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Overview of NREL's Photovoltaic Advanced R&D Project

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OVERVIEW OF THE NATIONAL RENEWABLE ENERGY LABORATORY's PHOTOVOLTAIC ADVANCED RESEARCH AND DEVELOPMENT PROJECT

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The National Renewable Energy Laboratory's (NREL's) Photovoltaic Advanced Research and Development (PV AR&D) Project supports the U. S. Department of Energy's National Photovoltaics Program in assisting the development and commercialization of photovoltaics (PV) energy technology. The NREL program is implemented through in-house research and subcontracts, with over 50% of the annual budget awarded through competitive solicitations to universities, large and small businesses, and other research centers. These activities include cost-shared, multiyear, government/industry partnerships and technology initiatives. The research has resulted in a better fundamental understanding of materials, devices, and processes, the achievement of record efficiencies in nearly all PV technology areas, the identification of promising new approaches to low-cost photovoltaics, and the introduction of new PV technology products into system experiments and PV markets. This paper presents an overview of NREL's PV AR&D Project in terms of the project organization and budgets, near- and long-term project objectives, research participants, and current and future research directions. Recent progress in the in-house and subcontracted research activities is described.

1. INTRODUCTION

The National Renewable Energy Laboratory (NREL), formerly the Solar Energy Research Institute (SERI), is the U. S. Department of Energy's (DOE's) primary laboratory for solar and renewable energy research. NREL's Photovoltaic Advanced Research and Development (PV AR&D) Project is conducted for DOE's Photovoltaics Division under the Office of Solar Energy Conversion, under the Office of Utility Technologies. NREL, as one of two research centers designated by DOE, shares responsibility with Sandia National Laboratories ([SNLA], Albuquerque, New Mexico) for the conduct and management of federal photovoltaic research as presented in the new DOE *Photovoltaics Program Plan, FY 1991 - FY 1995* [1]. The previous DOE PV research plan [2] placed heavy emphasis on materials and cell research. The current, balanced plan builds on the results achieved under the previous plan, emphasizing cost reduction and the transfer of technology to the private sector as well as continuing basic laboratory research. The plan represents a consensus among researchers and manufacturers as well as current and potential users of photovoltaics.

The mission of the national PV program is to develop photovoltaic technology for the large-scale generation of economically competitive electric power in the United States, making PV a significant part of our energy mix. Table 1 quantifies the DOE PV program's mid- and long-term goals as well as the current (1991) achievements. In addition to meeting technical and cost goals, the program aggressively supports the development of the industrial base needed for PV to penetrate the various energy end-use sectors. Program activities include continuing efforts at forming partnerships with PV manufacturers, utilities and other users, universities, and federal and state agencies.

The purpose of NREL's PV AR&D Project is to conduct, foster, and manage high-payoff research, development, and application activities in PV that will result in a domestic technology base that promotes U. S. national energy security, industrial growth and competitiveness, and a clean environment. NREL's PV AR&D Project activities range from fundamental and supporting research, to materials, cells, and modules research, to manufacturing technology development, to systems and market

Factor	Current Achievements (1991)	Mid-term Goals (1995-2000)	Long-term Goals (2010-2030)
Module Efficiency (%)	5 - 15	10 - 20	15 - 25
Electricity Price (¢/kWh, $ 1990)	25 - 50	12 - 20	5 - 6
System Lifetime (years)	10 - 15	20	30
Installed Capacity (MW)	<50	200 - 1,000	10,000 - 50,000

Table 1. DOE Photovoltaics Program goals [ref. 1]

MASTER

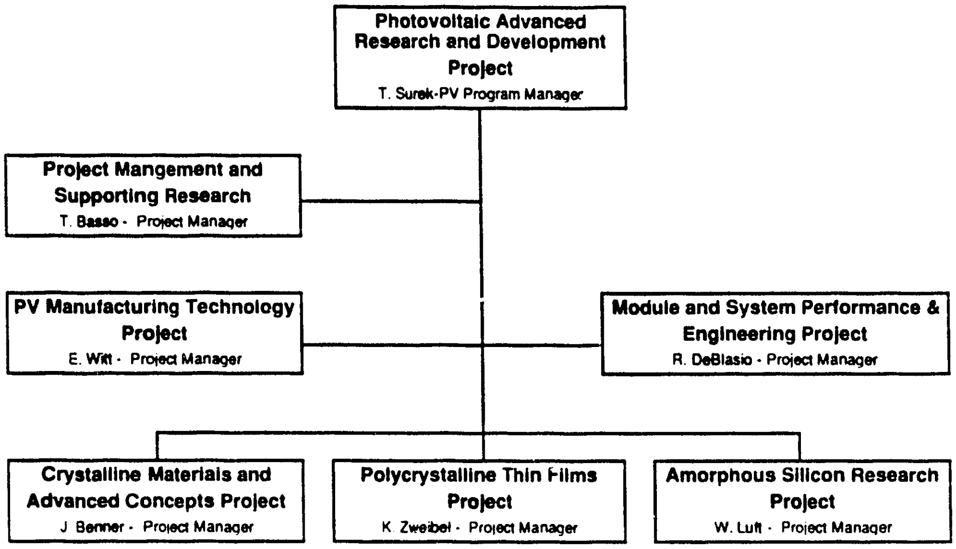

Figure 1. Organization of NREL's Photovoltaic Advanced R&D Project

development. The project emphasizes a balanced research and development (R&D) path from improving current technologies to the development of promising new approaches to photovoltaic cells, such as new silicon technologies, and thin-film and multijunction concepts. Increasing emphasis is being directed to working more closely with industry, utilities, and other end users on PV manufacturing technology, systems, and marketing needs.

The PV AR&D Project's specific activities involve conducting basic, applied, and engineering research, managing subcontracted R&D, performing research complementary to subcontracted work, developing state-of-the-art measurement and characterization capabilities, performing PV manufacturing technology and module development, transferring results to industry, and evolving viable partnerships for PV system and market development. The primary PV research activities are conducted in advanced photovoltaic material and device technologies, including amorphous silicon materials, polycrystalline thin films (such as thin crystalline silicon, copper indium diselenide, cadmium telluride, and related alloys), and crystalline silicon, gallium arsenide, and other III-V high-efficiency materials. This paper presents an overview on the PV AR&D Project. A review of project organization and budgets is given in section 2. Sections 3 to 7 provide reviews of the major project elements, including project objectives, research directions and participants, and recent technical highlights.

2. PV AR&D PROJECT ORGANIZATION AND BUDGET

The PV AR&D Project organization is shown in Figure 1. Three technology-specific projects address the major PV material areas: silicon and III-V materials (under the Crystalline Materials and Advanced Concepts Project); $CuInSe_2$ (or CIS), CdTe, and thin-film polycrystalline silicon (under the Polycrystalline Thin Films Project); and amorphous silicon and alloys (under the Amorphous Silicon Research Project). The Photovoltaic Manufacturing Technology (PVMaT) Project covers all PV technology areas from flat-plate to concentrator modules. The PV Module and Systems Performance and Engineering Project is another cross-cutting activity for all technology areas (with emphasis on flat-plate rather than concentrator modules/systems) from cell and module measurements, to solar radiation research, to system and market development. These projects are discussed in the following sections.

