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SERI/CP-211-2109
(DE84013003)

ABSTRACTS. NATIONAL PHOTOVOLTAICS PROGRAM ANNUAL REVIEW MEETING

DR # 1769-0

April 30, 1984

Work Performed Under Contract No. AC02-83CH10093

Solar Energy Research Institute
Golden, Colorado

Technical Information Center
Office of Scientific and Technical Information
United States Department of Energy

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Price: Printed Copy A09
Microfiche A01

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Printed in the United States of America
USDOE Office of Scientific and Technical Information
Oak Ridge, Tennessee

SERI/CP-211-2109
(DE84013003)
Distribution Category UC-63

Abstracts

National Photovoltaics Program Annual Review Meeting

Hyatt Orlando
Kissimmee, Florida
30 April 1984

Sponsored by the
U.S. Department of Energy

Coordinated by
Solar Energy Research Institute
for the U.S. Department of Energy under
Contract No. DE-AC02-83CH10093
by Midwest Research Institute

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For copies of the videotape, "The Making of a Billion Dollar Industry", contact:

Solar Energy Industries Association
David Gorin - or - Scott Sklar
1156 - 15th Street, N.W.
Washington, D.C. 20005
(202) 293-2981

REMARKS BY
ROBERT SAN MARTIN

AT

DOE NATIONAL PHOTOVOLTAIC PROGRAM ANNUAL REVIEW MEETING

KISSIMMEE, FLORIDA
APRIL 30, 1984

INTRODUCTION

Good evening ladies and gentlemen.

I appreciate the opportunity to be here this evening to discuss the national outlook for renewable energy technologies. As the Deputy Assistant Secretary for Renewable Energy in the Department of Energy, it is my responsibility to manage and implement renewable energy programs which include: solar thermal, photovoltaics, wind, biofuels, geothermal, small-scale hydropower, ocean thermal and the active and passive solar energy programs.

NATIONAL ENERGY POLICY AND STRATEGIES

The goal of our national energy policy is to foster an adequate supply of energy at reasonable costs. By "adequate supply," we mean, a flexible energy system that avoids undue dependence on any single source of supply—foreign or domestic—thereby contributing to our national security and economic stability. The strategies for achieving this goal include:

- minimizing federal control and involvement in energy markets while maintaining public health, safety and environmental quality, and
- promoting a balanced and mixed energy resource system.

Renewable energy resources can play an important role in reaching a balanced and mixed energy supply system. Renewables offer supply diversity, modularity of system sizes, and flexibility in meeting a variety of end use demands. Collectively, their modularity and flexibility in direct thermal applications, bulk electricity supply, or in meeting requirements for liquid and gaseous fuels, make them highly attractive alternatives for private sector development and deployment. As technological advances improve renewable technology viability, there will be increased diversity within the nation's future energy supply infrastructure and an increase in competition within the energy marketplace.

Currently, the federal strategy for renewable energy R&D is to concentrate on scientific and enginering research which will lead to a better understanding of: the characteristics of renewable energy resources; the mechanisms for converting these resources to more useful energy forms; and the materials to insure that these systems can achieve the necessary reliability and efficiency.

As these requirements are met, it is important that the results are transferred to the private sector in a timely and efficient manner. Our technology transfer mechanisms include seminars and workshops, publications, operation of the Conservation And Renewable Energy Inquiry and Referral Service (CAREIRS) and one-on-one discussions between DOE scientists and private entrepreneurs—to name a few. However, DOE considers technology tranfer a two-way process. We view it not only as a mechanism to transfer research results, experiences and "lessons learned" to the private sector, but also as an opportunity to obtain industrial priorities early in the federal planning process. Thus, technology transfer is a vital link between the public and private sectors in the research and development process.

RENEWABLE ENERGY DEVELOPMENT

Renewable technologies represent an extremely broad technology grouping where many specific resource and technology options remain within the research and development cycle. For several renewable energy options, however, industry has begun the process of introducing specific concepts and products into the marketplace.

State and local governments, local citizens' groups, individual and regional utilities, financiers, developers and builders can all greatly influence the rate of introduction of commercial quality technology into the marketplace. As you heard this week, several renewable energy options are ready for application today; and many innovative and promising organizations have greatly contributed to the degree of commercial success accomplished to date for these technologies.

While the department does not compile comprehensive statistical data for each renewable energy technology, renewables have shown substantial growth over the past several years in contributing to our national energy supply. For instance:

- Total wood energy consumption increased nearly 50% between 1975-81, to a record level of 2.2 quads of energy. Between 1978-81, there was an average annual increase of approximately 4% in the use of wood energy.
- During 1974-83, solar collector shipments increased from 2 million square feet to 18 million square feet—a 20% average annual increase in shipments. From 1980-81, revenues increased 53% from $360 million to $554 million. The number of installed active systems exceeds 700,000; and passive homes exceed 90,000.
- The wind market in 1980 recorded 3 megawatts or approximately $10 million in sales. In 1982, sales increased to $180 million—adding 70 megawatts to the energy supply base. Estimates for 1983 include a market of $500 million, supplying 300 megawatts of power.

Also, the increased awareness and willingness to plan these renewable systems into the bulk energy supply infrastructure is encouraging. Two major utilities, Southern California Edison and Pacific Gas and Electric, recently announced that, at least for the next ten years, their new capacity will be derived from renewable energy technologies. A recent survey of 120 utilities found that currently only 1.25 percent of the total generating capacity comes from non-conventional technologies. However, the respondents predicted that electricity from renewables will nearly quadruple to 12,500 megawatts within the next decade.

While it is significant that major utilities are recognizing renewable energy as a viable power surce, it is equally encouraging that energy consumers are aware of the potential advantages of renewable resources. As you know, many successful applications of solar energy are already in place here in the Tennessee Valley. TVA's solar water heater demonstration program has provided for the installation of over 3,600 systems to date. The estimated cumulative capacity savings total 4.8 megawatts. We believe this program provides a sound body of experience which should lead to an expanded interest in the marketplace for solar water heating systems within the southeast region.

In addition, you had the opportunity this week to tour the new TVA solar office complex which tangibly illustrates the energy savings afforded by solar technology. TVA also encourages the use of passive solar energy in new homes and buildings and assisted in the design and development of energy efficient modular solar homes which reduce conventional heating and cooling by half.

The geographic distribution of renewable resources provides an opportunity for a diverse mix of systems to satisfy the supply requirements of the various localities within the U.S. For example, solar energy is the most widespread resurce in the continential U.S. There are regional differences in the nature of the solar resource such as the degree of seasonal fluctuations and the mix of direct and diffuse radiation, but the majority of locations have enough solar insolation to justify at least one generic application of solar energy. This may be space heating, water heating, industrial process heat, or electricity.

Here in the southeast region, you are fortunate to have a broad range of renewable options. Obviously, active and pasive solar systems have been successfully employed, as well as hydropower, biofuels, photovoltaics, wind, and solar thermal energy.

Since forest covers a large portion of the land area in the southeast, wood resources and residues can play a significant role in supplying energy to the area. For example, wood resources are currently being utilized in North Carolina where a major paper company is participating in cooperative plantings of hardwoods to assess their potential as short-rotation involves intensive tree management and repeated harvesting of the regrowth from the tree stumps following harvest of the original tree. In addition to evaluating productivity, coppice growth and harvesting techniques, a comprehensive economic analysis is being conducted to assess the feasibility of short-rotation woody crops for biomass production in the southeast.

A wood burining gas turbine is also currently being built for installation at Red Boiling Springs, Tennessee. Utilizing locally available sawdust and wood residue, it is anticipated that this 3 MW system will be supplying power to the TVA electric grid sometime this summer.

In photovoltaics, the southeast residential experiment station in Florida is determining the feasibility, and producing operating data on grid interactive residential PV system configurations in the southeastern U.S. The project will include photovoltaic experiments at the primary site, Florida Solar Energy Center, and at multiple field sites, namely: Georgia Institute of Technology and Georgia Power Company in Atlanta; the Tyndall Air Force Base in Panama City, Florida; the Alabama Solar Energy Center in Huntsville; and the Tennessee Valley Authority. These prototypes will provide an understanding of degradation reactions, performance issues, utility interfacing and possible low cost installation techniques.

In addition, studies are currently being conducted by TVA on the Valley's wind resources to determine the feasibility of utility-scale wind installations and small wind turbines for onsite power production. TVA has installed one small wind energy conversion system for commercial application and has identified 70 potential sites within the five state area.

A solar thermal system is in place just 35 miles southeast of here in Dalton, Georgia. The system, operational since October 1981, uses 10,000 square feet of parabolic trough collectors to produce pressurized steam at 370°F for use in the manufacture of latex foam at the Dow Chemical Company.

These are just a few examples of renewable energy applications in this region. There are certainly many more, but time does not permit a discussion of each. However, these few examples indicate that the energy potential of renewable technologies is being discovered by users and producers of power. Our current responsibilities at DOE are focused on sponsoring research to improve overall system efficiencies and to lower costs. These efforts should provide an increased understanding of those options currently in limited use and also open up entirely new options for the future. We believe our activities should provide a basis for sustaining the future growth of renewable energy applications.

I would like now to briefly describe the R&D program within the Department of Energy.

DOE R&D ACTIVITIES

The renewable energy program underway at DOE is part of our strategy to develop a full range of energy technologies whih compete in a free market environment. The federal program recognizes and defines problems in the renewable area and helps resolve them in ways that are acceptable to industry and the consuming public.

For example, in the mid-1970's, DOE's passive solar program was focused primarily on heating systems research in single-family, detached housing. With the development of wide-scale interest in the use of passive solar for home heating, DOE research emphasis shifted to commercial buildings in recognition of the fact that the relatively simple technology applicable to home heating could not readily be utilized in large scale buildings. In the process of developing a commercial building technology base, we have identified new opportunities for energy savings through the use of natural sunlight to illuminate both perimeter and interior spaces.

When these new challenges became apparent in 1982, DOE's passive program was redirected to the new research needs. Research is now underway to develop what are called "smart glazings." These glazings, which could replace conventional window and door materials, utilize materials with special characteristics which cause them to accept additional sunlight during heating periods and resist high amounts of sunlight penetration during cooling periods. Certain characteristics of "smart glazings" can also provide them with thermal resistance properties equivalent to fiberglass wall insulation. This research and other work such as the development of thermal diodes, desiccant cooling components and latent heat storage materials, could substantially alter our whole approach to the lighting, heating and cooling of commercial buildings. If we are successful, these new materials and heat transport concepts will, of curse, also provide the residential sector with new energy saving opportunities.

Another dramatic example of modern day innovation in energy technology is photovoltaics. This technology was initially conceptualized and developed in the space program for use as a power source on our spacecraft. Since 1975, the federal government and the U.S. photovoltaic industry have worked together in the pursuit of low cost, high performance photovoltaic systems for land-based power production. Through this cooperation, the U.S. photovoltaic industry has established itself as the world leader. Applications in the marketplace today include residential, commercial, agricultural and central power utility systems.

The world's largest operating photovoltaic system, a 1 MW electric power plant, located in California, produces enough electriciy to power up to 400 homes. DOE research in photovoltaics today emphasizes activities that will lead to cost reduction and system efficiency improvements and make photovoltaics a more broadly viable energy alternative. In terms of efficiency for example, a few years ago achievement of production cell efficiencies above 10% was extremely difficult. Today, multi-junction cell research has advanced to the point where recent experimental efficiencies of 22% were recorded and scientists and engineers openly debate the most suitable concepts to reach conversion efficiencies of 35%.

Progress in other areas of renewable energy is likewise encouraging. The department's program in wind energy is developing a wind technology base in support of the growing private sector effort. As I mentioned previously, the wind energy market has experienced tremendous growth since 1980 and turbine reliability has greatly increased due to windfarm operating experience and product improvement. Currently, there are over 4,000 wind turbines with a total capacity of approximately 250 megawatts in operation throughout the country.

The results of this genetic research, which have already more than doubled conventional production rates, are establishing confidence that an assured, cost-effective biomass feedstock can be available for use by operators of thermal or electric generation facilities. Recent reports indicate that biomass-fueled facilities being planned or under construction total some 2,000 megawatts. We are optimistic that the development of improved feedstocks and conversion technology can provide the basis for substantial increased use of biomass energy in the future.

As previously mentioned, DOE uses various technology tranfer mechanisms to transmit these other research findings to the private sector research and manufacture communities; and I commend the U.S. renewable industry for their efforts in bringing these new technologies to the marketplace.

We can all be pleased with the progress that has been made to date in renewable energy. From an exotic energy idea ten years ago, we have reached a level where renewable resurces are viewed as a legitimate contributor to a balanced and mixed energy resource system.

CONCLUSION

Let me conclude by assuring you that we are steadily advancing in renewable technologies. As you are aware, the research, development, application and growth of any new technology is a long and difficult task. We have made a tremendous amount of progress in the last few years, and through continued public and private sector cooperation and an effective technology transfer program, we can continue the technological accomplishments and sustain the momentum that we have achieved to date.

Thank you for the opportunity to be with you this evening.

KEYNOTE ADDRESS

REMARKS BY
HONORABLE DON FUQUA

AT

DOE NATIONAL PHOTOVOLTAIC PROGRAM ANNUAL REVIEW MEETING

KISSIMMEE, FLORIDA
APRIL 30, 1984

I am delighted to be here this morning to talk about photovoltaics: where we have come from and where we can expect to go.

Although the field of photovoltaics is one of the most exciting and unique of all our energy technologies, its continued development and growth require both an attitude and an environment not unlike that of other technologies. So, in my remarks this morning, I want to begin with some comments about energy in general and then review in particular our progress in photovoltaics.

Energy has been an issue of great concern and debate for this nation for over a decade. At this time, we are able to look back and review the experience of those early years in energy programs and policies and, hopefully, use that experience in planning an energy future that will best serve the nation's long term needs. I might add that photovoltaics figures to play an important part in that energy future.

During this period, we have developed some important understandings about energy as an issue. One of the most significant understandings and perhaps the most difficult to deal with was expressed in an editorial in the EPRI Journal. It said, "Everyone, it seems, has learned through the tumult of the last 15 years not to take the future for granted; when it comes to the affairs of energy, reality can and does change its face abruptly. This lack of clarity about the future has been one of the most compelling lessons of the past decade for energy planners."

When we consider that energy planning, by its very nature, requires not only a *vision* of the long-term but a development and implementation period, *frequently of decades rather than years*, we can see the inherent conflict that faces us.

It seems to me that in order to make reasonable decisions about energy, the situation dictates two distinct understandings and approaches. On the one hand, we must hold a long-term perspective, especially in terms of the research and development of various energy technologies, despite the fluctuations of events in the present. And on the other hand, we must maintain a flexibility within our current conditions that will allow us to adjust to a range of economic and social changes both here and abroad that effect energy matters. This is not a simple task, but one of great importance.

In terms of energy research and development, much of its future depends upon what we have learned from the patterns of the past in this work. Let me be more specific.

Energy has been a major area of Federal R&D support for a number of years. However, this support has been generally characterized by frequent shifts in the size of funding and in the nature of program direction in rapid response to changing events. The present administration has brought a new and different approach to the energy issue than what has prevailed previously and accordingly, energy R&D priorities have been reordered.

If we survey the period 1971-1983 for federal support to energy R&D programs, we can observe three distinct cycles. In the very early seventies, before the Arab Oil Embargo, our chief R&D emphasis was on the development of commercial nuclear reactors. Funds were also included for the beginning stages of work to develop an economic Liquid Metal Fast Breeder Reactor to meet future electric power needs. There was also some funding to support research in the basic energy sciences.

The fall of 1973 brought the Oil Embargo and a national energy crisis. With it came the nation's initial shock of realizing that our heavy dependence on imported oil made us vulnerable to every action and reaction of the OPEC community. This, in turn, brought the increasing recognition that our future energy security could not rest with any one energy source, but rather must depend on a mix of many diverse sources and technologies.

As a result, non-nuclear energy R&D programs began to show significant growth in 1974 and increased more than sevenfold by 1980.

The 1982 budget reflected a contrast to the strong federal buildup in the fossil and renewable energy programs that occurred from 1975 until 1981. Federally sponsored work on these energy sources was markedly de-emphasized. Thus, we can see a pattern of wide fluctuation much like a ballon that shrinks and expands. Balloons, however, are more resilient than R&D programs.

Over many years, energy R&D produces new knowledge and understanding about energy and, in turn, new technologies for energy use. Stable funding for energy R&D creates an environment for steady progress with confidence in the continuation of the program to reach a projected goal. Unstable funding for R&D programs creates a roller coaster environment for a task that ordinarily requires a strong commitment and a reasonably long time-frame for its exercise.

At the Committee on Science and Technology, I believe we have approached energy R&D policies, plans, and programs with the paramount understanding that the R&D process cannot be short-sighted. We have also worked to maintain a balance in energy R&D even when a national fashion for one energy resource or technology seemed to capture overwhelming attention and funding in other places. This has not always been an easy task.

Within this broad perspective, let us now look at how we have dealt with photovoltaics. What I must first report in this annual program review is that photovoltaics is "alive and well"—and we can thank many of you here today for that healthy and thriving prognosis.

In November of 1978, the Solar Photovoltaics Energy Research, Development and Demonstration Act became Public Law. The findings and policy stated in this original act, even then, spoke to the promise and prospects of photovoltaics. In quoting from the Act itself:

> "There appears to be no insoluble technical obstacles to the widespread commercial use of solar photovoltaic energy technologies"
>
> and
>
> "An aggressive research and development program should solve existing technical problems of solar photovoltaic systems; and supported by an assured and growing market for photovoltaic systems during the next decade, should maximize the future contribution of solar photovoltaic energy to this Nation's future energy production."

With a sense of both excitement and assurance, we are beginning to see the fruition of those projections. The proof is in our actual progress. In the last seven years, we have seen enormous advances in photovoltaics technology. This is in no small way due to the wise and careful use of DOE research and funds, and the outstanding management of the overall program. We can proudly boast that costs have been reduced by a factor of ten and efficiencies have been improved by as much as a factor of five.

In the last three years, manufacturers have made serious commitments to produce PV modules. We are also seeing the investment of R&D funds by oil companies in photovoltaics. This is a positive indication of the technology's perceived potential and market viability.

These things are all proof of our progress. However, long before the Arab Oil Embargo and national concern about energy sources and technologies, the original photovoltaic cells were fabricated for use in our nation's space program. They were beautiful in their simplicity - direct conversion of sunlight to electrical energy. They offered a silent, inexhaustible, pollution-free source of electrical power.

They came with only two disadvantages. The cell efficiencies were low and the cost for energy generated was not even remotely competitive with conventional sources of electricity. Neither of these disadvantages was a significant issue at the time. The cells, as they were used in space, were pointed toward the sun 24 hours a day and, thus, had constant absorption of sunlight. And the cost, although high, was part of the price we as a nation needed to pay to establish American preeminence in space.

