

# Ready for the PV Challenge?

It has been a busy summer for the PV community, with Colorado the setting for many PV-related conferences and workshops. Each one focused on a specialized area of research and development. Yet as the summer comes to a close, PV scientists are challenging each other to step beyond the usual and explore other areas of PV.

Take the IEEE meeting in Alaska this September, for example. Specialists will be encouraged to mingle with experts outside their own research areas, as well as with architects, builders, and the general PV-buying public in hopes of inspiring new and creative future development.

In Colorado's beautiful Rocky Mountains, many conferences took place this summer that promoted cooperation among PV scientists from different technological areas. In Denver, the Materials Research Society held an international symposium devoted to silicon solar cells, modules, and fabrication techniques. In addition, the MRS Workshop on Transparent Conducting Oxides helped to identify prospects, needs, and challenges in materials and process development to keep pace with the burgeoning applications of TCOs. At NREL, the REAP/HBCU conference brought together all the universities involved in research through the HBCU program and showcased some of their recent developments in PV.

Farther west, Snowmass Mountain at Aspen drew hundreds of scientists and engineers involved in photochemistry research and development—but it was dye-sensitized solar cells that stole the limelight. Then the crystal growers converged on Vail for the 12th American Conference on Crystal Growth and Epitaxy, which included a silicon PV session. Copper Mountain was the setting for the 10th Workshop on Crystalline Silicon Solar Cell Materials and Processes, which looked at the progress of Si PV over the last 10 years, as well as opportunities for the future.

These are but a few of the conferences and workshops held this summer. Many of them were chaired by scientists who rose to the challenge and ventured outside their usual research areas to garner support for interdisciplinary research.



# NREL PV

## Working With Industry

Third Quarter, 2000

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# Going North to Cross the Hall

## An Editorial by John Benner



John Benner, NREL/P1X04801

*NREL's John Benner (in dogsled) and Spectrolab's Ron Diamond braved Alaska's harsh climate in April to scout out the perfect spot for the IEEE Conference—the Anchorage Hilton. When not mushing the Arctic wilds, Benner manages the Electronic Materials and Devices division of the National Center for Photovoltaics.*

Contact John Benner at 303-384-6496

We're going to Alaska to mine the rich veins of photovoltaic knowledge to be found at the 28th IEEE Photovoltaics Specialists Conference. Professionals in PV research, technology, and applications will pan through new findings and recent advances presented September 17–22 in Anchorage to assess the prospects of reported advances, reveal nuggets of new insight, and bring back a wealth of information. I am not exactly sure why I felt that someone needed to say that, but somehow I feel at ease and can now get on with this editorial.

I serve as this year's conference program chairman, leading an organizing committee of about 50 PV experts in the processes of structuring the technical program, reviewing contributed abstracts, and preparing an agenda that will satisfy the attendees. The final program needs to meet several objectives. The Specialists Conference is sponsored by the Electron Device Society of the Institute of Electrical and Electronics Engineers and must abide by their technical standards. These standards and the conference heritage make the event the premier forum for exchange among the scientists and engineers who specialize in PV. The conference also serves those with a more general interest in PV, such as power systems engineers, architects, environmentalists, and investors.

Our community presents the challenge of balancing the program structure among the needs of those who want to become aware of all aspects of PV, those who will focus on a single area of PV, and those PV specialists seeking more information in areas outside their primary interest. This last group appears to be only a small portion of the PV community, and I find this troublesome. PV specialists must learn to broaden their sometimes too parochial view of PV R&D and see how their work fits into the larger context of the success and growth of the PV industry.

Photovoltaics is poised for growth at rates that will double PV shipments every 2 to 3 years. Financing this growth will require a large capital commitment from public and private sources for both production capacity and systems sales. Instilling confidence in the PV technology and business among these investors is a challenge that the PV community must address collectively. At a time when we are developing a vision for growth and a roadmap to keep technology advancing at the needed pace, it is essential that all segments of the PV community examine what resources they can contribute to the shared effort of making PV more widely accepted. This might start by attending a conference session “across the hall” from that of your primary focus.

“Crossing the hall” is the first step toward creating a consistent message within the PV community to garner greater support; we can then extend these benefits of collaboration to using existing investments more effectively. We can avoid duplicate R&D and equipment development projects. Standardizing on a few materials specifications can help vendors bring costs down. Marketing can build on a competitor's investment to more effectively promote growth in the entire PV business. Perhaps most importantly, the same spirit of crossing the hall within a PV conference can be applied to seeking alliances with other industries that have experienced growth through the stages PV is entering now. We may learn of proven models for surmounting barriers (materials supply, cost, equipment) that we currently or will soon face. Opportunities abound for shared development and alliances.

A trip to Alaska has always carried an air of adventure—exciting, like pushing the limits in photovoltaics.

## PV Web Sites

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

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

**The Center for Basic Sciences** ..... [www.nrel.gov/basic\\_sciences](http://www.nrel.gov/basic_sciences)  
Capabilities • Optoelectronics • Crystal Growth and Devices

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

**Million Solar Roofs** ..... [www.eren.doe.gov/millionroofs](http://www.eren.doe.gov/millionroofs)  
Initiative Goals • Scope • Solar Technologies • Solar Registry

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

**PV Silicon Materials Research** ..... [www.nrel.gov/silicon](http://www.nrel.gov/silicon)  
Thin-Layer Si Growth • Research with Industry

**Surviving Disaster with Renewables** .. [www.nrel.gov/surviving\\_disaster](http://www.nrel.gov/surviving_disaster)  
Renewables to the Rescue • NREL's Work • Solar Recovery

# Inspiring Minds Meet at NREL

Inspiration was the theme of the second annual Historically Black Colleges and Universities (HBCU) Photovoltaics Research Program Review Meeting. Held in conjunction with the Renewable Energy Academic Partnership (REAP) Symposium, the conference took place August 9–11 at NREL's Visitors Center. About 50 students and faculty from eight HBCUs, as well as NREL and DOE participants and mentors, attended.