The NREL in-house research and project management activities are carried out primarily under two research divisions: the Photovoltaics Division (including the Measurements and Characterization Branch, PV Device Development Branch, and PV Engineering and Applications Branch) and the Basic Sciences Division (including the Materials Science Branch). NREL's Analytic Studies Division supports some of the solar radiation research activities under the project. Approximately 100 highly qualified scientists, engineers, technicians, managers, analysts, and other professionals at NREL conduct the research, along with some 30 visiting scientists and part-time students. As a measure of NREL's PV research contributions, we have received more than 30 patents and 6 R&D 100 Awards, and publish some 200 technical papers annually on PV-related research. (Specific research activities carried out by each of the branches are outlined in Tables 3 to 7 in the following sections.) Table 2 shows the distribution of subcontract funds by material category or program element, along with a historical summary of the funding. The NREL in-house funding emphasis is similar to that of the subcontracted program. More than 50% of the PV AR&D Project budget is allocated yearly to subcontracts; historically, more than 56% of the project funds were spent on subcontracted research (the amounts in Table 2 include 10% to 15% for program management and fees). In fiscal year (FY) 1992, some 70 organizations are carrying out subcontracted research activities

	FY 1978-90 ($M)	FY 1991 ($M)	FY 1992 ($M)
NREL In-House			
Research	83.8	12.3	14.2
Capital Equipment	15.3	0.6	1.4
Subtotal: In-House	99.1	12.9	15.6
Subcontracts[(a)]			
a-Si Thin Films	72.9	3.3	3.8
Polycrystalline Thin Films	45.4	4.5	4.4
High-Efficiency	34.5	1.3	1.2
Crystalline Silicon	23.2	0.9	0.9
New Ideas	18.4	0.3	0
University Program	6.1	0.8	0.6
PV MaT	1.7[(b)]	6.7	11.0
Module and Systems Eng'g.	(c)	2.0	0.3
Subtotal: Subcontracts	202.2	19.8	22.2
Total: NREL PV AR&D Project	**301.3**	**32.7**	**37.8**

(a) Includes 10% to 15% for program management, fees, etc.
(b) Project initiated in FY 1990.
(c) No significant subcontract funding prior to FY1991.

Table 2. Budget history for the NREL PV AR&D Project

under the project, with the total annualized level (on a 12-month basis) of the research being in excess of $25 million. Industry is expected to provide some $9 million additional in cost-sharing of the subcontracts. Figure 2 shows the breakdown of the FY 1992 budget for the project by subcontractor business category. Nearly two-thirds of the subcontracts are with universities, with FY 1992 funding of approximately $4 million (the annualized level of the research activities is nearly $6 million).

The project management and supporting research activity (see Figure 1) provides the overall program and line management (division and branch) oversight for the NREL PV program. This project element is responsible for program management, integration, analysis, administration, budget control, and reporting as well as for oversight and development of staff, equipment, and facilities to provide the foundation for consistent program progress and growth. The project also provides overall leadership and direction for the NREL PV program as well as support for the DOE PV program in terms of program strategy and development. The overall management team also ensures that program-specific environment, safety, and health, as well as quality assurance requirements, are planned and implemented.

3. CRYSTALLINE MATERIALS AND ADVANCED CONCEPTS PROJECT

The objectives of this project are threefold: (1) to assist the crystalline silicon industry in analysis and optimization of their materials and post-growth cell fabrication processes; (2) to develop cost-effective materials preparation technology for high-efficiency photovoltaics; and (3) to support fundamental and exploratory research leading to higher efficiency photovoltaic modules.

Crystalline Silicon Materials Research: Although crystalline silicon (c-Si) technologies for material growth and device processing are considered to be mature for a variety of applications, there remain a host of issues about which the current understanding is only marginal. These issues pertain to the role of defects and impurities in altering the properties of silicon and silicon solar cells. It is generally recognized that the presence of impurities/defects in the substrate can degrade the cell performance; however, recent data show that, in the presence of crystal defects, the influence of impurities on the cell performance is somewhat mitigated. It is also known that some defects can be passivated by the presence of hydrogen or oxygen, although a detailed knowledge of these effects is certainly lacking. Clearly, these issues are critical to photovoltaic technology based on use of low-cost c-Si substrates that contain high concentrations of impurities and/or defects. The research program is conducted in close collaboration with the c-Si industry to ensure that industry research needs, pertaining to basic material issues, are adequately addressed. In this coordinated research effort between industry, universities, and NREL, the NREL role is primarily to support the area of test device fabrication and analysis in order to relate material characteristics directly to solar cell performance. We established at NREL the capability for routine fabrication of diagnostic devices with baseline efficiencies of 15% in Czochralski material.

The c-Si research program is aimed at developing an understanding of the basic mechanisms related to the influence of

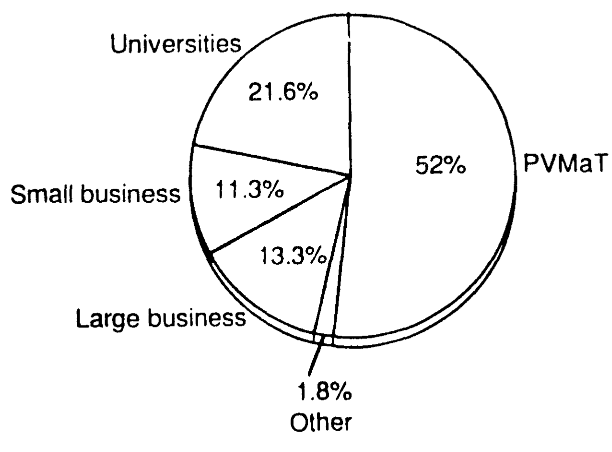

Figure 2. FY 1992 subcontract funding by business category (total subcontracts = $18.5 million, cost-share by industry = $9 million [est.])

impurities and defects on the important photovoltaic parameters in silicon. In particular, emphasis is placed on development of post-growth processes that can be applied to low-cost substrates, preferably as a part of the solar cell fabrication process. Major areas of research are: (1) mechanisms of hydrogen and oxygen interaction in low-cost silicon; (2) mechanisms of hydrogen passivation and kinetics of hydrogen diffusion; (3) effects of hydrogen on solar cells containing different types of crystal defects; (4) development of techniques for impurity characterization in silicon containing crystal defects; and (5) non-destructive testing of the photovoltaic parameters of commercial c-Si materials. In the coming year, an effort will be made to develop some low-cost cell processing techniques that incorporate the knowledge obtained from this research to fabricate high-efficiency cells on commercial solar cell silicon. The subcontracted portion of the program (see Table 3) was recompeted towards the end of FY 1991, and awards are expected to be made in early 1992.

In silicon materials development at NREL, crystal growth researchers have focused on float-zone silicon crystal growth for material defect studies, with particular emphasis on microdefect responses to nitrogen and oxygen impurities, and grain boundary/grain size effects on the PV performance of thin solar cells. Growth studies are under way on low-oxygen Si materials. Investigations are also proceeding on novel techniques for depositing thin c-Si materials from solutions. Initial experiments in porous silicon at NREL yielded photo-stimulated light emission.

