NREL PV

Working With Industry

Spring/Summer 1996

Eye on IEEE

Papers, posters, presentations.

The days before the 25th IEEE PV Specialists Conference were certainly focused on polishing these forms of communication to showcase NREL researchers' work with and for industry. Some 40 articles were submitted by our researchers, spanning topics from various PV technologies, to market development, to project management.

We are proud to summarize in this issue of *PV Working With Industry* the results of NREL's work presented at the IEEE meeting during May 13–17, in Washington, D.C. The main results or conclusions of each paper are highlighted briefly to give you a thumbnail sketch of current projects. And this is done under one of nine categories, which indicate our areas of expertise in the PV field.

The meeting was a great success, with more than 700 attendees from around the world. This gathering continues to be an important forum for announcing our accomplishments to the PV community, while also learning about the latest work of others. Photovoltaics will be advanced by the open sharing of such information.

It is our hope and goal that NREL's efforts will contribute to the further development and growth of this great power-generating technology.

Features

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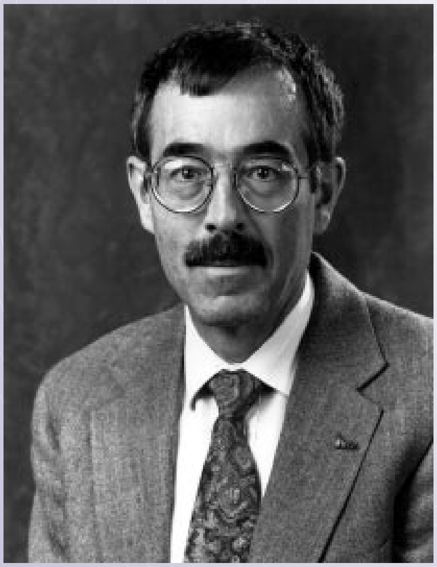
PVSC: Twenty-Five and Going Strong

An Editorial by Eldon Boes



Warren Gretz, NREL

Eldon Boes, Manager of the Washington D.C. Office of NREL, served as General Chair for this year's 25th IEEE PV Specialists Conference.

This 25th anniversary of the IEEE Photovoltaic Specialists Conference (PVSC) has served as a testament to both the vitality of the research and development of photovoltaics and the rapid expansion of the contributions of PV power systems to the quality of life worldwide. Photovoltaics—our favorite power technology—is clearly at a stage where continued R&D will lead to substantial advances and technological evolution for decades to come. At the same time, the rapid expansion of applications and markets suggests that we are seeing just the tip of the iceberg in terms of the ultimate role of photovoltaics as a source of clean and renewable power.

The quantity, breadth, and depth of the abstracts submitted for this conference gave us our first clue that the presentations on the R&D of PV would report fruitful progress in essentially all program areas—from established topics such as crystalline Si cells and space power systems, to relatively new technology areas such as thermophotovoltaics.

As an interesting example that highlights the changes we have seen over the years of this conference, one speaker reminded us that there were predictions in the 1960s that total space-based PV power would never exceed 1 kilowatt. In contrast, many of today's communications satellites carry several kilowatts each, and the next generation will be 10s of kilowatts per satellite. We also heard an interesting report on fabricating crystalline Si cells by the chemical vapor deposition of Si on a new, high-temperature glass. And there were reports of increasing deployment of thin-film arrays in terrestrial PV power systems, although crystalline Si arrays still dominate that market.

An exciting movement in terrestrial applications, reported here and at other recent PV conferences, is the incorporation of PV collectors in the "built" environment, especially in building facade and roofing and fenestration materials.

The International Applications Forum at the beginning of the conference provided a very effective means for sharing information on the burgeoning markets for PV throughout the world. This meeting is especially valuable for comparing approaches and results on common issues such as financing, establishing distribution and maintenance networks, and education and training programs.

The Conference Exhibition included an impressive collection of PV modules, PV-powered products, and related technologies. We thank the exhibitors for their considerable efforts to put together this most informative exhibition.

As photovoltaics technology has developed over the past 4 decades, this R&D conference has added an emphasis on public education and outreach through such efforts as our High School Program, opening our Exhibition to the public, and various tutorial and auxiliary program activities. I urge us to continue those efforts without compromising the quality of the R&D information exchange in our Technical Program—the heart of the conference. As "photovoltaic specialists," we have a duty to inform the public about this technology, and this conference offers a unique opportunity for a concerted educational effort on a regular basis.

The Secretary of the U.S. Department of Energy, Hazel O'Leary, gave our high school program a unique recognition at this conference by meeting with the students and having them explain their projects to her.

We owe a special thanks to three of our PV specialists—Mo Forestieri, John Meakin, and Larry Kazmerski—for helping us celebrate our 25th anniversary by providing a special luncheon program that was a perfect combination of interesting PVSC history and inside humor.

We also note that Jim Rannels, the director of the Photovoltaics Technology Program at DOE, helped to entertain us at our evening social, the Gala at the Galleria, by serving with our conference chair as a pair of "nerds" to support the Capital Steps group in their last musical number.

Thank you to all who contributed to the success of this conference, especially to the conference committees, the authors and speakers, the exhibitors, and Fran Hodson for her exceptional contributions.

I look forward to seeing you at the 26th IEEE Photovoltaic Specialists Conference in Anaheim, California, in 1997!

T.F. Ciszek, T.H. Wang, R.K. Ahrenkiel, R. Matson, "Properties of Iron-Doped Multicrystalline Silicon Grown by the Float-Zone Technique."

B.L. Sopori, L. Jastrzebski, T. Tan, "A Comparison of Gettering in Single- and Multicrystalline Silicon for Solar Cells."

Y.S. Tsuo, P. Menna, J.R. Pitts, K.R. Jantzen, S. Asher, M. Al-Jassim, T.F. Ciszek, "Porous Silicon Gettering."

T.H. Wang, T.F. Ciszek, R. Reedy, S. Asher, D. King, "Surface Segregation as a Means of Gettering Cu in Liquid-Phase-Epitaxy Silicon Thin Layers Grown from Al-Cu-Si Solutions."

M. Cudzinovic, B. Sopori, "Control of Back Surface Reflectance from Aluminum Alloyed Contacts on Silicon Solar Cells."

Of the more than 360 papers presented at the PV Specialists Conference, some 90 papers reported research results on crystalline silicon materials and devices. Those papers presented by the silicon solar-cell industry reflected the optimism that the industry is profitable, with a good prospect for an expanding worldwide market. Major U.S. crystalline silicon solar cell manufacturers—Siemens Solar, Solarex, AstroPower, ASE Americas, and Solec—all reported recent capacity expansions, planned expansion, or both. A record silicon solar-cell module efficiency of 22.3% (AM1.5, 787-cm^2 aperture area) was reported by the University of New South Wales, indicating potential for continued efficiency improvements for commercial silicon solar modules. In fact, the 22.3% value is the highest efficiency reported for a solar-cell module of any material. Frauhofer ISE reported a record solar-cell efficiency of 21.7% for Czochralski silicon.

In his acceptance speech, Dr. Allen Barnett, this year's William R. Cherry Award winner, emphasized the potential and importance of continued research on thin-film polycrystalline silicon solar cells. A number of researchers reported on the development of thin-film crystalline silicon solar cells on low-cost substrates. For example, a University of New South Wales group reported achieving a 17.6% conversion efficiency for a thin-film silicon solar cell deposited by chemical vapor deposition onto a highly doped, electrically inactive silicon wafer.

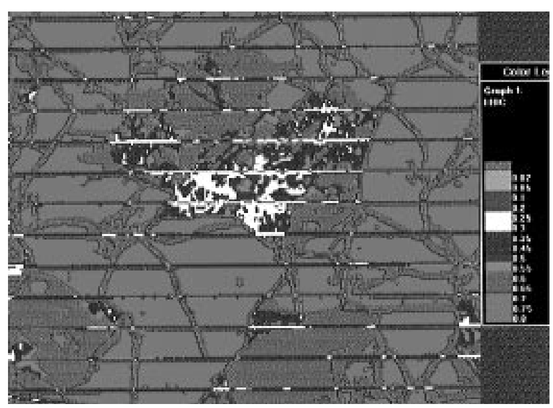
At NREL, researchers are gaining a better understanding of the detrimental effects on cell performance of impurities within silicon. Ciszek and others used the float-zone technique to grow multicrystalline Fe-doped Si ingots from high-purity feed rods. They determined the effects of low levels of Fe-impurity concentrations on cell performance by measuring minority charge carrier lifetime and by examining grain structure and electron-beam-induced-current response of grain boundaries on cut wafers. Lifetimes decreased monotonically with increasing Fe content for similar grain sizes.

Another research focus at NREL is gettering techniques. Sopori, working with researchers from the University of South Florida and Duke University, identified mechanisms that cause differences in gettering results and looked for methods to produce wafers and devices with a uniformly high minority-carrier diffusion length and solar-cell response. They have defined a gettering model for multicrystalline silicon.

Tsuo and others proposed a new type of low-cost substrate that can be used for epitaxial growth of thin-film polycrystalline silicon without impurity contamination. The substrate, made from metallurgical-grade Si, was purified using gettering sites produced by surface regions of the proposed porous-silicon etch. The presence of photons during high-flux solar furnace annealing enhances gettering efficiency.

Wang and others demonstrated that, by using the natural surface segregation phenomenon, Cu can be gettered to the surface from the bulk of Si layers so that its concentrations in liquid-phase-epitaxy layers are much lower than its solubility at the layer growth temperature. Surface segregation can be used to effectively getter Cu and other fast-diffusing impurities from bulk Si when the impurity concentration exceeds its room-temperature solubility and the Si crystal is in thin forms of a few hundred microns.