The HBCU PV conference gave students, faculty, and researchers the opportunity to discuss their research and inspired students to pursue educational and professional opportunities in the field of renewable energy. The program review meeting included technical presentations made by students and principal investigators focusing on the progress of projects funded by DOE/NREL.

The REAP symposium was designed to supplement the HBCU conference, which included workshops, tours, and networking opportunities for students. Fannie Posey Eddy, NREL's HBCU PV Program technical monitor and this year's conference chair, said, "We wanted to bring the whole HBCU group together to meet and form a network for future communication." NREL's Syl Morgan-Smith, who handles Colorado government relations, helped Eddy organize the conference, including bringing in inspirational speakers such as Mae Jemison and Howard Adams. Jemison, an astronaut who went up in the space shuttle in the early 90s, spoke about her goals in life and strategies for success. Adams, a professor at Clark Atlanta University and former Executive Director of the National Consortium for Graduate Degrees for Minorities in Engineering and Science, covered tapping one's full potential by using mentors. One of those mentors was NREL's Tom Stoffel, who held a Solar Radiation Workshop with the help of several HBCU summer interns. NREL's Bob McConnell, Senior Project Leader at the National Center for Photovoltaics, opened the conference. "We are here not only to share research, knowledge, and information. We are here to *inspire* each other."

## Shining Examples

Among the inspired students who presented their research at the conference was Adwoa Akuffo, a junior at Howard University in Washington, DC, who presented a paper on the fundamentals of photovoltaics. At NREL, she worked with Ben Kroposki compiling performance measurement data collected from 30 PV modules at NREL's Outdoor Test Facility. At Howard, Akuffo assists Professor James Momoh and a group of graduate students performing PV research funded by DOE/NREL grants. As a student

of electrical engineering, Akuffo had been unsure of what she wanted to do. With Momoh's encouragement, she plans to pursue PV research in graduate school.

Robert Easley, another NREL summer intern, presented his work on modeling the performance of InP solar cells. Easley, who will be a senior at Morehouse College in Atlanta this fall, is a physics major with a long interest in alternative energy. He discovered an opportunity to work on PV research with Professor Gerald Grams at Clark Atlanta University. Easley says that "interning at NREL reaffirms my working with renewable energy. I'm becoming more and more interested in PV. The challenge of making a better solar cell keeps me on the edge of my seat—there are no dull moments."

## A Successful Partnership

In 1995, DOE's National Photovoltaics Program funded the HBCU-PV Research Program through seven universities for a period of 3 years. Funding was renewed for four universities in 1999 for another 3-year period. Two new participants entered the program and two continued on extended subcontracts. The purpose of the HBCU program is to advance undergraduate knowledge of PV, primarily through research investigations, and to encourage students to pursue careers in PV.

The HBCUs involved in the program now are: Central State University, Clark Atlanta University, Hampton University, Howard University, Mississippi Valley State University, North Carolina Central University, Southern University, and Texas Southern University. Each school has a subcontract with DOE/NREL to perform specific PV research. Each project has a principal investigator and a number of research associates performing the work. Some of the associates began their work as undergraduates and have stayed with the project to the graduate level.

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Tom Stoffel, NREL/PIX04683



*HBCU PV research associate, Robert Easley (left), and his NREL mentor, Tom Stoffel, discuss the instrument platform at the Solar Radiation Research Lab. This platform is similar to the one used at the HBCU Solar Measurement Network—a five-station solar resource monitoring network in the southeastern United States that collects solar irradiance data for renewable energy applications.*

# Photochemistry Reaches New Heights

Each winter, Snowmass Mountain at Aspen draws celebrities and other winter sports fans to ski its high peaks and take in its majestic beauty. This August, however, Snowmass drew some 330 scientists and engineers from more than 31 countries around the world to the Thirteenth International Conference on Photochemical Conversion and Storage of Solar Energy.

The photochemistry conference, held July 30–August 4, was chaired by Arthur Nozik, who heads NREL's Chemical Sciences Team. It dealt with new developments in solar energy conversion, involving biological and artificial photosynthesis, photocatalysis, environmental chemistry, and photoelectrochemistry.

Conference participants found one area of photoelectrochemistry particularly intriguing—the dye-sensitized solar cell. Unlike traditional solar cells, which may be based on silicon, the dye cell is based on titanium dioxide ( $\text{TiO}_2$ ) sandwiched between two conducting glass sheets that can function as a window or other parts of a building. The cell can be made into a variety of colors and can be used for everything from photovoltaic windows in high-rise buildings to recharging surfaces on notebook computers.

“Research in dye-sensitized solar cells was one of the most exciting topics at the conference,” says Satyen Deb, director of NREL's Center for Basic Sciences. “More than 80 papers were presented in this one area alone. This shows the extent of interest in this technology in the world community.”

Deb has much to be excited about. He holds one of the first patents in the dye-sensitized solar cell technology. He's also considered the father of electrochromics. His early research in the field led to the first basic patents on electrochromic devices, and his involvement in the field has continued up to the most current dye-sensitized, titanium-dioxide devices. Deb has also found that dye-sensitized solar cells and electrochromic windows complement each other well. He is trying to generate funding to combine these two technologies. Some work has already been done at NREL to do just that, and we should expect to see some new patents coming out on this very soon, he says.