High-Efficiency Materials and Cells: The objective of the research on high-efficiency materials and cells is to evaluate and develop advanced photovoltaic technologies capable of energy conversion efficiencies in excess of 20% for flat-plate modules and greater than 25% for concentrator modules. These goals are discussed in the DOE five-year plan [1] as commercial technology targets for the 2010-2030 period. Even on this longer-term horizon, it is difficult to envision a technology capable of achieving such high efficiencies without incorporating the demonstrated performance of crystalline III-V semiconductors. Thus, high-efficiency materials and cells research has become synonymous with III-V compound semiconductor research.

NREL's program of research in high efficiency has approached the terrestrial photovoltaics goals from the direction of first demonstrating the feasibility of exceeding the efficiency targets, and then assuring that production engineering trade-offs between performance and cost can be accommodated. Recent advancements by the community researching high-efficiency technologies provide a high level of confidence that the efficiency goals can readily be met.

The achievement of 25% efficiency in commercial concentrator modules will likely require production cells having more than 30% efficiency. The system cost-target for that efficiency corresponds to cell costs of less than $10/cm^2. At least three organizations have demonstrated a single-junction GaAs cell at nearly this efficiency level. Recent successes in multijunction devices show encouraging progress toward fulfilling the promise

Research Organization	Research Area
High-efficiency Subcontracts	
Boeing Aerospace & Electronics	Feedstock generation for single crystal $CuInSe_2$ cells on GaAs
Colorado State University	Feedstock generation for MOCVD
Kopin Corporation	High-eff. thin-film III-V cells
Purdue University	New III-V cell design approaches
Rensselaer Polytechnic Inst.	MOCVD crystal growth
Research Triangle Institute	Quaternary materials for ultra-high-efficiency
Spire Corporation	New growth for GaAs/Si cells
University of Southern California	Atomic layer epitaxy for low-temperature growth of GaAs
Crystalline Silicon Subcontracts	
Six awards expected in 1992	Crystalline Si Materials RFP
Colorado School of Mines	Industrial silicon analysis
Georgia Institute of Technology	Impurity characterization and device fabrication support
University Participation Subcontracts	
North Carolina State Univ.	High-efficiency III-V solar cells
North Carolina State Univ.	Remote plasma deposition of a-Si
Stanford University	Photon-assisted doping of II-VIs
University of Utah	Electronic processes in a-Si
New Ideas Subcontracts	
Institute of Energy Conversion	Solution growth of ZnTe and ZnSe films
Research Triangle Institute	Inverted AlGaAs/GaAs cell
University of Southern California	Epitaxial optical reflector high-efficiency cell
National Renewable Energy Laboratory	
Materials Science Branch	Theory, basic studies, crystal growth, III-V growth, silicon processing
Measurement and Characterization Branch	Characterization, analyses, reliability, cell and module meas.
PV Device Development Branch	Device fabrication and characterization of Si, and III-Vs; InP-based cells
PV Engineering and Applications Branch	Module/system performance and engineering, reliability, market development

Table 3. Research supported by the Crystalline Materials and Advanced Concepts Project

of providing commercial cells with more than 35% efficiency. However, a fivefold reduction in processing costs would be needed to meet the cell cost-target for concentrator cells. Much of this reduction can be achieved through use of larger wafers and higher throughput deposition systems. Research supported by this program benefits future development efforts by strengthening the understanding of basic mechanisms that affect uniformity of doping, composition, and thickness over large-area wafers, from wafer-to-wafer and from run-to-run. Efficient utilization of source materials and evaluation of potentially superior sources (based on cost, purity, control, safety, and other factors) are also important topics for research. Continued improvement in cell efficiency is also a critical factor in reaching cost-effectiveness for the technology. The subcontracted program in high efficiency (Table 3) focuses on these issues for high-efficiency materials and cells.

Researchers at NREL have been among the leaders in developing high-efficiency multijunction devices. Olson and co-workers developed a lattice-matched $GaInP_2/GaAs$ multijunction cell of 27.3% one-sun efficiency; the efficiency should approach 35% under concentrated sunlight. Three companies are involved in the commercialization of this cell technology for which the NREL researchers received the prestigious R&D 100 Award in 1991. Wanlass and co-workers developed two concentrator multijunction cells that measured in excess of 30% under concentration (the work was supported, in part, by the Naval Research Laboratory). A three-terminal, monolithic InP/GaInAs tandem solar cell was measured at 31.8% efficiency (50 suns) and 30.7% efficiency (100 suns), while a four-terminal, mechanically-stacked GaAs/GaInAsP cell was measured at 30.2% efficiency (40 suns). The former result represents the first time a monolithically-grown multijunction structure exceeded 30% efficiency.

Flat-plate technologies have several advantages relative to concentrator technologies because the ability to utilize both the direct and diffuse components of the solar resource increases the geographical range of operation, simplifies system design and operation, and opens a variety of market opportunities for small installations. High-efficiency modules can be achieved either through development of multijunctions and/or development of processes for low-cost deposition of single crystal thin films. Two technologies have already reached performance levels consistent with the efficiency goals. One approach, which produces thin crystalline films separated from a reusable substrate in a process called CLEFT (cleaved lateral epitaxial films for transfer), has reached cell efficiencies of 23.3% (4-cm^2 area). A 16-cm^2-area CLEFT mini-module was measured at 21% efficiency. Thin films of GaAs grown on silicon substrates are also closing in on the 20% efficiency target, having improved from 11% to 17.6% efficiency in the past two years.

Fundamental and Exploratory Studies: The third task area covers fundamental research and advanced concepts. This includes in-house efforts in solid-state theory, establishment of new capabilities for growth and analysis of PV materials and devices, and evaluation of new material systems for potential PV applications. The subcontract programs in University Participation and New Ideas are also included here.

NREL's research on solid-state theory focuses on achieving a better understanding of the electronic and structural properties of existing and future PV semiconductors. This has led to innovative concepts and the selection of novel materials and configurations for further R&D. A recent important contribution was the theoretical prediction of spontaneous ordering in semiconductor alloys, specifically in the Ga-In-P system now undergoing technology transfer to industry.

The ***New Ideas Program*** identifies innovative approaches to existing technology, new materials, new device configurations, and new photovoltaic concepts. We periodically issue requests for letters of interest (LOI) to identify new concepts, and the most promising ones receive funding for one year. If a concept shows significant potential, it is supported for an additional year, with the possibility of transferring the project to the appropriate major PV program area for extended support. To date, more than 50% of the initial research conducted under this program has been worthy of further research funding, patents, or commercial product development. We issued a LOI solicitation in late FY 1991 and received more than 100 responses; subcontract awards are expected to be made in the late FY 1992/early FY 1993 timeframe. Research is continuing in three projects selected in 1989 (Table 3). The Bragg-reflector concept proposed under the University of Southern California subcontract has already resulted in significant improvements in open-circuit voltages of experimental devices (fabricated by Spire Corporation) and has opened up the possibility of reaching 30% efficiency in single-junction GaAs solar cells.

The objective of the ***University Participation Program*** is to maximize the contribution of universities to the future of PV technology by focusing on the traditional needs and strengths of that community. Thus, it provides a forum in which the university researchers identify research topics critical to the advancement of PV technology with minimal influence from current programmatic interests. The selected participants are then permitted to pursue the proposed basic and applied research ideas in an environment designed to foster creativity by limiting requirements for delivery of reports, samples, and achievement of specific goals. Reporting is limited to annual reports and journal publications. Research symposia, organized by the participants, are held periodically and are open to all students, program participants, and outside researchers. The intent of the program is to provide continuity of funding over a minimum three-year period, which allows universities to build and support interdisciplinary teams with specialized expertise that can be applied to furthering the technology base of photovoltaics. Such a program is expected to attract the most highly qualified university research teams to the DOE National Photovoltaics Program. The program also supports the PV industry through the technology transfer that occurs not only by publication of research results in the technical literature, but also through enhanced student awareness of PV technology and the education of future professionals (see Table 3 for current participants).