Light-trapping is being studied by Cudzinovic and Sopori, who described processes for forming specular and diffuse aluminum back contacts on Si that maintain a high interface reflectance and low contact resistance. These processes result in only a 7% decrease in the reflectance from the Si/Al interface, limiting the parasitic losses of light. The optical properties of these contacts make them ideally suited for light-trapping schemes, and they are formed rapidly and at low temperatures, which make them favorable for commercial solar-cell manufacturing.



Bhushan Sopori, NREL/PIX03521

LBIC mapping can highlight the dislocation density in gettered vs. ungettered silicon cells (see Sopori et al.).

For further information, contact Simon Tsuo (303) 384-6433.

Amorphous Silicon

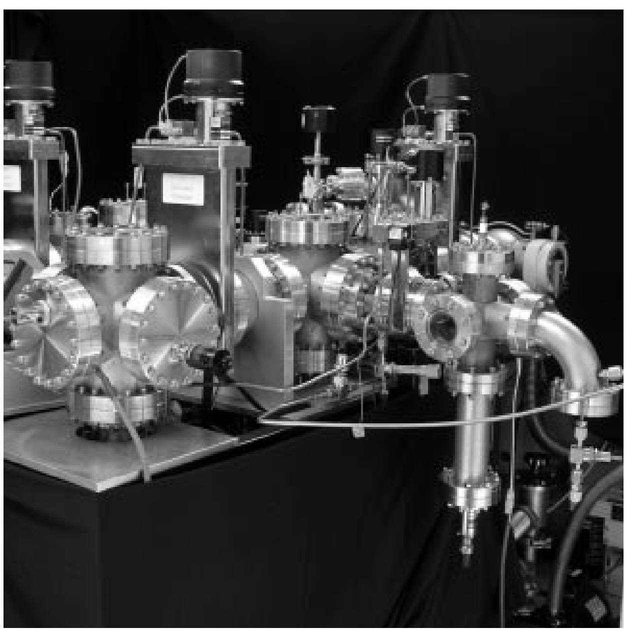
R.S. Crandall, Q. Wang, "Density-of-States Measurements in a p-i-n Solar Cell."

Q. Wang, R.S. Crandall, E.A. Schiff, "Field Collapse Due to Band-Tail Charge in Amorphous Silicon Solar Cells."

A.H. Mahan, E. Iwaniczko, B.P. Nelson, R.C. Reedy Jr., R.S. Crandall, S. Guha, J. Yang, "Hot-Wire-Deposited Hydrogenated Amorphous Silicon Solar Cells."

As part of the PV Specialists Conference, United Solar Systems Corporation (USSC) described its latest amorphous silicon (a-Si) cell and module world-record efficiencies: an 11.8% stable triple-junction cell and a 10.2% 1-ft^2 module. USSC's venture into the PV-roofing shingle market is off to a good start, with demonstration roofings on a townhouse development.

The proposed expansion in the a-Si PV industry in 1997 totals 25 MW, which is a significant portion of the world module shipments in 1995. The most significant development in this area is the Amoco/Enron 10-MW plant in Virginia, with module shipments planned by 1997. A study by Cody and Tiedje to project cost and performance in thin-film photovoltaics concluded that this venture—using a reasonable learning-curve prediction with an addition of one 10-MW facility per year—could be producing electricity at a cost of less than 4 cents per kWh (1994$) in 2005.



Jim Yost Photography/PIX01813

NREL researchers use this hot-wire unit to deposit thin layers of amorphous silicon (see Mahan et al.).

In the area of new device configuration, the University of Neuchatel presented data for its "micromorph" tandem solar cell, which uses a microcrystalline bottom cell in conjunction with an a-Si top cell. The advantage of this cell configuration is that the bottom cell is completely stable. The university reported a 10.6% initial efficiency and an 8.9% stable efficiency. An improved a-Si top cell should result in higher stabilized efficiencies.

A fundamental ingredient in modeling solar cells is knowing of defects and their distribution in space and energy. Using a drive-level capacitance technique, NREL's Crandall and Wang have a picture of the density of states throughout the doped layer in a p-i-n device. The states in the central region are neutral dangling-bond defects, whereas those near the interfaces with the doped layers are charged dangling bonds.

Using the Analysis of Microelectronic and Photonic Structures (AMPS) simulation program, Wang, Crandall, and Schiff showed that the decrease in fill factor (FF) as light intensity increases in a-Si:H p-i-n solar cells is caused by photogenerated space charge trapped in the band-tail states rather than in defects. Photocapacitance experiments, coupled with AMPS results, verified that a decrease in the electric field causes the FF to decrease with increasing light intensity.

Mahan and other NREL researchers, along with Guha and Yang of United Solar Systems Inc., have continued their work on hot-wire (HW) deposition of a-Si:H. They were able to fabricate high-efficiency substrate solar cells, where the n and i layers were deposited by HW at high substrate temperatures and at high deposition rates. They measured efficiencies of up to 6.8% for a cell with a 4000-Å-thick HW i layer, which degraded less than 10% after a 900-hour light soak.

For further information, contact Richard Crandall (303) 384-6676.

D.H. Levi, B.D. Fluegel, R.K. Ahrenkiel, A.D. Compaan, L.M. Woods, "Dynamics of Photoexcited Carrier Relaxation and Recombination in CdTe/CdS Thin Films."

H.R. Moutinho, R.G. Dhere, K. Ramanathan, P. Sheldon, L.L. Kazmerski, "Growth Analysis of Cadmium Sulfide Thin Films by Atomic Force Microscopy."

X. Li, P. Sheldon, H. Moutinho, R. Matson, "Enhanced Performance of CdS/CdTe Thin-Film Devices Through Temperature Profiling Techniques Applied to Close-Spaced Sublimation Deposition."

D.H. Rose, D.H. Levi, R.J. Matson, D.S. Albin, R.G. Dhere, P. Sheldon, "The Role of Oxygen in CdS/CdTe Solar Cells Deposited by Close-Spaced Sublimation."

D.L. Schulz, M. Pehnt, E. Urgiles, D.W. Niles, K.M. Jones, C.J. Curtis, D.S. Ginley, "High-Quality CdTe Films from Nanoparticle Precursors."

A wide range of CdTe deposition techniques were reported to produce efficient CdS/CdTe devices, including close-spaced sublimation (CSS) (Matsushita, Solar Cells Inc., University of South Florida, and NREL), rf sputtering (University of Toledo), spray deposition (Golden Photon Inc.), electrodeposition (Colorado School of Mines), and physical vapor deposition (Institute of Energy Conversion). Matsushita reported producing a 1-cm^2 device with an AM1.5 efficiency of 15.05%, having chemical-vapor-deposited CdS and CSS-deposited CdTe. In addition, USF reported the highest efficiency for an all-CSS-deposited device structure (both CdS and CdTe layers) with an efficiency of 14.2%. Granata and others discussed the effect of CdS thickness on CdS/CdTe device quantum efficiency using samples from the participants in the CdTe Thin-Film Partnership Team. Modules, produced by SCI and tested and reported on by both SCI and NREL, were stable over the 2-year test period and exhibited a very small temperature coefficient compared to crystalline silicon. Two 25-kW CdTe arrays, supplied by both SCI and GPI, were reported to be deployed at China Lake, CA.

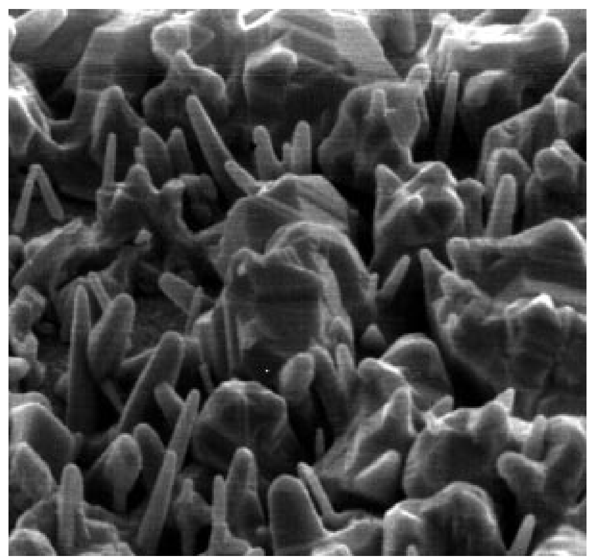
Levi and others at NREL, the University of Toledo, and Golden Photon presented the first direct optical measurements (time-resolved spectroscopy) of the relaxation and recombination pathways of photoexcited carriers in the CdS window layer. Their results showed that the photoexcited holes are captured very rapidly by a defect site acting as a deep hole trap. This trapping produces a very short diffusion length for holes, preventing any contribution to the current from photons absorbed in the CdS layer. This result is consistent with Granata's analysis of the effect of CdS thickness on CdS/CdTe device quantum efficiency.

Moutinho and NREL coworkers studied CdS films deposited by solution growth on SnO_2 and glass substrates. Nucle-ation on SnO_2 occurs faster and in thinner conformal layers than on glass. Optical measurements, along with atomic force microscopy, showed that the band-gap of CdS films deposited on SnO_2 depends mainly on substrate structure. Hydrogen heat treatment does not affect the surface morphology of the samples, but decreases bandgap values.

Li and others developed and applied a temperature-profile technique for depositing CdTe thin films. Using a multi-segment temperature profile, they grew large-grain material, plugged pinholes, and improved CdS/CdTe device performance by about 15%, while maintaining deposition temperatures compatible with commercially available substrates.