With the Arab Oil Embargo and the realities it brought, we began to examine every source and technology as a possibility for generating energy. Photovoltaics was high on our list. John Cummings, Director of Renewable Resource Systems for EPRI, recently wrote, "Solar Energy attracted the greatest attention among the renewables and of all the options, none has engendered an excitement equal to that for photovoltaics."

With our photovoltaic experience in the space program, we were already familiar with the advantages. Thus, the focus of our program to develop the PV technology for conventional energy production was quickly directed toward the two weaknesses, the interrelated factors of cell efficiency and cost competitiveness. As I mentioned a moment ago, we can be rightfully inspired by our success in those areas to date.

The uncertain course of energy events has underscored the importance of trying to establish continuity in our energy research and development programs. I believe that we have become particularly attentive to this quest within the PV program.

Last July, the Science Committee issued a staff report entitled, "A Multi-Year Framework for Federal Solar Energy Research and Development." In the photovoltaics section it reads, "staff recommends the restoration of a balanced photovoltaics R&D program at $65 million per year for the next five years."

This program should consists of four types of activities:

- Advanced R&D on PV cell materials and devices
- Technology Development
- Systems Engineering and Standards
- Tests and Applications

Obviously, in this regard, we are both pleased with and strongly support the "Five Year Research Plan for the National Photovoltaics Program." Prepared by DOE, it provides an essential set of guidelines for the appropriate allocation of federal resources to accomplish a national goal within both time and funding constraints.

A key factor in reaching this goal is the continuation and expansion of the partnership between government and industry that has operated so successfully in the flexible and informal framework they have developed. Within this framework, there is the recognition that research will be complementary to private sector activities and that industry will be prepared to adopt the successful research results.

In this partnership, the Members of the Science Committee have high words of praise for the consistently excellent work being done at SERI, Sandia, and the Jet Propulsion Laboratory in addressing the critical research issues that must be resolved.

I would not want to leave the misunderstanding here that our universities are not vitally involved in this process too. As always, they provide a well-spring of ideas and theories as well as a reservoir of manpower.

Surely, the most critical technological challenge of our photovoltaic work is raising cell efficiences. And as we continue to do this, we will improve the cost-to-performance ratio of the systems.

During the last several years of testing many ways to generate electricity directly from sunlight, researchers have narrowed the field to several PV technologies. Each of these has its own unique advantages. I believe it is wisest to assume that no one technology should prevail across the board, but rather that the choice would depend on the application. Each technology might well have its own market segment.

In all of the deliberations and decisions about the direction of America's photovoltaic program, we must remain constantly aware of the international photovoltaic picture. In the past few years, Europe and Japan have made formidable progress in PV technology development. Although America still remains ahead in this area because of the lead established by our program in 1975-1980, this competition poses an increasing force in the globe marketplace.

In Japan's Sunshine Project for 1984, there appears to be about $60 million available for photovoltaics. Their program has a strong emphasis on product-technology development. The Science Committee's concern about this technology emphasis was a prominent reason for the Committee's concerted effort to redirect the Administration's decision to concentrate our PV program solely on basic research. We were convinced that without maintaining a greater balance within the program, the U. S. would begin to lose its world prominence in the field. The United States is in the forefront of this very promising high-technology area, and we want to continue in just that capacity.

Our confidence and continued excitement about the long-term possibilities are surely amplified by the conclusions reached in independent studies conducted by EPRI, the Harvard University, and the Exxon Company regarding the future for photovoltaics. They seem to concur that if cell efficiencies can be raised so that systems are producing electricity at a current year cost of $.15 per kilowatt-hour by the turn of the century, that electricity from photovoltaics will be cheaper than electricity generated by oil-fired power plants and just slightly more costly than power generated by coal-fired plants.

As our photovoltaics program has evolved, we have developed this growing confidence in the prospect of solar cells for the bulk power market. This is a long way from those first solar cells that generated power for our space program. We can all take pride in the progress that has brought us to this new horizon.

Photovoltaics is alive and well — and getting better all the time.

PRESENT STATUS OF THE SUNSHINE PROJECT PHOTOVOLTAIC PROGRAM

Y. HAMAKAWA

Faculty of Engineering Science, Osaka University
Toyonaka, Osaka, Japan 560

SUMMARY

The Sunshine Project is a long term, large scale national project scheduled to run from 1974 to 2000, with the goal of developing sufficient alternative energy sources to supply considerable portion of Japan's total energy demand by the year of 2000. It includes R&D subprograms for solar energy-, geothermal energy-, coal gasification and liquification-, hydrogen energy-technologies. In addition, some basic researches on ocean-thermal energy and wind energy conversion technologies, and other supporting R&D for the total energy systems are involved in the project. Fig.1 shows the project organizations of the headquater office in AIST (Agency of Industrial Science and Technology), MITI (Ministry of International Trade and Industry) (1).

In November 1979 which is corresponding to the beginning of second five years period, a new strategy on "Accelerative Promotion of the Sunshine Project" has been started, and two new offices: "New Energy Development Organization (NEDO)" and "New Energy Foundation (NEF)" are organized (2). In the new strategy, a short-term goal was set forth to develop alternative energy sources sufficient to supply 5 percent in the Japan's total energy demand by 1990, increased from 1.6% percent in the original plan. The NEDO is an active lead center of the project promotion and managing the contract work for technological developments energy technologies, as well as the implementation of international programs for development of energy technologies.

For the sound promotion of research and development and subsequent commercialization activities of the Sunshine Project, the NEF has been organized by raising private enterprize funds. In the NEF, investigations of new energy technologies, various case studies for the economic feasibility, marketing researches making the new proposal, and also international cooperations are carried out. In the promotion of effective international cooperation, aiming at efficient progresses of research and development activities, as well as aiming

at dilution of risks in the case of failures, positive efforts are underway in carrying out cooperative IEA programs. Fig.2 shows relation between the Sunshine Project HQ Office, NEDO and NEF, and action flow diagram of the contract works in the solar energy division are illustrated. In the photovoltaic subproject which is one of three subprojects in the solar energy division, aiming at rapid expansion of practical application of solar photovoltaic cells, intensive efforts must be payed on the earliest establishment of production technologies of solar cells during FY 1980.

Figure 3 shows the structure of photovoltaic R&D program (3). As can be seen from this figure, amorphous silicon (a-Si) solar cell project is identified as an important item. Development of a new technology for this film solar cells might be one of the most direct approach to the cost reduction of photovoltaic system in a view of material saving and automated assembly in the cell production processing. In the Sunshine Project Photovoltaic Committee Meeting, a severe analytical study has been initiated in 1977 to define the possibility of a-Si as a low cost solar cell material, and a proposal of new project on the a-Si solar cell R&D has been made from the FY 1978. Mainly, basic research on a-Si material and cell production technologies on various foreign substrates have been carried out by 1982 as the basic studies.

The budget transitions in recent five years are shown in Fig.4. As is seen from this graph, a steep increase by the injection of special account is carried out with the accerelative promotion strategy in the FY 1980, and the fraction of the photovoltaic budget is gradually increased year by year in recent few years with finishing up the photo-thermal subproject. In fact, FY 1984 budget for the photovoltaic project is 7891 Million¥ (corresponding to about 33.6M$) which is including the general account of 868 Million¥. This is about 20% increase against FY1983 budget in photovoltaic subproject. While, the total budget for the Solar Energy Division in 1984 is 9321 Million¥ (4). With the general account budget, mainly basic research and device physics research are contracted directly by the Sunshine Project HQ Office. As shown in Fig.3, eight subprojects, which is the main part of R&D work, are carried out under the NEDO contract with the special account (7023 Million¥ in 1984).

Concrete subprojects of the contracted subprojects are listed in Table I together with their locations and status. In this table, the program (a) is the development of prototype low cost solar cell massproduction plants for 500 KW/year/line including low cost production of TGS ($SiHCl_3$) and metallugical silicon powder processing. While, (b) to (d) are experimental demonstration facilities for various solar photovoltaic systems from 3 KW to 1 MW. Flow chart of this massproduction line from TGS - MG-Si powder - 250 KWx2 solar cell module are shown in Fig.5. The short term program by 1990 for these subprojects are illustrated in Fig.6.

With aids of the accelerative promotion strategy of Sunshine Project, AIST, MITI, and also the Special Research Project supported by the Ministry of Education, which was carried out by FY1980-82, a remarkable progress has been seen in the field from film growth technology to cell fabrication processes on the heterojunction and/or multijunction structure solar cells utilizing new materials such as a-SiC:H and microcrystalline Si etc. (5). As the results, more than 12% conversion efficiency has been attained in a small area laboratory phase cell with the a-Si/poly c-Si stacked junction structure (6). For the large area solar cells 10x10 cm^2 module, more than 7% efficiency are presently quite common elsewhere in the industrial production (7). Market size and industrializations of a-Si solar cells are growing quite smoothly. Fig.7 shows the transitions of cell efficiency for various types of a-Si solar cells since 1976. As can be seen from this figure, a step-like increase of the cell efficiencies is seen in the region -1981, while the slope A before 1981 corresponds to the improvement of the film quality and routine cell fabrication progresses. The key technologies that produced the steep slope change from A to B at 1981, were development of heterojunction solar cells with a-SiC:H (8) and a-SiGe:H (9). Due to a recent advance of material synthesis technology by controlling the carbon fraction in a-SiC:H (8) and of the optimum design theory (10) based upon the concept of the drift type photovoltaic process, this type of heterojunction solar cell has continued to improve its efficiency with the slope B. The recent world record 10% efficiency by RCA (11) and Sanyo (12) groups are also obtained in this type of a-SiC/a-Si heterojunction solar cell.

A wide variety of application systems are developed in a recent few years particularly, consumer electronics applications (7). For instance, about 3.0 Million sets/month of a-Si drived pocketable calculators are fabricated in Japan. Fig.8 shows the transitions of annual product of solar cells in Japan. While, the most consumer applications are deviced by a-Si solar cells in a recent few years (13).

ACKNOWLEDGEMENT

The author wishes to thank Dr. T. Mukai and Dr. K. Sakuta and Mr. Myoi of the Sunshine Project Promotion Office Headquaters for their useful advices and releasing the Sunshine Project Document. The works referred to were partly supported by the Sunshine Project a-Si solar cell development contract.

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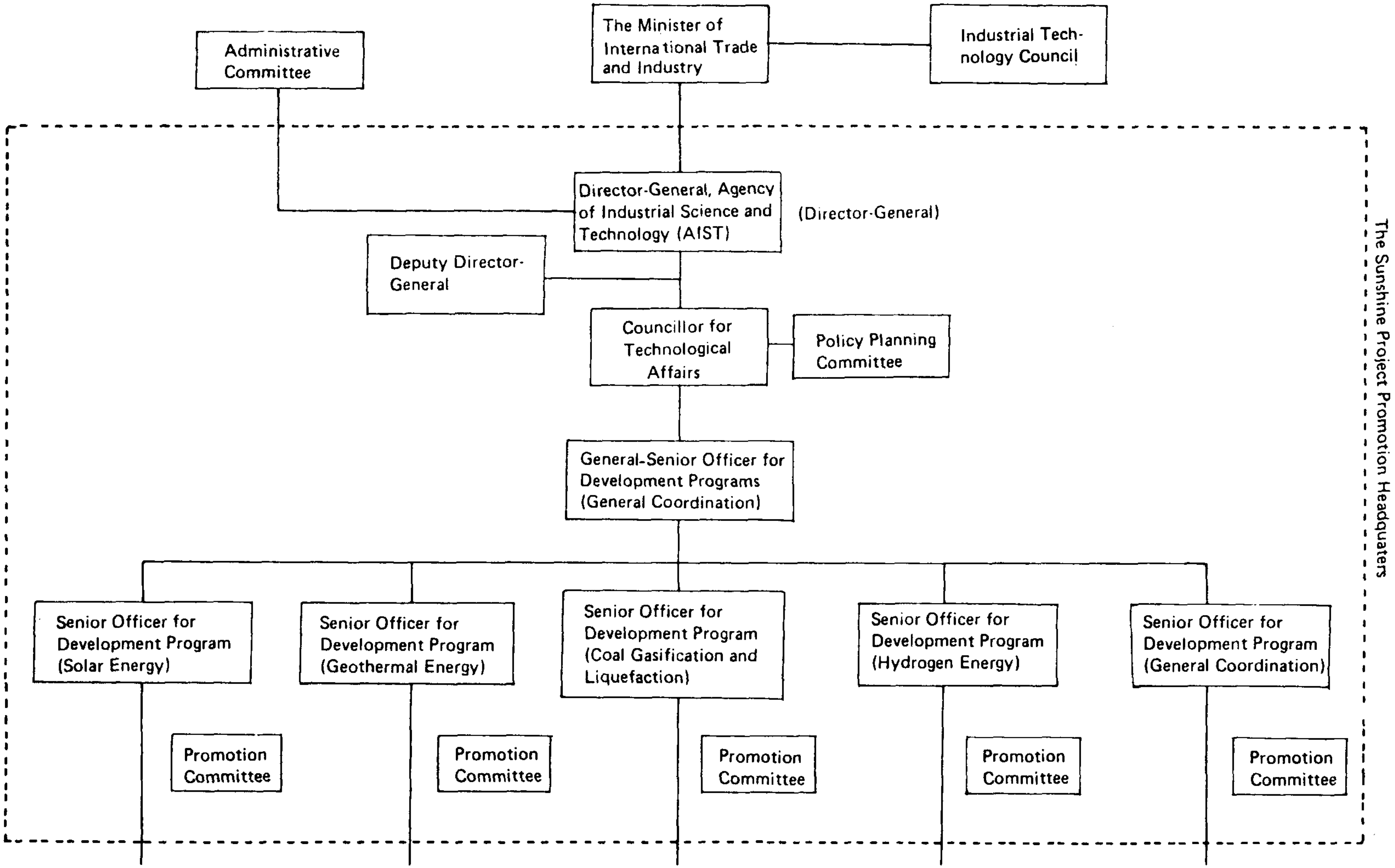

Fig.1 Organization of the Sunshine Project.

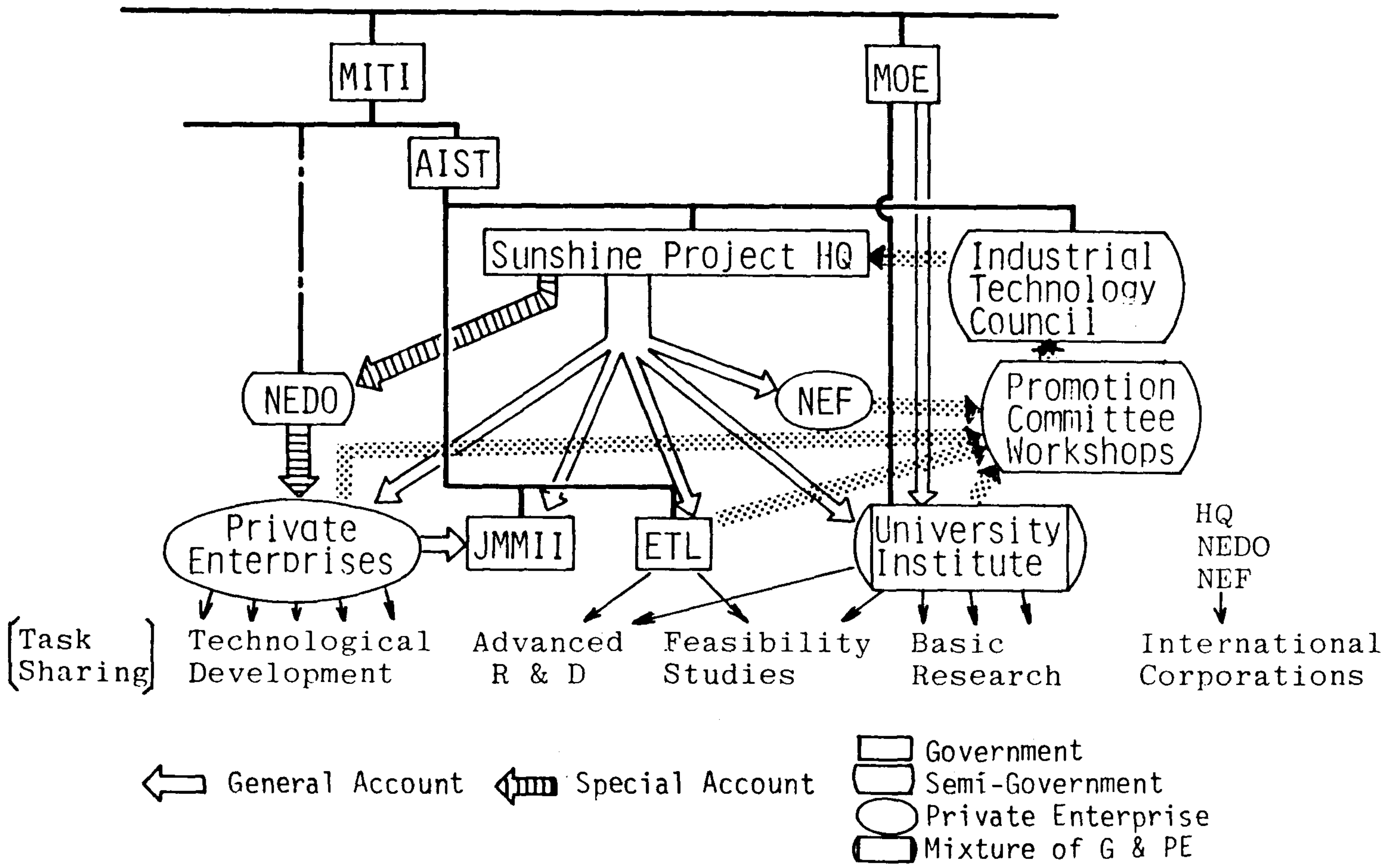

Fig.2 Action flow diagram of Sunshine Project Photovoltaic Division.