4. POLYCRYSTALLINE THIN FILMS PROJECT

The objective of this project is to develop thin-film, flat-plate modules that meet DOE's long-term goals of reasonable

Research Organization	Research Area
Government/Industry Subcontracts	
AstroPower	Silicon-film PV submodules
Boeing Aerospace & Elect.	$CuInGaSe_2$ thin-film devices
International Solar Electric Technology	E-beam-sputtered Cu,In layers and selenization; submodules
Martin Marietta	Sputtering techniques for $CuInSe_2$ and CdTe modules
Photon Energy	Large-area CdTe submodules
Siemens Solar, Inc.	High-efficiency $CuInSe_2$ modules
Solarex Corporation	Sputtered $CuInSe_2$ submodules
Solar Cells, Inc.	Close-spaced sublimation CdTe modules
University Subcontracts	
California Institute of Technology	Contact investigation of $CuInSe_2$/Mo interface
Colorado State University	Characterization and modeling of CdTe and $CuInSe_2$ cells
Georgia Institute of Tech.	MOCVD CdTe and CdZnTe cells
Institute of Energy Conversion	Selenized and evaporated $CuInSe_2$; CdTe cells; device modeling
Purdue University	Modeling $CuInSe_2$ and CdTe cells
University of Colorado	Rapid thermal processing Cu/In/Se films made by electroplating or sputtering
University of Illinois	Sputtered/evaporated $CuInSe_2$ cells
University of South Florida	MOCVD and close-spaced sublimation of CdTe & ZnTe cells
University of Toledo	Laser-ablation fabrication of CdTe
Colorado School of Mines Georgia Institute of Tech. Purdue University Univ. of Central Florida Univ. of South Florida Washington State Univ.	Fundamental University Research Competition (awards under negotiation)
National Renewable Energy Laboratory	
Measurement and Characterization Branch	Characterization, analyses, reliability, cell and module meas.
PV Device Development Branch	Growth, characterization, device fabrication of $CuInSe_2$ and CdTe
PV Engineering and Applications Branch	Module/system performance and engineering, reliability, solar radiation research, market dev.

Table 4. Research supported by the Polycrystalline Thin Films Project

efficiencies (15%-20%), very low cost (near $50/m^2), and long-term reliability (30 years). The approach relies on developing PV devices based on highly light-absorbing compound semiconductors such as $CuInSe_2$ (CIS) and CdTe, and on low-cost thin-film silicon using light-trapping techniques. The underlying approach is to fabricate modules with minimal material and processing costs. The project task areas include subcontracted research (government/industry partnerships and a university research program), NREL in-house CIS and CdTe research, and a coordinated program of NREL characterization research.

Substantial technical progress has been made in this project in the recent past. The major advancements include (1) accelerated growth of the U. S. industrial infrastructure supporting CIS, CdTe, and Si-film; (2) a breakthrough total-area thin-film CdTe solar cell efficiency of 14.6% (1-cm^2 area) for a cell fabricated by Professor T. Chu and co-workers at the University of South Florida; (3) achievement of a record thin-film CIS power module (4-ft^2) aperture-area efficiency of 9.7% by Siemens Solar; (4) improved aperture-area (near 1-ft^2) efficiency of 8.1% for a thin-film CdTe module by Photon Energy; (5) progress in improved CIS/Mo adhesion by addition of a very thin tellurium layer between the Mo and the CIS (resulting in patent awards to International Solar Electric Technology [ISET]); (6) continued success of multiyear outdoor stability tests of prototype CIS and CdTe modules; and (7) the demonstration (by AstroPower) of a monolithically interconnected thin-film silicon mini-module.

The improved efficiencies and larger areas of CIS and CdTe devices, and their apparent stability, are the major recent advances in these technologies. But polycrystalline thin-film cells require continued development to achieve 15%-20% conversion efficiencies. The major strategy is development of improved single-junction cells. Improvement of the single-junction technologies has been steady and reliable. Potentially achievable cell efficiencies approach 20%, and projections indicate the likelihood of fabricating modules of more than 15% efficiency. A key to achieving the higher efficiencies is to improve the fundamental understanding of the materials and device structures. NREL and university researchers have been the major contributors in this area. Studies at NREL on CIS-based materials have provided comprehensive information on film processing parameters versus properties (electrical, optical, microstructural, and morphological). More recently, the emphasis is on understanding the phase behavior and microstructure of the Cu/In precursor used for selenization. Modeling studies are guiding ways to help improve the solar cell parameters and to develop higher efficiency cell designs. The fundamental university research program in CIS and CdTe was recompeted in FY 1991, and awards will be made in early 1992 to six university subcontractors (see Table 4).

The coordinated characterization task at NREL is focused on developing and refining characterization techniques tailored to the special demands of polycrystalline thin films. The task maintains close ties with industry and university researchers to maximize cooperation and relevance. Current focus of the characterization task is on problems of CdS/CdTe interface alloying, CdTe grain size as a function of growth conditions and film thickness, junction characteristics of CdTe/CdS and CIS/CdS devices, defects in CdTe grains and grain boundaries, minority carrier lifetimes in CIS and CdTe films, and secondary phases and compositional variations in CIS films.

Developing scalable, low-cost fabrication methods is important in providing industry with a foundation for future large-area, high-throughput commercial processes. Research methods for fabricating polycrystalline cells include (1) for CIS: sputtering followed by selenization (Siemens Solar, Martin Marietta, International Solar Electric Technology, Solarex, and NREL), a reactive-sputtering and hybrid sputtering/evaporation method (University of Illinois and Solarex), and evaporation (Boeing, IEC, and NREL); and (2) for CdTe: close-spaced sublimation (Solar Cells, Inc., University of South Florida [USF], and NREL), evaporation (Institute of Energy Conversion [IEC]), metal-organic chemical vapor deposition (Georgia Institute of Technology and USF), and spraying (Photon Energy). For CIS, we are also investigating non-H_2Se selenization methods at NREL and IEC. We also initiated work at NREL in sputtering of CdTe. In addition, with the recent retirements of Professors T. Chu and S. Chu from USF, we have transferred the CdTe and CdS capabilities from USF to NREL (with assistance from the professors).

An initiative in the Polycrystalline Thin Films Project was begun with the release of a request for proposals (RFP) in FY 1989. The objective of the solicitation was to stimulate progress in CIS and CdTe submodule development and to deepen the U.S. industry participation in these promising technologies. The private sector responded favorably, and several new cost-shared (30% to 50%) subcontracts resulted from the RFP. Additional companies joined this government/industry cost-shared program in 1991 (Table 4). Three of the industry participants (Siemens Solar [CIS], Photon Energy [CdTe], and AstroPower [thin-film Si]) have been selected by the Photovoltaics for Utility Scale Applications (PVUSA) project to deliver 20-kW PV systems for deployment in a grid-connected experiment at PVUSA's site in Davis, California. The companies are continuing the development work aimed at prototype production of modules in their respective thin-film technologies.