Rose and others found that the presence of oxygen during CSS increased nucleation-site density of CdTe, thus decreasing pinhole density and grain size. Oxygen decreases material quality in the bulk of the CdTe film, but positively impacts the critical CdS/CdTe interface. They concluded that the use of oxygen during CSS deposition of CdTe can be useful, but it is not essential for producing high-efficiency (13% AM1.5) cells.

Schulz and coworkers demonstrated that nanoparticulate precursors coupled with spray deposition offers an attractive route into electronic materials with improved smoothness, density, and lower processing temperatures. CdTe thin-film formation was achieved by spray depositing the 25–75-Å-diameter particles onto substrates at temperatures of 280°–440°C, with no further thermal treatment.



Rick Matson, NREL

SEM micrograph, about 15 microns wide, showing faceted crystal structure of CdTe nucleated on a CdS/SnO_2/glass substrate (see Li et al.).

For further information, contact Pete Sheldon (303) 384-6533.

Copper Indium Diselenide

J.R. Tuttle, T.A. Berens, J. Keane, K.R. Ramanathan, J. Granata, R.N. Bhattacharya, H. Wiesner, M.A. Contreras, R. Noufi, "Investigations into Alternative Substrate, Absorber, and Buffer Layer Processing for Cu(In,Ga)Se_2-Based Solar Cells."

D.W. Niles, M. Contreras, K. Ramanathan, R. Noufi, "Determination of the Valence-Band Offset of CdS/CIS Solar-Cell Devices by Target Factor Analysis."

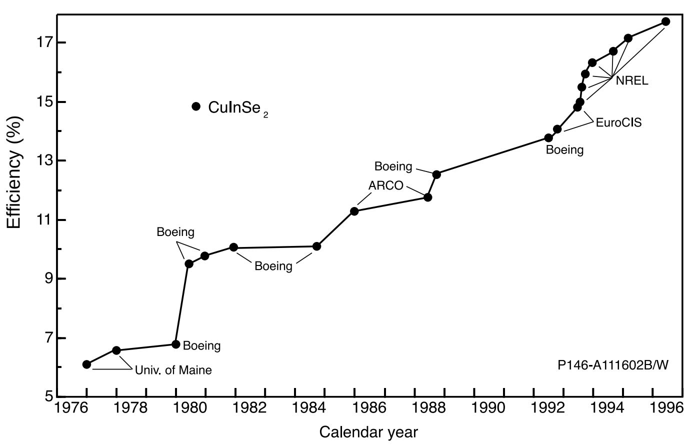
K. Ramanathan, M.A. Contreras, J.R. Tuttle, J. Keane, J. Webb, R. Dhere, A.L. Tennant, F.S. Hasoon, R. Noufi, "Effect of Heat Treatments and Window Layer Processing on the Characteristics of $CuInGaSe_2$ Thin-Film Solar Cells."

F. Abulfotuh, T. Wangensteen, R. Ahrenkiel, L.L. Kazmerski, "Optical Properties and Defect Levels in a Surface Layer Found on $CuInSe_2$ Thin Films."

M.A. Contreras, H. Wiesner, D. Niles, K. Ramanathan, R. Matson, J. Tuttle, R. Noufi, "Defect Chalcopyrite $Cu(In_{1-x}Ga_x)_3Se_5$ (0<x<1) Materials and High-Ga-Content Cu(In,Ga)Se_2-Based Solar Cells."

As indicated by the chart below of conversion efficiency, NREL's latest 17.7%-efficient, small-area copper indium gallium diselenide (CIGS) cell supports the goal of thin-film modules with 15% efficiency. And at the PV Specialists Conference, significant results presented on CIGS-based solar cells centered around three areas.

The first area was alternative processing—with the intent of simplifying manufacturability—and the characterization of various layers. Tuttle and coworkers in NREL's CIS Team studied alternative substrate, absorber, and buffer layer processing. Cell performance varies considerably when alternative substrates are used. These variations are narrowed with the addition of Na via a Na_2S compound. Sputtered and electrodeposited CIGS precursors and completed absorbers show promise as alternatives to evaporation. A recrystallization process is required to improve their quality. $(In,Ga)_ySe$ buffer layers contribute to cell performance above 10%.



NREL researchers achieved 17.7% cell efficiency for CIGS in 1996. Such progress supports the idea that low-cost thin films will eventually reach 15% module goals.

Ramanathan and coworkers focused on the interaction between chemical-bath-deposited (CBD) CdS and ZnO window layers. Optical absorption spectra show that CdS and ZnO intermix upon annealing. Modest heat treatments to CdS/ZnO structures produce significant changes in the optical and electrical properties. The interdiffusion increases the short-wavelength collection, and hence, the current density of the devices.

Niles and NREL coworkers compared the valence-band offsets (VBOs) for CdS grown by CBD on single-crystal and thin-film CIS. The VBO was determined to be 1.06±0.15 eV for both interfaces. This value—about 0.25 eV larger than many previously reported estimations of CdS grown by physical vapor deposition on CIS—helps explain the performance of CdS/CIS PV devices.

Abulfotuh and coworkers, using photoluminescence and wavelength scanning ellipsometry, determined the defect states and optical prop-erties of the In-rich chalcopyrite defect compound (CDC) layer, which is usually segregated on the surface of the absorber of high-quality CIS devices. They found that the thickness of this layer is about 250 Å and has a gradual change of composition (Cu content) with depth, which results in a gradual change in optical properties.

In work by others outside of NREL, the Tokyo Institute of Technology group reported on the use of In_ySe and $ZnIn_ySe$ in place of CdS, with cell performance in the 14%–15% range. Also, the Washington State group reported success on using chemical-vapor-deposited ZnO as a buffer layer in place of CdS.

A second area of CIGS work presented at the conference was the examination and implementation of higher-Ga-content devices (Ga/[Ga+In]>0.3). Contreras and coworkers in NREL's CIS Team postulated that the traditionally poor device performance of uniform high-Ga-content absorbers (x>0.3) was due to a relatively inferior character—both structural and electrical—at the chalcopyrite/defect-chalcopyrite interface. This situation can be circumvented (for absorbers with x>0.3) to improve efficiencies by engineering such an interface with reduced Ga content in the region near the surface of the absorber. Also reported was that the CIS group at the Institute of Energy Conversion successfully produced 13%–15%-efficient devices with Ga contents as high as 60%.

The third area was the scale-up of laboratory processes to module scale. The Swedish group, Energy Photovoltaics, and Solarex all reported on scaling evaporation-type processes to 50-cm^2 and 1000-cm^2 module-size scales. Mini-modules with 13%–14% efficiencies (50-cm^2 aperture-area) have been fabricated by the Solarex and European groups.

For further information, contact Rommel Noufi (303) 384-6510.

D.J. Friedman, "Modelling of Tandem-Cell Temperature Coefficients."

D.J. Friedman, Sarah R. Kurtz, K. Sinha, W.E. McMahon, J.M. Olson, J.B. Lasich, A.X. Cleeve, I. Connaughton, "On-Sun Concentrator Performance of GaInP/GaAs Tandem Cells."

Sarah R. Kurtz, M.J. O'Neill, "Estimating and Controlling Chromatic Aberration Losses for Two-Junction, Two-Terminal Devices in Refractive Concentrator Systems."

Sarah R. Kurtz, J.M. Olson, K.A. Bertness, K. Sinha, B. McMahon, S. Asher, "Hidden But Important Parameters in $Ga_{0.5}In_{0.5}P$ Cell Growth."

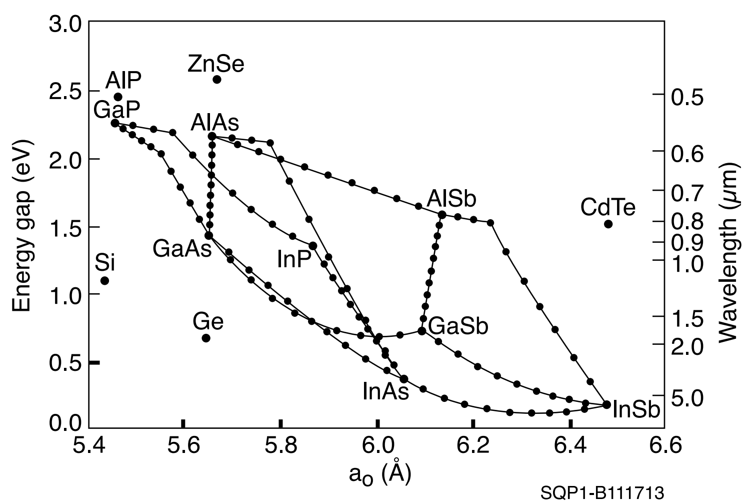
T.J. Coutts, M.W. Wanless, J.S. Ward, S. Johnson, "A Review of Recent Advances in Thermophotovoltaics."