Among the plenary speakers at the conference was researcher Michael Grätzel, from the Swiss Federal Institute of Technology, who talked about the current state of dye-sensitized solar

cells. Grätzel is credited as the inventor of the current version of the dye-sensitized  $\text{TiO}_2$  solar cell, which bears his name in recognition of his contribution to the technology. The Grätzel cell works in a way similar to photosynthesis in plants. A layer of light-sensitive dye, together with titanium dioxide in ceramic form, is laminated between two sheets of conducting glass; the dye harvests light energy and transfers it in the form of electrons to the ceramic. The electrons are collected at the transparent back contact, where they enter the external circuit and deliver power to a load. They reenter the cell at the second sheet of conducting glass. Recent research in Switzerland has shown that making dye cells with nanosized titanium-dioxide particles, each with a single layer of dye molecule adsorbed onto their surface, can produce efficiencies as high as 11% at AM 1.5.



Jaou van de Lagemaat/PIX03468

*Michael Grätzel, from the Swiss Federal Institute of Technology, spoke with enthusiasm about dye cells. “This meeting was a critical one because we are seeing implementation of this technology by companies all over the world.”*

Research at NREL is under way to improve the efficiency of the dye cell by examining the fundamental science of the device. “If we can understand that first, then we can make better decisions about how to improve cell efficiency,” says Arthur Frank, of NREL's Chemical Sciences Team. Among the important technological advancements pointed out by Grätzel at the conference was a new sealant, supplied by Frank's lab, to hold the device together. Unlike the old sealant, the new sealant doesn't melt or get soft at relatively low temperatures. As a seal softens, the cell becomes more susceptible to solvents escaping and oxygen flowing into it. Frank says that the new sealant appears to retain its integrity at temperatures as high as 85°C. However, he adds, “more research is required to verify its thermal stability.”

Outside the Grätzel group, Frank's lab may have the second highest efficiency for a dye cell—9.2%. Frank along with Jaou van de Lagemaat and Kurt Benkstein, is researching the mechanism and dynamics of electron transport in dye-sensitized cells and how they limit the cell performance. The group is also investigating how electron transport and recombination limit the current-collection efficiency, and thus, the photon-to-current conversion efficiency.

Frank says that his group and Grätzel's are cooperating with each other to advance the technology. In fact, the two worked together before Grätzel joined the faculty at the Swiss Federal Institute of Technology and Frank joined NREL. Grätzel has since spent several sabbaticals at NREL and is today a consultant for the NREL Photochemical Solar Cell Project, an

# in Snowmass

integrated program of basic and applied research that is jointly funded by DOE's Office of Science and Office of Energy Efficiency and Renewable Energy. Leaders of the project are Arthur Nozik, Brian Gregg, and Arthur Frank.

Nozik is looking at another area of photoelectrochemistry relating to quantum dots. The focus of his group is on fundamental aspects of their behavior. "Photochemistry is related to PV in that PV uses electrons to make electricity and photochemistry uses electrons to produce electricity through chemical processes," says Nozik. Some of the ideas in photochemical solar conversion can be traced to photosynthesis. "In photosynthesis, chlorophyll molecules harvest photons, which eventually are transduced into electron-hole pairs. PV does this also. If we can learn how nature does it, perhaps we can make organic solar cells in the future based on molecular systems, not solid semiconductors."

If photosynthesis shows there are other ways to make electricity, so also does the recent developments in quantum solar energy conversion. Paul Alivisatos from the University of California at Berkeley, whose research was funded by NREL's "University R&D for Future Generation PV Technologies" solicitation, is researching how to make and control microscopic crystals dubbed "quantum rods" and understanding their fundamental properties to make solar cells. The rods range in size up to about 10  $\mu\text{m}$  long and 1  $\mu\text{m}$  thick. Given the right chemistry, quantum rods will line up neatly, side by side, into strips up to 25  $\mu\text{m}$  long. This suggests that quantum rods could be grown into large plates that emit light bright enough to serve as light-emitting diodes, which are found today in many consumer electronics and appliances. Similarly, large quantities of quantum rods could be grown to make solar cells. Alivisatos says quantum rods are 20 times better than quantum dots in converting light to electricity.

Aside from the exciting scientific advancements being made in photochemistry research, conference participants were also interested in the commercialization advances of companies throughout the world, particularly in Australia and Japan.

Sustainable Technologies Australia (STA) is commercializing the dye-sensitized  $\text{TiO}_2$  solar cell, marketed as the Titania Solar Cell, which resembles a tinted glass tile that can be integrated into building roofs, windows, or walls. STA asserts that its cells perform well in low light and shade and consistently over a wide range of temperatures. Because the cells operate efficiently in both direct or low light, building architects can be more flexible in terms of location on the building, something important in dense urban areas.

Meanwhile, Toshiba Corporation in Japan presented a paper describing an organic dye-sensitized solar cell that uses a gel, rather than liquid, electrolyte and has an efficiency of 7.3%. The gel electrolyte resists melting up to about 250°C. The gel



STAPIX03467

*Graeme Evans, Sustainable Technologies Australia, displays a wall panel made with Titania Solar Cells, which can be integrated into roofs, windows, and walls.*

electrolytes may make it possible to use a plastic substrate for the  $\text{TiO}_2$  film; the resulting cell is estimated to be between 20% and 50% lighter than cells using glass. However, Toshiba is still doing research to further increase the cell's conversion efficiency.

Grätzel believes that although Toshiba's gel electrolyte is not a solid, it is a step in the right direction because manufacturers prefer to work with a non-liquid electrolyte.

What makes dye-sensitized solar cells so interesting to industry is that they are simple to make and have the potential for low cost—and as the market expands, the cost will decrease further, says Frank. "We haven't seen the last word in dyes, either. Any number of things can be used to make dye, including fruit juice." His lab, as well as others, are working on a screen-printing process for making dye cells to reduce the manufacturing cost. The screen-printing process is similar to ones used for T-shirts. After screen-printing the  $\text{TiO}_2$  nanoparticles on a substrate, it can be placed on a conveyor belt, which passes through an oven, to "sinter" the particles together for electrical contact. The simplicity and potential low cost of producing the cells make them attractive from a manufacturing perspective.