Although intrinsic device stability appears to be excellent with all polycrystalline thin films, and initial outdoor tests of prototype modules are extremely promising, there are issues at the module level that require attention as these technologies move into the market. For example, CIS and CdTe are sensitive to chemicals used in sealing modules, so various approaches need to be developed for minimizing chemical interactions. CdTe modules are sensitive to water vapor, so careful sealing is a necessity. Issues with CIS modules tend to be associated with specific layers, such as the adhesion between Mo and CIS. To date, the results of outdoor tests are very promising. Two Siemens Solar CIS modules are producing power at 99.8% and 97.5% of their original levels after nearly three years of outdoor exposure. The outdoor tests for Photon Energy's CdTe modules are promising, but some issues remain. While some modules have shown good stability over a two-year period, others have degraded. Photon Energy and NREL scientists believe the instability in these modules is the result of different encapsulation and edge-sealing schemes. Thus, the achievement of 30-year life for these polycrystalline thin-film technologies appears to require attention to specific processing details as well as careful module design and sealing.

5. AMORPHOUS SILICON RESEARCH PROJECT

The objectives of the Amorphous Silicon Research Project (ASRP) are to foster a viable amorphous silicon (a-Si) PV industry in the United States, to develop cost-effective a-Si technology, and to help industry achieve a PV program goal of 10% efficient commercial thin-film modules by 1995 [1]. As part of the research program, we aim to achieve 12% stable prototype module efficiencies by 1994, in accordance with the goals of the five-year plan [1], through better understanding and improvement of the optoelectronic properties of amorphous-silicon-based alloy materials. A transition in program emphasis occurred in FY 1990 from single-junction cell and submodule research to multijunction module research, and from initial efficiency goals to stabilized efficiency goals. NREL implemented the transition in FY 1991 to focus industrial and university subcontractors on *stabilized* efficiencies, rather than on maximizing initial performance and minimizing degradation.

The ASRP activities consist of three tasks (see Table 5 for list of projects): (1) subcontracted research; (2) NREL a-Si research; and (3) surface and interface analysis. Within the subcontracted research, there are two principal activities: (1) multidisciplinary research activities with industry; and (2) fundamental research activities. The subcontracted multidisciplinary research activities are performed under cost-shared programs between government and industry by broad-based research teams located at the individual industrial facilities that perform research ranging from feedstock materials through the development of prototype modules. The subcontracted fundamental research activities involve basic and supporting research by universities and research laboratories to aid the industry groups' advances of the technology base. The cost-shared subcontracts with industry address issues related to all aspects of two-terminal amorphous silicon multijunction cells and modules using same-bandgap or different-bandgap device structures. Research is performed to advance the stabilized conversion efficiency of multijunction modules having areas of at least 900 cm^2 using glow-discharge deposition as the primary method of fabricating the amorphous silicon films. The stability of these devices is examined for fundamental changes in the bulk material properties, for temperature effects such as diffusion, for fabrication and area-related defects, and for extrinsic degradation related to module encapsulation and framing issues. Transparent conductors are studied to improve the electrical conductivity while achieving optical transmissions greater than 85%. The quality and controlled texturing of ZnO transparent conductors based on low-cost processes are areas of emphasis. The optoelectronic properties of a-SiGe:H and a-SiC:H alloy materials are being investigated to determine the limits of these materials with regard to their use in practical multijunction devices. The interconnection of cells in a series-connected module configuration is a major issue being studied, since it impacts conversion efficiency through the inactive area losses, influences stability through changes over time in the contact resistance, and influences cost through its impact on yield and on the number and types of processing steps.

Cost-shared industry subcontracts were initiated in FY 1990 to transfer the small-area technology developed under previous government/industry initiatives to large-area multijunction modules that are stable, reliable, reproducible, and have potentially low cost. For this purpose, a new three-year government/industry program was started with three subcontract awards initially (Solarex, Glasstech Solar [GSI], and United Solar Systems Corporation [USSC]). One of these (GSI) was subsequently terminated after six months of work. Another award was negotiated (with Advanced Photovoltaic Systems [APS]) in 1991. The principal objectives of these programs are: (1) to conduct research on semiconductor materials and non-semiconductor materials to enhance two-terminal, multijunction, thin-film, large-area, all-amorphous-silicon-alloy device performance; (2) to develop high-efficiency, *stable*, *reproducible*, and *low-cost* multijunction photovoltaic modules based on all-amorphous materials; (3) to demonstrate stable, 12% aperture-area efficiency for different-bandgap modules; and (4) to demonstrate stable, 10% aperture-area efficiency for same-bandgap modules. The modules will be at least 900 cm^2 in area and consist of at least two integrally stacked devices using all-amorphous-silicon alloy materials. This type of government/industry program in a-Si has been highly successful in the past and significant advances have been made in cell/submodule performance.

The ***subcontracted fundamental research*** program (with the exception of ZnO transparent electrode development by Harvard University) was recompeted in FY 1990 (see list of subcontractors in Table 5). The following general areas are being addressed in support of the multidisciplinary activities: light-induced stability, alternative material deposition approaches, amorphous silicon alloy materials, and material characterization. Several models are being proposed to explain metastable effects observed in amorphous silicon films, and research is under way to differentiate between the often subtle aspects and predictions of the models. More importantly, research is being carried out on devices to correlate light-induced changes in the films with light-induced changes in the device performance. Continued research is under way on both high- and low-bandgap alloys to determine the relationship of observed structural inhomogeneities to electrical transport properties. Alternative deposition methods are being explored to improve or develop discrete component layers such as wide-bandgap, high conductivity doped layers, or alloy films. As the amorphous silicon technology matures, more sophisticated measurement and characterization techniques are needed for studies from the atomic level to characterization of materials in efficient photovoltaic devices. Collaborations among the fundamental research groups, government/industry research groups, and NREL internal researchers are maintained through sample exchanges, workshops, and joint publications.

Research Organization	Research Area
Government/Industry Subcontracts	
Advanced Photovoltaic Systems	Dual-junction a-Si modules; same-bandgap
Solarex Corporation	Triple-junction a-Si modules
United Solar Systems Corporation	Triple-junction a-Si modules
Fundamental Research Subcontracts	
Colorado Sch. of Mines	Microvoid studies
Harvard University (Gordon)	Transparent conductive oxides
Harvard University (Paul)	Low-band-gap alloys
Institute of Energy Conversion	a-SiGe:H films and devices
Iowa State University	Deposition by ECR-PECVD*
Jet Propulsion Laboratory	Deposition by ECR-PECVD*
Nat'l Inst. Stds. & Tech. (Boulder)	Microstructure studies of a-Si films
North Carolina State University	Deposition of a-Si:H and microcrystalline-Si by remote-PECVD*
Pennsylvania State University	Deposition/stability studies
Syracuse University	Modeling studies; transport properties
University of Illinois	Deposition by rf-magnetron sputtering
Univ. of North Carolina	Metastability studies
University of Oregon	Metastability studies
Xerox	Metastability studies
National Renewable Energy Laboratory	
Materials Science Branch	Metastable effects, basic studies, alloys, and deposition methods
Measurement and Characterization Branch	Surface and interface analysis, reliability, cell and module measurements
PV Engineering and Applications Branch	Module/system performance and engineering, reliability, solar radiation research, market development
* ECR-PECVD: electron-cyclotron-resonance plasma-enhanced chemical vapor deposition	

Table 5. Research supported by the Amorphous Silicon Research Project

The objective of the ***NREL in-house amorphous silicon research*** is to provide technical leadership and innovation, provide linkage between industry and universities, ensure effective scientific collaboration, provide for research continuity, and verify the validity of external research results. The NREL in-house research emphasizes four major areas: (1) use of alternate deposition methods such as hot-wire thermal decomposition deposition, hydrogen ion-implantation, and remote plasma hydrogen-radical chemical vapor deposition for improved material properties; (2) fabrication of good quality p-i-n solar cells for device physics and photo-degradation studies; (3) maintaining state-of-the-art measurement facilities as well as developing new methods for material and device characterization; and (4) investigation and modeling of photo-degradation phenomena with particular emphasis on correlating microstructure and defect properties with the light-induced degradation.