This PV Specialists Conference clearly demonstrated the growing importance of the GaInP/GaAs cell. This technology, invented and developed at NREL, has now been adopted by both TECSTAR and Spectrolab. Tecstar's Linder reported on manufacturing experience with the GaInP/GaAs, dual-junction technology grown on Ge. AM0 efficiencies between 20% and 22% were reported for all manufactured coupons, with the more recent ones being closer to 22%. Yamaguchi of the Toyota Technological Institute reported an AM1.5 Global efficiency of 30.3% for a 2-cm x 2-cm GaInP/GaAs cell grown by Japan Energy as a part of the Japanese super-high-efficiency program. This new world record—the highest efficiency ever reported for a monolithic, two-terminal, one-sun device—tops NREL's previous record of 29.5% for this technology. One of the goals of this aggressive Japanese program is a 35%-efficient, 1-cm^2 cell by the end of fiscal-year 1996. Spectrolab also reported a record efficiency of 25.7% for an AM0 GaInP/GaAs/Ge triple-junction cell. Other interesting reports included an 18.2% (AM1.5G) efficient GaAs cell grown on optical-grade polycrystalline Ge by the Research Triangle Institute (under NREL funding) and a 12% AM0, radiation-hard InP-on-Si device grown by Spire and the Naval Research Laboratory.

Collaborating with workers at Solar Research Corporation, NREL fabricated and tested a GaInP/GaAs tandem cell "on-sun" in a real-world concentrator system. The device achieved an on-sun efficiency of 27%±1% in the range of about 80–400 suns with test-bed operating temperatures of 32°–50°C; this demonstrated the exceptionally high performance of III-V concentrator systems. Also discussed were ways to further improve performance. In supporting work, Friedman analyzed the temperature dependence of the GaInP/GaAs cell performance.

Two-junction, series-connected cells used in a refractive concentrator system may suffer losses when the top-cell light is focused at a different place than the bottom-cell light. Kurtz and O'Neill gave an analytical definition and calculation method for estimating these chromatic aberration losses. They studied the effects of sheet resistance of the midlayers of the cell, total irradiance, incident spectrum, cell width, and diode quality factor. Also described was a method for measuring the midlayer resistance in finished cells. Kurtz and coworkers have also explored the "hidden" parameters that are usually not reported, either because they are unknown (e.g., impurity levels) or because they are considered to be of little importance. They specifically focused on the effects, and how to reduce them, of three things: growth parameters in nearby layers (diffusion), impurities (oxygen), and the cooldown atmosphere (hydrogen passivation).

In the area of thermophotovoltaics (TPV), Coutts and coworkers reviewed recent advances, including materials and devices and applications. The two main approaches to TPV generators are broad-band radiators (coupled with converters with bandgaps in the range 0.4–0.7 eV) and narrow-band emitters (coupled with lower-cost Si converters).



Variation of bandgaps with lattice constant for some III-V compounds and alloys. Materials around 0.5 eV bandgap are potential TPV converters (see Coutts et al.).

For further information, contact Daniel Friedman (303) 384-6472, Sarah Kurtz (303) 384-6475, or Tim Coutts (303) 384-6561.

Cell and Module Testing

K. Emery, J. Burdick, Y. Caiyem, D. Dunlavy, H. Field, B. Kroposki, T. Moriarty, L. Ottoson, S. Rummel, T. Strand, M.W. Wanless, "Temperature Dependence of Photovoltaic Cells, Modules, and Systems."

T.J. McMahon, T.S. Basso, S.R. Rummel, "Cell Shunt Resistance Measurement and Photovoltaic Module Performance."

B. Kroposki, D. Myers, K. Emery, L. Mrig, C. Whitaker, J. Newmiller, "Photovoltaic Module Energy Rating Methodology Development."

C.R. Osterwald, S. Anevsky, A.K. Barua, J. Dubard, K. Emery, D. King, J. Metzdorf, F. Nagamine, R. Shimokawa, N. Udayakumar, Y.X. Wang, W. Zaaiman, T. Wittchen, A. Zastrow, J. Zhang, "Results of the PEP '93 Intercomparison of Reference Cell Calibrations and Newer Technology Performance Measurements."

B. Kroposki, T. Strand, R. Hansen, R. Powell, R. Sasala, "Technical Evaluation of Solar Cells, Inc., CdTe Module and Array at NREL."

T. Strand, B. Kroposki, R. Hansen, D. Willett, "Siemens Solar CIS Photovoltaic Module and System Performance at NREL."

E.E. van Dyk, T. Strand, R. Hansen, "Technical Evaluation of Two 6-kW Mono-Si Photovoltaic Systems at NREL."

At the PV Specialists Conference, several papers—discussing the behavior of cells, modules, and systems as a function of temperature and irradiance—presented results on a variety of commercial and advanced PV structures for terrestrial and space applications. Other papers gave details on the effects of spatial and spectral nonuniform light on single- and multijunction cells, describing the effects of sheet resistance on cell parameters. The PV systems papers presented a variety of lessons learned. For example, Durand and Hernandez cautioned that battery overcharging occurred in hybrid systems used in Coast Guard installations. And for the first time at IEEE, an overview was given of module qualification testing; Bishop and Ossenbrink, presenting results from Ispra, Italy, said they commonly observed failure modes. This year also saw an increase in the number of papers on building-integrated PV.

In the area of performance testing, NREL's Emery and coworker surveyed the temperature dependence of crystalline and thin-film, state-of-the-art, research-size cells, modules, and systems measured by a variety of methods. They discussed various error sources and measurement methods that contribute to differences in temperature coefficient for a given cell or module measured with various methods; various strategies and precautions were also given for measuring the temperature coefficients under simulated and natural sunlight. The temperature coefficients vary within given technologies with irradiance level and spectrum.

Warren Gretz, NREL/PIX01347

The performance of this 6-kW$_{ac}$ PV array on the east wing of NREL's Solar Energy Research Facility was compared to an identical array on the west wing (see van Dyk et al.).

McMahon and others described a two-terminal diagnostic method to directly measure the shunt resistance of individual cells in a series-connected module non-intrusively, without de-encapsul-ation. Measurements and calculations show how a cell's shunt resistance diminishes the module power output capacity under operational conditions where light levels are reduced, as they are in real-world conditions. Shunt losses were contrasted with recombination losses with regard to the impact on a module's energy rating.

NREL has also been involved in developing a module energy rating (MER) and overall standards for modules. Kroposki and others described a consensus-based method to calculate the energy output of a PV module. The method develops a simple measure of PV module performance for a realistic estimate of how a module will perform in specific applications. The approach uses weather data profiles and emphasizes performance differences between various module types. The MER consists of 10 estimates of how much energy a single typical module of a particular type will produce in one day, one for each of five different weather/location combinations and two load-types.

Osterwald and numerous others from international agencies and laboratories presented the results of the Photovoltaic Energy Project 1993 intercomparison. Two sample sets were circulated for PV performance measurements and calibrations. One set had 20 Si reference cells that would hopefully form the basis of an international PV reference scale. For the first time, a group of worldwide national laboratories have agreed on a single scale for PV reference calibrations. The 2-sigma of the normalized I_{sc} from 4 labs for twenty 2-cm x 2-cm Si reference cells was 1.9%. A second sample set of newer-technology PV devices circulated worldwide gave a 2-sigma of 5.7% for the normalized max power.

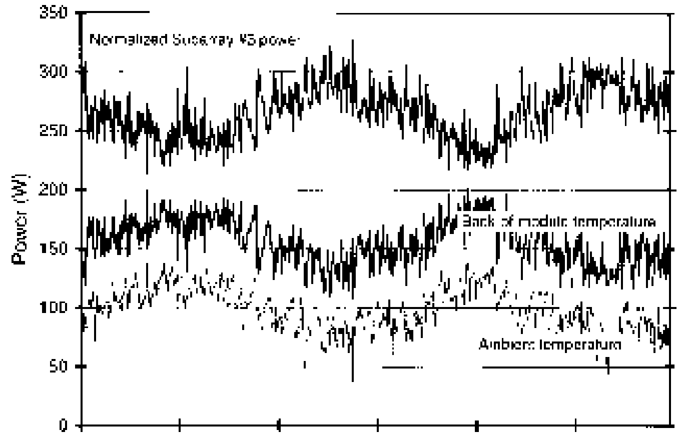
NREL researchers have evaluated various types of modules and systems under actual operating conditions. Kroposki and others evaluated the performance of Solar Cells, Inc.'s (SCI's) CdTe modules and arrays by correlating individual module and array performance. They examined the performance and stability of the modules and array over a period of more than one year. They calculated temperature coefficients for module and array parameters. Temperature had little effect on P_{max}, I_{sc}, and I_{max} at both the module and array level. The values of temperature coefficients for P_{max} showed good correlation between the module and array data. Current was not affected much by temperature. The SCI CdTe modules had a very small temperature coefficient as compared to crystalline Si, and they were very stable.

Strand and others evaluated individual module and array performance of Siemens Solar Industries' copper indium diselenide (CIS) polycrystalline thin-film technology. CIS exhibited a strong inverse correlation between array power and back-of-module temperature; fill factor exhibited an inverse correlation with temperature. The temperature-corrected module and array performance was relatively stable over the 2-year evaluation period.

van Dyk and others analyzed the performance data on the two 6-kW$_{ac}$ grid-connected PV systems atop NREL's Solar Energy Research Facility. The study showed the expected seasonal trends and indicated that system monitoring is a valuable tool in assessing performance and detecting faulty equipment. The systems were overrated by about 7%–8%, perhaps due to the design inverter efficiency being estimated at 95%, compared with the measured value ofabout 87%, and the aperture-area efficiency being overestimated. An analysis of the system losses revealed that, excluding temperature effect, the average array losses amounted to 10.6% of potential energy production as measured relative to standard testing conditions (STC) array rating. The cumulative effect of all the system losses was about 30% of the dc array rating at STC.

For further information, contact Roland Hulstrom (303) 384-6420 or Larry Kazmerski (303) 384-6600.

A PV array study at NREL's Outdoor Test Facility reveals a strong inverse correlation between subarray power and back-of-module temperature (see Strand et al.).



