaT) project. Our domestic PV industry—virtually nonexistent at the start of our terrestrial program—has risen impressively to its current leadership position in the world PV marketplace.

The "snapshots" in the following articles accurately reflect some of the major industry successes in production, manufacturing, and new product innovation, and in reducing costs, enhancing yields, and improving technology. At first glance, it looks like we've made it—or at least *close* to it! Barriers are coming down, the technology is here, partnerships have succeeded, and the industry is beginning to be profitable. However, I'm both optimistic and cautious as I look back and look forward.

Looking back, one could get the impression that all these successes were just handed to the industry ("Give them the money and they will succeed"). In fact, though, the PVMaT successes, as well as the other business accomplishments of the PV industry, have *not* come easily. Industry members certainly took risks, provided their own start-up financing, marketed their programs, invested in the best available photovoltaic staff, experienced some failures and redirections, maintained their businesses—and had to work damn hard.

Furthermore, the economic and political climates were not always conducive to helping industry members. They made the best use of their strengths and collaborated effectively with the available resources of the PV Program at universities and government laboratories. Also interesting to me is how many technical and operational leaders in the industry arose from the research trenches of the PV Program. This may account, in part, for the value that industry attaches to its base in fundamental and applied research.

Looking to the future, the industry and the DOE PV Program are positioning themselves for continued successes with two major, linked planning exercises. The *DOE PV Program Five-Year Plan for 2000–2004* will be a "rolling plan," with reviews and updates every two years. This slimmed-down version will be based on input from the DOE Program partners from university, industry, and federal laboratories. Under way now, the plan should be available by the end of the year, and it will reflect the guidance of a more encompassing effort—the *PV Industry Roadmap*.

The roadmap activity belongs to, and is led by, the U.S. PV industry. It covers a longer planning horizon—from 2000 to 2020. This needs-driven guide will help to identify, select, and develop technology pathways to reach major, quantifiable end points. In 2020, for example, this end point is to provide at least 15% of new U.S. electrical generating capacity—projected to be about 3200 MW of new PV power systems. As currently evolving, this comprehensive roadmap will focus on four "technology development areas": Fundamental and Applied Research; Manufacturing, Equipment, and Processes; PV Components, Systems, and Integration; and Markets and Applications. This reflects the focus areas defined by some fifty NCPV partners who participated in the NCPV Workshop on PV Program Strategic Directions in July 1997. A skeletal roadmap, scheduled for May, will be the basis for a June stakeholders meeting, where the document will be molded into a more complete industry-guided plan to be released this September.

The past has had its accomplishments. And the future holds much promise. The increased *proposed* budget for FY 2000 mirrors the growing confidence that the government has in PV technology, the PV Program, and the PV industry. Together, the PV industry and the rest of the National Center for Photovoltaics are making sure that we are ready to respond to the opportunities and challenges ahead... making PV the power of choice.

PV Web Sites

DOE PV Program .....*http://www.eren.doe.gov/pv*
About Photovoltaics • News and Information • About Our Program

National Center for Photovoltaics .....*http://www.nrel.gov/ncpv*
World Class R&D • Partnering and Growth • Information Resources

Photovoltaic Manufacturing Technology ....*http://www.nrel.gov/pvmat*
Overview • Partners • Fact Sheets • News and Events • Contacts

Measurements and Characterization..*http://www.nrel.gov/measurements*
Virtual Lab • Capabilities • Doing Business • Data Sharing

Million Solar Roofs .....*http://www.MillionSolarRoofs.org*
Initiative Goals • Scope • Solar Technologies

The Center for Basic Sciences .....*http://www.nrel.gov/basic_sciences*
Capabilities • Optoelectronics • Crystal Growth and Devices

PVMaT—Big Gains Since 1992

When it comes to manufacturing PV modules, success is measured in seconds shaved and pennies saved. Make the product better, quicker, and cheaper and the market awaits.

The Photovoltaic Manufacturing Technology (PVMaT) project exists for just that reason. Maintaining and enhancing a healthy domestic PV industry benefits the U.S. economy in so many ways, from creating a technology-oriented job base to offsetting trade imbalances by shipping a valuable commodity to burgeoning world PV markets.

The goals of the PVMaT project are to improve PV manufacturing processes and products for terrestrial applications, accelerate PV manufacturing cost reduction, and lay the foundation for significantly increased production capacity—and to do so in an environmentally safe manner.

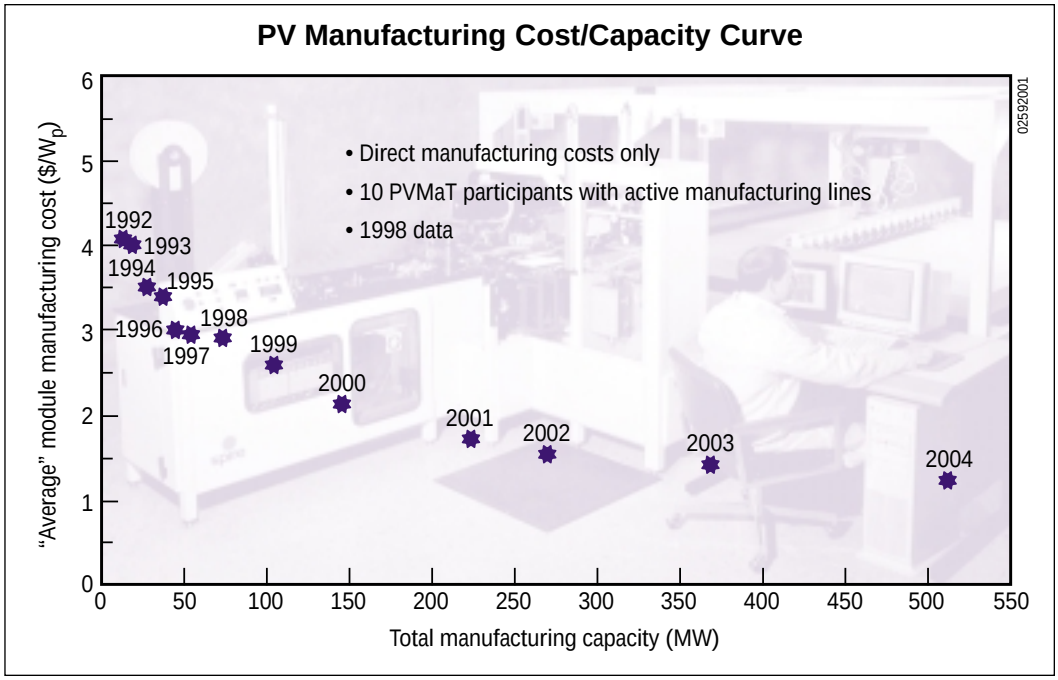
PVMaT is a subcontract program open to all U.S. industrial organizations and/or teams with activities related to the manufacture of PV products, systems, and components. The U.S. Department of Energy initiated the project in 1990; NREL and Sandia have managed the PVMaT subcontracts as a team effort since then. Through six solicitations and $166 million worth of cost-shared R&D, this government/industry partnership has delivered the goods.