*For more information, contact Arthur Nozik at 303-384-6603 or Arthur Frank at 303-384-6262.*

# North to Alaska and IEEE

**Y**ou're sailing through the icy waters of the northern Pacific when suddenly an eagle cries above. Below you, humpback whales splash playfully nearby, and all around you, glacier ice crackles while you talk to friends, both old and new. You're on your way to the 28th IEEE PV Specialists Conference (PVSC) held in Anchorage, Alaska this September by way of a preconference cruise arranged by the conference organizing committee.

With an organizing committee like that, you can imagine attendance is always good at PVSC, which is sponsored by the Institute of Electrical and Electronics Engineers' (IEEE) Electron Devices Society. Among this year's organizing committee are Ajeet Rohatgi, conference chair, from the Georgia Institute of Technology (a PV Center of Excellence) and NREL's John Benner, program chair.

“What makes this conference different than previous years is that it is designed to encourage PV specialists to look at PV technology outside their own area, in hopes that this will increase their overall understanding of the technology and inspire their imaginations,” says Benner. For example, a Tutorial Program is planned for professionals new to a specific PV technology. Tutorial topics are polycrystalline compound thin-film devices (from cells to modules); solar electric buildings; recent developments in crystalline silicon solar cells; and characterization of PV materials.

Also used to encourage a broader understanding of PV technology by specialists and nonspecialists alike is a special Auxiliary Program, chaired by Dennis Flood from NASA's Glenn Research Center. A public exhibition program is planned with Steven Strong, president of Solar Design

Associates, who will demonstrate various applications for solar electricity in buildings, both in use now and potentially in use in the future. Strong is also offering a virtual tour of many solar-enhanced homes that his architectural firm has designed over the years.

Auxiliary Program workshops include one on environmental interactions of photovoltaic arrays in space, how to integrate PV into buildings, and how to use PV in Alaska, which is aimed at helping Native Alaskan villagers improve their quality of life while stimulating or increasing the market for the U.S. PV industry. The keynote speaker at the conference luncheon is Clint (Jito) Coleman, president of Northern Power Systems, who will talk about the importance of renewable energy in the world's polar regions.

Exhibitors from companies around the world will display many aspects of space and terrestrial PV power systems technology, including cells and modules, controllers, storage batteries, system design tools, manufacturing equipment, instrumentation, and complete PV power systems. Also on display will be the latest and greatest PV space technology and concentrator systems.

The conference's main feature is the technical program, which includes both fundamental and applied research on the science, technology, and applications of photovoltaic materials. The technical program is divided into six sections: silicon devices and materials, II-VI materials and devices; amorphous and nanostructured devices; space cells, space systems, and III-V devices; terrestrial modules and balance-of-system components; and terrestrial systems and applications. The opening lectures for the oral sessions highlight some of the most exciting recent results for state-of-the-art PV technology. Among the more than 600 registrants from around the world are about 40 researchers from NREL; many of them collaborated on presentations that were chosen by the program committee to open the oral sessions.

Harin Ullal, who leads NREL's Thin Film PV Partnership Program with Ken Zweibel and Bolko von Roedern, will update participants on the significant technical progress being made in materials research, device development, manufacturing technology, and early commercialization of thin-film products based on copper indium diselenide and cadmium telluride. He will also talk about the status of various PV manufacturing technologies being developed by companies worldwide.



Solar Design Associates, Inc./PIX08663

*Solar Design Associates, which will hold a public exhibition of many of its solar-enhanced homes, designed this house in coastal Maine that generates its own electricity from a 4.25-kW PV system beautifully integrated into the rooftop.*





*ENTECH's 100-kW high-efficiency concentrator PV system, modified under NREL's PV Manufacturing R&D project, operates reliably for the Central and South West Services Solar Park in Fort Davis, Texas.*

ENTECH/PIX03657

From NREL's high-efficiency concentrator research area, Dan Friedman, Jerry Olson, Sarah Kurtz, Scott Ward, Tom Moriarty, and Keith Emery, in conjunction with Spectrolab, will present their findings on germanium concentrator cells for III-V multi-junction devices. More specifically, they address how they identified and solved a failure-mode problem for the germanium junction caused by a photoactive back-contact. Correction of the problem increases the cell's voltage and paves the way for even better high-concentration efficiencies.

Team (headed by NREL's Cecile Warner and DOE's Richard King) with PV cells donated by NREL. NCPV Director Larry Kazmerski will lead the PVSC Fun Run, a 5-K "jog" along a scenic harbor route near the Anchorage hotel.

The 28th IEEE PV Specialists Conference is the first major PV conference held in America in the new millennium. It's an international meeting designed to showcase cutting-edge research worldwide, while enriching the educational experience for PV professionals and the general public. It's a place where new contacts can be established, both in research and business. Conference organizers hope this event will provide a major stimulus to the scientific community and business sector of PV.

*For more information, contact John Benner at 303-384-6496.*



Members of NREL's spectroscopy teams have been hard at work, too. Dick Ahrenkiel's group, in conjunction with the University of Florida and Germany's Institute for Surface Modification, will discuss the role and effect sodium has on defect structures in copper indium diselenide. Dean Levi, from the same spectroscopy characterization group, will talk about the effects of CdCl<sub>2</sub> on CdTe electrical properties using a new theory for grain-boundary conduction, a theory advanced in conjunction with Colorado State University.