Encapsulants

A.W. Czanderna, F.J. Pern, "Estimating Service Lifetimes of a Polymer Encapsulant for Photovoltaic Modules from Accelerated Testing."

F.J. Pern, I.L. Eisgruber, R.H. Micheels, "Spectroscopic, Scanning Laser OBIC, and I-V/QE Characterizations of Browned EVA Solar Cells."

F.J. Pern, S.H. Glick, "Thermal Processing of EVA Encapsulants and Effects of Formulation Additives."

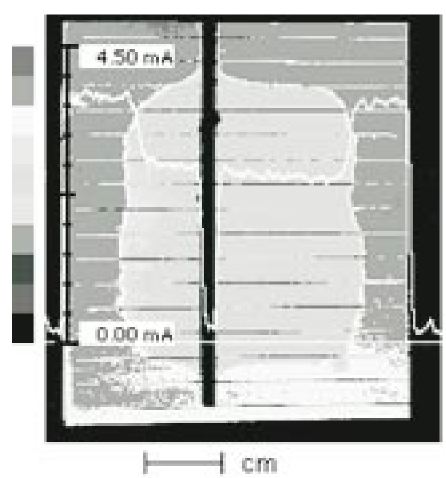
Springborn Laboratories updated its data concerning the decrease in the rate of photothermal-induced browning of ethylene vinyl acetate (EVA) pottants by using cerium-oxide-containing superstrates. They also reported data for (1) Tefzel superstrates that do not yellow because of photobleaching reactions due to permeating oxygen and water vapor, and for (2) newly developed EVA encapsulants, designated X9903P, X9923P, X9933P, and X15303P, in which the yellowness index did not exceed 4.8 after 22 weeks in an Atlas WeatherOmeter. These new formulations have the same processing properties and costs as A9918P and 15295P EVA. The data were all obtained with specimen configurations of superstrate/EVA/glass substrate without operating PV cells.

The Florida Solar Energy Center reported on the performance and properties of ARCO, Mobil Solar, and Photowatt crystalline-Si modules deployed in the hot, humid, ocean-salt environment near Florida's Cape Canaveral. All modules showed extensive or partial browning, but no significant power loss occurred in 10 years. One significant result is that the wet insulation resistance values of a majority of all modules were lower than values recommended in the draft IEEE Standard 1262.

At NREL, Czanderna and Pern have studied the complexity of the encapsulation problem, including performance losses in PV systems deployed since 1981. They pointed out weaknesses in experimental design, Arrhenius interpretation, and projected lifetime, and they outlined an acceptable method for making service-lifetime predictions of polymer encapsulants.

Pern, and others at Materials Research Group and Polestar Technologies, used various techniques to characterize browning of EVA cells. The yellowness index increased from the -80 to -90 range to the -20 to 15 range, as EVA changed from clear to brown. Quantum-efficiency loss at 633 nm was 42%–48% of the loss at 488 nm, whereas transmittance loss at 633 nm was 38% of the loss at 488 nm.

Finally, Pern and Glick studied two commercial as-formulated EVA films, A9918P and 15295P, and solution-cast films of Elvax impregnated with various curing agents and antioxidants. Results showed that the actual measured temperatures of EVA lagged significantly behind the programmed profiles for the heating elements and were affected by the total thermal mass loaded inside the laminator chamber. The antioxidant Naugard P greatly enhanced the formation of undesirable UV-excitable, short chromophores upon curing, whereas other tested antioxidants did not enhance chromophore formation.



Rick Matson, NREL

A scanning laser OBIC map of a 4.5-cm-wide PV cell, where the central shaded area indicates browned EVA and the white curve shows the quantum efficiency (see Pern et al.).

For further information, contact Al Czanderna (303) 384-6460.

Market Development

C. Herig, A. Houston, "The Value of Customer Preference."

R. Taylor, D. Arent, S. Baldwin, R. McConnell, J. Stone, H. Ullal, C. Warner, W. Wallace, P. Klimas, E. Richards, C. Hanley, J. Strachan, "Opportunities and Issues in International Photovoltaic Market Development."

W.L. Wallace, Y.S. Tsuo, "Sino/American Cooperation for PV Development in the People's Republic of China."

C.L. Warner, R.W. Taylor, C.M. Ribeiro, M. Moszkowicz, A.J.V. Borba, "PV-Hybrid Village Power Systems in Amazonia."

Those people at the Photovoltaics Specialists Conference who had an interest in PV applications and markets were able to attend two half-day tutorials: one on "hybrid power systems" and the other on "PV in the building environment." Each tutorial was presented by an international panel of experts.

In the regular presentation session on PV for buildings, speakers reported on results of key efforts under the DOE-funded program Building Opportunities in the United States for Photovoltaics (PV:BONUS). These efforts included the alternating-current module work by Solar Design Associates and Solarex, as well as the roofing systems by Energy Conversion Devices/ United Solar Systems Corporation. One event of potential major significance was the entry as a conference exhibitor of Pilkington Solar International.

Roger Taylor, NREL/PIX01878

In country-specific, pilot-project partnerships (as in Brazil shown here), NREL seeks to team up with strong in-country affiliates to build on the existing in-country institutional capability.

On the domestic scene, NREL's Herig and Houston discussed customer preference or green pricing as a possible financial hedge for electric supply industry integration of PV. They expanded the concept of customer preference to include both voluntary and involuntary customer contributions, then categorized the features of existing and proposed customer-preference programs.

NREL personnel presented several papers on international projects. Taylor and others discussed pilot projects launched by NREL and Sandia National Laboratories in several countries throughout the world during the last 3 years. The focus of these projects in Brazil, India, China, South Africa, Mexico, and elsewhere has been to develop in-country institutional capabilities necessary to deliver the promise of PV electricity to rural populations.

Wallace and Tsuo reported on the growing interest in China to develop renewable-energy resources and technologies to meet energy demands and help mitigate pollution problems. Under the Energy Efficiency and Renewable Energy Protocol Agreement, projects using PV for rural electrification are being conducted in Gansu Province in western China and Inner Mongolia in northern China.

Warner and others described the technical aspects of two hybrid systems being installed in the Amazon region of Brazil through the cooperative effort of multiple partners: the U.S. DOE (through NREL), and the Brazilian CEPEL/ Eletrobras and state electric utilities. The designs of the two systems are significantly different. The Campinas system will meet the entire load requirement with PV-generated electricity, and the Joanes system will operate in a "peak shave" mode, transferring the peak demand of the village to "off peak" periods at the diesel generation plant.

For further information, contact Roger Taylor, (303) 384-6432.

News at Press Time

Denver, Colorado—Downtown Denver played host for the World Renewable Energy Congress (WREC) from June 16–21. With almost 800 attendees, this conference brought together people from more than 100 countries, interested in various renewable energy technologies. While here, some individuals and groups took advantage of the proximity to NREL to visit the Lab, discuss specific needs and opportunities with PV Program personnel, and check out the world-class facilities and capabilities for future collaborative work. Below are news briefs on three such visits from representatives involved in PV work in India.

S.K. Deb, J.P. Benner, "DOE/OER-Sponsored Basic Research in High-Efficiency Photovoltaics."

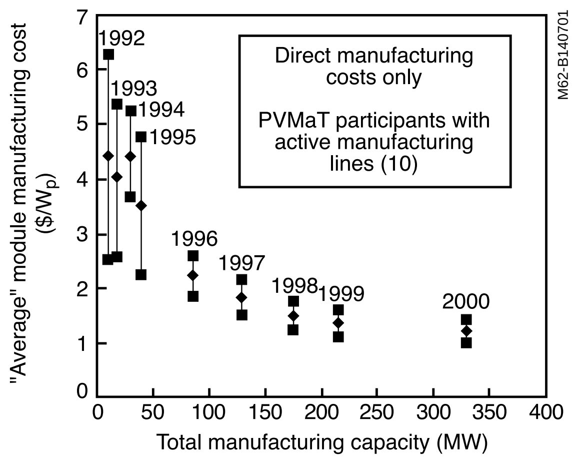
R.L. Mitchell, C.E. Witt, H.P. Thomas, L.O. Herwig, D.S. Ruby, C.C. Aldrich, "Benefits from the U.S. Photovoltaic ManufacturingTechnology Project."

K. Zweibel, H.S. Ullal, B. von Roedern, "Progress and Issues in Polycrystalline Thin-Film PV Technologies."

NREL seeks to work with industry and univers ty partners in programs related to basic research, PV manufacturing, and thin-film research and development. Deb and Benner summarized a high-efficiency PV project involving many national laboratories and several universities initiated under the umbrella of the DOE's Center of Excellence for the Synthesis and Processing of Advanced Material. The objectives are to generate advances in fundamental scientific understanding that will impact the efficiency, cost, and reliability of thin-film PV cells. There are two areas of focus: Silicon-Based Thin Films, involving amorphous and polycrystalline silicon thin films, and Next-Generation Thin-Film Photovoltaics, considering non-silicon-based materials.

Mitchell and others have analyzed the PV Manufacturing Technology (PVMaT) Project, initiated in 1990. They showed that PVMaT has contributed to improvements in PV module manufacturing processes, increased product value, and reduced the price of today's PV products. The evaluation of this project's success was conducted using data from 10 of the PVMaT industrial participants in late FY 1995. These data indicated a reduction of 56% in the weighted average module manufacturing costs from 1992 to 1996. During this same period, U.S. module manufacturing capacity increased by more than a factor of 6. Finally, the analysis indicated that both the public and the manufacturers will recapture the funds expended in R&D manufacturing improvements well before 2000.