The figure (below) shows average direct costs for module manufacturing versus total manufacturing capacity. The plot is based on data from the ten 1998 PVMaT participants with active production lines. The value of "average module manufacturing costs" is a weighted average based on the manufacturing capacity of each of these participants. As seen for the ten manufacturers, PV manufacturing capacity has increased by more than a factor of five since 1992—from 13 to 73 megawatts (MW). And the weighted-average cost for manufacturing PV modules has been reduced by 29%—from $4.08 to $2.91 per peak watt. Projections through 2004 indicate a steady decline to an average module manufacturing cost of $1.25 per peak watt with just over 500 MW of capacity by 2004.

More good news came last December when *Popular Science* published its "100 Best of What's New" technological advances. Two of the winners have strong PVMaT ties: Ascension Technology's SunSine™300 AC PV modules, with a built-in microinverter that eliminates the need for DC wiring; and Advanced Energy System's microinverter, which is small, easy to install, and compatible with PV modules made by several manufacturers.

PV industry members have generally identified PVMaT as one of the most—if not *the* most—important projects in the DOE Program.The reason why is apparent from the list of products now emerging in the marketplace. A recent issue of *Solar Today* displayed advertisements for several products that benefitted from PVMaT support for R&D on design and manufacture, including AstroPower's Silicon-Film™ and the aforementioned SunSine™300 AC PV modules. Spire Corporation's ad included automated assembly equipment such as the SPI-ASSEMBLER 5000, which was developed under a PVMaT subcontract. The magazine's "New Products" section highlighted the Underwriters Laboratories (UL) listing of Solar Electric Specialties' Modular Autonomous Photovoltaic Power Supply (MAPPS) system. MAPPS system development, manufacturing improvement, and UL listing were all supported as part of a PVMaT subcontract.

As the market base for PV technologies expands and more consumers are exposed to enhanced PV products, it is more important than ever to maintain performance and reliability—and to steadily upgrade PV manufacturing processes leading to increased yields, more efficient production, and, consequently, lower costs. This the PVMaT partnership continually strives to do.



Production is up, costs are down—the numbers are moving in the right direction for PVMaT's cost-share partners. The background photo shows the SPI-ASSEMBLER 5000, which was developed by Spire Corporation under a PVMaT subcontract.

The Path to PV Manufacturing Success

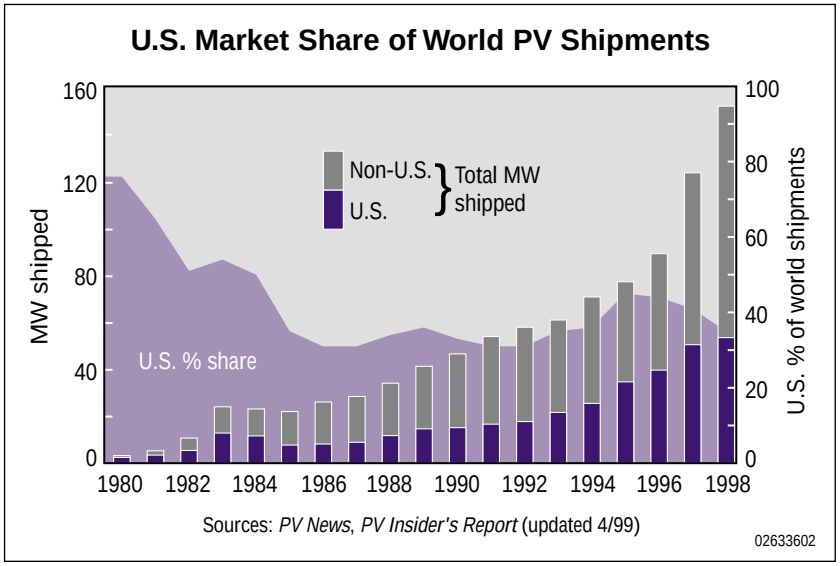
Since Henry Ford introduced the assembly line in 1913, mass production paired with U.S. industrial ingenuity has created an economy that's the envy of—and emulated by—the world. Streamlined manufacturing techniques guided by superior quality control leads to products that cost less and work better. And when those products fulfill a need in the marketplace, mass consumption is likely to follow.

The need for clean energy derived from renewable technologies such as photovoltaics is strong, both at home and abroad. Few would disagree that, in the case of PV technology, mass consumption would definitely follow mass production. Helping to realize this scenario—by improving manufacturing processes and producing reliable, cost-competitive PV products—lies at the heart of the PVMaT project.

The Start-Up

By the late 1980s, the need for a method of boosting domestic PV manufacturing had become clear. U.S. market share of world PV production was declining, which raised concerns in Congress and within DOE, NREL, and SEIA (Solar Energy Industries Association). Ed Witt, manager of PVMaT since its inception, credits Ed Sabisky (then of NREL) with planting the PVMaT seed. Sabisky used to comment that all the support then being given to amorphous silicon was good, and that thin films had come a long way and it was time for an open competition. PVMaT was born in 1990 when the Bush administration found $1.5 million for a fact-finding mission.

PVMaT was organized by two teams with one representative each from DOE, SEIA, NREL, and Sandia National Laboratories. The Implementation Team included Lloyd Herwig (DOE), Ed Witt (NREL), Dave Hasty (Sandia), and Rick Sellers (SEIA); on the Oversight Team was Bud Annan (DOE), Jack Stone (NREL), Don Schuler (Sandia), and Scott Sklar (SEIA).