A significant improvement in a-Si material quality was accomplished by decomposing silane gas using a hot filament (i.e., the hot-wire [HW] process). NREL's technique produces both a-Si:H and a-SiGe:H materials that are superior to those produced by the standard glow discharge (GD) method. In addition, a-Si:H films produced by the HW process are more resistant to light-induced defect production. HW films have the lowest stabilized defect densities (2 to 3×10^{16} cm^{-3} versus 8×10^{16} cm^{-3} for GD), the highest initial diffusion lengths (220 nm versus 130-140 nm for GD), and the highest stabilized diffusion lengths (150 nm versus <100 nm for GD) of any a-Si:H films produced to date. NREL researchers also achieved the highest initial diffusion length for 1.5 eV a-SiGe:H produced by the HW process (96 nm versus 70 nm for GD). These are important parameters for stable, high-efficiency devices. The fabrication of devices by the HW process is awaiting relocation of the NREL a-Si laboratories to a new facility where the building-code safety criteria for the use of concentrated silane can be satisfied. Deposition activities are planned to be resumed in mid-1992.

NREL researchers have continued to make significant contributions to the understanding of the light-induced effect in a-Si. The researchers have shown unambiguously that the metastable defects are charge-trapping defects. This implies that charged dangling bonds transform into neutral dangling bonds. The researchers also found an upper limit for hydrogen diffusion at room temperature (10^{-10} nm/s) that is not observably affected by light exposure.

Perhaps the most significant advancement in a-Si technology is the recent progress in stabilized efficiencies of amorphous silicon modules. A triple-junction (a-Si/a-Si/a-SiGe) prototype module fabricated by Solarex stabilized at 7.2% efficiency (962-cm^2 aperture area), while a dual-junction (a-Si/a-Si) production module from USSC stabilized at 6.3% efficiency (3676-cm^2 aperture area) after 2000 hours of light-soaking. These stabilized efficiencies of 6% to 7% for modules are a significant improvement from the 3% to 4% efficiencies seen a couple of years ago. It is also significant that commercial a-Si modules (produced by APS, UPG, and USSC) have passed PVUSA qualification tests that are based on NREL's interim qualification tests and procedures for thin-film modules [3]. Private sector activities and commitments continue to reflect confidence in a-Si technology as a viable photovoltaic option. Iowa Thin Films Technologies is producing flexible, lightweight amorphous silicon modules on 13-in.-wide rolls of polymer. USSC has upgraded its production line and is selling a significantly improved module. Two organizations started development of 10-MW/year production lines for multijunction modules. APS has started installation of their *Eureka* modules (nominally 1.2-m^2 area) at the PVUSA site; this will be a 400-kW utility-scale system using an innovative, low-cost balance-of-system approach. NREL has measured the initial power output of one *Eureka* module at nearly 78 W outdoors under prevailing conditions. Earlier, NREL measured a different module with a power output of 50 W; APS reported that this module was stabilized by 130 days of outdoor exposure. The research and development supported by the DOE/NREL program is being continually integrated into newer modules with improved efficiencies, increased reliability, and lower cost.

6. PHOTOVOLTAIC MANUFACTURING TECHNOLOGY PROJECT

The Photovoltaic Manufacturing Technology (PVMaT) project is a government/industry photovoltaic manufacturing research and development project composed of partnerships between the federal government (through the U.S. Department of Energy) and members of the U.S. PV industry. It is designed to assist the U.S. PV industry in improving manufacturing processes, accelerating manufacturing cost reductions for PV modules, increasing commercial product performance, and generally laying the groundwork for a substantial scale-up of U.S.-based PV manufacturing plant capacities. The aim of the project is to reverse the declining trend in the competitiveness of the U. S. PV industry -- the U. S. industry's share of worldwide PV markets has decreased from more than 60% in the early 1980s to less than 31% in 1991. The PVMaT project is a five-year, three-phase, $55-million technology transfer project (with industry providing a similar amount in cost-sharing) that is expected to reduce PV manufacturing costs and expand U. S. production capacity.

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

The Phase 1 portion of the PVMaT project, the ***problem identification phase***, was completed early in 1991 with the award of 22 subcontracts. This effort involved competitive bidding open to any U. S. firm with existing PV manufacturing capabilities, regardless of material or module design. Each of these subcontracted efforts was funded at a level of up to $50,000 and involved a duration of three months. The problems identified by the research in this phase of the project were process-specific in nature, and represented opportunities for individual industrial participants to improve their manufacturing processes, reduce manufacturing costs, increase product performance, and/or support a scale-up of U.S.-based manufacturing plant capabilities. These opportunities have since been detailed in the approaches suggested by these organizations for Phase 2 research, as discussed below.

Phase 1 awards included 5 subcontractors working on flat-plate crystalline silicon technology, 11 working on flat-plate thin-film modules (one on thin-film crystalline silicon, 6 on amorphous silicon, and 4 on polycrystalline thin films), 6 working on concentrator systems, and 2 working on general equipment/ production options (see Table 6; two subcontractors worked in two different technology areas). Final reports have been received from all Phase 1 subcontractors and are available to the public from the National Technical Information Service (NTIS) [4]. At this time, we do not anticipate another Phase 1 solicitation (i.e., problem identification). The procurement under this phase was only meant to precede and support the Phase 2A solicitation.

Phase 2 of the PVMaT project is now under way. This is the ***solution phase*** of the project and addresses problems of specific manufacturers. The final selection of successful bidders under the first Phase 2 solicitation, called Phase 2A, has been completed. Subcontract negotiations are under way at this time, and the award of subcontracts is expected in early 1992. This Phase 2A solicitation was only open to subcontractors in the Phase 1 effort. It is anticipated that approximately six subcontract awards will be made under this phase; successful bidders will be supported to develop improvements to their manufacturing processes. The subcontracts under Phase 2 may be up to three years in duration and will be highly cost-shared by the industrial participants. A second, similar process-specific solicitation (Phase 2B) is planned to be issued shortly and will be open to all U.S. PV manufacturing companies.