Zweibel and coworkers summarized the substantial progress that has occurred in polycrystalline thin-film PV technologies in the past 18 months. Despite the progress however, many issues obstruct the successful introduction of CIS and CdTe thin films in the marketplace. The effort to overcome these technical issues is well under way, though. New approaches (flexible substrates, non-CdS designs, new processes) and new corporate entries reflect the ongoing technical vitality of the field. Record efficiencies at all levels (cells through modules) are a strong reminder of the potential of these technologies if they can be developed to full commercial success. They highlight the joint R&D efforts being performed in the U.S DOE/ NREL Thin-Film Photovoltaic Partnership Program.



PVMaT "average" module direct manufacturing costs vs. total manufacturing capacity (see Mitchell et al. for full discussion of assumptions).

For further information, contact Satyen Deb (303) 384-6405, Ed Witt (303) 384-6402, or Ken Zweibel (303) 384-6441.

Secretary B. R. Prabhakara, Ministry of Non-Conventional Energy Sources (MNES), India, visited NREL just before the start of WREC and heard presentations from NREL personnel on photovoltaics, solar thermal electric, biomass electric, and wind activities. He also toured the PV Outdoor Test Facility and the National Wind Technology Center site. Secretary Prabhakara thanked NREL for actively participating in the implementation of the Memorandum of Understanding (MOU) between NREL and MNES. He hopes the existing MOU will be extended to include other areas of cooperation. The Secretary also supports NREL's proposal to the Indian Renewable Energy Development Agency (IREDA) in the area of distributed utility concepts. His expectations for India are that in the future, subsidies to end-users for electricity will decline and will eventually be eliminated. The bottomline will be that the urban end-users will be able to afford the power, and those in rural areas will have diminishing access to grid-supplied power. The result will be a huge demand for systems powered by renewable energy to meet the energy demands of farmers and villagers.

Continued on page 14

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.

The **DOE/NREL Thin-Film Partnership** has organized the U.S. thin-film research community into focused R&D teams for a-Si, CIS, CdTe, and ES&H (more than 100 members from about 40 U.S. companies, universities, and NREL). The teams develop collaborative R&D plans to be carried out cooperatively. To enhance communication, two of the teams have developed a means by which team members can exchange messages over the Internet. Servers for the CdTe and CIS Teams are at the **University of South Florida** (Tampa) and **University of Florida** (Gainesville) respectively. Considerable exchange of messages has taken place, and the research community is highly enthusiastic about this new information medium. **(Ken Zweibel, 303-384-6441)**

NREL Metrology and Instrumentation Team members, supported by the PV Radiometric Measurements and Evaluation Task, worked as members of the **Council for Optical Radiation Measurements (CORM)** and with the **National Institute of Standards and Technology** to develop, chair, and present technical papers at the 1996 24th Annual Conference of the CORM at Gaithersburg, MD, from May 21–23, 1996. **Theodore Cannon** of NREL chaired this meeting, which had 36 speakers in 4 technical sessions, and 124 other attendees, including 14 from 8 foreign countries. **Lawrence Kazmerski** of NREL presented the Frank Grum Memorial Lecture honoring one of the late founders of CORM. CORM consists of individual members representing industry (**Kodak, 3M, Osram-Sylvania, Boeing, Rockwell, Hewlett-Packard**, and many smaller companies), government (**NIST, NREL, NASA**) and national standardizing laboratories (**NPL**, England; **VIINOFI**, Russia; **BNM**, France; **PTB**, Germany; **NRC**, Canada; **CENAM**, Mexico). Meetings address many issues faced in the optical metrology activities of NREL's Center for Renewable Resources Assessment and Data and the Center for Performance Engineering, Qualification, and Reliability. **(Theodore Cannon, 303-384-6763; Daryl Myers, 303-384-6768)**

The GaInP/GaAs tandem cell was invented and developed at **NREL**, and **TECSTAR (ASEC)** and **Spectrolab** are both incorporating it into their production. Although the materials are near ideal and growth of the device is relatively straightforward, the sensitivity of the AlInP window layer to small amounts of oxygen causes potential loss in production yield. We concluded from our most recent study that oxygen causes loss of blue response in all cells and causes a problematic increase in series resistance for p-on-n GaInP cells when the front contact is made through the AlInP window. The sensitivity to oxygen was reduced by higher doping of the AlInP and by using the n-on-p configuration. These results will help us identify when oxygen is a problem in our growth system at NREL and should also help those who monitor production at TECSTAR and Spectrolab. **(Sarah Kurtz, 303-384-6475)**

The **Environmental, Safety and & Health (ES&H) Team** of the Thin-Film PV Partnership met at IEEE in Washington, D.C., in May. Attendees from **NREL, Solar Cells Inc., Golden Photon, ITN,** and several universities and members of the waste management (**Drinkard Metalox**) and minerals industry (**Noranda**) were present. **Paul Moskowitz (Brookhaven National Laboratory)** and **Ken Zweibel (NREL)** co-chaired the meeting. Two winners of DOE Small Business Innovation Research Phase I module recycling awards, **Bob Goozner** of Drinkard Metalox and **John Bohland** of SCI, presented their Phase I findings. In both cases, methods were developed for stripping metals from CdTe modules. Both of the new methods could also be adapted for other inputs, including CIGS modules and non-PV wastes. Cost estimates by the companies suggest that modules could be recycled for a reasonable 4 to 6 cents/watt. **(Ken Zweibel, 303-384-6441)**

The **Thin-Film PV Partnership's CIS and CdTe teams** met in May during the IEEE PVSC in Washington, D.C. At the CIS team meeting, presentations were made by both the existing Junction (**Kannan Ramanathan, NREL; Li Wang, MRG; Larry Olsen, WSU**) and Absorber (**John Tuttle, NREL**) working groups. Results were presented on with- and without-background solution dips, before the deposition of CdS by chemical-bath deposition, plasma vapor deposition, and sputtering. Also, Mo samples obtained from various groups, namely, **Energy Photo-voltaics, International Solar Electric Technology (ISET), Lockheed Martin (LM), NREL, Siemens Solar Industries (SSI)**, and **Solarex**, were used for device fabrication, with efficiencies from 4.5% to 17.3%. The existing team structure was changed to five working groups (with leaders in parentheses): (1) Present Junction (**Kannan Ramanathan, NREL**), (2) New Junction Concepts (**Bill Shafarman, Institute of Energy [IEC]**), (3) Substrate/ Mo Impact (**Bulent Basol, ISET**), (4) Transient Effects (**Dale Tarrant, SSI**), and (5) Diagnostic Development (**Bob Birkmire, IEC**). About 35 people from DOE, industry, NREL, and universities attended the meeting.

At the CdTe team review, presentations were made by team leaders **Chris Ferekides** (Thin CdS) and **Tom McMahon** (Stability). Considerable discussion focused on experiments needed to study the stability of cells and modules. Although stability of devices vary from group to group, SCI's cells, minimodules, modules, and systems tested at SCI, Toledo, OH; NREL, Golden, CO; and PVUSA, Davis, CA, have demonstrated remarkably robust performance. To test the effect of humidity, a 0.5-kW SCI array will be installed at **Florida Solar Energy Center**, Cocoa, FL. About 30 people from industry, NREL, and universities attended the meeting. **(Harin Ullal, 303-384 6486)**

Rajiv Arya and **Dave Carlson** of **Solarex** (Newtown, PA) visited **NREL** to meet with **H. Ullal** (CIS subcontract); **J. Benner** (new PV Center); **S. Deb, A. Nozik, D. Ginley, B. Gregg, J. Turner, A. Frank** (Graetzel cells); **T. Surek, H. Ullal, B. Von Roedern, K. Zweibel, J. Stone, E. Witt, R. Noufi** (PV Program Roundtable); **R. Crandall** and **H. Mahan** (a-Si hot wire); **T. Strand** and **R. DeBlasio** (Outdoor Test Site and 1-kW array);

Continued on page 15

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 1995 through June 1996, we awarded 150 subcontracts (examples listed below) totaling more than $18 million. For further information, contact Tom Surek (303-384-6471).

University of Central Florida
CdTe Module Testing and Study of Transient and Irreversible Effects in CdTe Thin-Film Cells
$30,000 (5/96–5/98)

Enertech Engineering
Installation of NREL Delta Tracker Project
$15,920 (4/96–8/96)

University of Colorado at Denver
Prototype Custom-Made PV Encapsulant and Solar Cell Degradation Monitor
$217,711 (3/96–9/97)

United Solar Systems Corp.
Thin-Film a-Si Alloy Research Partnership
$32,000 (1/96–7/96)

Antares Group Inc.
Studies and Analytical Support
$30,000 (4/96–6/96)

McNeil Technologies
PV Technology, Application, and Market Analysis Support$198,345 (6/96–10/96)

Crowder College
1996 Solar Bikerayce USA
$50,000 (4/96–10/96)

American Institute of Architecture
PV in Buildings: Self Study Course for Architects
$90,000 (4/96–10/97)

Applied Power Corp.
Earth Day Park PV Power System
$49,400 (4/96–7/96)

Tata Energy
Roundtable on Environmentally Sound Technologies
$10,000 (2/96–4/96)

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. 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).

Gwinner, D., ed. NREL Preprints for the Photovoltaic Specialists Conference of IEEE 25. May 1996; 166pp. NREL/TP-410-21091. NTIS No. DE96007880.(This document contains the complete text for all 40 papers summarized in this PVWWI newsletter.)