NREL's Xuanzhi Wu, Ramesh Dhere, David Albin, Tim Gessert, Sally Asher, Dean Levi, Helio Moutinho, and Pete Sheldon will present their findings on how modifying the device structure of cadmium-telluride-based thin films yields improved performance and reproducibility. Members of that same group will also show how introduction of a copper source into the back-contact will significantly improve device performance.

Extracurricular conference activities include a local high school PV design contest, sponsored by the School Program



***Wronski to Receive Research Award***

The William R. Cherry Award, named in honor of an early pioneer in PV, will be presented to Christopher Wronski, a professor at Pennsylvania State University. Wronski worked

with David Carlson, the inventor of the hydrogenated amorphous silicon solar cell, on the cell's early development. His work resulted in several key discoveries of novel optoelectronic phenomena such as the Staebler-Wronski Effect. Wronski is also involved with NREL in future-generation research and development. In 1999, his research group at Penn State was awarded \$300,000 for its research in real-time optics for the growth of textured silicon film solar cells using optical analysis for the growth of thin-film microcrystalline silicon.

*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.*

**NREL's Tom Surek, Harin Ullal, DOE's Jeff Mazer, and Sandia's James Gee** visited **SunPower**, Sunnyvale, CA; **Photovoltaics International**, Sunnyvale, CA; **BP Solar**, Fairfield, CA, and **PowerLight**, Berkeley, CA; June 21–23.

**SunPower** (SP) President, **Dick Swanson**, gave a presentation about organization, business plans, and future growth areas for the business. Revenues are expected to grow by 50% for the next few years. The business is divided into three main areas: specialty PV arrays, energy systems, and infrared detectors. In the PV arrays area, the main markets include race cars, stratospheric platform, aerostats, and special applications using high-efficiency Si cells (21%–22%). The selling price of cells is about \$300/watt and directed toward niche markets where efficiency is the main criterion. SP is also developing the Fresnel lens for current markets and high-concentration modules (250–500 X) using a low-profile micro-concentrator approach for future-generation low-cost applications. The latter product is being developed with the assistance of a National Institute of Standards and Technology contract. Infrared detectors are currently a major portion of SP's business. SP is the only concentrator PV company in the world that makes its own high-efficiency Si solar cells.

**Bill Bottenberg**, Vice President of **Photovoltaics International** (PVI), gave a detailed presentation of the linear concentrator PV technology that included modeling and actual field data from the Sacramento Municipal Utility District. The following conclusions were reached after this study in order for the linear concentrator technology to be competitive with flat-plate PV: you need a 2-axis tracking system, the module efficiency should be 22%–25%, and you need at least a concentration of 250 X. PVI has a new sister company, **EcoEnergies**, that will focus on a range of renewable energy technologies, including hybrid, diesel, solar, and wind. **Peter Carrie** is the president.

**Doug Skinner**, General Manager, **BP Solar**, gave a presentation of the company's new organizational structure. From an operational standpoint, BP Solar in Fairfield reports to **Scott Albertson**, VP Thin Film Operations, and from a Technology standpoint, reports to **Peter Bihuniak**, VP Technology.

Also, BP Solar has recently been given the green light by its management to go into full-scale commercial production of 8 MW of thin-film CdTe Apollo power modules. Initial sales of products are expected in spring 2001. The power module is essentially 0.94 m<sup>2</sup> (24" x 61"). **NREL** has confirmed an aperture-area efficiency of 10.6% and power output of 91.5 W for

this size module. For a nominally 0.5 m<sup>2</sup>, an aperture-area efficiency of 10.8% was confirmed by NREL. Initial market plans are to install the Apollo power modules at BP gas stations. Only modules with efficiencies of over 9.5% will be sold as commercial products.

**Tom Dinwoodie**, President, **Powerlight Corporation** (PL), gave an overview of the companies activities. PL has been supported by PVMaT and PV:BONUS in its manufacturing R&D efforts. PL is essentially a systems integrator and has a unique approach for installing PV, mainly on existing roofs. The benefits of its PowerGuard products are that they increase the life of the existing roofs, improve the insulation, and provide solar electric power. PL is one of the few companies that is able to show an attractive internal rate of return to potential customers for a grid-tied PV system by taking advantage of other benefits from the packaging. PL has installed or will install several PV systems at substantially lower cost, with systems sizes varying from 10 to 400 kW. The 400-kW system is ready for shipment to Pleasanton, CA, for installation on a new building. Contact: **Harin Ullal**, 303-384-6486

Six new photovoltaic modules were deployed on the Performance and Energy Ratings Testbed (PERT) at **NREL's Outdoor Test Facility** this June, inaugurating a long-term (2–4-year) experiment. The experiment is designed to assess the actual power and energy production capacities of polycrystalline silicon (poly-c-Si) technology under field conditions encountered in Golden, CO, from six modules—two each from three different manufacturers. The PERT-system modules situated on the roof of the Outdoor Test Facility are connected to data acquisition systems (DAS) that monitor their current-voltage characteristics once every 30 minutes during all daylight hours; at all other times, the DAS continuously maintain the modules at their peak-power-point loads. The peak-power data can be used to derive the total energy produced by each module every day. The three manufacturers that supplied the six modules for this experiment are **BP Solar**, **Kyocera Solar**, and **Photowatt**. The modules are all commercially available and are nominally rated and marketed as 40-watt units. This experiment will allow side-by-side comparison of actual energy and power production in a variety of climates represented in Golden, CO—nice, hot-sunny, and cold-sunny—and analysis of the meteorological factors entering into energy and power production capacities of poly-c-Si PV modules. In addition to the module electrical characteristics, extensive

*Continued on page 11*

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 1999 through July 2000, we awarded more than \$20 million to new and existing subcontracts (examples listed below). For further information, contact Irene Medina (303-384-6492).