There are "general" R&D problems in the PV industry that are relatively common problems to the industry as a whole, to a number of companies, or to the design and deployment of PV systems. Phase 3, the ***generic R&D phase*** of the PVMaT project, will address these problem areas through a teamed-research approach. An RFP on generic manufacturing technology was released in October 1991 (RFP No. RR-2-11219: *Teamed Research and Development on Photovoltaic Manufacturing Technology, Phase 3A - Shared Process Issues*), with proposals due on March 2, 1992. Participants for these generic research activities may come from a consortia of industrial companies, individual companies, combinations of companies and university groups, or other groups with special capabilities for solving a particular problem. These proposed research organizations will focus on module-related R&D problems found to be common to several industrial PV manufacturers. They will also work in tandem with material and component manufacturers to help strengthen the PV industry.

Flat-Plate Crystalline Silicon
Crystal Systems, Inc., Salem, Mass.
Mobil Solar Energy Corporation, Billerica, Mass.
Siemens Solar Industries, Camarillo, Calif.
Solarex Corporation, Rockville, Md.
Westinghouse Electric Corporation, Pittsburgh, Penn.
Flat-Plate Thin Films
Thin-film silicon
Astropower Inc., Newark, Dela.
Amorphous silicon
Chronar Corporation, Lawrenceville, N. J.
Energy Conversion Devices, Inc, Troy, Mich.
Glasstech Solar, Inc., Golden, Colo.
Iowa Thin Films Technologies, Inc., Ames, Iowa
Silicon Energy Corporation (UPG), Chatsworth, Calif.
Solarex Corporation, Rockville, Md.
Polycrystalline $CuInSe_2$ or CdTe
Boeing Aerospace and Electronics, Seattle, Wash.
Photon Energy, Inc., El Paso, Texas
Siemens Solar Industries, Chatsworth, Calif.
Solar Cells, Inc., Toledo, Ohio
Concentrators
Alpha Solarco, Cincinnati, Ohio
ENTECH, Inc., Dallas, Texas
Kopin Corporation, Taunton, Mass.
Solar Engineering Applications Corp., San Jose, Calif.
Solar Kinetics, Inc., Dallas, Texas
Spectrolab, Inc., Sylmar, Calif.
Other (manufacturing equipment)
Global Photovoltaic Specialists, Inc., Canoga Park, Calif.
Spire Corporation, Bedford, Mass.

Table 6. Phase 1 subcontractors under the PVMaT Project

7. PV MODULE AND SYSTEM PERFORMANCE AND ENGINEERING PROJECT

The objectives of this project are: to conduct state-of-the-art PV module, system, and application research, engineering, testing, evaluation, and analysis; to provide technical results and solutions to technical issues, and develop PV applications and application opportunities; and to ensure that project capabilities and facilities are enhanced, maintained, and available as *DOE centers-of-excellence* for meeting DOE PV program objectives [1], conducting cooperative research and testing projects with the U.S. PV community. Project activities are carried out in five primary task areas: (1) cell and module standardized characterization performance; (2) module and system performance testing; (3) module reliability research; (4) solar radiation research; and (5) system and utility applications.

Cell and module standardized characterization performance task activities are directed toward providing comprehensive evaluations of PV cell and module performance, including standardized and traceable efficiency measurements and reference cell calibration. PV performance data continue to be traceable to primary reference cells calibrated at NREL. Simulator-based measurements and procedures use reference cells, and spectral-mismatch corrections are provided for secondary PV calibrations and accurate efficiency measurements. A multisource solar simulator is used to evaluate multijunction PV devices of up to 15 cm in diameter. Module performance is evaluated both under simulators and natural sunlight (outdoors). The SPI-SUN 240A pulsed solar simulator and large-area pulsed solar simulator (LAPSS) are used to evaluate the performance of modules in sizes up to 80 cm x 130 cm and 1.5 m x 1.5 m, respectively. Current versus voltage measurements under natural sunlight are performed at the NREL outdoor PV test facility. Absolute spectral responsivity measurements are also conducted on cells and modules in sizes up to 32 cm x 32 cm. Other activities include developing new and improved measurement techniques, and test and measurement systems, and participation in developing U. S. and international consensus measurement standards. Typically, some 300 cell and 200 module standardized characterization measurements are conducted and reported each month.

Through the operation of NREL's outdoor field test facilities and failure analysis laboratories, ***module and system performance testing task*** activities focus on emerging PV module/system technology validation, module qualification testing, module/array performance testing, and PV module and systems consensus standards development. Efforts include designing, constructing, installing, and monitoring the performance of emerging technology modules, arrays, and small system experiments of up to 1 to 2 kW at NREL's outdoor test facility. Several emerging PV module technology procurements and array/system field experiments are anticipated, including PVUSA-designated technology validation of candidate modules requiring field testing before acceptance for emerging technology (EMT-3) deployment by PVUSA. We recently started installation of a 2-kW amorphous silicon system in a cost-shared project with USSC.

Task activities also include conducting and developing qualification tests and the technical basis for future revisions to the NREL-developed *Interim Qualification Tests and Procedures for Terrestrial Photovoltaic Thin-Film Flat-Plate Modules* [3]. Efforts are under way to develop an all-encompassing flat-plate module qualification test procedure within the Institute of Electrical and Electronics Engineers (IEEE) SCC21 consensus standards process. We recently ordered a module mechanical flexure apparatus, a hail impact test equipment, and a hot-spot/bypass-diode thermal test and measurement instrumentation system. These systems will establish full test-equipment capability for exploratory qualification testing and permit more interactions with the PV industry and DOE/NREL subcontractors in conducting the required qualification tests. These interactions will provide the mechanism for identifying module and encapsulation system failure modes and developing new qualification tests based on module-related failure mechanisms, field failure data, and new module designs. Significant efforts are under way on module/array stability testing, light-soaking, and thermal annealing of thin-film modules under outdoor and simulated environmental test conditions, as discussed in sections 4 and 5 above. As part of this task, we also participate in module and system consensus standards development with the IEEE (SCC21) and oversee a subcontract for the IEC TC-82 Secretariat (with the Solar Energy Industries Association [SEIA]). We coordinate U.S. technical advisory group involvement in international PV standards development, with emphasis on developing consensus qualification testing and energy rating standards.

The ***module reliability research task*** efforts include identifying the causes of failure or change in ethylene vinyl acetate (EVA) and other pottants that limit the service life or reduce the performance of PV modules. Research efforts are directed toward addressing generic issues dealing with the degradation of EVA and other pottants, and PV technology-specific compatibility and durability issues at cell/module material interfaces. We are investigating new or improved pottant materials that offer greater promise for a module life-expectancy of 30 years. The EVA issue arose from the observation of *browning* of certain c-Si modules in locations where the operating temperatures were relatively high (near the 85°C rating for EVA). EVA also appears to be sensitive to long-term exposure to sunlight. NREL researchers identified the chemical reaction causing EVA degradation and found that there is probably more than one mechanism involved in browning. The researchers found that an ultraviolet (UV) stabilizer, called Cyasorb™ UV-531, is depleted, and acetic acid is formed from the EVA polymer. The remaining polymer contains a light-absorbing double-carbon bond that discolors the EVA. Once formed, the acetic acid further catalyzes the discoloring reaction, and the degradation proceeds at an even faster pace. The acetic acid can also cause corrosion to metallic components in the modules. The two-part strategy to deal with this problem includes an attempt to find a UV stabilizer that minimizes degradation and/or an effort to find a better performing encapsulant material.