Arya, R.R.; Bennett, M.; Bradley, D.; Chen, L.; Jansen, K.; Li, Y.; Maley, N.; Newton, J.; Poplawski, C.; Rajan, K.; Yang, L. Amorphous Silicon Research: Annual Subcontract Report, 1 Oct 1994–30 Sept 1995. Feb 1996; 61pp. NREL/TP-411-20708. NTIS No. DE96000526.

Arya, R.; Fogleboch, J.; Kessler, J.; Russell, L.; Skibo, S.; Wiedeman, S. Research on Polycrystalline Thin-Film Submodules Based on $CuInSe_2$ Materials: Final Subcontract Report, 11 Nov 1990–30 June 1995. Jan 1996; 64pp. NREL/TP-413- 20566. NTIS No. DE96000514.

Deng, X. Development of High Stable Efficiency, Triple-Junction a-Si Alloy Solar Cells: Annual Subcontract Report, 18 July 1994–17 July 1995. Feb 1996; 86pp. NREL/TP-411-20687. NTIS No. DE96000530.

Froyen, S.; Zunger, A. Surface Segregation and Ordering in III-V Semiconductor Alloys. *Phys Rev B, Condensed Matter*. 15 Feb 1996-II; 53(8); pp.4570-4579.

Guha, S. Thin Film Amorphous Silicon Alloy Research Partnership, Phase I: Annual Technical Progress Report, 2 Feb 1995–1 Feb 1996. Apr 1996; 51pp. NREL/TP-413-21089. NTIS No. DE96007863.

Hall, R.B.; Rand, J.A.; Cotter, J.E.; Ford, D.H. Light-Trapped, Interconnected, Silicon-Film™ Modules: Annual Subcontract Report, 18 Nov 1994–18 Nov 1995. Mar 1996; 25pp. NREL/TP-413-20809. NTIS No. DE96000535.

Herwig, L.O., ed. U.S. Department of Energy Assessment of the PV Industry's Needs, Priorities, and Views Regarding the DOE Photovoltaic Program: A Summary of Feedback from Visits to 22 PV Companies. Feb 1996; 40pp. DOE/GO-10096-258. NTIS No. DE96000536.

Izu, M. Continuous Roll-to-Roll a-Si Photovoltaic Manufacturing Technology: Final Subcontract Report, 1 Apr 1992–30 Sept 1995. Feb 1996; 91pp. NREL/TP-411-20588. NTIS No. DE96000531.

Morel, D.L.; Ferekides, C.S. Advanced Processing Technology for High-Efficiency, Thin-Film $CuInSe_2$ and CdTe Solar Cells: Final Subcontract Report, 1 Mar 1992–30 Apr 1995. Jan 1996; 49pp. NREL/TP-451-20590. NTIS No. DE96000513.

Nowlan, M.J.; Hogan, S.J.; Breen, W.F.; Murach, J.M.; Sutherland, S.F.; Patterson, J.S.; Darkazalli, G. Automated Solar Cell Assembly Teamed Process Resesarch: Final Subcontract Report, 6 Jan 1993–31 Oct 1995. Feb 1996; 84pp. NREL/TP-411-20794. NTIS No. DE96000537.

Continued on page 15

The **Thin-Film PV Partnership CdTe and CIS Guidance Teams** met in February at **NREL**. The members of the CdTe Guidance Team are: **H. Ullal, K. Zweibel, L. Kazmerski, NREL; J. Mazer, DOE; P. Meyers, University of Delaware, Institute of Energy Conversion**; and **C. Ferekides, University of South Florida**. The members of the CIS Guidance Team are: **H. Ullal, R. Noufi, K. Zweibel, D. Ginley, L. Kazmerski, NREL; J. Mazer, DOE; J. Sites, Colorado State University**; and **T. Peterson, Electric Power Research Institute**. The Guidance Team agreed to invite all funded industry participants (**Siemens Solar Industries, International Solar Electric Technology, Energy Photovoltaics, Solarex**) to join the Guidance Team as advisors for subsequent meetings.

The **Thin-Film PV Partnership CdTe Team** meeting was held at the **Institute of Energy Conversion (IEC) at the University of Delaware**, Newark, DE, in January. The "Thin CdS" Team presented data on devices made by **Colorado School of Mines** (CSM), **IEC, NREL, Solar Cells, Inc.** (SCI), **University of South Florida** (USF), and **University of Toledo** (UT). The CdS thickness was varied from about 500 to 3000 Å. Detailed analysis and compilation of data of these devices were performed by **Colorado State University** (CSU). The Stability Team reported on recent studies done at NREL on SCI submodules, and on data on modules and arrays being tested at NREL. The **CIS Team** meeting was also held at **IEC**, Newark, DE, in January. The "Absorber" Team presented detailed observations and interpretations of the "NREL Blue Book" compiled for the previous meeting held in May 1995. Characterization techniques used included PL, SEM, SIMS, and XPS, with samples submitted by **Energy Photovoltaics** (EPV), **IEC, ISET, NREL,** NREL/**Lockheed-Martin** (LM), **Siemens Solar**, and **Solarex**. For the "Junction" Team, activities focused on data analysis and relationships between material properties, processes, and the resulting device performance. A new "NREL Pink Book" was compiled by NREL. **(Harin Ullal, 303-384-6486; Rommel Noufi, 303-384-6510)**

This summer, two Historically Black Colleges and Universities students and their professors will travel to Africa to work on PV projects. **Oral LaFleur** and **Professor Joshua Hill** of **Texas Southern University** will spend about one month at **Port Elizabeth Technikon** in South Africa to help develop PV training for South Africa's Renewable Energy for South Africa program. **Tosha Cameron** and **Professor Tuhfeh Habash** of **Wilberforce University** will spend one month in northeast Ghana to support a developing PV project for the United Nations Development Program. Four students, **Tameka Page** (**Southern University**), **Danisha Williams** (Southern University), **Raymond Haraway** (Wilberforce University), and **Natalie Bunkley** (**Hampton University**) started in June at NREL on projects in cell and module testing, flywheel energy storage, PV demonstrations for visitors and conferences, and buildings research. One student, **Christopher Trammel** (Southern University), will work on module testing with NREL subcontractor **Neelkanthe Dhere** at the **Florida Solar Energy Center**. NREL (or NREL subcontractor) mentors will guide these projects to provide meaningful work experiences for these undergraduates. **(Robert McConnell, 303-384-6419)**

News at Press Time, Continued from p. 11

Following the WREC meeting, NREL was visited by Mr. Ajit Gupta, Director (Power), Ministry of Non-Conventional Energy Sources. Mr. Gupta is responsible for India's larger, mostly grid-connected, renewable-energy system projects. He was interested in distributed utility concepts, and he supports NREL's efforts to make a proposal in this area to IREDA. Mr. Gupta will be splitting his time between MNES and the U.S. Agency for International Development during this coming year, and he represents an important contact for NREL in expanding its interactions in India. And in mentioning the U.S. Agency for International Development (USAID), NREL was visited by Dr. Dick Goldman and Ms. Kavita Sinha from USAID in New Delhi. They discussed the ongoing implementation of the MOU between NREL and MNES for which USAID has furnished travel expenses for both the Indian and U.S. participants. Goldman is interested in collaborating with NREL in the training planned for the Ramakrishna Mission project in West Bengal. The USAID visitors also were interested in NREL's education and training resources to be applied in India, as well as NREL's plans for doing a low-cost housing project with India's Housing and Urban Development as part of the original agreement between Secretary O'Leary and MNES Minister Kumar. (NREL Contacts: **Jack Stone, 303-384-6470; Harin Ullal, 303-384-6486)**

Industry Updates, Continued from p. 12

and **K. Touryan** (CIGS license). They also received an update concerning their 1-kW prototype a-Si array, which is undergoing stability testing at NREL's Outdoor Test Facility. **(Ken Zweibel, 303-384-6441)**

NREL has verified an aperture-area efficiency of 9.1% for a large-area, thin-film CdTe module (6728-cm^2) fabricated by **Solar Cells, Inc.** (SCI), Toledo, OH. This is the highest efficiency for any thin-film module in the world of this or similar size. The device structure is glass/SnO_2/ CdS/ CdTe/contact. The module parameters are J_{SC}=0.966 A, V_{OC}=95 V, FF=0.668. There are 116 cells monolithically interconnected in series by laser scribing. Also, NREL has verified a total-area efficiency of 13.1% for a thin-film CdTe solar cell fabricated by SCI on a low-cost, soda-lime glass substrate. **(Harin Ullal, 303-384 6486)**

NREL has received shipment of a battery-charging station from **Applied Power Corporation** (APC). The unit duplicates the two units being shipped to India as part of the **Ramakrishna Mission Project**. APC, working with the staff at NREL's Outdoor Test Facility, will develop plans for testing the unit and deploying it as part of the small systems applications for non-grid-connected applications. Battery charging is an important function for village applications, and NREL's demonstration should attract visitors interested in applying PV systems in the rural environment. **(Jack Stone, 303-384-6470)**

Miguel Contreras of NREL's CIS Team is concluding on-site work at **Lockheed Martin** (LM) under a CRADA agreement. The purpose of this work is two-fold: (1) transfer CIS fabrication techniques as taught by the intellectual property covered under NREL's related CIS patents, an (2) aid LM in operation and optimization of hardware (processing system). LM built a prototype large-area processing machine—the Dynamic Research System (DRS)—to investigate scale-up of CIS. This multichamber in-line DRS machine can process CIS by both sputtering and evaporation. Initially, efforts focused on implementing reaction pathways to fabricate $CuInSe_2$ only (no Ga), under the constraints imposed by the design and starting materials of the DRS. **(Miguel Contreras, 303-384-6478; Rommel Noufi 303-384-6510)**