Although the United States is still the world's single largest shipper of PV products, more and more countries are commanding a share of this soaring market.

Open to All Technologies

Early on, the principals decided PVMaT would be a cost-shared, subcontracted partnership between industry and government that was wide open to all technologies. The first step was the problem-identification phase, in which 22 contractors were awarded $50,000 each. The second solicitation was open only to companies that had participated in the first round. Since then, PVMaT solicitations have been open to all U.S. industrial organizations and/or teams with activities related to the manufacturing of PV products, systems, and components.

"We don't limit the solicitations," says Witt. "We tell companies the onus is on you to demonstrate how you will contribute to achieving PVMaT's main goal—a stronger U.S. PV industry through improved manufacturing processes and products."

The initial focus of PVMaT was on module manufacturing. In 1994, the scope was broadened to include manufacturing for balance-of-systems components as well as system and component integration to bring together all elements for a PV product.

In a nutshell, the goals of the PVMaT project are to:

- Help the U.S. PV industry improve module manufacturing processes and equipment
- Accelerate manufacturing cost reductions for PV modules, balance-of-systems components, and integrated systems
- Increase commercial product performance and reliability
- Enhance the investment opportunities for substantial scale-ups of U.S.-based PV manufacturing plant capacities.

Multiyear projects are carried out through cost-shared awards resulting from competitive solicitations. Each proposal is evaluated by a panel of experts selected from technology, manufacturing, business planning, and applications (including utility) areas. Thus far, there have been six rounds of PVMaT solicitations, with a seventh in the planning stages for this year.

The PVMaT Team

In addition to Project Manager Ed Witt, the PVMaT group includes Rick Mitchell, who brought his thin-film background to the project in 1991 and continues as a subcontract team leader. Holly Thomas came on board in 1993 and now leads the subcontract monitoring teams in the area of PV products, systems, and components. Martha Symko-Davies is the newest PVMaT group member, having joined in 1998. She, too, serves as a subcontract team leader. From the Sandia side, Doug Ruby is actively involved in PVMaT, providing input to the content of new solicitations and the makeup of the teams that monitor the subcontracts.

The combined NREL/Sandia Technical Monitoring Teams comprise engineers and scientists from both labs. This teamed monitoring has worked very well throughout the PVMaT project, creating a forum for both NREL and Sandia to stay abreast of ongoing manufacturing R&D efforts and needs of

the PV community. This teaming also provides a means for the subcontractors to identify unique areas where the laboratories can provide support (such as special measurements or testing).

New Solicitation, New Web Site

The upcoming 1999 PVMaT solicitation (contingent on government funding) has been prompted by an interest in in-line diagnostics (or intelligent manufacturing), and will be released in the near future. "Once again, industry members should convince us the work proposed will have an impact," says Witt. "Cover your bases succinctly. I'd put my money on a proposal with a set of bullets that covers the work well, and shows a mastery of the subject, versus 15 pages of explanation."

An excellent resource for staying abreast of this solicitation is the new PVMaT Web site (*http://www.nrel.gov/pvmat*). The site has much other useful information, too, including a history of each solicitation, PVMaT publications and fact sheets, and names and contact information for PVMaT partners.

Five Years from Now

As at the beginning of PVMaT, it remains a project goal to increase U.S. market share in PV manufacturing. Witt thinks this goal may be elusive, however, "because the rest of the world spends five times what we do on research."

He is willing to speculate about prospects for the photovoltaics industry in the near future—even within the next five years. "The time is right for someone to have a startling success. A manufacturing improvement could well be the impetus for that, especially in thin films, which are primed for some revolutionary advances."

For more information, contact: Ed Witt, 303-384-6402.

PVMaT by the Numbers

During the past several years, the numbers produced by the PVMaT project are quite impressive. In the following, we highlight some of them.

- AstroPower produced **1** mile of Silicon-Film™ sheet material during a 24-hour continuous production run under a PVMaT subcontract for research on the production of "Large-Area Silicon-Film™ Panels and Solar Cells."
- Since the second round of PVMaT solicitations, **24** companies have participated in PVMaT as first-tier subcontractors.
- Industry partners will contribute an average of **48%** via cost-sharing for the PVMaT subcontracts awarded in 1998.
- Testing by Sandia showed a **97%** peak-power efficiency for Utility Power Group's integrated power processing unit, which combines a tracker, inverter, and controller in one unit. The company's PVMaT improvements—factory-assembled PV array, integrated power processing unit, and simplified installation—have reduced its total system cost by **23%** and the balance-of-systems portion by more than **50%**.
- Under the subcontract "High-Throughput Manufacturing of Thin-Film CdTe PV Modules," First Solar is doing just that. Pilot runs demonstrating coating speeds of more than **1000** square feet per hour, and 16-hour continuous coating runs for both cadmium sulfide and cadmium telluride, have spurred a new production-coater design with a projected throughput rate of **1920** square feet per hour.
- Siemens Solar Industries racked up many successes under its recently completed "Photovoltaic CZ-Silicon Module Improvements" subcontract, but one in particular stands out. By implementing wire sawing on the production line, the company now gets **52** wafers per inch of material—which is a **65%** productivity increase in this one area alone.

Rusty Ristin/PIX05668

Is there a PV panel in your future? *What mass production did for Ford, and the entire auto industry, it could do for PV technologies. Here, a sheet of Silicon-Film™ emerges from the growth chamber of AstroPower's manufacturing plant. AstroPower has been a PVMaT partner since 1992.*

Work Under Way on the Latest PVMaT

With 14 subcontracts awarded, 1998 was a busy and productive year for the PVMaT group. The subcontracts are expected to total about $60 million during a 3-year period, with 48% subcontractor cost-sharing. Two of the subcontractors, Solarex and Crystal Systems, are addressing a topic of concern to the entire PV industry—increasing the supplies and quality of silicon feedstock available to PV manufacturers. Three companies—Crystal Systems, Global Solar Energy, and PowerLight—are first-time participants, bringing new ideas and direction to the PVMaT partnership.

The following nine projects fall under the PV Module Manufacturing Technology portion of the 1998 awards.