**Energy Photovoltaics (6/00–9/00)**

Thin-Film CIGS Photovoltaic Technology  
\$332,000

**Evergreen Solar (6/00–9/00)**

Continuous, Automated Manufacturing of String Ribbon Si PV Modules  
\$310,846

**Global Solar Energy (6/00–9/00)**

Process Development of Large-Area, Thin-Film CIGS-Based PV Modules  
\$381,260

**International Solar Electric Technology (7/00–9/00)**

CIS-Type PV Device Fabrication by Novel Techniques  
\$182,128

**North Carolina State University (6/00–9/00)**

Characterization and Ti Gettering of PV Substrates  
\$78,267

**Pennsylvania State University (7/00–9/00)**

Stable a-Si:H-Based Multijunction Solar Cells with Guidance from Real-Time Optics  
\$95,2000

**Washington State University (7/00–9/00)**

Novel Characterization Method for Microcrystalline Silicon  
\$74,310

**Weizmann Institute (6/00–9/00)**

Identifying and Overcoming Degradation Mechanisms in CdTe Solar Cells  
\$67,000

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 Irene Medina (303-384-6492).

**Balcioglu, A.; Ahrenkiel, R. K.; Friedman, D. J.** (2000). "Evidence of an Oxygen Recombination Center in p+n GaInNAs Solar Cells." *Applied Physics Letters*. Vol. 76(17), 24 April 2000; pp. 2397–2399; NICH Report No. JA-520-27727.

**Branz, H. M.** (2000). "Hydrogen Collision Model: Theory and Experiment." *Journal of Non-Crystalline Solids*. Special Issue: Proceedings of the Eighteenth International Conference on Amorphous and Microcrystalline Semiconductors—Science and Technology, 23–27 August 1999, Snowbird, UT. Vol. 266–269, 1 May 2000; pp. 391–396; NICH Report No. 28664.

**Ciszek, T. F.; Wang, T. H.** (2000). *Silicon Float-Zone Crystal Growth as a Tool for the Study of Defects and Impurities* (Preprint). 16 pp.; NICH Report No. CP-520-28569.

**Erickson, K.; Dalal, V. L.** (2000). "Growth of Microcrystalline Si and (Si,Ge) on Plastic Substrates." *Journal of Non-Crystalline Solids*. Special Issue: Proceedings of the Eighteenth International Conference on Amorphous and Microcrystalline Semiconductors—Science and Technology, 23–27 August 1999, Snowbird, UT. Vol. 266–269, 1 May 2000; pp. 685–688; NICH Report No. 28652.

**Geisz, J. F.; Friedman, D. J.; Olson, J. M.; Kurtz, S. J.; Reedy, R. C.; Swartzlander, A. B.; Keyes, B. M.; Norman, A. G.; Reedy, R.; Swartzlander, A. B.; Keyes, B. M.; Norman, A. G.** (2000). "BGaInAs Alloys Lattice Matched to GaAs." *Applied Physics Letters*. Vol. 76(11), 13 March 2000; pp. 1443–1445; NICH Report No. JA-520-27585.

**Moutinho, H. R.; Ballif, C.; Al-Jassim, M. M.; Dhere, R. G.; Kazmerski, L. L.** (2000). "Cross-Section AFM and EFM Examination of Thin-Film Solar Cells." *Program and Proceedings: NCPV Program Review Meeting 2000*, 16–19 April 2000, Denver, CO. BK-520-28064. Golden, CO: National Renewable Energy Laboratory; pp. 273–274; NICH Report No. CP-520-28200.

**Myers, D. R.; Kurtz, S. R.; Whitaker, C.; Townsend, T.** (2000). "Preliminary Investigations of Outdoor Meteorological Broadband and Spectral Conditions for Evaluating Photovoltaic Modules and Systems." *Program and Proceedings: NCPV Program Review Meeting 2000*, 16–19 April 2000, Denver, CO. BK-520-28064. Golden, CO: National Renewable Energy Laboratory; pp. 69–70; NICH Report No. CP-560-28187.

**Nelson, B. P.; Xu, Y.; Webb, J. D.; Mason, A.; Reedy, R. C.; Gedvilas, L. M.; Lanford, W. A.** (2000). "Techniques for Measuring the Composition of Hydrogenated Amorphous Silicon-Germanium Alloys." *Journal of Non-Crystalline Solids*. Special Issue: Proceedings of the Eighteenth International Conference on Amorphous and Microcrystalline Semiconductors—Science and Technology, 23–27 August 1999, Snowbird, UT. Vol. 266–269, 1 May 2000; pp. 680–684; NICH Report No. 28649.

**Norman, A.; Al-Jassim, M.; Friedman, D.; Geisz, J.; Olson, J.; Kurtz, S.** (2000). "Structural Studies of Potential 1 eV Solar Cell Materials." *Program and*

Continued on page 11

**NREL's Dick DeBlasio** chaired the International Electrotechnical Commission (IEC) PV Standards Meeting hosted by the United States at **Arizona State University** (ASU) on May 15–19, 2000. More than 40 representatives from Australia, Canada, China, France, Germany, Switzerland, Japan, Netherlands, Spain, United Kingdom, and the United States participated in 5 days of coordination and working meetings to develop PV international standards. Progress on standards projects were reviewed by delegates on modules, systems, BOS, certification, and storage. Working groups (WG 1-7) met before and after the general IEC TC82 meeting (May 15–17). Members of the committee were greeted by **Charles Backus**, ASU, Provost, at the start of the meeting, with a closing banquet provided by Salt River Project. Tours of the APS STAR facility and ASU PV Test Laboratory were also provided during the 5-day meeting. Progress has been excellent during the past 18 months, with a sustaining portfolio of over 23 IEC PV standards developed and maintained to date since the inception of IEC TC82 in 1981. Contact: **Dick DeBlasio**, 303-384-6452

In August, the Colorado mountains were “teeming” with meetings on crystalline silicon research. The most prominent was the 10th Workshop on Crystalline Silicon Solar Cell Materials and Processes at Copper Mountain from August 14–16, 2000. A satellite meeting, on August 13, was co-sponsored by **DOE's Office of Basic Energy Sciences** on thin-film silicon. Finally, a Silicon Photovoltaics session took place at the 12th American Conference on Crystal Growth and Epitaxy on August 17 in Vail, CO.