Solar radiation research task activities are in direct support of characterizing, measuring, testing, designing, and understanding the performance of PV cells, submodules, modules, and systems by providing the scientific and engineering understanding of incident solar irradiance, and through the development of instruments and/or measurement methods. Specific activities focus on providing technical support to the cell and module standardized characterization, module reliability, and system and utility applications tasks. Solar irradiance measurements, monitoring, instrumentation, and instrument calibrations are provided, as needed, for the successful operation of these tasks. Efforts include developing spectro-radiometric calibrations and broadband solar irradiance data sets in support of cell and module performance measurements, instrumentation and data sets for system and utility applications, and improved instrument and measurement methodologies. Recently, we completed an experiment involving the NREL-patented Atmospheric Optical Calibration System (AOCS). Comparisons of AOCS data and PV module efficiency data have confirmed that the AOCS is capable of defining and eliminating atmospheric effects on module/cell efficiency data. We are also continuing a joint project with the Electric Power Research Institute (EPRI) to evaluate a device called the *rotating shadowband radiometer* (RSR). In a single, simple instrument, the RSR provides all three components of solar radiation: direct, diffuse, and global horizontal. We are working with EPRI to develop methods for utility-site-specific solar radiation resource validation and prospecting.

The ***system and utility applications task*** is comprised of three major activities addressing supply-side applications, demand-side applications, and solar PV-powered electric vehicles. Supply-side applications are directed toward increasing utility and regulatory agency acceptance of PV systems. This is accomplished through technology transfer means such as facilitating contacts between utility users and PV manufacturers, increasing public awareness of PV's potential, and providing technical information and supporting analysis to utilities and regulatory bodies. As part of this effort, we worked with the Public Service Company of Colorado (PSCo) on a technical feasibility study of the partial repowering of the Fort St. Vrain nuclear power plant with PV, and on a conceptual study to repower White Pine, Colorado with a PV/hybrid system in lieu of a new line extension. (We also established solar radiation monitoring stations at Fort St. Vrain and White Pine, in cooperation with PSCo, as part of the ongoing study.) We provided technical support to the Colorado Public Utility Commission resulting in their "PV line-extension rule," and are in the process of publishing a handbook, entitled *Regulator's Guide to Photovoltaics*, aimed at educating the utility regulatory community.

Demand-side applications efforts focus on promoting and evaluating the use of PV in and on buildings as a key intermediate market opportunity for the PV industry and as a demand-side management (DSM) opportunity for utilities. To assist industry in developing the PV buildings market, DOE/NREL is in the process of launching a new initiative called "Building Opportunities in the U. S. for Photovoltaics" or *PV:BONUS* for short. The objective of *PV:BONUS* is to support the development of cost-effective PV products and product-supply/product-user relationships that provide a sustainable market for PV in the buildings sector. The program is presently envisioned as a five-year, $25 million government (DOE)/ industry cost-shared program. Development of the supplier/user infrastructure will be accomplished through a phased financial assistance program administered jointly by DOE's NREL Area Office and NREL, in coordination with other DOE support offices. The three phases of the program are: concept development, product development and testing, and field demonstration and performance verification. This industry-driven program will be supported by technology validation (testing) activities at NREL and a cooperative government/industry education and training program.

A number of subcontract programs provide support for this project (see Table 7). These include industry/utility PV power projects, domestic and international standards development, a study of DSM incentives for photovoltaics, assessments of roof-mounted PV modules, and an assessment of the matching of solar resource and utility loads. The industry/utility power projects are the result of a competitive solicitation, issued in FY 1991, entitled *Amorphous Silicon Utility/Industry Photovoltaic Power Project* (RFP No. RF-1-11061). Multiple awards will be made to various industry/user teams in early 1992.

Finally, NREL was designated to manage the collegiate solar car competition, called *Sunrayce '93*, sponsored by DOE, the Environmental Protection Agency (EPA), General Motors, and others. The themes of *Sunrayce '93* are "energy, education, and the environment." Sixty-four proposals were received from colleges and universities in North America (including proposals from Canada, Puerto Rico, and Mexico) in the recent solicitation. Thirty-six participants will be selected shortly to compete in *Sunrayce '93* to be held on June 20-26, 1993. The race will start in Dallas, Texas and finish in Minneapolis, Minnesota.

Research Organization	Research Area
Subcontracted Research	
Awards under negotiation	RFP for a-Si industry/utility power project
Florida Solar Energy Center	PV/hydrogen generation
Florida Solar Energy Center	Evaluation of roof-integrated PV module designs
Princeton University	PV/hydrogen system studies
State University of New York at Albany	Assessment of solar resource and utility load matching
Southwest Technology Development Institute	Long-term environmental effects on roof-mounted modules
University of Delaware	Evaluation of demand-side-management incentives for PV
National Renewable Energy Laboratory	
Measurement and Characterization Branch	Surface and interface analysis, reliability, cell and module meas.
PV Engineering and Applications Branch	Module/system performance and engineering, reliability, solar radiation research, market dev.

Table 7. Research supported by the Module and System Performance and Engineering Project

8. SUMMARY

Through NREL's PV AR&D Project, national PV research and services to industry have led to significant improvements in PV technology performance and lowered costs. New generations of PV technologies continue to provide gains in sunlight-to-electricity conversion efficiencies, a bottom-line measure of research progress. Lower module costs, increased field experience, and a greater scientific understanding of module reliability and manufacturing processes are providing the U. S. PV industry with means to compete in the expanding worldwide marketplace for PV products. Continued partnerships with industry, such as the PVMaT project, progress by university and NREL researchers, and increased applications of PV from today's value-added markets to tomorrow's large-scale bulk power systems should accelerate the growth of PV as an environmentally safe and secure supply of cost-competitive energy.

On September 16, 1991, the National Renewable Energy Laboratory (NREL) was designated as the DOE's tenth national laboratory by President George Bush. In addition, DOE authorized building permanent laboratory facilities for NREL PV scientists: the Solar Energy Research Facility (SERF) and a new Outdoor Test Facility (OTF). Designs of both buildings were completed in 1991, and construction is set to begin in 1992. These new, state-of-the-art laboratory facilities will considerably enhance our ability to support development of PV technology. The national laboratory designation and financial support to build new facilities underscores DOE's long-term commitment to the PV program.

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REFERENCES

This paper has drawn liberally, and without reference, from the research results of NREL subcontractors and in-house researchers. Further information is available from various NREL annual reports on the subcontracted and in-house programs (e.g., by contacting the managers identified in Figure 1; see Appendix for telephone numbers). Proceedings of PV AR&D review meetings are also available. Many of the research results are presented in conference proceedings such as those of the IEEE Photovoltaic Specialists Conferences. Additional references are cited below; PV program-related documents are available from NTIS [4].

1. *Photovoltaics Program Plan, FY 1991- FY 1995*, U. S. Department of Energy, DOE/CH10093-92, DE91002139, October 1991.

2. *National Photovoltaics Program: Five Year Research Plan, 1987 1991*, U. S. Department of Energy, DOE/CH10093-7, May 1987.

3. *Interim Qualification Tests and Procedures for Terrestrial Photovoltaic Thin-Film Flat-Plate Modules*, Solar Energy Research Institute, SERI/TR-213-2364, DE90000321, January 1990.

4. National Technical Information Service, U. S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.

APPENDIX: NREL PV AR&D Project -- Contacts for More Information*

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