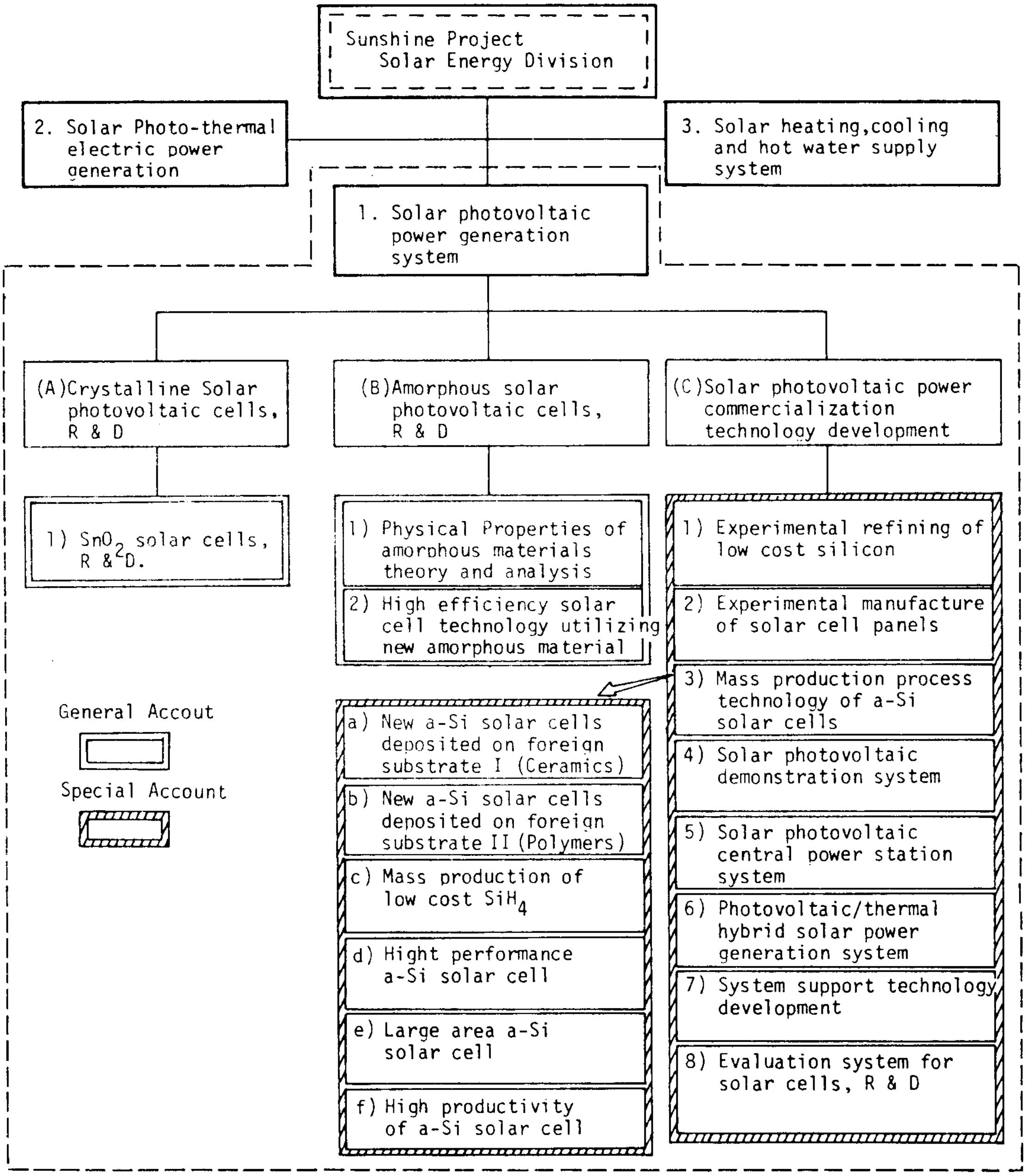

Fig.3 Sunshine Project program structure of R & D in Solar Photovoltaic Division.

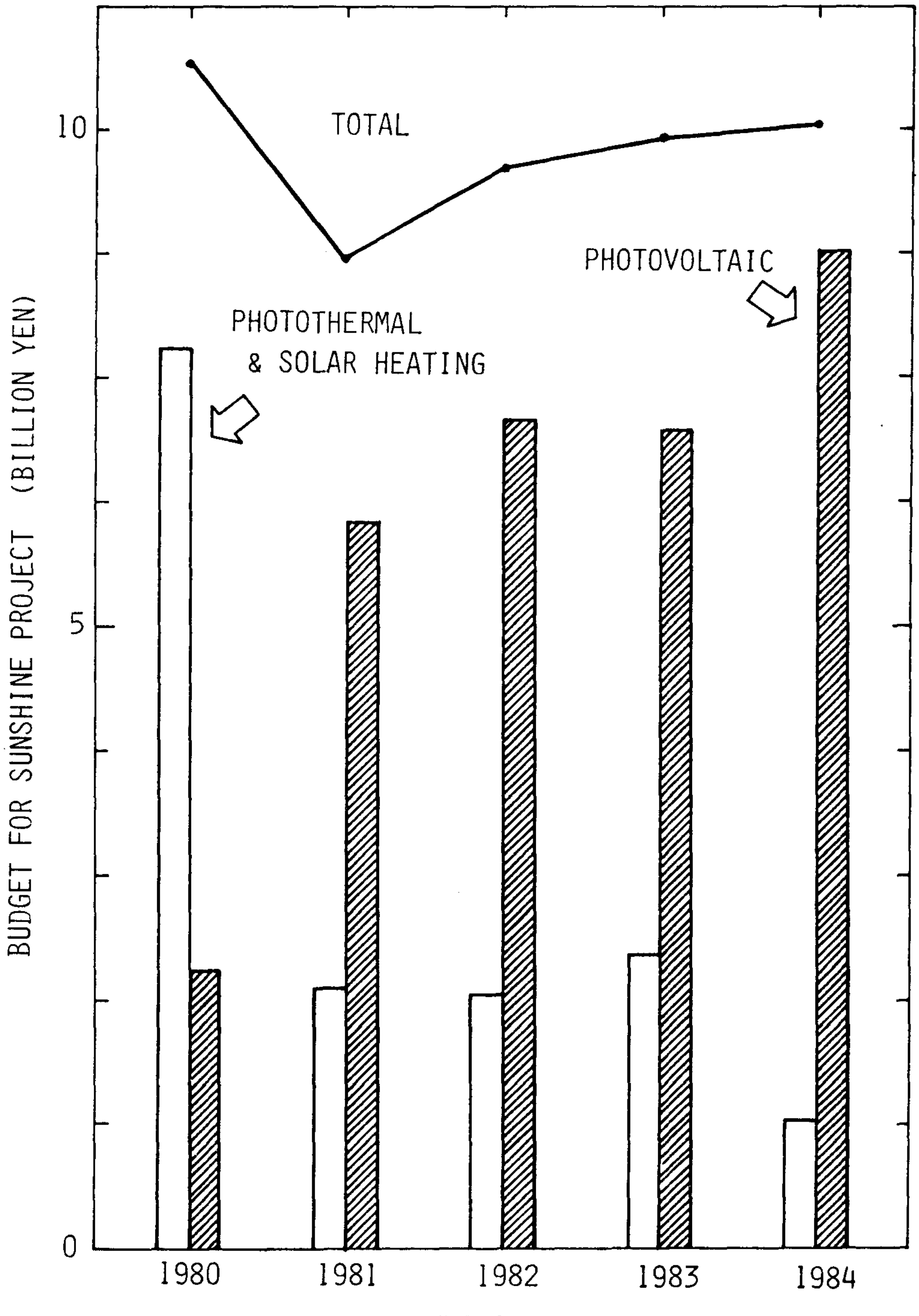

Fig.4 Budget transition of the recent five years in Solar Energy Division in Sunshine Project.

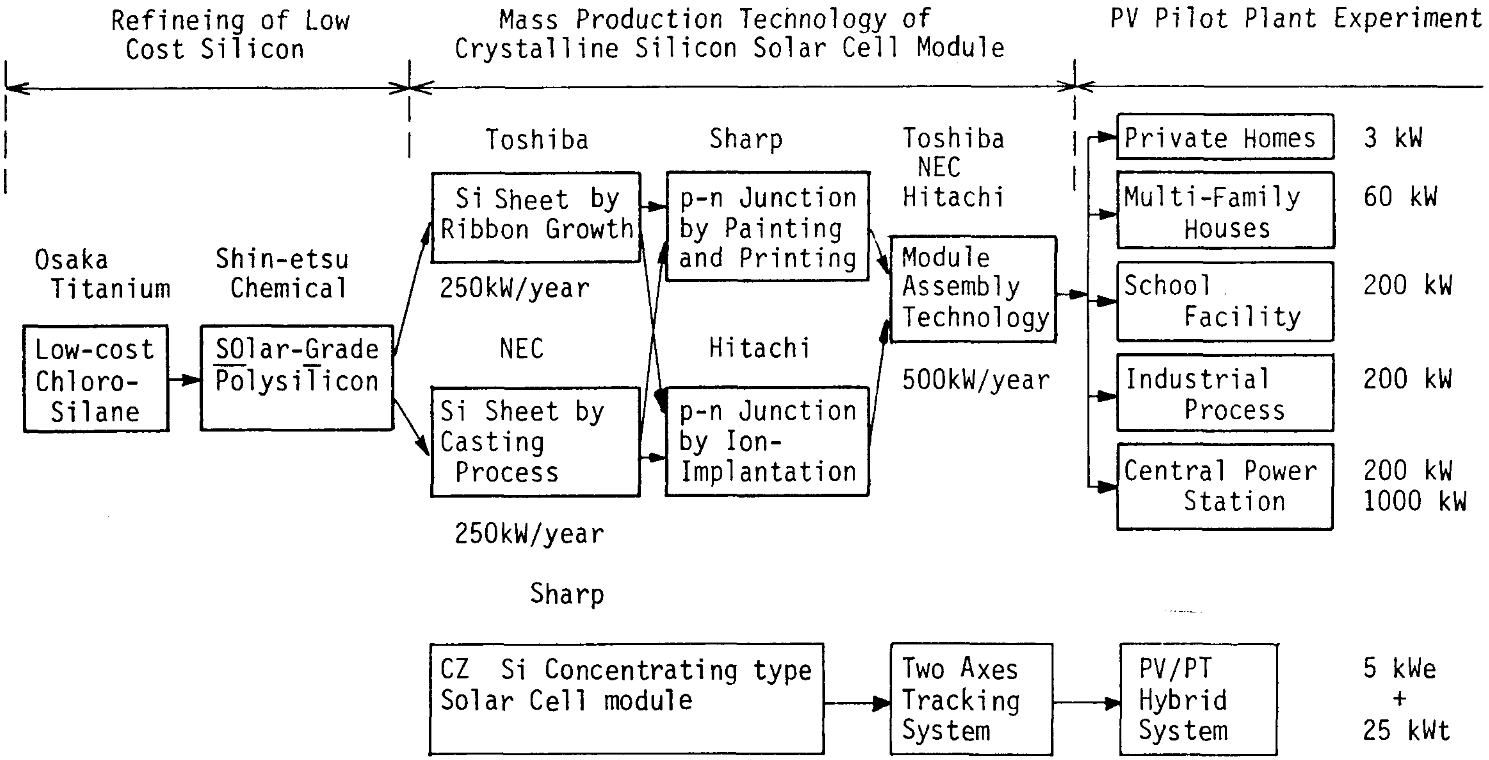

Fig.5 Solar PV module mass production processes and pilot plant (Sunshine Project, special account: NEDO contract).

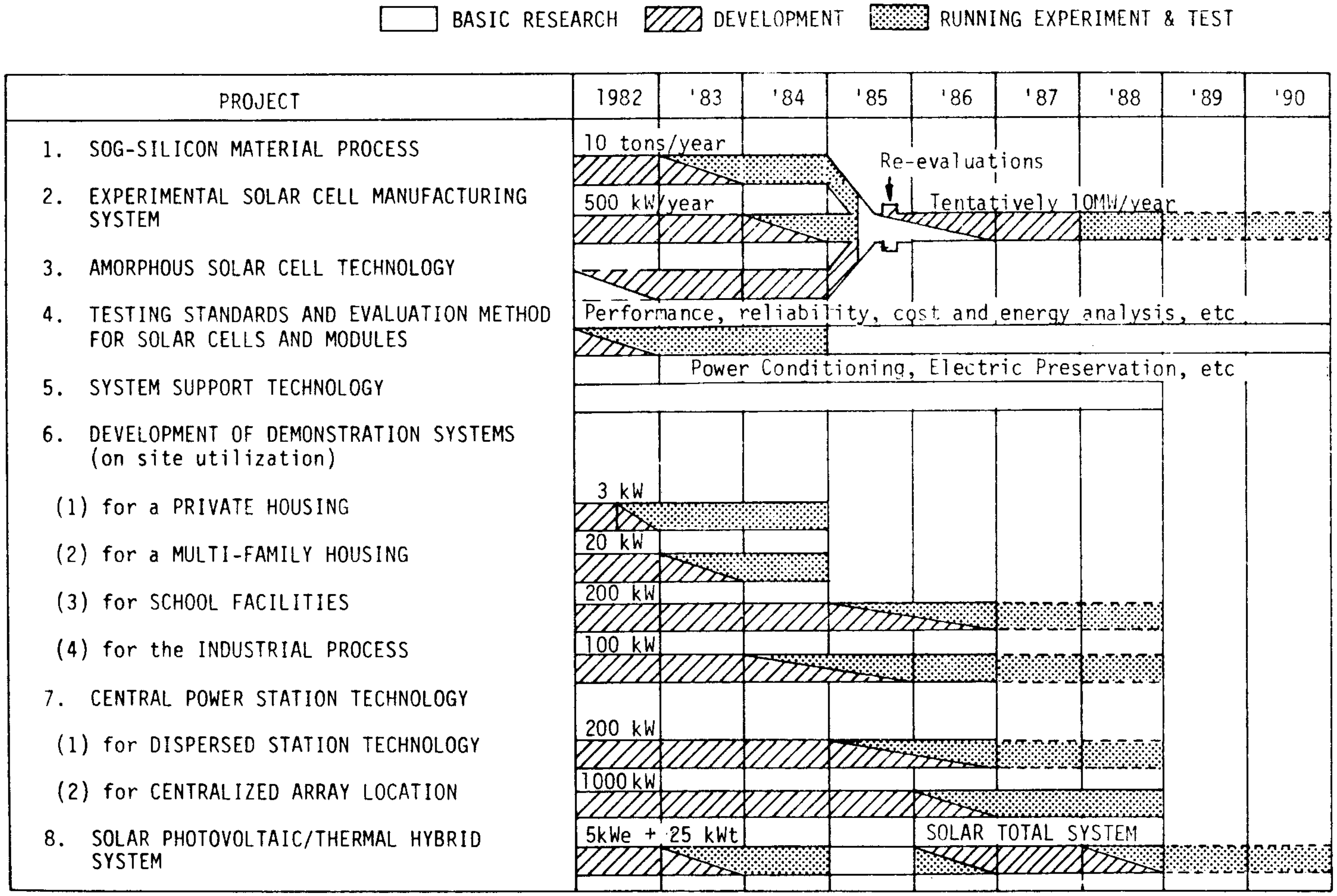

Fig.6 Sunshine Project solar photovoltaic energy R & D program by 1990.

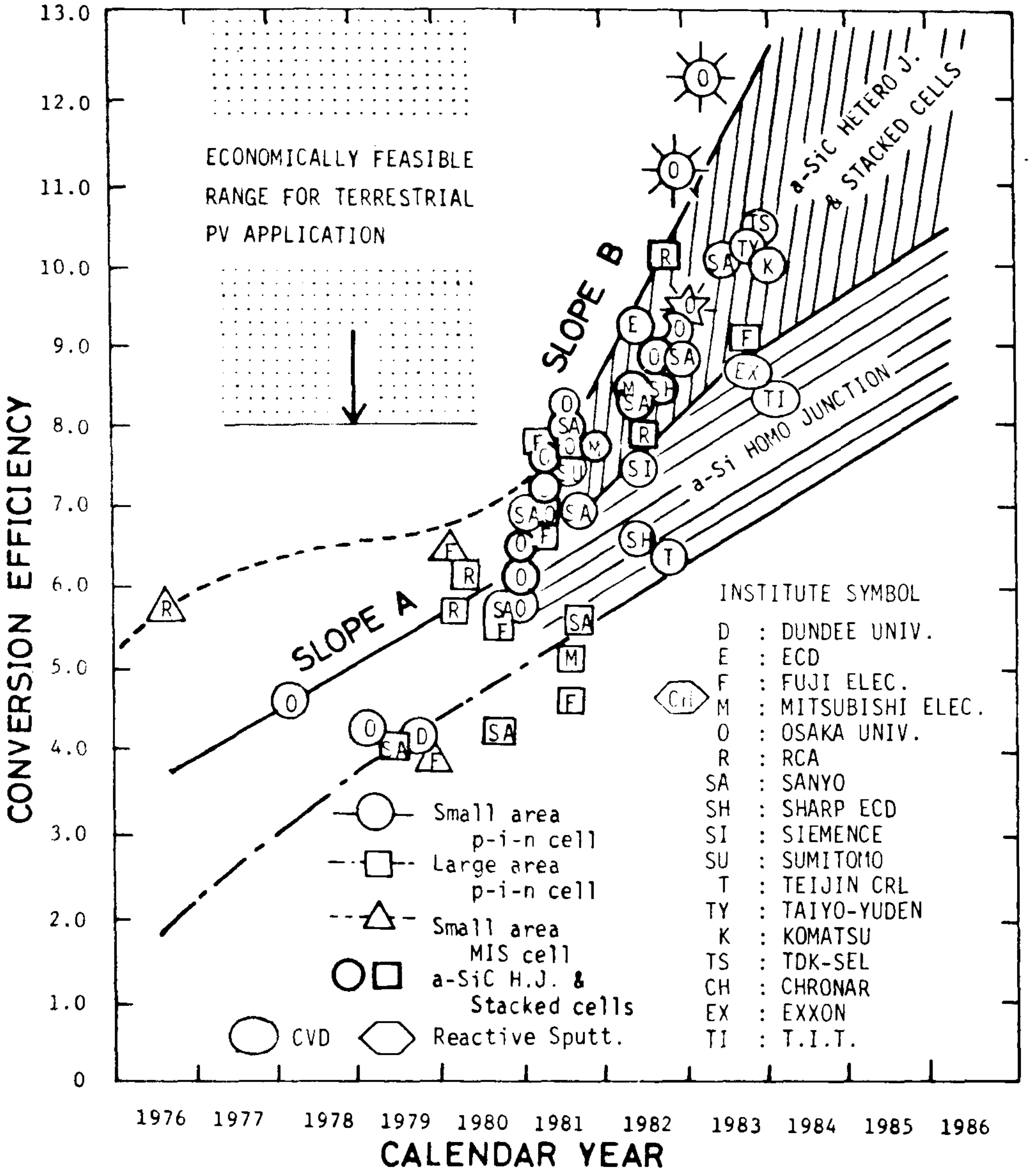

Fig.7 Progress of a-Si solar cell efficiencies for various types junction structures as of April, 1984.