ASE Americas, Inc.—The EFG High-Volume PV Manufacturing Line
ASE Americas is reducing yield losses in electrical and mechanical performance and reducing chemical waste. ASE will also develop processes that can be scaled to high volumes in the growth of thin EFG (edge-defined, film-fed growth) cylinders with improved productivity, and to the production of solar cells from much thinner wafers. This includes work in laser-cutting technology to increase speed for cutting wafers, R&D to ensure a stronger EFG wafer, and improved cell processing to achieve 15% solar cell efficiencies.

AstroPower, Inc.—Silicon-Film™ Solar Cells by a Flexible Manufacturing System
AstroPower's improvements are expected to lead to the design and construction of a new machine for the continuous Silicon-Film™ sheet production at speeds in excess of 2.4 m/minute and capable of producing 14%-efficient solar cells. AstroPower has already completed the first phase of this three-year subcontract (three months ahead of schedule!), bringing on-line a new 60,000-ft^2 manufacturing plant for Silicon-Film™ solar cells and modules that is projected to be running at 9 MW per year by the end of 1999.

This 5-megawatt solar-cell production equipment at United Solar, built by Energy Conversion Devices (ECD), is dedicated exclusively to triple-junction cell production. ECD's goals under its 1998 PVMaT subcontract are to reduce module cost by 25%–30% and increase manufacturing capacity by 60%.


ECD/PIX06675

Energy Conversion Devices (ECD), Inc.—Efficiency and Throughput Advances in Continuous Roll-to-Roll a-Si Alloy PV Manufacturing Technology
ECD's manufacturing R&D is directed toward: achieving more accurate temperature control; developing a set of in-line, real-time, material-quality monitoring systems for production machines; demonstrating the feasibility of using a new process to prepare ZnO layers for high-performance back-reflectors; and redesigning internal hardware for a-Si intrinsic layer (i-layer) deposition chambers. ECD's goals are to reduce module cost by 25%–30% and to increase United Solar's (49% of which ECD owns) manufacturing capacity by 60%.

Evergreen Solar, Inc.—Continuous, Automated Manufacturing of String-Ribbon Si PV Modules
Evergreen Solar is reducing labor and material costs, and capital costs of additional furnaces, through increased automation and efficiency. The company is also developing high-throughput automated-cell and module-manufacturing line processes such as: a continuous glass etch; high-speed drying and application of decals; and automation in diffusion, glass etch, high-speed drying, printing and application of contact decals. Evergreen is expected to save $1.35–$1.50/watt by implementing a virtually continuous, 7-MW/year, high-throughput crystal growth facility for cell processing and module manufacturing.

First Solar (contract originally with Solar Cells, Inc.)—R&D on CdTe Product Manufacturing
First Solar is developing, designing, and implementing its EVA (ethylene vinyl acetate) lamination process, potting procedure, and laser-scribing technique for its CdTe module production line. The company will also complete qualification testing of its frameless, 60-cm x 120-cm module with pigtails and other advanced module designs. In addition, First Solar will work toward refining and improving ES&H programs throughout its facilities and initiating activities related to obtaining ISO14000 certification.

Global Solar Energy, L.L.C.—Throughput Improvements for Thin-Film-Based CIGS Modules
Global Solar Energy is refining an all-laser, multiple-beam, high-speed scribing method for the CIGS (copper indium gallium diselenide) layer, developing a process for ink-jet printing for insulating scribed areas, and integrating this process onto its production line. The company is also developing and integrating a high-rate CIGS deposition process for a moving flexible substrate onto its manufacturing line and developing an alternative back-contact material that is compatible with CIGS processing on a flexible substrate.

Siemens Solar Industries—R&D on Siemens Cz-Silicon Product Manufacturing
Developing and integrating optimized cell-fabrication processes for 17%-efficient, 125-µm-thick cells—with a 30% reduction in the cell manufacturing cost—is Siemens' focus. Also, the company will develop large-area cell production capability for 200-mm-diameter, 4.5-watt prototype solar cells and low-cost prototype modules. Siemens' ES&H activities are directed toward reducing its hazardous waste by more than 50% through recycling and reuse of slurry materials in its wire-saw process.

Awards

Solarex—Improvements in Polycrystalline-Silicon PV Module Manufacturing
Solarex is working with a lower-tier subcontractor to produce silicon feedstock from commercial-grade H_2SiF_6. Also, Solarex will refine production-line process areas for improved product and materials handling and improved casting and wafer-sawing processes, leading to implementing a cost-effective, robust, process that produces a minimum average cell efficiency of 15%. Rounding out the package is development of an encapsulation system that meets technical and reliability requirements and can be laminated and cured more quickly (in 6 minutes) in the present Solarex laminators.

Spire Corporation—Post-Lamination Manufacturing Process Automation for Photovoltaic Modules
With an eye toward automating the assembly of PV modules, Spire is developing an integrated module-edge processing system, combining automated edge trimming, edge sealing, and framing; an automated junction-box installation system; a final module test system combining high-voltage isolation testing and performance testing in a SPI-SUN SIMULATOR™; and an automated buffer storage system. Solar-cell laminates and other materials provided by industry will be used to evaluate the automated processes. The systems can be used with either crystalline-silicon solar cells or thin-film solar-cell laminates.

These projects represent the System and Component Technology portion of the PVMaT 1998 awards.

Ascension Technology, Inc. (ATI)—Manufacture of the Advanced SunSine™325 AC Module
ATI is refining its SunSine™300 inverter for improved manufacturabilty, lower cost, and enhanced performance. Midway through its first phase, ATI estimates at least a 50% cost reduction in the product, and physical size will also be reduced. Circuit-board design and layout is being optimized, and the parts count is now down by 25%. The SunSine™325 is designed so the user can add PV capacity in units of 300 W_{ac}, making PV power readily incorporated by the purchaser and easily added as the user can afford it.

Crystal Systems, Inc.—Production of Solar-Grade Silicon by Refining of Liquid Metallurgical-Grade Silicon
Crystal Systems has begun work on producing solar-grade silicon feedstock by further refining metallurgical-grade silicon in the liquid state with the Heat Exchanger Method™, using thermochemical reactions for low-cost purification. The reduction of boron, phosphorous, and other metallic impurities is of great concern to the final product and are included as an element of the thermochemical calculations. Significant labor cost savings and increased throughput are anticipated, with the production cost goal of solar-grade silicon at less than $20/kg.