But the attendees at the 10th Workshop in Copper Mountain took “teaming” literally by recommending the creation of four industry/university teams focusing on critical research topics in crystalline silicon. With more than 15 companies, almost 20 universities (8 funded by the DOE/NREL crystalline-silicon university research program), and a half dozen research institutes from 8 countries in attendance, the generic nature of the topics took precedence over global boundaries. The purpose of the teams is to bring together scarce resources to address complex technical challenges. These challenges were: (1) a replacement for screen printing (a related topic is research on selective emitters), (2) the development of a low-cost, nonvacuum hydrogenation process (a related topic being silicon-nitride processes), (3) the handling of thin wafers (including fundamentals of mechanical properties and their impact on yield), and (4) understanding and mitigation of “bad” regions in crystalline silicon. **NREL's Tom Surek** noted that the discussion leading to the creation of these teams was similar to those leading to the CIS and a-Si teams within DOE's **Thin Film PV Partnership**. A difference was the global interest in these topics on the part of the attendees. Contact: **Bob McConnell**, 303-384-6419 ☼

According to Rambabu Bobba, principal investigator at Southern University, there are excellent reasons for DOE/NREL to partner with HBCUs. The HBCU institutions are well established—most are over 100 years old—and their infrastructure is enormous, but their funding is low. HBCUs, therefore, are an excellent place to make an investment.

Bobba also emphasizes the special importance of higher education and training opportunities for undergraduate minority students. Undergraduate students in the program are published in journals, participate in conferences, and acquire real work experience in PV. The program also exposes students to the rewards of going on to graduate school where minorities are seriously underrepresented, says Bobba.

Branislov Vlahovic, a professor at North Carolina Central University, agrees. He points out that the program helps to recruit minority students. Many minority students are from low-income families and must work while they go to school, which takes time and attention away from their studies. With DOE/NREL funds, students get paid to do work in the sciences with faculty and graduate students. This opportunity not only prepares them for work after graduation, but improves their overall academic performance, as well.

Industry can also benefit from partnerships such as the HBCU-PV program. University partnerships are very cost effective—a student stipend is significantly less than a full-time employee's salary. In addition, the flexible and creative atmosphere of an academic institution encourages risk-taking and innovation. Minority students also bring an awareness of PV back to their own communities, helping to spread the use of the technology.

### **A Positive Influence**

When McConnell opened the HBCU-REAP conference, his words foreshadowed the effect the students would have not just on each other, but on all those attending the conference: “You have really served as an inspiration for me.” The students' intense desire for success was palpable. They seized the opportunity to learn more, expand their skills, and discover new opportunities. With a mentor-to-student ratio within the program of one to one, the mentors offer enormous support to ensure student success. Grams, the Clark Atlanta University physics professor who encouraged Robert Easley to pursue the NREL internship, offered remarks about the positive effect the HBCU-PV program has had on Easley: “Robert could have learned a lot just by doing what Tom Stoffel had for him to do, but he went out of his way to do even more. Now, whether he goes on to graduate school or works in the PV industry, he already has a foot in the door.”

experiments should yield results beginning in a 1- to 2-year time frame. This demonstration and comparison of energy and power production capacities from nominally similar poly-c-Si modules from three separate manufacturers should aid consumers in choosing appropriate modules of this technology for their applications. Contact: **Joe del Cueto, 303-384-6104**

NREL's work with **Sovlux** appears to be paying off as Sovlux is ready to market lightweight, portable, and versatile PV products. Sovlux is a joint venture between the Russian State organization **KVANT** and **Energy Conversion Devices (ECD)**. NREL supported KVANT with two subcontracts under the Newly Independent States/Initiative for the Prevention of Proliferation Program; both subcontracts were completed in April 2000. Sovlux garnered significant interest in its products at the **Federal Emergency Management Agency (FEMA)** Workshop and Exhibition (Colorado Springs, CO, June 12–14). Sovlux was the only exhibitor that showcased products that were not manufactured in North America. There was interest by some FEMA personnel and by some retailers of green energy products (e.g., **EcoEnergies, CA**) in the lightweight portable photovoltaic systems. The Russian First Vice Minister (**Y. Vorobiov**) and the Second Vice Minister (**M. Falejev**) for Emergency Situations visited the Sovlux Exhibit and asked Sovlux to exhibit at a similar workshop/exhibition later this year in Moscow. Beyond the FEMA workshop, visits to NREL, ECD, and **United Solar** (June 10–24) were also helpful to further product development and commercialization. For example, during the visit to NREL by **Andrey Polisan** (deputy director and chief technologist for Sovlux), significant time was spent discussing the results of outdoor and accelerated testing of our framed modules and how to improve processing steps. The portable array was exhibited in the lobby of NREL's **Solar Energy Research Facility**. **Tim Ellison** of ECD was visiting NREL and participated in some of these discussions. The accelerated testing on the EVA encapsulation materials was discussed in detail. Contact: **Bolko von Roedern, 303-384-6480** ❀

*Proceedings: NCPV Program Review Meeting 2000*, 16–19 April 2000, Denver, CO. BK-520-28064. Golden, CO: National Renewable Energy Laboratory; pp. 129–130; NICH Report No. CP-520-28192.