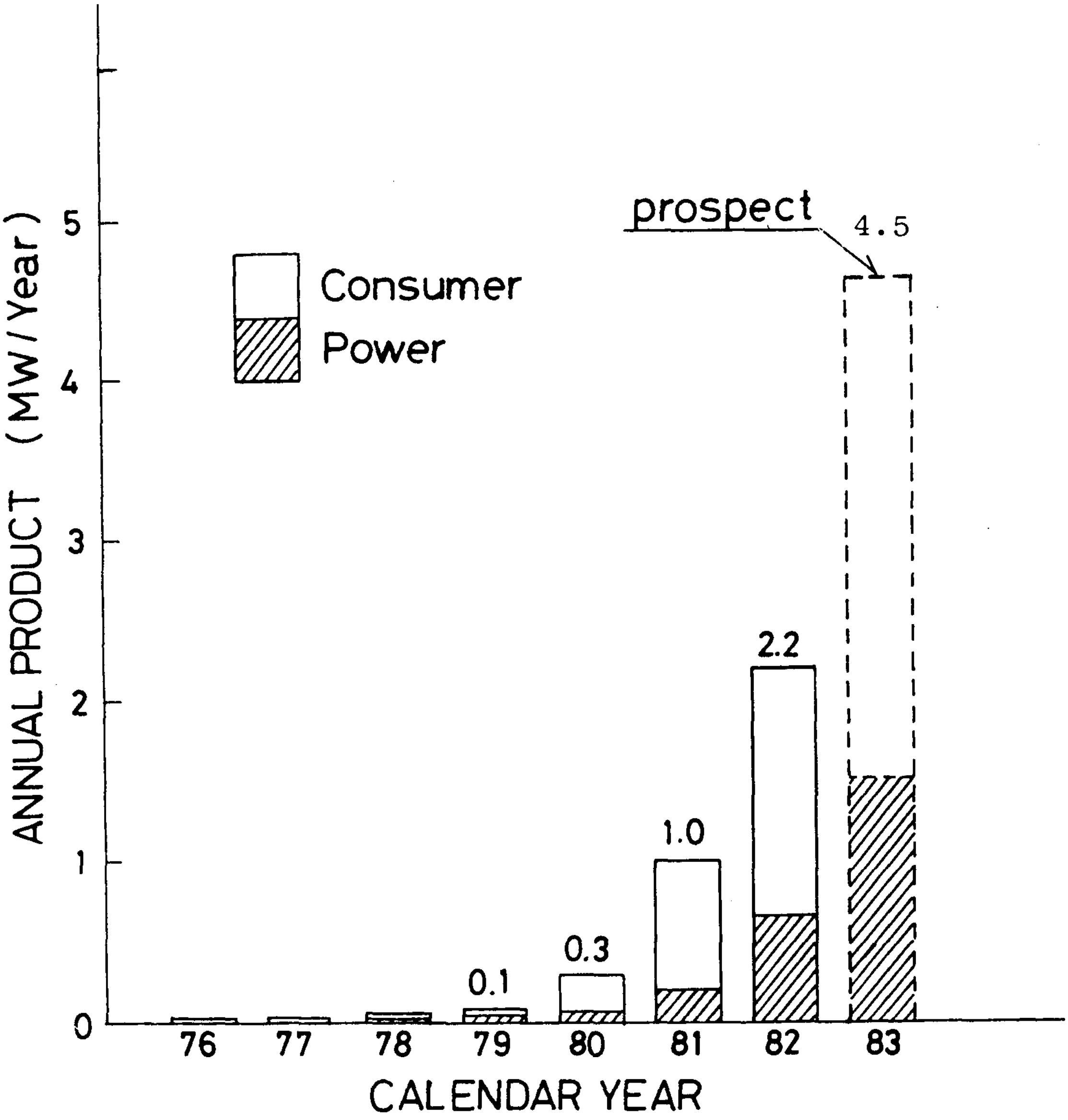

Fig.8 Growth of the annual products of solar cells in Japan. a-Si solar cells occupied more than 90% consumer use applications.

Table I PV pilot plants and development schedule

Facility	Location	Status/Schedule
Solar photovoltaic power generation systems (a) – fabrication facilities –	Naoetsu city, Niigata Pref. Hitachi city, Ibaraki Pref. Kawasaki city, Kanagawa Pref. Amagasaki city, Hyogo Pref. Himeji city, Hyogo Pref. Shinjo city, Nara Pref.	Construction of 500 kW/yr production experimental plant scheduled to be completed in FY 1982. Operational research is scheduled to start in FY 1983.
Solar photovoltaic power generation systems (b) – application facilities – ● single family house ● apartment house ● school building ● factory building	Yokosuka, Kanagawa Pref. Tenri city, Nara Pref. Tsukuba city, Ibaragi Pref. Hamamatsu city, Shizuoka Pref.	Costruction of each application system has been underway since FY 1981. A single family house was completed in 1981. An apartment house is to be completed by FY 1982. Operational research is scheduled after the completion of construction.
Solar photovoltaic central power station systems (c) ● distributed location type ● centralized location type	Ichihara city, Chiba Pref. Saijo, Ehime Pref.	Construction of each system has been underway since FY 1981.
Solar photovoltaic/solar thermal hybrid power (d) generation systems	Aki, Hiroshima Pref.	Constrution commenced in FY 1981, and scheduled to be completed in FY 1982. An operational research is to be started in FY 1983.

NOTES

EUROPEAN PROGRAM IN PHOTOVOLTAICS

R. Van Overstraeten, ESAT, Katholieke Universiteit Leuven,
Kard. Mercierlaan 94, 3030 Heverlee, Belgium

W. Palz, Commission of the European Communities,
200 Rue de la Loi, 1049 Brussels, Belgium.

Abstract

A. The Solar Energy R & D Program of the Commission of the European Communities (Directorate General XII) covering the period july 1979 - june 1983 had an overall budget of 46 million ECU. The photovoltaic power generation is referred to as project C and has approximately one third of the budget. Other projects are solar energy applications to dwellings, tower power plant Eurelius, photobiological and photochemical processes, energy from biomass, solar radiation data, wind energy and solar energy applications in agriculture and industry.

The photovoltaic power generation project has several actions :
1. an assessment study of the potential of photovoltaics in Europe and an assessment of photovoltaic power conditioning systems.
2. R & D projects on silicon cells, on alternative cells and on concentration.

The studies on silicon cells include :
- cell process development (screen printing,chemical vapour deposition)
- ion implantation (optimisation of an ion implanter without mass separation, laser annealing, laser induced diffusion, pulsed laser annealing).
- materials (casting, solar grade silicon, classification of crystal defects, the RAD process or the growth of silicon sheet on carbon ribbon like substrates).
- modules (new encapsulation materials, improved potting and cover materials).

The studies on alternative cells include :
- amorphous silicon (junctions produced by gas-phase doping and ion implantation, hydrogenated a-Si, sputtered films).
- CdS - Cu_2S (spray technique, electrolytical preparation and conditioning of cuprous sulfide, electrophoreted thin films).
- CdSe (the development of a cadmium-selemide solar cell).

The studies on concentration include :
- a pilot plant for irrigation.
- test and demonstration of Sophocle under mediterranean conditions.
- spherical metal membrane glass laminated mirrors.
- fluorescent collectors.
- development of hybrid thermal and photovoltaic collector.
- holographic thin film system for multijunction solar cells.
- spectral splitting and Si-GaAlAs coupled cells.

3. System studies. Although most system studies are part of the pilot projects, some studies were carried out independent. They relate to

- a system analysis of rural electrification
- an economical evaluation of supporting wood structures
- supporting structures for large photovoltaic generators
- comparison of various small PV systems with Eurelius
- design, manufacture and installation of 2 helioman two axis tracking systems with 5.3 kW polysilicon cells
- grid interactive photovoltaic system for residential applications
- photovoltaic energy supply of a danish standard house
- PV energy supply for a house in Germany
- electrical supply to individual homes on Gavdos Island
- research on solar house for Mediterranean climatic conditions
- integration of a photovoltaic generator in an ancient house.

4. Pilot projects, which are the highlight of the European R & D program. The call for tenders was launched at the beginning of 1980. After a selection procedure, 15 projects were started in 1981 (list in appendix 1). The first plant to enter operation in october 1982 was the one in Crete. The plant works very reliably and delivered as much as 15000 kWh of electricity to the village, making any back-up by Diesel sets unnecessary.

The total budget was approximately 30 million ECU. One third of the cost was borne by the Commission and the rest by the member countries and by other institutions. Co-funding by the industry was very important (in some cases up to 50%).

The Commission's services in Brussels assumed general management responsibility throughout the program.

Some interesting details are given now.

a. Modules

The modules were supplied by AEG, Siemens, France Photon, Photowatt, Pragma, Ansaldo, BP Solar, IDE/Photon Technology. The modules were qualified by the Commission's Joint Research Centre at Ispra in a special test campaign.

Single and polycrystalline silicon cells were employed. Module size ranges from 20 to 120 W. Several encapsulation techniques are used. The European module development benefited considerably from this action.

b. Arrays

The internal array loss due to mismatch of modules, cabling and diodes could generally be kept as low as 2%.

c. Power conditioning

All plants use AC systems, except three (one is linked to a water electrolysis unit, one to a water desinfection unit and the other to DC compression motors). Inverters are solid state with one exception (motor). Inverters are either designed for grid connection or stand-alone operation, some are for both. Some systems use maximum power trackers, others do not. Microprocessor control has been widely used for the power management. High efficiency of approximately 90% even at 10% load or 10% of maximum possible insulation was achieved either in simple systems with one inverter or multiple switching units.

A full range of DC/AC inverters from 1 kVA to 75 kVA has been developed by nine different European manufacturers : Jeumont Schneider, Aérospatiale, Leroy Somer, ETCA, Filectron, Italenergy, AEG, Siemens, Holec.

d. Support structures

All structures are fixed, some allowing seasonal adjustment. Two arrays are roof integrated and the others are installed either on flat roofs or on the ground. Several different designs and construction materials (metal or wood) were used. The cost of the structures depends on the terrain. In several cases the cost did not exceed 3 to 4% of the total plant cost.

e. Batteries

Improved design batteries of Oldham and Varta were used.

f. Monitoring

All plants employ the same standard monitoring system. The raw data is transmitted for exploitation to the Joint Research Center in Ispra, acting as the Commission's monitoring center for this program. The J.R.C. in Ispra also developed a new portable device which measures the power of sub arrays up to 10 kW.

B. The Joint Research Center in Ispra operates the ESTI - European Solar Test Installation. The facility includes :

- solar simulators for cells and modules
- durability and qualification facilities
- data acquisition systems.

ESTI supports the implementation of the pilot plant projects, by

- testing of cells and modules
- PV pilot plant acceptance testing
- monitoring of the pilot plants.

ESTI now also has a photovoltaic systems test facility. It consists of a 1 kW photovoltaic generator with automatic two axis sun tracking, with a relay-box for selection of the module to be tested, a DC powerline for connection to a charge controller and battery set and multiple line cables for connection to the data acquisition system and computer. ESTI also develops performance criteria and standard test procedures.

C. Conclusion

The R & D Program of the Commission of the European Communities contributed immensely to the development of a European industry in the field of photovoltaic energy conversion. Through other programs the Commission was also among the first to sponsor early PV applications in developing countries.

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Annex 1

EEC PV Pilot plants

Site	Power	Application	Lead. Contractor	Co-sponsor
Pellworm Island (D)	300kW	Power for recreation centre	AEG	German Government
Kythnos Island (GR)	100kW	Island grid	Siemens	German Govt., Greek utility PPC
Chevetogne (B)	63kW	Swimming pool, lighting	IDE / ACEC	Belgian Government
Aghia Roumeli (GR)	50kW	Village grid	Renault	French Govt., Greek utility PPC
Mont Bouquet (F)	50kW	TV emitter	Photowatt	French Govt., Télédiff. de France
Nice Airport (F)	50kW	Tower control	Photowatt	French Govt., Chamber of Commerce
Fota Island (IRL)	50kW	Dairy farm	U.Cork, AEG	Irish + German Govts., Irish utility
Terschelling (NL)	50kW	Marine school	Holec	Dutch and German Govts.
Kaw (French Guy.)	35kW	Village grid	Renault	French Government
Hoboken (B)	30kW	Electrolysis	ENI	Belgian Government
Rondulinu, Corsica (F)	30kW	Village power	Leroy-Somer	French Govt. and French utility EDF
Marchwood (UK)	30kW	Grid interaction	BP Solar	UK Government
Tremiti Island (I)	65kW	Seawater desalination	Italenergie	Italian Government
Giglio Island (I)	45kW	Water disinfection, cold store	Pragma	Italian Government, Toscana, Giglio Comm.
Vulcano Island (I)	80kW	Village power	ENEL	Italian utility ENEL

SERI PHOTOVOLTAICS RESEARCH

Donald W. Ritchie
Solar Energy Research Institute
Golden, Colorado

The focus of this paper is on the Solar Energy Research Institute's Solar Electric Research Division and its photovoltaic research activities. The primary areas of activity in the Solar Electric Research Division are the Photovoltaics Advanced Research and Development Project and the Wind Energy Program. The fiscal year funding for photovoltaics is $21.8M, of which 55% is focused toward subcontracts to industry organizations, universities, and other federal agencies and approximately $1M for the Wind Program.

The Mission of the Solar Electric Research Division is stated as:

"Identify and conduct basic and applied research and development on solar electric concepts in order to advance fundamental scientific understanding and to establish a technology base from which industry can select options for further development and introduction into the competitive energy market."

Photovoltaic systems continue to be one of the most attractive energy options for the United States. Photovoltaics has enjoyed the lime-light for the past 25 years as a prime energy source for our space program. More recently, it has influenced our thoughts as a terrestrial energy option for the future. The main obstacle at this time is the relative high cost. However, through federally funded research and the innovation and implementation of United States industry, costs have been reduced by a factor of 100 over the past 25 years. Through the federally funded DOE research activities and joint efforts sponsored by the industry, we are developing several thin film options to the recognized "workhorse" of photovoltaics, the single crystal silicon cell. These options, if successful, can potentially reduce the costs of terrestrial photovoltaic systems by another factor of 10. The thrust of the DOE National Photovoltaic Program is concentrating on several of these exciting high risk options, without abandoning research needed to enhance our basic understanding and to raise cell efficiencies of the single crystal silicon device. Recent reported single crystal efficiency values exceed 19%.

The level of excitement in the photovoltaic field for these new material options and their potential pay-off, is what the micro-computer industry may have experienced in the mid-70-'s. Now, nearly ten years later, it is a multi-billion dollar industry! Already, the United States Photovoltaic Industry is approaching the half billion dollar level, with indicators of doubling in 1984.

Evidence that the photovoltaic industry is alive, growing and innovative is demonstrated by the many photovoltaic installations throughout the United States. Most notable of these is the ARCO, PG&E and Edison joint-venture for the Carrisa Plains installation with almost 5 MWe operational.

A contributing factor to the growth of the photovoltaic industry research base is the internal photovoltaic research performed at the SERI Solar Electric Research Division laboratories. The Institute, has , through the years, developed an outstanding research team which has contributed to the basic knowledge of photovoltaics. The team includes several leading research scientists dedicated to photovoltaics and has made many significant contributions to the National Photovoltaic Program. The Solar Electric Division has a major responsibility for both internal and sub-contracted photovoltaic research which supports the DOE National Photovoltaic Program. The sub-contracted research activities which are managed by the Division are discussed in "Recent Developments in the Sub-Contracted Photovoltaic AR&D", by Dr. Tom Surek.

The internal photovoltaic research activities include the following technical areas and Principal Investigators:

Solid State Research - Satyen Deb

Semiconductor Crystal Growth	Ted Ciszek
Semiconductor Purification	Jerry Olson
Amorphous Thin Films	Arun Madan
Thin Film Compound Semiconductors	Rommel Noufi
High Efficiency Multi-Junctions	Jerry Olson
Solid State Theory	Alex Zunger
Devices	OPEN

Devices and Measurements - Larry Kazmerski

Materials Characterization	Ben Yacobi
Electro-Optical Characterization	Richard Ahrenkiel
Cell Performance	Carl Osterwald

Surface Analysis	Sam Ireland, John Dick
Device Characterization	Richard Ahrenkiel
Measurement Research	Branch
Outdoor measurements and Solar Insolation -	Roland Hulstrom
Spectral Solar Radiation Models and Data Sets	Richard Bird
Insolation Models, Algorithms and Data Base.	Tom Stoffel
Spectral Solar Radiation Instrumentation, Measurements and Analysis - Indoor and Outdoor	Ted Cannon
Outdoor Solar Radiation Research Laboratory	Tom Stoffel
Advanced PV Cell Sunlight Testing	Dick DeBlasio

Over the past year, the research of these scientists has been significant, and well recognized throughout the photovoltaic community.

The research contributions highlighted are to be covered in more detail in the IEEE 17th Photovoltaic Specialists Conference and Proceedings, and the SERI Annual Research Report. The accomplishments include:

- Development of techniques for single crystal growth of $CuInSe_2$ by three methods: melt growth, Chemical Vapor Transport (CVT), and by Hydro Thermal Growth.
- Determination of growth Form and Growth Rate anisotropies for high speed silicon growth.
- Establishment of a baseline silicon device process which routinely produces cells at 15.6%.
- An invention resulting in a patent for an improved silicon purification method by a novel vapor transport filtration technique using Cu_3Si:MGSi, and the achievement of a 12.6%, single crystal, cell from the electrorefined silicon.
- First theory of electronic and material properties of transition metal impurities in semiconductors.
- Theoretical analysis of optical properties of ternary chalcopyrites and prediction of more than 20 new ternary compounds.

- New theoretical explanation of optical bowing in alloys of binary semiconductors.
- Fabrication of state-of-the-art all amorphous Si:H p-i-n junction solar cells, (8.7%).
- Deposition and characterization of amorphous Si:Sn:H alloy for multijunction high efficiency solar cells.
- Developed a ZnS-coated Al transparent conductor as an alternative to ITO in a-Si devices.
- Achieved 8.9% active area efficiency without AR-coating in a $CuInSe_2$/CdS thin film solar cells.
- Determined the carrier type and concentration as a function of stoichiometry of $CuInSe_2$ thin film.
- Found a novel solution to the problem of morphological instability in the MOCVD growth of GaAs/GaAsP superlattice structure with high phosphorous concentration.
- Fabricated a GaAsP/GaAs cascade cell.
- Evaluated over 1000 materials and device samples (efficiency, spectral response, digital laser scanning) during the past 12 months.
- An automated spectral response system has been developed and is operational
- Developed a digital laser scanning system, capable of spatially resolving photoresponse, photocapitance, quantum efficiency, and photoconductivity. This system provides several unique features that allow the micro-characterization of the photo-properties of devices, as well as determining device areas with high arrcuracy
- Using a new technique combining C-V and photoconductivity, the minority carrier diffusion length has been measured in (CdZn)S/$CuInSe_2$ solar cells.