Omnion Power Engineering Corporation—Manufacturing and System Improvements for 1- and 2-kW Inverters
With a goal of manufacturing 5000 units a year, Omnion is producing Series 2500 1- and 2-kW single-phase inverters for utility-interconnected applications. The targeted price is less than $0.50/watt for the 2-kW unit and $0.75/watt for the 1-kW unit. Omnion will work closely with system users, integrators, and module manufacturers as the product specifications are refined. On completion of the preproduction units, Omnion will deploy several units for beta testing at sites to include both NREL and Sandia.

PowerLight Corporation—Advanced Powerguard® Manufacturing
PowerLight is enhancing its PowerGuard® product, a lightweight, PV-insulating roof tile, with the goal of reducing cost, increasing capabilities, and providing PV systems that incorporate financing options. PowerLight expects to demonstrate system costs of $3.05/watt and to achieve a production capacity of 16 MW/yr. The products are being designed to meet UL and international requirements, and integrated warranties will be developed. In addition, PowerLight is working with Trace Technologies to upgrade the control board for its grid-tied inverter.

Utility Power Group, Inc. (UPGI)—Development of a Fully Integrated PV System for Residential Applications
UPGI is developing a residential-rooftop PV system consisting of a PV array, power control and conversion called a Power Module, and optional battery storage. The company originally proposed a 4–6-kW system, but has since revised its design to be closer to 10 kW, with a possible peak-power rating as high as 20 kW. UPGI reports that market aspects favor this size, because the homeowner can use several electric loads at once, even if the grid is not available. The system is planned for use as a back-up power system, operating primarily in the grid-connected mode. Through a range of integrating steps, UPGI plans to achieve a 30% reduction in total non-module-related system costs.

For more information about the above projects, contact Rick Mitchell at 303-384-6479, Holly Thomas at 303-384-6400, or Martha Symko-Davies at 303-384-6528.

Ascension Technology/PIX07363

Ascension Technology's award-winning SunSine™300 AC PV inverter is mated to the ASE Americas large-area module. The built-in micro-inverter eliminates the need for DC wiring. A smaller, more powerful, less expensive SunSine™ 325 is the thrust of the company's 1998 PVMaT subcontract.

NREL PV researchers and managers interact with industry on several levels. Although we freely share our research results and the nonproprietary results of our subcontractors, many of our interactions involve the exchange of confidential information, including the results of certain measurements. The following are some notable recent interactions.

United Solar Systems Corp., Troy, MI, has produced new, large-area roofing products designed to be easily installed on flat roofs. These roll-out modules are 18 feet long. **NREL** measured two of them at 155 W (initial), which is 7.0% total-area efficiency—an excellent result for this important new PV product. The module is rated at 125 W (stable), with an expected degradation of less than 20%. United Solar has developed a series of lightweight PV roofing products using its *R&D 100* award winner, the triple-junction a-Si stack cell design. The cells are embedded in roofing material and look almost indistinguishable from conventional roofing products. The products were partially supported by a **Thin Film PV Partnership** subcontract and were received as deliverables from that subcontract. The 18-foot-long, flexible modules—the largest ever measured at NREL—posed several measurement problems, requiring a custom mount be built to ensure that the module was flat. Contact: **Ken Zweibel, 303-384-6441**

Siemens Solar Industries, Camarillo, CA, has set yet another world record for monolithically integrated thin-film CIGSS power module. **NREL** has verified an aperture-area efficiency of 12.1%, with a power output of 44.3 W. This is the highest efficiency for any thin-film technology for this or any size and is comparable to commercial Si modules. The module size is 3651 cm^2. The previous record of 11.8%, also held by Siemens Solar, was verified and reported just a few months ago. In this previous batch of 28 CIGSS modules, the average efficiency was 11.4%. The module structure is ZnO/CdS/CIGSS/Mo/glass. There are three scribes used for the module interconnects—one laser and two mechanical. This is an important improvement for the company, as it readies the thin-film CIGSS power module technology for commercialization. Specialty products of 5 W and 10 W are already commercially available through Siemens Solar distributors. Contact: **Harin Ullal, 303-384-6486**

In March, **NREL's Harin Ullal** and **Kannan Ramanathan** traveled west to visit **Siemens Solar** and **International Solar Electric Technology** (ISET), Inglewood, CA. As part of the **Thin Film PV Partnership Program**, Siemens Solar reported on two new CIGSS products that have been introduced into the marketplace—20-W and 38-W CIGSS modules. This was announced at a trade show in Germany. Siemens Solar is also doing considerable cooperative research with the **National CIS R&D Team**, studying the transient effects in CIGSS modules, and collaborating with NREL (Kannan Ramanathan) on transient-effect studies. ISET staff reported on the new contacts they have developed for CIS-based devices that could potentially replace Mo contacts. ISET will be collaborating with NREL for analysis and characterization and for device fabrication on this newly developed contact. The company has also developed an innovative approach to use alternate interconnect schemes for CIS submodule fabrication, resulting in 8% submodule efficiency. In addition, ISET is setting up a demonstration line for fabricating 1-ft^2 CIS modules based on the nonvacuum absorber technique. Contact: **Harin Ullal, 303-384-6486**

Representatives from **DOE, NCPV,** the **Environmental Protection Agency,** and the **Federal Emergency Management Administration** met at the Forrestal Building in December 1998 to hear company president and CEO, **Steven Glidden**, and cofounder **Greg Alker** describe **Live Oak Solar's** line of mobile or portable PV-powered generator sets (gensets). Live Oak's products have already been used by the Department of Defense for emergency operations. Glidden and Alker asked for opinions on their units' viability and for ideas on marketing. Attendees stressed the importance of being on the General Services Administrations (GSA) solar procurement list. Live Oak is currently manufacturing prototypes of a 2.1-kW mobile genset, one of which is to go to **Sandia National Laboratories** for testing. Contact: **John Thornton, 303-384-6469**