**Park, N.-G.; van de Lagemaat, J.; Frank, A. J.** (2000). “Comparison of Dye-Sensitized Rutile- and Anatase-Based TiO<sub>2</sub> Solar Cells.” *Program and Proceedings: NCPV Program Review Meeting 2000*, 16–19 April 2000, Denver, CO. BK-520-28064. Golden, CO: National Renewable Energy Laboratory; pp. 173–174; NICH Report No. CP-590-28188.

**Schulz, D.; Ribelin, R.; Wu, X.; Jones, K. M.; Matson, R. J.; Curtis, C. J.; Gessert, T.; Ginley, D. S.** (2000). “Solar Cell Contacts Using Nano-Sized Dispersions.” Komarneni, S.; Parker, J. C.; Hahn, H., eds. *Nanophase and Nanocomposite Materials III: Proceedings of the Materials Research Society Symposium*, 29 November–2 December 1999, Boston, MA. Materials Research Society Symposium Proceedings Vol. 581. Warrendale, PA: Materials Research Society; pp. 157–162; NICH Report No. 28677.

**Sopori, B.; Chen, W.; Zhang, Y.** (2000). “PV Reflectometer: A Process Monitoring Tool for Solar Cell Manufacturing.” *Program and Proceedings: NCPV Program Review Meeting 2000*, 16–19 April 2000, Denver, CO. BK-520-28064. Golden, CO: National Renewable Energy Laboratory; pp. 189–190; NICH Report No. CP-520-28219.

**van de Lagemaat, J.; Frank, A. J.** (2000). “Non-linear Electron Transport Kinetics in Nanocrystalline TiO<sub>2</sub> Based Solar Cells.” *Program and Proceedings: NCPV Program Review Meeting 2000*, 16–19 April 2000, Denver, CO. BK-520-28064. Golden, CO: National Renewable Energy Laboratory; pp. 177–178; NICH Report No. CP-590-28190.

**van de Lagemaat, J.; Park, N. G.; Frank, A. J.** (2000). “Influence of Electrical Potential Distribution, Charge Transport, and Recombination on the Photopotential and Photocurrent Conversion Efficiency of Dye-Sensitized Nanocrystalline TiO<sub>2</sub> Solar Cells: A Study by Electrical Impedance and Optical Modulation Techniques.” *Journal of Physical Chemistry B*. Vol. 104, 2000; pp. 2044–2052; NICH Report No. 28682.

**Wu, X.; Sheldon, P.** (2000). “Novel CdTe Cell Fabrication Process with Potential for Low Cost and High Throughput.” *Program and Proceedings: NCPV Program Review Meeting 2000*, 16–19 April 2000, Denver, CO. BK-520-28064. Golden, CO: National Renewable Energy Laboratory; pp. 285–286; NICH Report No. CP-520-28214. ❀

# PV Calendar

**September 17–22, 2000, 28th IEEE PV Specialists Conference.** Location: Anchorage Hilton, Anchorage, AK. Contacts: Ajeet Rohatgi. Phone: 404-894-7692. Or John Benner. Phone: 303-384-6496. Web site: <http://ieeepvsc.nrel.gov/pvsc28home.html>

**October 2–5, 2000, UPVG Photovoltaic Experience Conference 2000.** Location: Baltimore, MD. Sponsor: Utility PhotoVoltaic Group. Contact: Tina Schneider. Phone: 202-857-0898. Web site: [www.upvg.org/upvg/upex2000](http://www.upvg.org/upvg/upex2000)

**October 2–6, 2000, American Vacuum Society, 47th International Symposium.** Sponsor: AVS. Location: Boston, MA. Contact: AVS. Phone: 212-248-0200. Web site: [www.vacuum.org/call/default.html](http://www.vacuum.org/call/default.html)

**October 22–27, 2000, 198th Meeting of the Electrochemical Society.** Sponsor: ECS. Location: Phoenix, AZ. Contact: [www.electrochem.org](http://www.electrochem.org)

**November 5–11, 2000, Renewable Energy: Advancing Technology for Industrialization and Sustainable Development.** Sponsor: International Networking Events. Location: Brighton, England. Contact: [network.events@britishcouncil.org](mailto:network.events@britishcouncil.org)

**November 27–December 1, 2000, Materials Research Society 2000 Fall Meeting.** Sponsor: MRS. Location: Boston, MA. Contact: MRS Headquarters. Phone: 724-779-3003. Web site: [www.mrs.org/meetings/fall2000](http://www.mrs.org/meetings/fall2000)

**December 4–7, 2000, Village Power 2000: Empowering People while Building Markets.** Sponsors: NREL, World Bank, Winrock International. Location: World Bank HQ Building, Washington, DC. Contact: Barbara Ferris, 303-275-3781. Web site: [www.nrel.gov/villagepower](http://www.nrel.gov/villagepower)

**January 15–19, 2001, DOE Distributed Power Program Review and Planning Meeting.** Sponsor: NREL. Location: Washington, DC. Contact: Kimberly Taylor, 303-275-4358.

**March 25–30, 2001, 199th Meeting of the Electrochemical Society.** Sponsor: ECS. Location: Washington, DC. Contact: [www.electrochem.org](http://www.electrochem.org)

**April 16–20, 2001, MRS Spring Meeting.** Sponsor: Materials Research Society. Location: San Francisco, CA. Contact: <http://www.mrs.org/meetings/spring2001>

**April 21–25, 2001, Solar Energy: The Power to Choose.** Sponsor: ASES, et al. Location: Washington, DC. Contact: [www.ases.org](http://www.ases.org)

**November 25–December 2, 2001, ISES Solar World Congress.** Sponsor: International Solar Energy Society. Location: Adelaide, Australia. Contact: “Events” at [www.ises.org](http://www.ises.org)

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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