- A new technique, based upon double-modulation C-V measurements, has been developed for determining carrier densities in very heavily doped semiconductors.

- Photoluminescence studies of the CuInSe$_2$ system have led to the identification of defect levels in that semiconductor. The technique is capable of measurements to 4^{o}K, and has been utilized to establish industrial quality in GaAs, GaAsP and InP systems.

- Fabricated device quality GaAs/Ge/Si structures using MBE. The 2000A Ge layer limits the propagation of misfit dislocations (less than 10^{7}.cm^{2} in the GaAs) and the quality of the GaAs is indicated by a photoluminescence response with 60% of the peak intensity and the same FWHM.

- Implemented simultaneous measurement of EBIC, Auger voltage contrast, SIMS and AES, with better than 500A resolution, to locate the positions of the metallurgical and electrical junctions in photovoltaic cells.

- A new method was developed, utilizing the volume indexing of digital SIMS signals, providing compositional information and impurity maps on internal materials/device interfaces. The data can be coded for ion species, spatial origin (x, y, z) and concentration level. Additionally, the output can be color-coded to represent these parameters. The segregation of oxygen and hydrogen passivation of grain boundaries was directly measured for the first time using this technique.

- Compositional standards for AlGaAs, CuInS$_2$, CuInSe$_2$, CdS, CdTe, InP, ITO were established. Oxides of these species have also been cataloged for identification.

- Investigations of the microstructure of hydrogenated silicon-tin alloys have been performed using scanning transmission electron microscopy (STEM). These studies have revealed compositional and structural inhomogeneities within these alloys. All silicon-tin films contained Sn precipitates, and the matrix shows a "cauliflower" microstructure indicative of a non-coalesced network. The density of the Sn precipitates decreases with Ar sputtering pressure, indicating that lower pressures are required to minimize tin segregation. Similar studies on silicon-tin alloys produced by glow discharge reveal no tin segregation problem.

- Discovered a decay of the EBIC signal in a-Si:H. The conditions for the non-destructive analysis of this material were identified. The EBIC studies have also revealed various fabrication defects that are the origin of the excess dark current in solar cells fabricated from this material.

- Determined minority-carrier lifetimes directly in InP, GaAs, CdTe and CdSe, using a specially-developed picosecond laser spectroscopy technique.

- Developed the outdoor Solar Radiation Research Laboratory (SSRL) which is capable of providing high quality insolation spectral solar radiation, and meteorological data for a wide variety of photovoltaic device measurements and tests.

- Completed an extensive evaluation of the algorithm/models used to generate the commonly used SOLMET and ERSATZ historical data bases.

- Initiated a thorough study of the relative amounts of insolation available to one axis tracking, two axis tracking, concentrator, and fixed tilt flat plate collectors. This includes an evaluation of new and historical algorithms for producing such data.

- Obtained selected terrestrial spectral solar radiation data sets for a south facing fixed tilt flat plate surface, under both clear and cloudy days.

- Produced a simple spectral model for predicting the

  terrestrial spectral solar radiation on fixed and/or tracking flat plate surfaces, for various atmospheric turbidities and relative air masses (clear sky).

- Initiated outdoor testing of amorphous silicon solar cells in support of subcontracted research.

- Initiated long term outdoor testing of $CdS/CuInSe_2$ to assess cell performance and stability.^{2}

The Solar Electric Research Division achievements are numerous and continue to enhance our Nation's knowledge of photovoltaics as evidenced by the dramatic increases in cell efficiencies over the past several years. In addition, the research activities in FY83 alone have resulted in:

1) Over 125 technical publications, including journal articles, conference papers and contributions or authorships to books;

2) Over 25 invited speakers talks at National and International scientific meetings;

3) Extensive collaboration with universities and industrial research laboratories

4) Over 15 visiting post doctoral and sabbatical scientists from many countries;

5) Extensive recognized technical excellence and leadership in many discipline areas.

SERI continues to provide a strong nucleus to the National Photovoltaic R&D Program.

NOTES

RECENT DEVELOPMENTS IN SUBCONTRACTED PHOTOVOLTAIC AR&D

Thomas Surek
Solar Electric Research Division
Solar Energy Research Institute
Golden, Colorado 80401

This presentation reviews recent developments in subcontracted research activities under the Solar Energy Research Institute's (SERI's) Photovoltaic Advanced Research and Development Project.

The accompanying figures outline the purpose, strategy and key research tasks of the SERI subcontracted activities. The corresponding research areas in the Department of Energy's "National Photovoltaics Program: Five Year Research Plan 1984 - 1988" are also identified. A brief history of the subcontract budget from FY77 to FY84 is given; the priority areas of the program, during the last two fiscal years, are seen to be Amorphous Thin Films, Polycrystalline Thin Films and High Efficiency Concepts. Significant industrial R&D involvement in the program is evident from the figure on research participants; approximately 50% of the current annualized level of subcontract funds go to private industry. The importance of University participation in the program is shown by the fact that 39 of the current 73 subcontracts are with Universities.

The key research directions and major accomplishments during the past year are described in the next set of figures for each of the six SERI research tasks: Amorphous Thin Films, Polycrystalline Thin Films, High Efficiency Concepts, Crystalline Silicon, Photoelectrochemical Cells and New Ideas. The major highlights include: (i) the multi-year initiative in amorphous silicon, under the newly-formed Amorphous Silicon Research Project at SERI, to improve the efficiency and stability of single-junction amorphous silicon cells, and to identify and develop new amorphous silicon alloy materials for multijunction cells - cost-sharing subcontracts were awarded to Chronar, 3M, Solarex and Spire; (ii) the reported achievement of 11% efficiency in thin-film (Cd, Zn)S/$CuInSe_2$ solar cells and the joint venture (SOVOLCO) to commercialize such solar cells; (iii) the achievement of high quantum efficiencies in GaInAs and GaAlAs cells grown in a monolithic, non-lattice matched stack, with 21.5% efficiency achieved in the GaInAs bottom cell under concentration; (iv) SERI verifications of several 18% efficient, 4cm^2 area crystalline silicon solar cells and measurement of 19.1% efficiency on a MINP solar cell supplied by the University of New South Wales; and (v) initiation of nine new research projects in the New Ideas task.

A summary of the extensive technology transfer activities under SERI's Photovoltaic AR&D Project is given in an accompanying figure. Timely and effective transfer of the research results is achieved through participation by industry and organizations external to the SERI programs in the various Subcontractor Review Meetings which are held periodically. Publications by SERI researchers and subcontractors in the open technical literature constitute another effective means of technology transfer. Over 280 such publications appeared in FY83; approximately 50 papers at the 17th IEEE Photovoltaic Specialists Conference were authored by SERI researchers and subcontractors. Further information on the SERI subcontracted programs is available in the review papers (1-6) which will appear in the Conference Proceedings.

The opportunities and challenges for the SERI Photovoltaic AR&D Project are summarized in the last two figures in terms of the goals of the DOE Five Year Research Plan.

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2. "Advances and Opportunities in the Amorphous Silicon Research Field" by E. Sabisky, W. Wallace, A. Mikhail, H. Mahan and S. Tsuo.

3. "DOE/SERI Polycrystalline Thin-Film Photovoltaic Research" by A. Hermann, K. Zweibel and R. Mitchell.

4. "Research Directions and Progress in the SERI Advanced High Efficiency Concept Program" by L.A. Cole and J.P. Benner.

5. "Research on Crystalline Silicon Solar Cells" by J.B. Milstein and Y.S. Tsuo.

6. "Research on Photoelectrochemical Cells Based on CdSe, $CdSe_{1-x}Te_x$ and Other Photoelectrode Materials" by W.L. Wallace.

SERI Photovoltaic AR&D Program Office

Recent Developments in Subcontracted Photovoltaic AR&D

T. Surek
Solar Energy Research Institute
Golden, Colorado

SERI Photovoltaic AR&D Program Office

Talk Outline

- Purpose and Strategy
- Key Research Areas
- Program Scope and Participants
- Research Thrusts and Major Accomplishments
- Technology Transfer
- Opportunities and Challenges

SERI Photovoltaic AR&D Program Office

Purpose

- Sponsor long-term, potentially high payoff research and development on newly-evolving photovoltaic concepts, materials and structures to advance scientific understanding and establish the technology base.
- Disseminate the research results promptly to permit private enterprise to choose options for further development and competitive application in U.S. electrical energy markets.

SERI Photovoltaic AR&D Program Office

Strategy

- Identify and assess research needs and opportunities; identify and select technologists to perform the research; evaluate and transfer the research results.
- Promote partnership with industry through cost-shared research efforts and long-term commitments; program benefits from industrial innovation and experience and prompt technology transfer.
- Promote involvement of universities to gain fundamental research support, identification of new research frontiers, and training of professional manpower.
- Utilize expertise at federal laboratories and other research institutions to provide basic research support, program continuity, and validation of industrial research results with advanced measurement techniques and equipment.

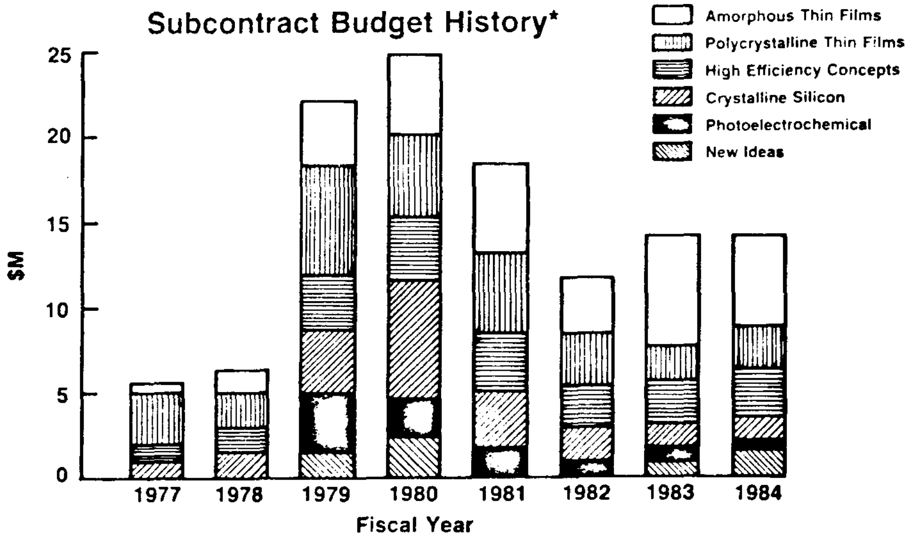
Photovoltaic AR&D Program Office

Key Research Areas

SERI Tasks	DOE Five-Year Plan
Amorphous Thin Films Polycrystalline Thin Films High Efficiency Concepts	Single Junction Thin Films High Efficiency Multi-Junction Concepts
Crystalline Silicon	Flat Plate Collectors
Photoelectrochemical Cells New Ideas	Innovative Concepts

Photovoltaic AR&D Program Office

Subcontract Budget History*



*Includes 10-20% for program management, fees, etc.

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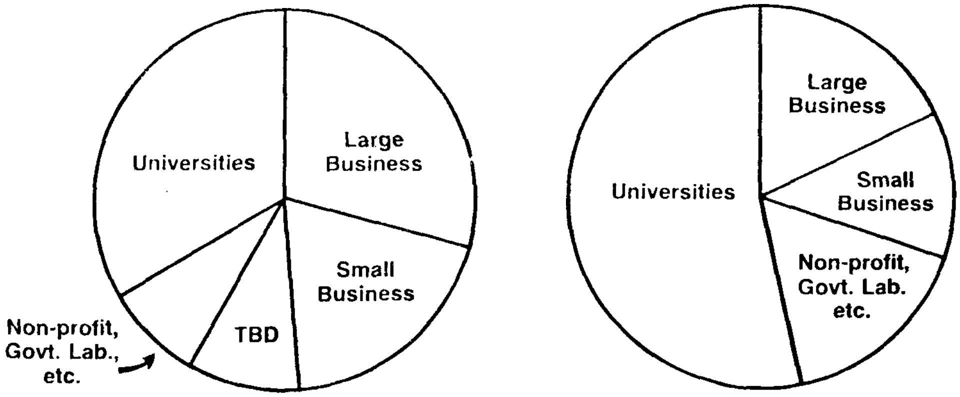
Photovoltaic AR&D Program Office

Research Participants



Annualized Level of
Current Subcontracts
= $15.3M

Number of
Subcontracts
= 73

SERI

Photovoltaic AR&D Program Office

Amorphous Silicon Research Project

(E. Sabisky, Manager)

Research Thrusts:

- **Continuation of multi-year initiatives to develop high efficiency, stable single-junction amorphous silicon solar cells and submodules, and multi-junction, stacked amorphous alloy thin-film solar cells.**
- **Investigations of light-induced effects, material deposition rate, alternate deposition methods, device testing and reliability, transparent conductors, and supporting research (theory, plasma kinetics, etc.)**

Amorphous Silicon Research Project

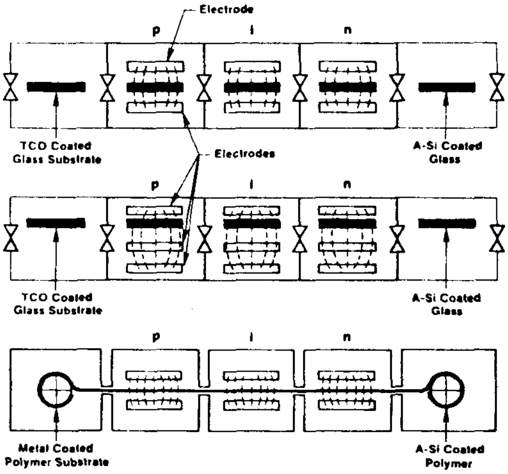
(continued)

Major Accomplishments:

- Multi-year research programs initiated in single-junction and multi-junction amorphous silicon solar cells; cost-sharing subcontracts awarded to Chronar, 3M, Solarex and Spire.
- Large area (up to 350 cm^2) amorphous silicon submodules made by RCA and Chronar achieved nearly 5% efficiency (measured at SERI).
- Four groups measured J_{sc} of 10 mA/cm^2 for CVD-prepared material using higher order silanes.
- Amorphous Silicon Research Project set up at SERI by DOE to direct all federally-funded activities in amorphous silicon.

Company	Approach
Chronar	• Single-Junction p-i-n Cells • RF Glow Discharge 2-Electrode • 3 Chambers • Glass Substrate
Solarex	• Single-Junction p-i-n Cells • DC Glow Discharge 3-Electrode • 3 Chambers • Glass Substrate
3-M	• Single-Junction p-i-n Cells • RF Glow Discharge 2-Electrode • 3 Chambers • Flexible Polymer Substrate

A-Si Deposition Method



Polycrystalline Thin Films

(A. Hermann, Task Manager)

Research Thrusts:

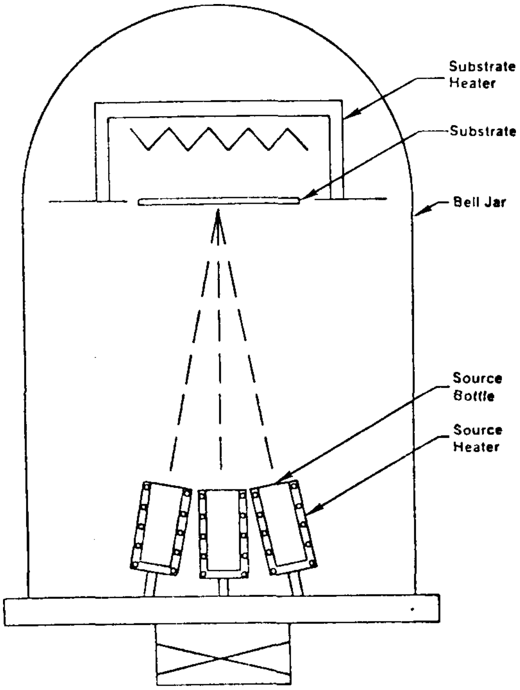
- Improvements in single-junction devices: $CuInSe_2$ and alloys to increase V_{OC}, CdTe and alloys to increase J_{SC}, new absorbers.
- Development of high-bandgap window materials to increase J_{SC}.
- Investigations of two- and four-terminal multi-junction devices with $CuInSe_2$ bottom cells.

Polycrystalline Thin Films

(continued)

Major Accomplishments:

- Joint venture (SOVOLCO) formed by Boeing/Reading and Bates to commercialize $CdS/CuInSe_2$ solar cells.
- 11% efficient thin-film (Cd,Zn) $S/CuInSe_2$ solar cell reported by Boeing; 8.2% thin-film ITO/CVD-CdTe device reported by SMU.
- Open-circuit voltage addition ($V_{OC} > 1V$) achieved in thin-film, two-terminal cascade [$CdS/CdTe/ITO/CdS/CuInSe_2$] device by IEC.



Three-Element Knudsen Source System for the Production of $CuInSe_2$ Films (IEC)

SERI Photovoltaic AR&D Program Office

High Efficiency Concepts

(J. Benner, Task Manager)

Research Thrusts:

- Research on ternary and quaternary III-V's for multijunction, high-efficiency concentrator cells.
- Investigations of GaAs and ternary III-V's on silicon for thin single-junction cells and flat-plate multijunctions.
- Development of thin-film single crystal or large grain polycrystal GaAs for flat-plate collectors.

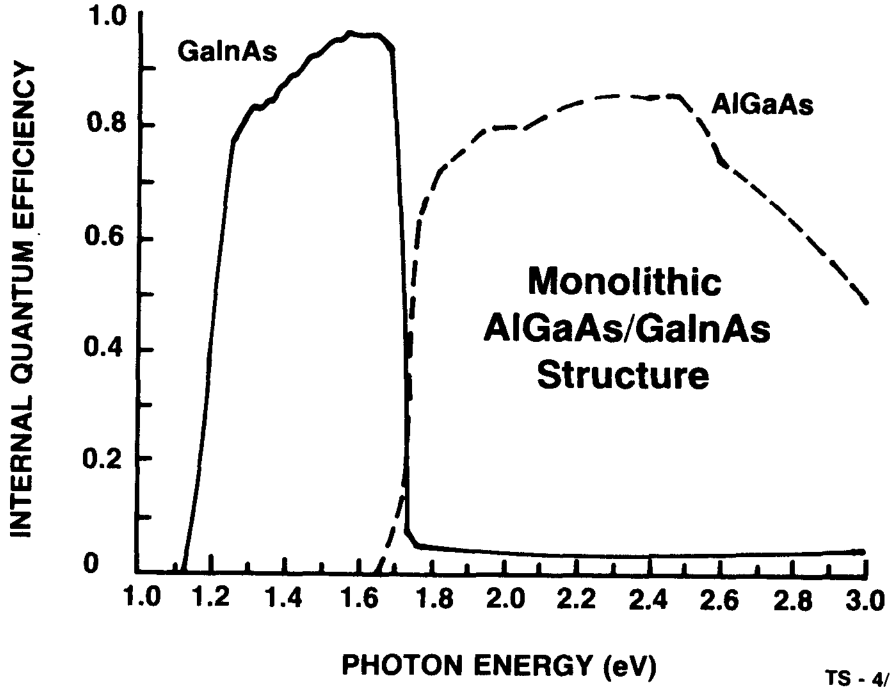
Photovoltaic AR&D Program Office

High Efficiency Concepts
(continued)

Major Accomplishments:

- 13% and 14% one-sun efficiencies, respectively, reported for ternary cells of GaAlAs and GaAsP by MIT/Lincoln Laboratory.
- High quantum efficiencies maintained for both GaInAs and GaAlAs cells grown in a monolithic, non-lattice matched stack by Varian; 21.5% efficiency achieved for GaInAs under concentration.
- 22% efficiency reported in a two-color, three-terminal monolithic GaAsP/GaAsSb concentrator cell by Chevron.