Modules from two PV manufacturers, **Solarex** and **United Solar Systems Corp.**, have been certified by **PowerMark Corporation** (PMC). This breakthrough event is the first time that PV modules have been given such a stamp of approval based on third-party certification within the United States. Representative modules (Solarex model MCX120, c-Si; and United Solar model SSR-64, a-Si) were tested by a PMC-accredited independent test laboratory and by third-party auditors, who reviewed and approved the manufacturing quality system in accordance with PMC-adopted criteria (based on the **DOE/NREL**-funded study for PV certification and test laboratory accreditation). The certification testing is based on module qualification test standards (IEEE 1262, IEC 1215, and IEC 1646) developed over the years through DOE support of the IEEE SCC21, ASTM E44.09, and IEC TC82 standards development committees, and in coordination with the Underwriters Laboratories industrial advisory group and the NEC code-making panel for PV. PMC certification recognizes product quality by providing evidence that modules meet both national and international PV consensus performance and quality standards. Contact: **Dick DeBlasio, 303-384-6452**

Solar Cells, Inc., of Toledo, OH, a major participant in the **DOE/NCPV PV Program**, has formed a joint venture (**First Solar**) with **True North Partners**. This joint venture will provide First Solar with the capital-

Continued on page 11

Subcontracts

Subcontracted research with universities and industry, often cost-shared, constitutes an important and effective means of technology transfer in NREL's PV Program. From October 1998 through March 1999, we awarded 25 new subcontracts (examples listed below) and awarded nearly $16 million to new and existing subcontracts. For further information, contact Ann Hansen (303-384-6492).

Siemens Solar Industries (9/98–9/01)
Commercialization of CIS-Based Thin-Film PV
2,400,000 (NREL) $2,400,000 (cost share)

PowerMark Corporation (11/98–11/99)
PV Certification and Accreditation Management Support
$60,000

Texas Southern University (12/98–12/01)
Design, Analysis, and Testing of PV Stand-Alone and Grid-Connected Systems and the Development of an Education Study Guide
$180,000

North Carolina Central University (1/99–1/02)
Investigation of Photovoltaic and Thermophotovoltaic Semiconductors
$179,853

Southern University and A&M College (1/99–1/02)
Thin-Film Electrodes and Electrolytes for Photoelectrochemical Cells
$129,816

Central State University (3/99–3/02)
HBCU Photovoltaics Associates Program
$77,060

Publications

Dissemination of research results is an important aspect of technology transfer. NREL researchers and subcontractors publish some 300 papers annually in scientific journals and conference proceedings, as exemplified by the recent publications listed below. PV program and subcontractor reports are available from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, VA 22161. For further information, contact Ann Hansen (303-384-6492).

Benner, J.P. "Viewpoint: Photovoltaics in Transit to Significant Role." *IEEE Spectrum*. January 1999; 36(1); pp. 66–67.

Bhattacharya, R.N., et al. "14.1% $CuIn_{1-x}Ga_xSe_2$-Based Photovoltaic Cells from Electrodeposited Precursors." *Journal of the Electrochemical Society*. October 1998; 145(10); pp. 3435–3440.

Ciszek, T.F.; Wang, T.H. "Float-Zone Pedestal Growth of Thin Silicon Filaments." Claeys, C.L., et al., eds. *Proceedings of the Fifth International Symposium on High Purity Silicon V, 1–6 November 1998, Boston, MA*. Electrochemical Society Proceedings , Vol. 98-13. Pennington, NJ: The Electrochemical Society, Inc.; 1998; pp. 85–89.

Cohen, J. D. *Identifying Electronic Properties Relevant to Improving Stability in a-Si:H-Based Cells and Overall Performance in a-Si,Ge:H-Based Cells*. November 1998; 68 pp. NREL/SR-520-25802. Work performed by Department of Physics and Materials Science Institute; University of Oregon; Eugene, OR.

Colorado Consumer's Guide for Buying a Solar Electric System. October 1998; 20 pp. Also available electronically at www/nrel.gov/ncpv/pdfs/025734m.pdf.

Deering, A.; Thornton, J.P. *Applications of Solar Technology for Catastrophe Response, Claims Management, and Loss Prevention*. February 1999; 16 pp. NREL/CP-520-25866. Presented to the Virtual Insurance Company Panel of the National Association of Independent Insurers (NAII), Joint Claims Committee Meeting, 18 February 1999, Brazelton, GA.

del Cueto, J. A. "Method for Analyzing Series Resistance and Diode Quality Factors from Field Data of Photovoltaic Modules." *Solar Energy Materials and Solar Cells*. 1998; 55; pp. 291–297.

Kazmerski, L.L. "Photovoltaics Characterization: A Survey of Diagnostic Measurements." *Journal of Materials Research*. October 1998; 13(10); pp. 2684–2708.

McConnell, R.D.; Surek, T.; Witt, C.E. "Progress in PV Manufacturing Technologies." Sayigh, A.A.M., ed. *Renewable Energy: Energy Efficiency, Policy and the Environment*. Proceedings of World Renewable Energy Congress V (WREC-V), 20–25 September 1998, Florence, Italy; Part I. New York: Pergamon Press; 1998; pp. 502–505.

Niles, D.W.; Waters, D.; Rose, D. "Chemical Reactivity of $CdCl_2$ Wet-Deposited on CdTe Films Studied by X-Ray Photoelectron Spectroscopy." *Applied Surface Science*. 1998; 136; pp. 221–229.

Photovoltaic Energy Program Contract Summary, Fiscal Year 1998. January 1999; 222 pp. DOE/GO-10099-721.

Photovoltaic Energy Program Overview, Fiscal Year 1998. March 1999, 20 pp., DOE/GO-10099-737.

Pitts, J.R., et al. "Ultra Accelerated Testing of PV Module Components." October 1998; 9 pp. NREL/CP-520-25696. Presented at the *National Center for Photovoltaics Program Review Meeting*, 8–11 September 1998, Denver, CO.

Webb, J.D., et al. "Fourier Transform Luminescence Spectroscopy of Semiconductor Thin Films and Devices." *Vibrational Spectroscopy*. November 1998; 14 pp. NREL/CP-520-25037. Presented at the *3rd International Symposium on Advanced Infrared and Raman Spectroscopy (AIRS III)*, 5–9 July 1998, Vienna, Austria.

Zhang, Y.; Mascarenhas, A.; Deb, S. "Effects of Excitons on Solar Cells." *Journal of Applied Physics*. 1 October 1998; 84(7); pp. 3966–3971.

University Corner

New materials, approaches, and brainpower are coming to the PV Program! Nearly $5 million will be awarded to 18 universities across the country—14 of which are new to the Program—as part of the "University R&D for Future Generation PV Technologies" solicitation. "Photovoltaics is one of the technologies we will depend on to help power the 21st century," Secretary of Energy Bill Richardson said, in making the announcement. Subcontracts are currently being negotiated for the following awards, with the names of the principle investigators (all professors) included.