NREL was visited by **Mohan Misra, Joe Armstrong**, and **Dean Spieth** of **ITN Energy Systems Inc.**, in Wheat Ridge, CO. The company wants to replicate the Ramakrishna Mission project in the state of Bihar, which is adjacent to West Bengal, India. Home lighting of 600 homes would be provided, with funding coming entirely from the state. ITN is interested in NREL's experiences with the West Bengal project and in having NREL provide technical information associated with the systems to be fielded in the Sundarbans. The project in West Bengal was a result of agreements between Secretary **Hazel O'Leary** and former Minister **Krishna Kumar** of the **Ministry of Non-Conventional Energy Sources**. **(Jack Stone, 303-384-6470 and Harin Ullal, 303-384-6486)**

A $20K work-for-others contract has been completed with the **Jet Propulsion Laboratory** for NREL's help with the power system for the New Millennium DS-1 mission. This new technology, named SCARLET (Solar Concentrator Array with Refractive Linear Element Technology), is based on the GaInP/GaAs multijunction cell developed at **NREL** and manufactured at **TECSTAR** and on a linear Fresnel lens designed by **ENTECH.** NREL's role is to help with risk mitigation: trying to identify potential problems and correct them in a timely way. If SCARLET is successful, it may become the industry norm, bringing us one step closer to a commercially viable, very-high-efficiency terrestrial concentrator technology. The outdoor system (cell and lens combined) efficiencies being measured at ENTECH (using production cells from TECSTAR) are often as high as 25%. **(Sarah Kurtz, 303-384-6475)**

From January through May, **NREL's PV Cell and Module Performance Characterization Team** performed 645 one-sun and concentrator I-V, 414 QE, and 121 dark I-V measurements on PV cells for a variety of groups. Internal to NREL: CdS/CdTe, CdS/CIGS with and without Cd, nano-crystal dye-sensitized electrochemical cells, GaInP/GaAs tandems, GaAs, GaInP, thinned InP/GaInAs, multi-Si with degraded EVA. External to NREL: **Alpha Solarco** (mono-Si), **ASE Americas** (multi-Si), **ASEC** (GaInP/GaAs tandems in cooperation with NREL), **AstroPower** (Si film), **ENTECH** (mono-Si cells with prismatic cover), **Institute for Energy Conversion** (a-Si, CdTe, CIGS), **Georgia Institute of Technology** (mono-Si and multi-Si), **Golden Photon** (CdS/CdTe), **ISET** (multi-Si, CIS), **Materials Research Group** (mono-Si), **MicroFab Technologies** (multi-Si), **Photon Technologies** (mono-Si), **Solar Cells Inc.** (CdTe), **Solarex** (multi-Si), **Siemens Solar** (CIGSS with and without Cd), **Solec Int.** (mono-Si), **Sunwize** (mono-Si), **Univ. of S. Florida** (CIGS, CdTe), **Univ. of Toledo** (CdS/CdTe), **United Solar Systems Corp.** (light-soaked a-Si/a-Si:Ge/a-Si:Ge cells), **Western Illinois Univ.** The team also evaluated cells for international groups in Australia from the **Univ. of New South Wales** (mono-Si and multi-Si), in Belgium from **IMEC** (mono-Si), in India from **RES PV, CEL, National Physical Lab, Udhya** (mono-Si), in Israel from the **Univ. of Tel Aviv** (GaAs and mono-Si), in Italy from **ENEA** (mono-Si), in Japan from **Japan Energy Co.** (GaInP/GaAs), and **Showa Shell** (CIGSS with no Cd in cooperation with **Siemens Solar**), in Russia with the U.S. company **L.D. Partners** (mono-Si), in Spain from **IES-University Politecnica Madrid** (bifacial Si), in Switzerland from the **Univ. of Neuchatel** (a-Si/micro-crystal-Si) and **EPFL** (nano-crystal dye-sensitized electrochemical cells and submodules), and in Taiwan from **I.T.R.I.** (mono-Si). **(Keith Emery, 303-384-6632)**

During January through May, 144 module measurements were performed outdoors under prevailing clear sky conditions and 396 on the SPIRE 240 solar simulator to support in-house contract deliverables, PVMaT, the technology validation program, the a-Si light-soaking program to determine the stabilized efficiency, the stability/reliability program, and the PV industry. Modules were evaluated from **APS** (a-Si/a-Si), **ARCO** (a-Si), **ASE Americas** (ribbon Si), **ASM** (a-Si), **AstroPower** (Silicon Film), **BP Solar England** (mono-Si), **CEL India** (mono-Si), **ECD/Sovlux** (a-Si/a-Si:Ge/a-Si:Ge), **Fuji** (a-Si/a-Si), **Golden Photon** (CdS/CdTe), **Iowa Thin Film** (a-Si), **Kaneka** (a-Si/a-Si), **Photocom** (mono-Si), **RES PV India** (mono-Si), **Siemens Solar** (mono-Si, CIS, CIGSS), **Solar Cells Inc.** (CdS/CdTe), **Solarex** (multi-Si, a-Si/a-Si:Ge, a-Si/a-Si/a-Si:Ge), **Solec Int.** (mono-Si), **Solvonics** (a-Si/a-Si:Ge), **United Solar Systems Corp.** (a-Si/a-Si:Ge/a-Si:Ge), **Sun Corp.** (Si ribbon), and **Utility Power Group** (a-Si, a-Si/a-Si). **(Keith Emery, 303-384-6632)**

Publications, Continued from p. 13

Rohatgi, A.; Chou, H.C.; Kamra, S.; Bhat, A. Development of High Efficiency, Thin Film CdTe Solar Cells: Final Subcontract Report, 1 Feb1992–30 Nov 1995. Jan 1996; 306pp. NREL/TP-451-20688. NTIS No. DE96000516.

Solar Electric Buildings: An Overview of Today's Applications. Feb 1996; 35pp. NREL/TP-411-20865. DOE/GO-10096-253. NTIS No.DE96000524.

Sopori, B.; Kimerling, K.; Schroder, D.; Mishra, K. Summary of the Second Working Group Meeting on the Minority Carrier Diffusion Length/Lifetime Measurement. Mar 1996; 7pp. NREL/ TP-413-20927. NTIS No. DE96007861.

Ullal, H.S.; Witt, C.E., eds. 13th NREL PV Program Review: Proceedings of the Review Meeting, 16–19 May 1995, Lakewood, CO. *AIP Conference Proceedings No. 353*. NY: American Institute of Physics; 1996:

Wang, L.W.; Zunger, A.; Mader, K.A. Direct Calculation of the Transport Properties of Disordered AlAs/GaAs Superlattices from the Electronic and Phonon Spectra. *Phys Rev B, Condensed Matter*. 15 Jan 1996-II; 53(4); pp.2010-2019.

Wei, S.H.; Zunger, A. Giant and Composition-Dependent Optical Bowing Coefficient in GaAsN Alloys. *Phys Rev Letters*. 22 Jan 1996; 76(4); pp.664-667.

Wohlgemuth, J. Cast Polycrystalline Silicon Photovoltaic Module Manufacturing Technology Improvements: Semiannual Subcontract Report, 1 Jan 1995–30 June 1995. Feb 1996; 38pp. NREL/TP-411-20589. NTIS No. DE96000527.

Zhang, S.B.; Zunger, A. Method of Linear Combination of Structural Motifs for Surface and Step Energy Calculations: Application to GaAs(001). *Phys Rev B, Condensed Matter*. 15 Jan 1996-I; 53(3); pp.1343-1356.

PV Calendar

August 12–14, 1996, *6th Workshop on the Role of Impurities and Defects in Silicon Device Processing*. Sponsor: NREL. Location: Snowmass Village, CO. Contact: Bhushan Sopori. Phone: 303-384-6683.

September 4–6, 1996, *Photovoltaic Performance and Reliability Workshop*. Sponsor: NREL. Location: Lakewood, CO. Contact: Heather Bulmer, Conference Coordinator. Phone: 303-275-4317.

September 16–19, 1996, *10th DGS International Solar Forum*. Sponsor: Deutsche Gesellschaft für Sonnenenergie e.V., Frauhofer-Institut für Solare Energiesysteme. Location: Freiburg im Breisgau, Germany. Contact: Deutsche Gesellschaft für Sonnenenergie e.V., Augustenstr. 79, D-80333, München, Germany. Telefax: +49(0)89-521668.

November 17, 1996, *Photovoltaics in Buildings: Design Guidance for Practicing Architects and Design Professionals*. Sponsor: American Institute for Architectural Research. Location: Los Angeles, CA. Contact: AIA, Stephanie Vierra. Phone: 202-879-7752.

November 18–22, 1996, *14th NREL/ Sandia Photovoltaics Program Review Meeting*. Sponsor: NREL. Location: Lakewood, CO. Contact: Jill Harty, Conference Coordinator. Phone: 303-275-4321.

April 25–30, 1997, *SOLAR 97: Energy for a Sustainable Prosperity*. Sponsor: American Solar Energy Society, U.S. DOE. Location: Washington, D.C. Contact: ASES. Phone: 303-443-3212

May 27–29, 1997, *The World Sustainable Energy Trade Fair*. Sponsor: Amsterdam RAI and Novem. Contact: European Media Marketing Ltd. Phone: +44-171-582-7278. Fax: +44-171-793-8007.

The purpose of this quarterly report is to encourage cooperative research and development by providing the U.S. PV industry with information on the activities and capabilities of the laboratories and researchers at NREL.

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