Photovoltaic AR&D Program Office



TS - 4/30/84

SERI Photovoltaic AR&D Program Office

Crystalline Silicon

(J. Milstein, Task Manager)

Research Thrusts:

- Investigations of the limits of efficiency attainable in crystalline silicon solar cells.
- Understanding of the generation, modification and passivation of electrically active defects.

SERI Photovoltaic AR&D Program Office

Crystalline Silicon

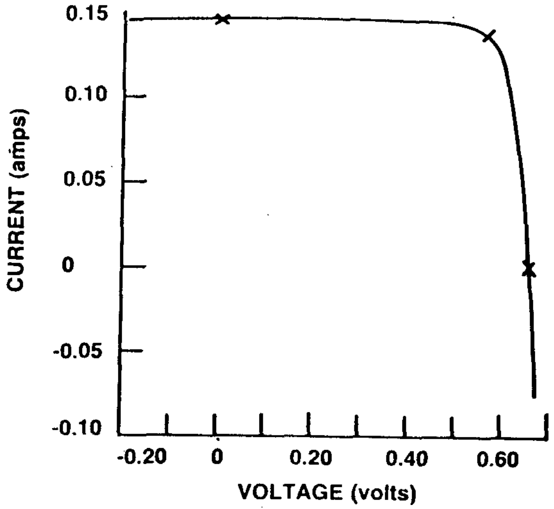
(continued)

Major Accomplishments:

- 18% efficiency, 4 cm^2 area solar cells fabricated by Spire and confirmed at SERI; goal met one year ahead of plan.
- 19.1% efficiency measured at SERI on 4 cm^2 area MINP solar cells made by Univ. New South Wales (not SERI-supported).
- First demonstration of significant efficiency improvements in dendritic web solar cells after 5 to 10 minutes of hydrogen ion beam treatment.

Photovoltaic AR&D Program Office

MINP Silicon Solar Cell



SAMPLE: SD2319
DATE: DEC 22 1983 11:13
TEMP = 28.0 C
AREA = 4.068 cm^2
Voc = 0.6526 volts
Jsc = 36.01 mA/cm^2
Fill factor = 81.14%
Efficiency = 19.07%

TS - 4/30/84

Photovoltaic AR&D Program Office

Photoelectrochemical Cells

(B. Wallace, Task Manager)

Research Thrusts:

- **Deposition and characterization of polycrystalline thin-film photoelectrode materials.**
- **Investigation and assessment of photoelectrochemical storage approaches.**
- **Fundamental research on photoelectrochemical processes.**

SERI Photovoltaic AR&D Program Office

Photoelectrochemical Cells
(continued)

Major Accomplishments:

- Demonstrated potential for greater than 10% efficiency thin-film cells; single crystal cell efficiencies are higher.
- Significant progress in cell stability; semiconductor/electrolyte systems identified with long-life potential.
- Photoelectrochemical characterization techniques found increased applications in solid-state research; advantages of simplicity, sensitivity and versatility.

SERI Photovoltaic AR&D Program Office

New Ideas
(J. Milstein, Task Leader)

Research Thrusts:

- Identification of new photovoltaic conversion concepts, cell geometries, materials and deposition methods, junction formation techniques and fabrication processes, and improvements in the understanding of basic mechanisms and measurement methods.

New Ideas

(continued)

Major Accomplishments:

- Nine research projects initiated as a result of solicitation issued in January 1983.
- Topics include: graded bandgap GaAs/GaAlAs cells, II-VI based materials ($CuInSe_2$, $Cd_{1-x}Pb_xS$, $ZnSnP_2$), organic dye p-n junction cells, and novel means of depositing amorphous silicon.
- New solicitation issued March 28, 1984. Responses are due May 14, 1984.

Technology Transfer

- Subcontractor review meetings held in Polycrystalline Thin Films (5/83), Crystalline Silicon(6/83), High Efficiency Concepts (10/83), Amorphous Thin Films (12/83) and Photoelectrochemical Cells (12/83); Workshop held on CdTe/HgCdTe (1/84).
- Extensive participation by industry and organizations external to the SERI programs in these review meetings.
- SERI/Photovoltaic AR&D Annual Review Meeting held May 1983; next meeting is scheduled for October 29-31, 1984 in Golden, Colorado.
- Over 280 papers published in FY83 by SERI subcontractors and researchers in the open technical literature.
- SERI-supported technologies have resulted in new commercial ventures in photovoltaics.
- Challenge to industry is to adapt and adopt research results for its own product development and commercialization.

SERI Photovoltaic AR&D Program Office

Opportunities and Challenges* - FY84 and FY85

- Achievement of 18% efficiency in crystalline silicon solar cells of 1 cm^2 area (FY84).
- Achievement of 12.5% efficiency in polycrystalline thin-film solar cells of 1 cm^2 area (FY84).
- Achievement of 30% efficiency in small-area, multi-junction cells under concentrated sunlight (FY84).
- Achievement of 12% efficiency in amorphous thin-film multi-junction cells of 1 cm^2 area (FY85).

*National Photovoltaics Program: Five Year Research Plan

SERI Photovoltaic AR&D Program Office

Opportunities and Challenges* - FY86 to FY88

- Achievement of 8% efficiency for amorphous silicon submodules of 1000 cm^2 area (FY86).
- Achievement of 12% efficiency for amorphous silicon solar cells of 100 cm^2 area (FY88).
- Achievement of 18% efficiency in amorphous thin-film multi-junction cells of 1 cm^2 area (FY88).
- Achievement of 20% efficiency in gallium arsenide thin-film solar cells of 1 cm^2 area (FY86).
- Achievement of 20% efficiency in crystalline silicon solar cells of 1 cm^2 area (FY86).
- Achievement of 15% efficiency in polycrystalline thin-film solar cells of 100 cm^2 area (FY87).
- Achievement of 35% efficiency in 1 cm^2 area, multi-junction cells under concentrated sunlight (FY88).

*National Photovoltaics Program: Five Year Research Plan

NOTES

THE SANDIA PHOTOVOLTAIC PROJECTS

G. J. Jones, D. E. Arvizu, and E. L. Burgess
Sandia National Laboratories
Albuquerque, NM 87185

The Sandia National Laboratories is responsible for management of the Systems Research, System Experiments, and Concentrator Collector Research projects of the U.S. Department of Energy's National Photovoltaic Program. This presentation reviews the status and progress of these projects over the past year. Some highlights are summarized below.

System experiments which have been operational for up to three years are providing data on system and subsystem performance. Detailed evaluation of these experiments have led to improvements in array performance, balance of system (BOS) costs and O&M philosophies. One very encouraging result is the lack of or very low rate of degradation which has been observed in the more mature arrays.

A major factor leading to BOS cost reductions is the concept of a modular building block array field. Fixed flat panel array fields are now projected to cost approximately $\$50/m^2$ in field sizes as small as 1 MW.

Significant progress has been made in the area of small power conditioning subsystem (PCS). Several 2-8 kW units are available "commercially" which have been put through a rigorous engineering evaluation program. They exhibit very good to excellent features operating in a utility interactive mode. One issue, harmonics, which has received much attention in the past has become a non-issue due to the excellent power quality produced by the PCS units.

High efficiency silicon concentrator cells (>19%) are now being produced in quantity with good yields (70-75%). In addition, theoretical modeling studies indicate that advanced structure silicon cells can reach efficiencies above 25%. Several advanced designs are being investigated to experimentally explore this possibility.

An alternate approach to obtaining higher efficiency concentrator cells is the use of III-V materials, either in single junction or multijunction devices. Two multijunction approaches being pursued in the Sandia program involve strained layer superlattices (SLS) and mechanically stacked cells. A pn junction has been grown in an SLS structure with good quantum efficiency considering the state-of-the-art of this technology. Also, progress has been made on thin AlGaAs cells for the mechanically stacked device; one such device was produced which exhibited a one-sun efficiency of approximately 16%.

Concentrator module efficiency continues to increase. Commercial modules using baseline silicon cells have now surpassed 15% peak efficiency. An experimental module designed to eliminate the most significant loss mechanisms has demonstrated a peak conversion efficiency of 17%. The next year of research is projected to produce some advanced modules with efficiencies breaking the 20% barrier.

Concentrator cost continues to come down as advances are made in efficiency. A 1 MW installed system using point focus concentrator arrays has recently been quoted at $\$7/W_p$. It is possible to project an installed system price using current technology and production rates of 150 MW/yr at about $\$2/W_p$; using advanced technology further price reductions are forecast.

What Does It All Mean?

Both flat plate and concentrator technologies are reliable and can be used in a variety of system designs. Array BOS costs have been reduced to near goals, removing economic barriers for PV systems formally experienced because of the cost of this part of the system. Utility interface studies and PCS development is removing utility resistance to the technology and utilities are becoming actively involved in PV system research. Because of high efficiency concentrators, this technology is becoming more established as a viable low cost option.

SIGNIFICANT RESULTS AND ISSUES

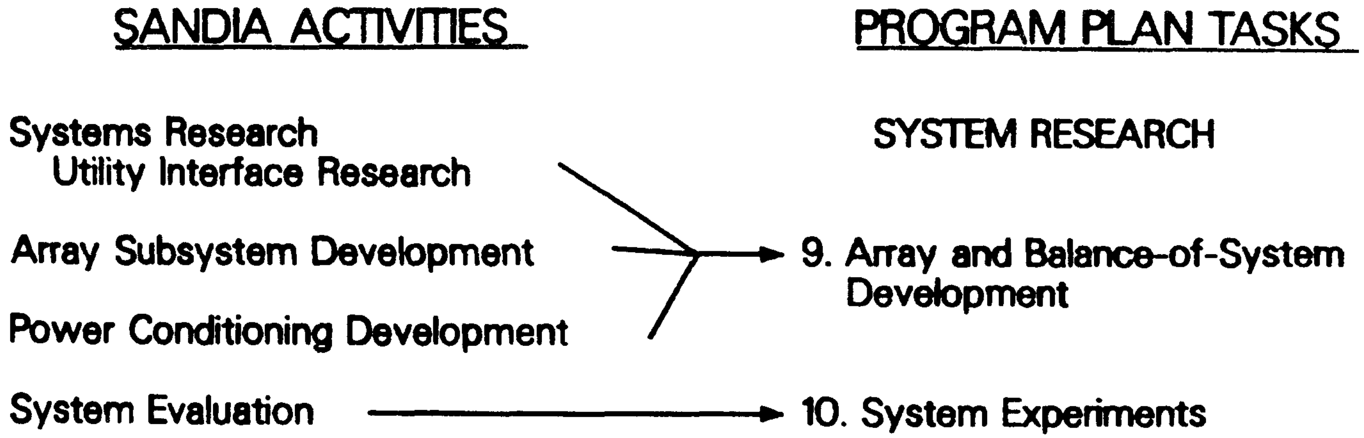
FROM THE

PHOTOVOLTAIC SYSTEMS DEVELOPMENT AND EVALUATION PROJECTS

SANDIA NATIONAL LABORATORIES

APRIL 30, 1984

SANDIA ACTIVITIES
VERSUS
PROGRAM PLAN BREAKOUTS



SANDIA ACTIVITIES

Systems Research
  Utility Interface Research

Array Subsystem Development

Power Conditioning Development

System Evaluation

PROGRAM PLAN TASKS

SYSTEM RESEARCH

9. Array and Balance-of-System Development

10. System Experiments

SYSTEM RESEARCH AND EVALUATION

G J Jones
M G Thomas

- Tracking is cost effective for large flat panel array fields and defines concentrator goals
- Prediction of energy output may be simple, aiding in Technology Transfer
- Analysis and field experience show residential BOS costs must be reduced
- Observed O & M costs are about $3/m^2 for 100 kW flat plate systems - most is unecessary
- System experiments are providing data on system and subsystem performance

SYSTEM PERFORMANCE
IN THE
INTERMEDIATE EXPERIMENTS

	EXPERIMENT	$\frac{\text{DC ENERGY} * 1\ \text{kW/m}^2}{\text{SOLAR/m}^2 * \text{RATING}}$	COMMENTS
A	EL PASO	.850	Constant voltage
	BEVERLY	.844	Max Pwr Trk - NE
	LOVINGTON	.866	Max Pwr Trk - SW
	DFW	.719	Constant temperature
B	OCSA	.523	Array overrated
	SAN BERNARDINO	.475	Array overrated
	APS	.553	PCS failures
C	BDM BUILDING	.431	Parabolic troughs fail to operate near projections
	KAUAI (HOSPITAL)	.328	
	MCCC	.198	

ARRAY SUBSYSTEM DEVELOPMENT

H N Post

- Bypass diode protection may be a significant cost driver - resolution is an open issue
- Low voltage (±400 volts) will be pursued for large fields in future analyses
- Concentrator "building block" installation verifies array field cost reduction
- Tracking flat plate building block under development - soon
- Fixed flat panel array field BOS is projected at \$52/m^2 (1983\$)

ARRAY FIELD BOS COSTS
FIELD EXPERIENCE AND STUDIES

	BATTELLE MOD. DESIGN			HUGHES MOD. DESIGN			BATTELLE
	1st	2nd	1MW	1st	2nd	1MW	100MW
Site Preparation	13.80	15.53	9.32	23.93	16.35	10.37	1.28
Structural Subsystem	103.11	49.44	30.80	87.50	59.80	37.89	22.40
Electrical Subsystem	29.21	13.41	18.53	43.98	30.06	19.00	27.97
Total	146.12	78.38	58.65	155.41	106.21	67.26	51.65

POWER CONDITIONING DEVELOPMENT

T S Key

- Advanced PCSs for multi-megawatt systems are in early stages of development - optimal approach not yet defined
- Major cost reductions are expected from advanced design of large PCS
- Understanding of PCS requirements for utility interconnection has matured through testing, with significant utility input
- Detailed evaluation of small PCS has accelerated design evolution process

PCS PROPERTIES
IMPACTED BY EVALUATION PROCESS

PARAMETER	ORIGINAL PERFORMANCE	PERFORMANCE AFTER MODIFICATION
Standby Power Req.	▨	●
Temperature Range	▧	▨
Max Power Tracking	▨	●
Utility Fault Response	▧	▨
Loss-of-Utility Run-on	○	●
Voltage / Freq. Operation	▨	●
Transient Overvoltage Prot.	▧	●
Electromagnetic Emissions	▧	▨

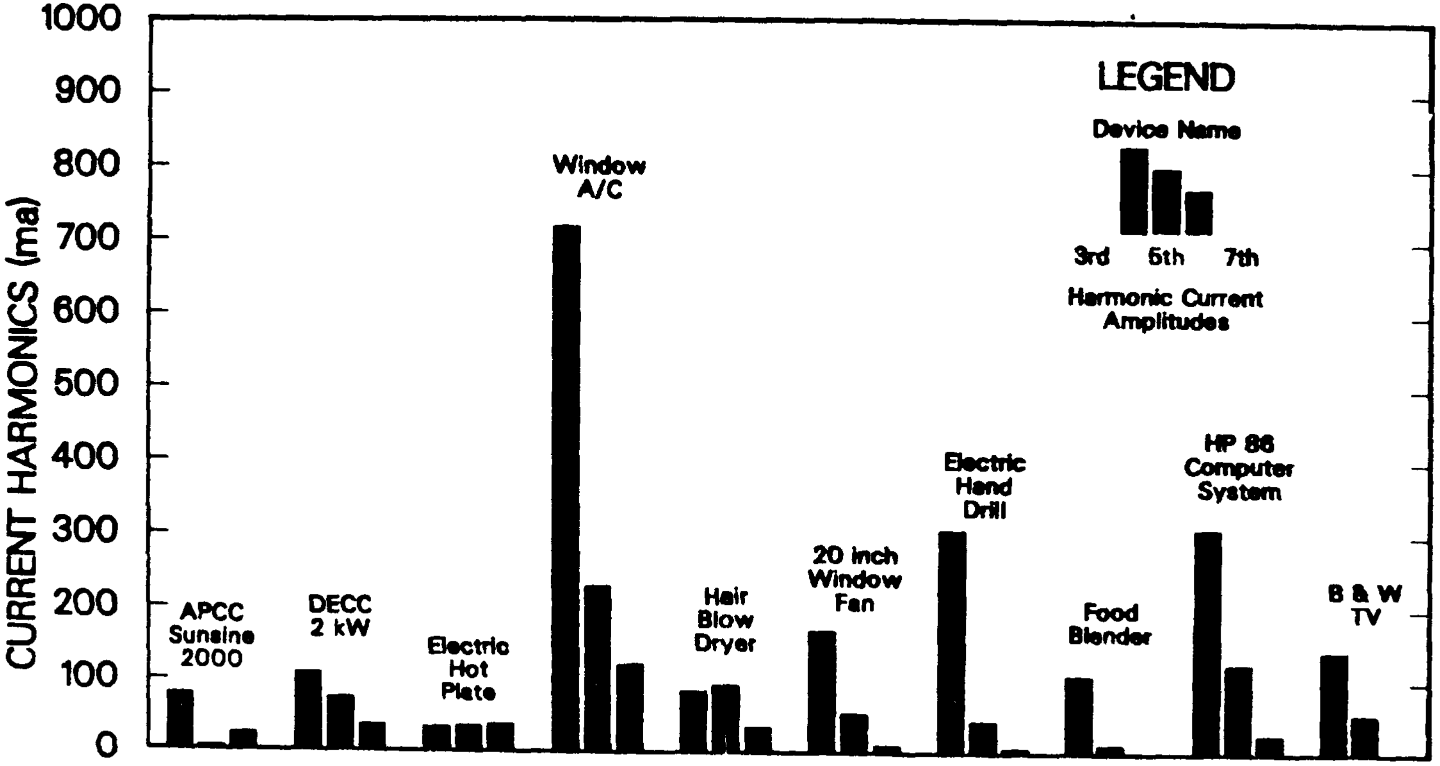
● EXCELLENT
▨ ACCEPTABLE
▧ MARGINAL
○ UNACCEPTABLE