Very High Efficiency Solar Cells

North Carolina State University, $268,000
Novel Growth Methods for GaInNAs for High-Efficiency Solar Cells—developing new approaches to growing high-efficiency III-V materials. **S.M. Bedair**

University of California, San Diego, $297,000
GaInNAs Structures Grown by MBE for High-Efficiency Solar Cells—developing a new III-V material for 40%-efficient solar cells. **Charles Tu**

University of California, Santa Barbara, with Harvard University, $260,000
Growth and Characterization of GaInNAs for High-Efficiency Solar Cells—studying a new III-V material for 40%-efficient solar cells. **Steven DenBaars, Jim Speck, and Venkatesh Narayanamurti**

Innovative Nanocrystalline Solar Cells

University of California, Berkeley, $291,000
Photovoltaic Devices Based on New Nanocrystal Composites—exploring the creation of a completely new type of solar cell. **Paul Alivisatos**

Vanderbilt University, $280,000
Biomimetic Photovoltaics Employing Semiconducting Nanocrystal Multicomposites—creating a completely new type of solar cell, with an approach that simulates aspects of photosynthesis. **Sandra Rosenthal**

West Virginia University, $300,000
Nanostructure Arrays for Multijunction Solar Cells—performing exploratory research to create a completely new type of solar cell. **Biswajit Das**

Thin-Film Silicon

California Institute of Technology, $270,000
Low-Temperature, High-Throughput Process for Thin, Large-Grained Polysilicon—creating templates for very thin solar cells, using about 100 times less silicon than today's solar cells. **Harry Atwater, David Goodwin**

Cornell University, $280,000
Elastic Properties of Thin-Film Silicon—studying the interfaces between microcrystalline and amorphous regions in thin-film silicon. **Robert Pohl**

Pennsylvania State University, $300,000
Real Time Optics for the Growth of Textured Silicon Film Solar Cells—using optical analyses for the growth of thin-film microcrystalline silicon. **Robert Collins, Christopher Wronski**

University of Rochester, $300,000
Porous Polycrystalline Silicon Thin-Film Solar Cells—conducting exploratory research to create thinner silicon solar cells. **Philippe Fauchet, Leonid Tsybeskov**

Washington State University, $320,000
Novel Characterization Methods for Microcrystalline Silicon—studying the electrical carrier dynamics in these thin films via the use of positrons. **Susan Dexheimer, Kelvin Lynn**

Fundamental R&D and Characterization for Advanced PV Technologies

Arizona State University, $240,000
Test Standards for Future Generation PV Technologies—developing standards for new PV technologies, especially PV concentrators. **Robert Hammond**

Northwestern University, $320,000
Improved Transparent Conducting Oxides for Photovoltaics—investigating an under-researched class of materials that are important to the conversion of sunlight into electricity. **Thomas Mason**

Pennsylvania State University, $260,000
Chemical Reaction Modeling for Encapsulants in Photovoltaic Modules—researching chemical reactions between organic polymers and inorganic oxides in PV modules to enhance module longevity. **David Allara**

State University of New York at Buffalo, $280,000
Synchrotron Radiation Studies of Photovoltaic Materials and Devices—exploring the microstructure and interface morphology in PV devices. **Y.H. Kao**

University of Illinois, $320,000
Medium-Range Order and Stability in Amorphous Silicon—investigating medium-range order in a-Si to better understand metastable defect formation. **John Abelson, J. Murray Gibson**

University of Minnesota, $206,000
Experimental Studies of Light-Induced Changes in Long-Range Disorder in Amorphous Silicon—studying fluctuations in electrical current to characterize disorder in a-Si. **James Kakalios**

University of Oregon, with Reed College, $200,000
Novel Capacitance Measurements in Copper Indium Gallium Diselenide Alloys—developing innovative techniques for measuring the electrical properties of CIGS. **David Johnson, John Essick**

The research activities resulting from this solicitation will enhance the fundamental understanding of today's newly evolving technologies and provide a range of innovative, nonconventional PV options for potential future development. Contact: **Robert McConnell, 303-384-6419**

News at Press Time

Sunrayce in the Spotlight

It may just be that Sunrayce 99 is ready for prime time. First the biennial solar car race for college teams was an answer on the nationally syndicated game show "Jeopardy." Now it has the "Hot Wheels" seal of approval, with Mattel recently issuing a replica of Cal State L.A.'s Solar Eagle III—the winner of Sunrayce 97. This is the first solar car to be included in the popular Hot Wheels series of miniature cars. Forty teams are expected to compete in Sunrayce 99 this year, which kicks off in Washington, D.C., on June 20. The opening ceremonies and race start may take place on First Street in front of the Capitol. Temporarily closing First Street between Independence and Constitution requires an Act of Congress, but Rep. Matt Salmon, R-Ariz., and Sen. Wayne Allard, R-Colo., have drafted Concurrent Resolutions authorizing the use of the Capitol grounds. If this falls into place, the visibility for PV and DOE will be outstanding. The race will finish on June 29 at EPCOT® Center, near Orlando, FL. EPCOT officials agreed to waive parking costs that day for Sunrayce visitors, to encourage public attendance at the finish line. Contact: **Byron Stafford, 303-384-6426**

Industry Update, Continued from p. 8

ization needed to make a major step into large-volume manufacturing—as much as 80 MW per year—of thin-film PV plates and modules. If successful, this would be the largest PV module manufacturing plant in the world and, alone, would more than double U.S. PV module manufacturing capacity. Initial plans call for early levels of manufacturing closer to 20 MW by the end of 2000. Success would bring to the marketplace a new level of PV manufacturing at a lower cost, a goal long sought by the PV program. In February, the Managing Director of First Solar, **Dan Sandwisch**, and his VP for Business Development, **Steve Johnson**, visited NREL to discuss the joint venture. Contact: **Ken Zweibel, 303-384-6441**

An ongoing collaboration between the **NREL Cadmium Telluride Team** and **First Solar** involves the application of a novel NREL-developed ZnTe-based contact onto production-grade CdS/CdTe devices produced at First Solar. Previously, this study has demonstrated that devices exceeding 10% efficiency can be fabricated onto First Solar material using completely dry processing (i.e., ion-beam milling for CdTe precontact surface conditioning and sputtering for contact-layer deposition). Previous best results for First Solar devices produced at NREL with this contact demonstrated performance of V_{oc} = 813 mV, J_{sc} = 18.61 mA/cm^2, fill factor = 71.1%, and efficiency = 10.7%. Recently produced devices show improvements: V_{oc} = 826 mV, J_{sc} = 17.3 mA/cm^2, fill factor = 76.6%, and efficiency = 10.9%. Although the higher V_{oc} of the recent results is noteworthy, the improvement in fill factor is more significant because it is the highest reported for a CdS/CdTe device contacted using completely dry processes, and possibly, the highest reported for any CdS/CdTe device. The high fill factor also suggests that more detailed studies of the steps in the contacting procedure may provide insight into what limits the performance of this and/or other CdTe-contacting processes. Contact: **Tim Gessert, 303-384-6451**

Nearly one year after **BP Solar** installed a 0.5-kW thin-film CdTe PV array at its outdoor test facilities in Fairfield, CA, the array is reported to have demonstrated stable performance. These are some of the very early modules fabricated in the Fairfield facilities. The typical module aperture-area efficiency is in the range of 6%–7%, with a power output of 25–28 W. The module structure is glass/SnO_2/CdS/CdTe/contact, and the encapsulation is glass/EVA/glass. The company has installed a grid-connected 2-kW thin-film CdTe PV array for outdoor testing at Fairfield, and has also sent its state-of-the-art CdTe modules to **NREL's Outdoor Test Facility** for evaluation. Commercialization of BP Solar's thin-film CdTe modules is scheduled for late this year. Contact: **Harin Ullal, 303-384-6486**

A test recently concluded at **NREL's Outdoor Test Facility** has verified a world-record efficiency for a **United Solar's** a-Si module—10.4% (SRC) after more than 1000 hours exposure. The performance of three modules, which were delivered to NREL as part of a **Thin Film PV Partnership** subcontract, was tested by light soaking conducted indoors in climate-controlled chambers. The modules consist of triple-junction a-Si technology deposited onto a stainless steel substrate. Their aperture areas measure just over 900 cm^2 each. The modules are environmentally protected encapsulated units. Crossing the 10%-stabilized-efficiency threshold for a-Si modules is important, lending credence to the belief that current stabilized efficiency values (5%–8%) obtained from commercial-quality a-Si modules may yet be substantially improved. Contact: **Joe del Cueto, 303-384-6104**

NREL Helps Energize DOE's Forrestal Building

On April 9, NREL engineers John Thornton and Ben Kroposki of the National Center for Photovoltaics (NCPV) completed installation of a 3-kW PV system on the south balcony of DOE's Forrestal building in Washington D.C. Energy Secretary Bill Richardson later dedicated the system as part of the Million Solar Roofs Initiative. The new system will produce as much as 4500 kWh of electricity annually. Contact: **John Thornton, 303-384-6469**

Outstanding Contributions from NCPV Staff

Several members of the NCPV were recognized for their outstanding contributions and were honored by colleagues at the NREL Staff Awards Expo in March. Howard Branz was cited for his work in developing the hydrogen collision model, which suggests ways to stabilize the efficiency of amorphous-silicon solar cells. Pat Dippo's award was for her great technical contributions in the area of photoluminescence measurements. John Thornton earned kudos for his "seemingly endless energy in promoting renewable technologies, especially photovoltaics." Xuanzhi Wu was cited for his outstanding contributions to the cadmium-telluride solar cell team and the thermophotovoltaics team. And lastly, Don Gwinner was honored for his excellence in technical communications for the NCPV. Contact: **Larry Kazmerski, 303-384-6600**

PV Calendar

June 12–17, 1999, *Solar 99: Growing the Market*. Host: The American Solar Energy Society. Sponsors: U.S. Department of Energy, Northeast Utilities, New England Electric System. Location: Portland, ME. Contact: Becky Campbell-Howe. Phone: 303-443-3130. Web site: *www.ases.org/conference/index.html*

June 20–29, 1999, *Sunrayce 99*. Sponsors: DOE, General Motors, EDS. Location: Race starts in Washington, D.C., and finishes at EPCOT® Center near Orlando, FL. Contact: Byron Stafford, NREL. Phone: 303-384-6426.

June 21–24, 1999, *PV Standards and Codes Forum*. Sponsor: NREL. Location: Winter Park, CO. Contact: Carl Osterwald, Chair. Phone: 303-384-6764.

July 4–9, 1999, *ISES 1999 Solar World Congress*. Sponsor: International Solar Energy Society. Location: Jerusalem, Israel. Contact: ISES Secretariat. Phone: 972-3-5140000. Web site: *http://tx.technion.ac.il/~meryzse/ises99.html*

August 9–11, 1999, *9th Workshop on Crystalline Silicon Solar Cell Materials and Processes*. Sponsor: NREL. Location: Breckenridge, CO. Contact: Bhushan Sopori. Phone: 303-384-6683.

September 20–24, 1999, 11th International *Photovoltaic Science and Engineering Conference*, Sapporo, Hokkaido, Japan. Contact: T. Sameshima, Tokyo A&T University. Phone: +81.423.88.7109, Fax: +81.423.85.9055, e-mail: tsamesim@cc.tuat.ac.jp.

October 18–21, 1999, *PV Performance Reliability and Standards Workshop*. Sponsor: NREL. Location: Vail, CO. Contact: Dick DeBlasio, Chair. Phone: 303-384-6452.

October 25–29, 1999, *American Vacuum Society, 46th International Symposium: Vacuum, Thin Films, Surfaces/Interfaces and Processing*. Sponsor: AVS. Location: Washington State Convention Center, Seattle, WA. Phone: 212-248-0200. Web site: *www.vacuum.org/call/cfp.html*

November 29–December 3, 1999, *Materials Research Society 1999 Fall Meeting*. Sponsor: MRS. Location: Boston, MA. Contact: MRS Headquarters. Phone: 724-779-3003. Web site: *www.mrs.org/meetings/fall99*

This quarterly report encourages cooperative R&D by providing the U.S. PV industry with information on activities and capabilities of the laboratories and researchers at NREL.

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