UTILITY INTERFACE RESEARCH

J W Stevens

- Utilities are concerned about large numbers of small systems - and are currently involved in evaluation effort
- Observed utility interface response of advanced PCS units is excellent
- Large photovoltaic installations could impact a utility's operations due to large power ramp rates - several simple solutions exist
- Harmonics are a non-issue with advanced power conditioners

HARMONIC CURRENT : ADVANCED PCS VS. HOUSEHOLD APPLIANCE



CURRENT SYSTEMS - RELATED QUESTIONS

1. SYSTEMS RESEARCH AND EVALUATION
    - Tracking flat plate versus concentrator : solar availability
    - A residential array "building block"
    - O & M, degradation and reliability
2. ARRAY SUBSYSTEM DEVELOPMENT
    - Diodes / Grounding / Faults
    - Tracking field definition
    - Small PCS / Large field

CURRENT SYSTEMS - RELATED QUESTIONS (CONT)

3. POWER CONDITIONING DEVELOPMENTS
   - A simple utility compatibility test
   - Large systems : The best PCS approach
   - The "ultimate" PCS topology
4. UTILITY INTERFACE RESEARCH
   - "Acceptable" power quality definition
   - Utility acceptance of advanced PCS
   - The remaining operations / T & D impacts

NOTES

NOTES

PHOTOVOLTAIC CONCENTRATOR RESEARCH

DAN E. ARVIZU

Sandia National Laboratories

Albuquerque, New Mexico 87185

CONCENTRATOR CELL RESEARCH

SILICON CONCENTRATOR CELLS

- HIGH EFFICIENCY CELLS ($>19\%$) CAN BE PRODUCED IN QUANTITY WITH GOOD YIELDS (70 - 75 %)
- LABORATORY BASELINE CELLS HAVE ACHIEVED $\eta_p = 20\%$ AT UP TO 150X
- MODELING STUDIES AT PURDUE INDICATE ADVANCED SILICON CELLS CAN ACHIEVE $\eta_p > 25\%$ AT CONCENTRATION WITH TECHNOLOGY IMPROVEMENTS
- SANDIA IS ASSESSING POTENTIAL OF ADVANCED SILICON STRUCTURES WITH DEVELOPMENT OF:
  - PATTERNED DIFFUSION CELLS
  - CARRIER CONTAINMENT THRU INSULATING LAYERS
  - BACK JUNCTION CELL
  - IMPROVED MEASUREMENTS/MODELING

CONCENTRATOR CELL RESEARCH

ADVANCED CONCENTRATOR CELLS

- SANDIA SOLID STATE PHYSICS LABORATORY HAS GROWN A PN JUNCTION IN AN SLS STRUCTURE WITH GOOD QUANTUM EFFICIENCY
- PROGRESS ON THIN AIGAAS CELLS FOR MECHANICAL STACK HAS PRODUCED ~ 16% ONE-SUN (1.64 ev) NON-THINNED CELL
- CONTINUING TO ASSESS POTENTIAL OF SINGLE AND MJ DEVICES WITH
  - OPTIMIZATION OF GAAS CELLS FOR MODULE APPLICATION
  - PLANS FOR LABORATORY DEMONSTRATION OF MECHANICAL STACK DEVICE
  - IMPROVED MODELING/MEASUREMENTS

MODULE RESEARCH

- 15.5% INTERSOL POWER CORP. COMMERCIAL MODULE
- 17% SANDIA EXPERIMENTAL SILICON MODULE
- 17% VARIAN 1000X GaAs CELL MODULE
- RESEARCH ON LESS EXPENSIVE POINT FOCUS FRESNEL LENS PROCESSING
  - 3M LENSFILM
  - INJECTION MOLDING
  - FACETS MOLDED TO GLASS
- IMPROVEMENTS CAN LEAD TO 18-20% Si CELL MODULES
  - SECONDARIES
  - GROOVED CELL COVERS
  - SMALLER, MORE EFFICIENT CELLS
  - LENS AR COATINGS

ARRAY RESEARCH

- **SOLERAS AND SKY HARBOR ARRAY FIELDS**
  - GREATER THAN 10% NOC EFFICIENCY
  - ARRAY POWER WITHIN 2% OF NEW
  - AVAILABLE AT LEAST 97% OF TIME
- **DALLAS - FT. WORTH LINE FOCUS ARRAY FIELD**
  - NEGLIGIBLE DEGRADATION (BEFORE HAIL STORM)
  - NEGLIGIBLE DOWNTIME
  - 9% ELECTRICAL AND 40% THERMAL EFFICIENCY
- **TWO NEW ARRAYS INSTALLED AT SANDIA**
  - 22.5 kW INTERSOL ARRAY, 13.3% NOC
  - 22 kW ENTECH ARRAY, 10.5% NOC

INSTALLED SYSTEM COST PROJECTIONS

	PRESENT PRICE (BASED ON QUOTES) 1 MW	PROJECTED PRICE CURRENT TECHNOLOGY 150 MW/YEAR	PROJECTED PRICE ADVANCED TECHNOLOGY 150 MW/YEAR
MODULES	540	120	190
TRACKING	130	60	60
INSTALLATION	160	70	70
TOTAL	$\$830/\text{M}^2$	$\$250/\text{M}^2$	$\$320/\text{M}^2$
DC FIELD RATING	127 W/M^2	145 W/M^2	230 W/M^2
DC FIELD PRICE	$6.54/W	$1.72/W	$1.39/W
INVERTER	$ .50/W	$ .10/W	$ .10/W
SYSTEM PRICE	$7.04/W	$1.82/W	$1.49/W

CONCENTRATOR RELIABILITY

- **ARRAY EXPERIMENTS (LESSONS LEARNED)**
  - 2% OF THE MODULES AT SOLERAS AND SKY HARBOR HAVE FAILED
    - BETTER QUALITY CONTROL DURING FABRICATION PROCESS NEEDED
    - DESIGN AND PROCESS CHANGES HAVE BEEN INTRODUCED IN GEN 2
  - TRACKING, MECHANICAL, AND CONTROL PROBLEMS HAVE BEEN CORRECTED ON CURRENT DESIGNS
- **LONG TERM MODULE RELIABILITY STUDIES**
  - LENS EVALUATION
  - CELL ASSEMBLIES
    - CELL TO MOUNT
    - ENCAPSULANT
    - ELECTRICAL CONNECTION
  - MODULE QUALIFICATION TESTING
  - CORRELATION OF ACCELERATED AND REAL TIME TESTS

CONCENTRATOR RESEARCH PROJECT SUMMARY

- INSTALLED ARRAY FIELDS ARE WORKING WELL
- TECHNOLOGY STATUS AND FUTURE

	PRESENT	FUTURE
Si CELL EFFICIENCY	19-20%	25%
ADVANCED CELL EFFICIENCY	20-24%	25-35%
Si TECHNOLOGY PEAK MODULE EFFICIENCY	15-17%	18-20%
GaAs PEAK MODULE EFFICIENCY	17%	20-25%
MULTIPLE JUNCTION PEAK MODULE EFFICIENCY	20%	25-30%
ARRAY LIFETIME	5 to ? YEARS	20-30 YEARS
INSTALLED SYSTEM COST	\$7 to 10/W	\$1.25-2.00/W

- THE CURRENT PV CONCENTRATOR TECHNOLOGY CAN REACH \$2 /W WITH LARGE SCALE PRODUCTION - NO TECHNOLOGY OR MATERIAL BREAKTHROUGHS ARE NEEDED.

WHAT DOES IT ALL MEAN ?

- FLAT PLATE AND CONCENTRATOR TECHNOLOGIES ARE RELIABLE AND CAN BE USED IN SMALL (FP) AND LARGE (FP, CONC.) SYSTEMS
- ARRAY BOS COSTS HAVE BEEN REDUCED TO NEAR GOALS REMOVING ECONOMIC BARRIERS FOR PV SYSTEMS
- HIGH EFFICIENCY CONCENTRATORS (19%+) ESTABLISH VIABILITY OF TECHNOLOGY
- UI STUDIES AND PCS DEVELOPMENT FOR SMALL SYSTEMS IS REMOVING UTILTIY RESISTANCE TO THE TECHNOLOGY AND IS RESULTING IN ACTIVE UTILITY SUPPORT FOR PV

NOTES

U. S.Department of Energy

Flat-Plate Solar Array Project

JPL

DOE ANNUAL PV PROGRAM REVIEW

April 30, 1984

William T. Callaghan
Manager

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109

JPL

Flat-Plate Solar Array Project

ROLE:

Encourage expansion of private-sector industrial capability of producing cost-competitive, long-life photovoltaic arrays.

OBJECTIVE:

Conduct research and development to establish technical feasibility for photovoltaic arrays whose price is consistent with an energy price of \$0.15/kWh.

FLAT-PLATE SOLAR ARRAY PROJECT (FSA)
ANALYSIS AND INTEGRATION AREA

P. K. Henry
Jet Propulsion Laboratory
Pasadena, California 91109

The objective of the Project Analysis and Integration Area (PA&I) is to support the planning, analysis, integration, and decision-making activities of FSA. Accordingly, PA&I supports the Project by developing and documenting Project plans based, in part, on the technical and economic assessments of the various technical options performed by PA&I. Goals for module technical performance and costs, derived from the National PV Program goals, are established by PA&I for each of the major technical activities in the Project. Assessments of progress toward achievement of goals are performed to guide decision-making within the Project.

The Photovoltaic Program's Five-Year Research Plan (May 1983) contains a redefinition of Program goals to include a near-term (1985) goal of 12%, $\$100/m^2$ module technology and a long-term (1988) goal of PV technology capable of producing $0.15/kWh electric energy. (All monetary units cited herein are 1982 dollars.) An analysis has been performed to determine the effects of the Program goal changes on FSA goals. Results of the analysis were presented at the 22nd Project Integration Meeting (PIM) in September 1983 and were updated at the 23rd PIM in March 1984. The results indicated very stringent, but not unattainable, requirements for module efficiencies and cost. The research and development priorities of FSA have been reoriented to reflect the new PV Program goals. An internal Project Implementation Plan has been drafted by PA&I to describe how the Project will implement the achievement of these goals.

Silicon materials costs represent both a cost driver and an area where improvement can be made in the manufacturing cost of photovoltaic modules. A study has been performed that analyzes the cost of three processes for the production of low-cost silicon, which are being developed under the National PV Program. The costing approach is based on probabilistic inputs and makes use of two models developed at the Jet Propulsion Laboratory: SIMRAND (SIMulation of Research ANd Development) and IPEG (Improved Price Estimation Guidelines). Distributions of possible costs for various silicon refinement process steps were developed to reflect uncertainty. These probability distributions were used as inputs for a probabilistic estimation of silicon manufacturing costs.

The value-added cost and performance effectiveness of several state-of-the-art and advanced metallization techniques were presented at the 22nd PIM. IPEG and a grid optimization model developed by PA&I were used to generate the cost and performance estimates, which were presented in an "efficient frontier" format. Data for the cost estimates were gathered from FSA contractors and other sources. The metallization study is being expanded to include an analysis of the electrical and optical properties of transparent conducting materials. Equations that solve for the transmittance and reflectance of absorbing films on an absorbing substrate will be used to determine what film characteristics will maximize the performance of a photoconductor as a solar cell when used alone or in combination with a metal grid.

PA&I, in cooperation with the Process Development Area and the Reliability and Engineering Sciences Area, completed a cost analysis of a wooden hardboard substrate module design. In the assumed manufacturing sequence, solar cells and electrical circuitry were encapsulated, then bonded to the substrate in a separate non-vacuum process. The module manufacturing cost was found to be about the same as that of superstrate modules because the lower material cost for the substrate module was offset by extra processing requirements. The cost equivalence was in manufacturing only and assumed no penalty for soiling or for a possible increase in operating temperature for the substrate module. Neither did the analysis consider any possible effects on reliability and module lifetime.

During the next 12 months and beyond, PA&I will initiate studies of the module economic impacts of high-efficiency devices. System life-cycle effects will be included as well as module manufacturing costs.

JPL

Flat-Plate Solar Array Project

ORGANIZATION AND AGENDA

PROJECT MANAGEMENT

W. Callaghan, Manager

DOE PROGRAM ELEMENTS	**PROJECT ANALYSIS & INTEGRATION** W. Callaghan (P. Henry)	**MATERIALS & DEVICES** M. Leipold	**PROCESS DEVELOPMENT** D. Bickler	**RELIABILITY & ENGINEERING SCIENCES** R. Ross
Single-Junction Thin Films			Amorphous Silicon Deposition	Thin-Film Testing
Silicon Materials		Silicon Materials		
Advanced Silicon Sheet		Advanced Silicon Sheet		
Flat-Plate Collector Research	Analysis & Integration	Device Research	Process Development	Advanced Module Development
Module Reliability				Reliability, Eng. Science, & Failure Analysis

ANALYSIS & INTEGRATION

OBJECTIVES

- Illuminate technical and economic tradeoffs and alternative technical paths available to the Project.

- Develop analytical tools and data base, and perform analysis to translate quantitatively between technical performance and economic performance.

ANALYSIS & INTEGRATION

ACCOMPLISHMENTS

- Performed sensitivity analysis of PV module technical and economic parameters to $0.15/kWh Program goal

- Drafted internal FSA implementation plan keyed on DOE "PV Program Five-Year Research Plan"

- Performed probabilistic projection of polysilicon required revenue (not market price) for several polysilicon refining processes

- Extended cell metallization grid optimization methodology to include transparent conducting films

ANALYSIS & INTEGRATION

PLANS

- Perform technical/economic assessments of emerging high-efficiency cell technical options
- Convert methodology programs from mainframe computers to microcomputers
- Increase insight into effect of module subsystem technical and economic performance on system-level, life-cycle considerations

FLAT-PLATE SOLAR ARRAY PROJECT (FSA)
MATERIALS AND DEVICES AREA

M. L. Leipold
Jet Propulsion Laboratory

Within the Materials and Devices Area of FSA, efforts have largely focused on critical research areas in keeping with the Project approach. All efforts within the Project involving silicon material preparation are focused on the generation and preparation of particles from the high-purity silane. Major emphasis is on the fluidized-bed reactor (FBR), process fundamentals (Jet Propulsion Laboratory), process engineering (Union Carbide Corp.), seed generation and graded-product withdrawal. A small effort involving free-space reactor (FSR) continues. The FBR results tare encouraging, with high deposition rates and low fines production being achieved. A minor problem has been encountered with some contamination reducing cell performance to approximately 90% of controls. Difficulty appears to stem from abrasion of the FBR chamber reactor; liners are expected to eliminate this problem.

A small FSR program at Caltech has resulted in the growth of 5µm to 10µm seed particles directly from silane. After scale-up, in process now, these particles are expected to be useful as seed materials, with some possibility of the method being useful as a total conversion method.

Ribbon investigation now focuses entirely on understanding and control of stress and strain within the ribbon during growth. Movement of the heat of fusion through the ribbon during crystallization results in large temperature gradients, which in turn induce stress and ultimately strain. Several different modes of deformation, including elastic buckling, plastic buckling, and plastic deformation have been identified. Information on the plastic properties of silicon at high temperatures is being compiled and augmented as necessary to provide input data. Several computer-modeling approaches are under development in an attempt to describe the stresses. These models in turn will identify desired thermal configurations, and it is hoped, ultimately to appropriate physical growth environments.

An integrated funding effort intended to accelerate the rate of technology development of dendritic-web growth, processing, and module development is in the planning stages. Funding partners will include DOE (SERI and JPL), EPRI, SCE, PG&E and Westinghouse.

The ever-clearer need for high-conversion-efficiency modules, 15% to 17% AM1.5, will result in a gradual reorientation of emphasis within the silicon sheet task. The need for more perfect silicon sheet will be stressed. This will include a revisit to ingot technologies to evaluate their potential for meeting the ultimate program goals (15¢/W, $\$90m^2$.

It is recognized that crystalline silicon module efficiency of 15% is required to establish cost-effective PV technology. This module efficiency requires cell efficiencies in the range of 18% to 20%. Development of such high-efficiency cells will require understanding and control of surface and bulk losses, modeling and design of innovative device structures, their experimental verification, and development of reliable measurement techniques to determine key device parameters. These requirements have led to a number of programs in the Devices and Measurements Research Task directed at identifying and resolving generic problems that limit crystalline silicon solar cell efficiency below 20%. Emphasis at present is on the development of measurement techniques to determine surface recombination velocity minority carrier lifetime, and characterization of bulk defects. The modeling efforts and some understanding of recombination losses led to a "float emitter" cell structure for a higher-than-20%-efficiency cell and development of SiN_x growth technique for surface passivation. Low-temperature EBIC has provided additional defect structure information on web material that was not obtainable from room temperature EBIC. A predictive model is being developed that will describe the performance of the solar cell as a function of its structure and material characteristics. It is expected that this will lead to definition of improved devices that then can ultimately be fabricated.

JPL

Flat-Plate Solar Array Project

ORGANIZATION AND AGENDA

PROJECT MANAGEMENT

W. Callaghan, Manager

DOE PROGRAM ELEMENTS	PROJECT ANALYSIS & INTEGRATION P. Henry (W. Callaghan)	MATERIALS & DEVICES M. Leipold	PROCESS DEVELOPMENT D. Bickler	RELIABILITY & ENGINEERING SCIENCES R. Ross
Single-Junction Thin Films			Amorphous Silicon Deposition	Thin-Film Testing
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Flat-Plate Collector Research	Analysis & Integration	Device Research	Process Development	Advanced Module Development
Module Reliability				Reliability, Eng. Science, & Failure Analysis

SILICON MATERIALS

OBJECTIVE

Develop technology capable of producing low-cost polysilicon suitable for high-efficiency solar cells.

SILICON MATERIALS

ACCOMPLISHMENTS

- Completed final report on development of dichlorosilane conversion process (Hemlock)

- Produced solar cells from FBR product
  - Efficiency was 90% of control cells
  - Decrease traced to reactor wall abrasion
  - Liner under development

- Operated FBR for 44 hours at Union Carbide

- Deposited silane at nearly 3kg/h for 8 hours at JPL using 50% silane

SILICON MATERIALS

PLANS

- Complete experimental operation of FBR at Union Carbide
- Complete dichlorosilane/FBR process feasibility report
- Issue report on scalability of electrorefinement of Cu_3 Si - Si process (EMC)
- Operate an integrated EPSDU-FBR at Union Carbide

SILICON MATERIALS

CONCERN

Economies of scale of integrated EPSDU-FBR will be calculated, not demonstrated.

ADVANCED SILICON SHEET

OBJECTIVE

Develop cost-effective Si sheet suitable for high-efficiency solar cells by emphasizing generic solutions

ADVANCED SILICON SHEET

ACCOMPLISHMENTS

- Held research forum on "High-Speed Growth and Characterization of Crystals"
- Completed initial model for reduced stress growth configuration in EFG ribbon (MSEC)
- Completed testing of first-generation computer design for dynamically controlled Si dendritic web (Westinghouse)
- Completed initial silicon ribbon buckling stress/strain model (U. of Kentucky)
- Reported on mechanical properties of silicon in fluid environment (U. of Illinois, Chicago)
- Held stress/strain working-group meetings

ADVANCED SILICON SHEET

PLANS

- Implement expanded dendritic web program under cooperative support of EPRI, PG&E, SCE, SERI, Westinghouse, and JPL
- Complete initial reduced-stress model for EFG ribbon growth (MSEC)
- Continue holding stress/strain working-group meetings
- Initiate study of float zone material feasability

ADVANCED SILICON SHEET

CONCERNS

- Suitability of ribbons for processing into 17% to 20% cells
    - High quality and purity
    - Diffusion length 300 µm
    - Cost range of $\$90/\text{m}^2$, DOE 5-year goal
- Basics of physics and chemistry of silicon materials
    - Stress/strain effects on ribbon and bulk silicon during growth
    - Effects of fracture mechanics and surface chemistry on efficiency

DEVICE RESEARCH

OBJECTIVES

- Identify and resolve generic limits to solar-cell efficiency in crystalline silicon
- Develop tests to define significant cell characteristics

DEVICE RESEARCH

ACCOMPLISHMENTS

- Developed simultaneous measurements of surface recombination velocity at surfaces & interfaces and minority carrier lifetimes (U. of Florida & U. of Penn.)
- Developed technique to grow SiN_x for surface passivation (U. of Washington)
- Proposed "Float Emitter" structure for >20% efficiency (C. T. Sah & Associates)
- Revealed defects using low-temperature EBIC technique

DEVICE RESEARCH

ACCOMPLISHMENTS

(Cont'd.)

- Reported interactions of dislocations with twins and carbon with grain boundary in EFG (Cornell)

- Revealed critical criteria for refractive index, extinction coefficients, and thickness with transparent conducting polymers by using a computer model

DEVICE RESEARCH

PLANS

- Hold "High-Efficiency Crystalline Silicon Solar Cell" research forum
- Investigate ultrathin oxide layer on light and heavy doped Si
  - Majority carrier transport
  - Minority carrier recombination
- Experimentally verify theoretical high-efficiency structures
- Establish relationships between oxygen-related and carbon-related defects and minority carrier recombination

DEVICE RESEARCH

PLANS

(Cont'd.)

- Evaluate surface passivants
- Complete computer coding for device performance evaluation
- Model and characterize transparent conducting films to validate advanced research in synthesis of new materials

DEVICE RESEARCH

CONCERNS

- Basic understanding of loss mechanisms in various regions of heavy doped silicon
- Correlation between model parameters and measured cell parameters
- Potential of ribbon as starting material for high-efficiency cell structures
- Available polymeric conductors do not yet meet the minimum performance requirements of a candidate TCM system

NOTES

FLAT-PLATE SOLAR ARRAY PROJECT (FSA)
PROCESS DEVELOPMENT AREA

D. B. Bickler
Jet Propulsion Laboratory
Pasadena, California 91109

A new program at JPL, in coordination with the Solar Energy Research Institute and funded under the Flat-Plate Solar Array Project, is to gather generic data on the deposition of amorphous silicon and extrapolate to 1000 cm^2 or larger areas. This work is to apply to the majority of amorphous deposition plants in the United States. Apparatus has been set up and experiments began in December 1983. The first goal will be to deposit intrinsic (i) layers of amorphous silicon on glass substrates. These layers are to have four orders of magnitude difference in conductivity between light and dark conditions. They must also be about 0.5 micrometer thick, mechanically sound, and uniform. With the successful completion of i-layer deposition, n and p doped layers will be experimented with. All three layer capability efforts will focus upon the development of large-scale processes aimed at DOE goals.

The last year has seen a continuing shift toward processes that will support higher efficiency cell and modules. As consideration for other costs (such as land area required) is brought into the analysis, higher efficiency will support more expensive processing. Increasing module operating life has the same effect.

In the thrust for higher efficiency, low-temperature processing is preferred. High-temperature processes tend to degrade the device and/or the semiconductor material. The study of amorphous-metal diffusion barriers is part of the effort to prevent or reduce degradation due to metal diffusion (especially commercial metals like copper). The metallo-organic metallization systems being studied at Purdue and the laser pyrolysis work at Westinghouse are directed toward high-efficiency cells.

This year started a special emphasis upon more advanced processes (lasers, ion clusters, new applications of microwaves, etc.).

JPL

Flat-Plate Solar Array Project

ORGANIZATION AND AGENDA

PROJECT MANAGEMENT

W. Callaghan, Manager

DOE PROGRAM ELEMENTS	PROJECT ANALYSIS & INTEGRATION P. Henry (W. Callaghan)	MATERIALS & DEVICES M. Leipold	PROCESS DEVELOPMENT D. Bickler	RELIABILITY & ENGINEERING SCIENCES R. Ross
Single-Junction Thin Films			Amorphous Silicon Deposition	Thin-Film Testing
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Module Reliability				Reliability, Eng. Science, & Failure Analysis

AMORPHOUS SILICON DEPOSITION

OBJECTIVE

- Develop and demonstrate large area amorphous silicon processing technology and equipment in joint effort with SERI.

AMORPHOUS SILICON DEPOSITION

ACCOMPLISHMENTS

- Designed, assembled, and operated large plasma reactor for deposition development
- Deposited large-area (1050 cm^2) a-Si layers with good uniformity

AMORPHOUS SILICON DEPOSITION

PLANS

- Develop large-area intrinsic layer capability
- Explore 'processing window' for optimum conditions
- Develop doped (n and p) layer capability
- Combine three layers in single process
- Develop equipment for complete device fabrication

PROCESS DEVELOPMENT

OBJECTIVES

- Develop cost-effective processes for high-efficiency and long operating life
    - 20% cell (15% module)
    - 30-year operating life

PROCESS DEVELOPMENT

ACCOMPLISHMENTS

- Developed liquid dopant processes for sequential formation of front and back junctions (Westinghouse)
- Identified stable amorphous metal diffusion barriers (Caltech)
- Demonstrated feasibility of low-temperature metallization using metallo-organic compounds (Purdue)
- Identified mathematical models for optimizing process performance
- Demonstrated feasibility of direct writing of metal grid lines on silicon using laser pyrolysis (Westinghouse)

PROCESS DEVELOPMENT

ACCOMPLISHMENTS

(Cont'd)

- Completed construction of ion cluster beam deposition system
- Non-Mass-Analyzed (NMA) ion implantation being commercialized (Spire)

PROCESS DEVELOPMENT

PLANS

- Verify mathematical processing experimentally
- Develop low-temperature processes
- Investigate processing effects upon surfaces
- Investigate diffusion across metal-semiconductor interfaces
- Improve metal pattern definition
- Explore new process energy sources (ion clusters, lasers, microwaves, etc.)

PROCESS DEVELOPMENT

CONCERNS

- Industry is understandably reluctant to release ongoing process sensitivity information (yield) because of competitive concerns
- Synergisms in multiple-step processes are difficult to define without contiguous process lines
- Various high-performance Si sheet types may respond differently to specific processes

FLAT-PLATE SOLAR ARRAY PROJECT (FSA)
RELIABILITY AND ENGINEERING SCIENCES AREA

R.G. Ross, Jr.
Jet Propulsion Laboratory
Pasadena, California 91109

The reliability and engineering sciences (R&ES) area of the FSA project is responsible for developing the technology base required to integrate emerging low-cost solar cell technologies into modules that meet the lifetime, safety and functional needs of future large-scale PV applications. This responsibility is articulated in the form of dual objectives and research activities within the area: one focused at achieving 30-year module life, the other focused at the needs of safety and effective functional operation.

Substantial progress has been made toward both of these objectives (see References 1 and 2); however, a number of important technical issues remain. Current reliability research activities are directed at the long-term failure mechanisms of electrochemical corrosion and breakdown of the electrical insulation between the solar cell and module frame, and degradation of the module encapsulant due to photothermal aging and bond delamination. Reliability of the solar cell, and its metallization system in particular, remains an important area of research.

Engineering Sciences activities include research on electrical-circuit issues associated with hot-spot heating in highly paralleled source circuits, cost-effective integration of bypass diodes, and optimal circuit redundancy to reduce the system impact of random shorted solar cells. Developing the technology for fire-resistant modules is an important research thrust focused at the needs of residential and commercial applications.

Complementing the above laboratory research activities is a continuing effort to identify emerging problems and to test developed solutions through the construction and testing of advanced prototype modules. Testing and failure analysis of Block V designs is ongoing, as is the development of an advanced high-efficiency module incorporating infrared reflectors to achieve lower operating temperature.

Recent accomplishments in the above research areas are noted in the accompanying presentation graphics.

Future research plans are best described in terms of the two status summaries toward the end of the R&ES presentation. Each summary, one for reliability activities and the other for engineering science activities, lists the principal technical issues in the left column and the various elements of a successful solution along the top. The status of the solution elements of each technical issue are noted by the degree of shading of the associated bullets.

In the area of reliability research, a number of degradation mechanisms have been reduced to 30-year-life levels, whereas a number of others are of unknown status. The cause of the unknown status is often a lack of knowledge of the current level of field failures of the particular type. With others the dependency of the failure rate on environmental and materials parameters is not sufficiently understood to predict the level of failures to be expected over a 30-year span. Planned near-term activities addressed to these issues are identified by the shaded areas.

In the area of engineering-sciences technology, future research is principally focused at remaining technical issues that interact strongly with achieving 30-year life. Module operating temperature is extremely important from this point of view, every 10°C reduction in operating temperature corresponding roughly to a doubling of module life. The development of circuit analysis tools for selecting optimal circuit redundancy is a second example; research on module flammability is a third.

<u>References</u>

1. Ross, R.G., Jr., "Flat-Plate Photovoltaic Module and Array Engineering," <u>Proceedings of the 1982 AS/ISES Annual Meeting</u>, Houston, Texas, June 1-5, 1982.

2. Ross, R.G., Jr., "Technology Developments Toward 30-Year-Life Photovoltaic Modules", <u>Proceedings of the 17th IEEE Photovoltaic Specialists Conference</u>, Orlando, Florida, May 1-4, 1984.

JPL

Flat-Plate Solar Array Project

ORGANIZATION AND AGENDA

PROJECT MANAGEMENT

W. Callaghan, Manager

DOE PROGRAM ELEMENTS	PROJECT ANALYSIS & INTEGRATION P. Henry (W. Callaghan)	MATERIALS & DEVICES M. Leipold	PROCESS DEVELOPMENT D. Bickler	RELIABILITY & ENGINEERING SCIENCES R. Ross
Single-Junction Thin Films			Amorphous Silicon Deposition	Thin-Film Testing
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Module Reliability				Reliability, Eng. Science, & Failure Analysis

RELIABILITY & ENGINEERING SCIENCES

OBJECTIVES

Develop reliability-durability technologies required to achieve 30-year-life flat-plate PV modules.

- Failure mechanism identification & understanding
- Module reliability prediction tools
- Test, measurement, & failure-analysis tools
- 30-year-life materials & designs

RELIABILITY & ENGINEERING SCIENCES

OBJECTIVES

(Cont'd.)

Develop engineering sciences technologies required to integrate low-cost cell & module technologies into cost-effective & safe arrays that meet future large-scale applications requirements

- Operational & safety requirements
- Electrical & fire safety technologies
- Structural design technologies
- Temperature control technologies
- Electrical circuit technologies

JPL Flat-Plate Solar Array Project

RELIABILITY & ENGINEERING SCIENCES

CURRENT ACTIVITIES

Module and Cell Reliability

○ Electrochemical corrosion

• Voltage breakdown

• Bond durability

• Photothermal degradation

○ Cell reliability (crystalline & thin-film)

Engineering Sciences

○ Hot-spot heating in highly paralleled circuits

⊕ Temperature prediction for residential arrays

○ Module flammability

○ Bypass diode optimization

• Series-parallel analysis for shorted cells

○ = IEEE Papers ⊕ = ASES Papers

RELIABILITY & ENGINEERING SCIENCES

CURRENT ACTIVITIES

(Cont'd.)

Module Performance and Failure Analysis

- Block V and advanced designs
- Continued testing and failure analysis
- ⊕ Electrical measurements
- IR reflectors for lower operating temperatures

⊕ = ASES Papers ◍ = IEEE Papers

RELIABILITY & ENGINEERING SCIENCES

RELIABILITY ACCOMPLISHMENTS

- Quantified parameter dependencies of electrochemical corrosion and influence on module life
- Developed new mechanical-rupture theory for electrical breakdown
- Developed experimental method for establishing parameter acceleration limits for photothermal aging
- Developed techniques for monitoring interfacial chemical bonds

RELIABILITY & ENGINEERING SCIENCES

RELIABILITY ACCOMPLISHMENTS

(Cont'd.)

- Drafted qualification test for bypass diodes
- Finalized algorithm quantifying breaking strength of glass
- Initiated reliability testing of amorphous Si modules
- Further quantified temperature-humidity degradation rates for various cells and encapsulants

RELIABILITY & ENGINEERING SCIENCES

ENGINEERING SCIENCES ACCOMPLISHMENTS

- Held Research Forum on "Array Design for Central Stations"
- Completed report on prediction of temperature of residential arrays at SW RES
- Completed study of array safety
- Developed and tested new flame resistant modules
- Developed computer program for quantifying effect of shorted cells on solar system power
- Completed study on bypass diodes
- Characterized influence of highly paralleled cells on hot-spot heating

RELIABILITY & ENGINEERING SCIENCES

MODULE PERFORMANCE ACCOMPLISHMENTS

- Completed 90% of Block V module testing
- Completed design of high-efficiency module (12% to 13% at NOCT)
- Conducted numerous reference-cell calibrations and intercomparisons

RELIABILITY & ENGINEERING SCIENCES

CONCERNS

- Very low level of allowable failures makes quantification of failure rates very difficult
  - Sensitive measurements
  - Quantified parameter dependencies
  - Long-duration testing
  - Large arrays for field data

- Selection of economic discount rate greatly affects impact of life-limiting mechanisms

NOTES

NOTES

PHOTOVOLTAIC HEALTH AND SAFETY ASSESSMENT

P.D. Moskowitz and L.D. Hamilton
Biomedical and Environmental Assessment Division
Brookhaven National Laboratory
Upton, New York 11973

The U.S. Department of Energy (DOE)-National Photovoltaics Program is currently sponsoring potentially high-payoff research and development in photovoltaic energy systems. Commercial viability of new materials, processes or application alternatives will depend on various factors including technical feasibility, need, cost, and possible health risk. Although public or occupational health risks from photovoltaic energy systems may not be large, it is commonly recognized that no energy system is risk free. The National Photovoltaics Program is sponsoring research at Brookhaven National Laboratory (BNL) to identify potential health and safety hazards of selected materials, processes, and application alternatives before large-scale commercialization so that mitigation strategies may be developed, design engineering costs can be reduced, and potential health risks can be minimized. Outputs from this activity also assist DOE in complying with its programmatic responsibilities including preparation of National Environmental Policy Act documents, and development of necessary monitoring, site evaluation, and control technology data.

This ongoing task is an extension of work begun in FY 1980. Since this activity's inception, the research was fully coordinated with activities in the DOE Office of Conservation and Revewable Energy, and in the Office of Health and Environmental Research, Office of Energy Research.

In FY 1983, two research efforts were sponsored by the National Photovoltaics Program:

- Identification of major health and environmental risks, and control technology availability for the fabrication of photovoltaic devices based on amorphous silicon and gallium arsenide thin-film production techniques.

- Examination of the environmental control technology costs for integrated plants and individual processes for silicon dendritic web photovoltaic cell fabrication.

Results of the first study suggested that toxic by-products of the deposition processes are likely to be produced in small quantities. Emissions can be controlled using available technology. Toxic, explosive, and flammable gases, however, may present significant occupational safety hazards; gas handling systems will need to be carefully designed. Furthermore, electrical and electromagnetic hazards from plasma generators will require close attention.

Results of the second study suggested that the annualized incremental environmental control costs would be 2.3¢ and 1.2¢ per watt for integrated and disaggregated dendritic web 10-MWp/yr plant designs, respectively. Capital costs ranged from 38 to 55% (integrated) and 26 to 40% (disaggregated) of the estimated costs. Because of the relatively small emission flows projected, treatment equipment to be used, for the most part, represented the smallest size readily available from equipment manufacturers. Consequently larger emission flows could be accommodated without additional capital costs.

In FY 1984, research efforts are underway in:

- Hazard identification (copper indium diselenide, cadmium telluride, and zinc phosphide)

- Hazard characterization (gallium arsenide, silane, and non-ionizing radiation)

- Hazard management (gallium arsenide and silane)

In addition, a two-day workshop with representatives from the private sector to discuss environmental, health and safety needs for emerging photovoltaic materials processes and application alternatives is being planned. Results from this workshop will be used to identify future program needs and priorities.

Purpose

IDENTIFY AND EXAMINE POTENTIAL HEALTH AND SAFETY BARRIERS OF PROCESS OR MATERIAL ALTERNATIVES BEFORE LARGE-SCALE COMMERCIALIZATION SO DESIGN ENGINEERING COSTS CAN BE REDUCED AND POTENTIAL HEALTH RISKS MINIMIZED.

Background

Ongoing task initiated in FY 1980. Research monitored by and fully coordinated with DOE offices of Health and Environmental Research and Conservation and Renewable Energy.

Past Efforts

- IDENTIFIED AND EXAMINED PUBLIC AND OCCUPATIONAL HEALTH AND SAFETY RISKS, AND CONTROL TECHNOLOGY AVAILABILITY FOR FABRICATION OF VARIOUS PHOTOVOLTAIC DEVICES.

- EXAMINED FIRE AND ELECTRIC SHOCK HAZARDS FROM RESIDENTIAL APPLICATIONS.

- ESTIMATED ENVIRONMENTAL CONTROL COSTS FOR BOTH INTEGRATED FABRICATION PLANTS AND INDIVIDUAL PROCESSES FOR SILICON DENDRITIC WEB PHOTOVOLTAIC CELLS.

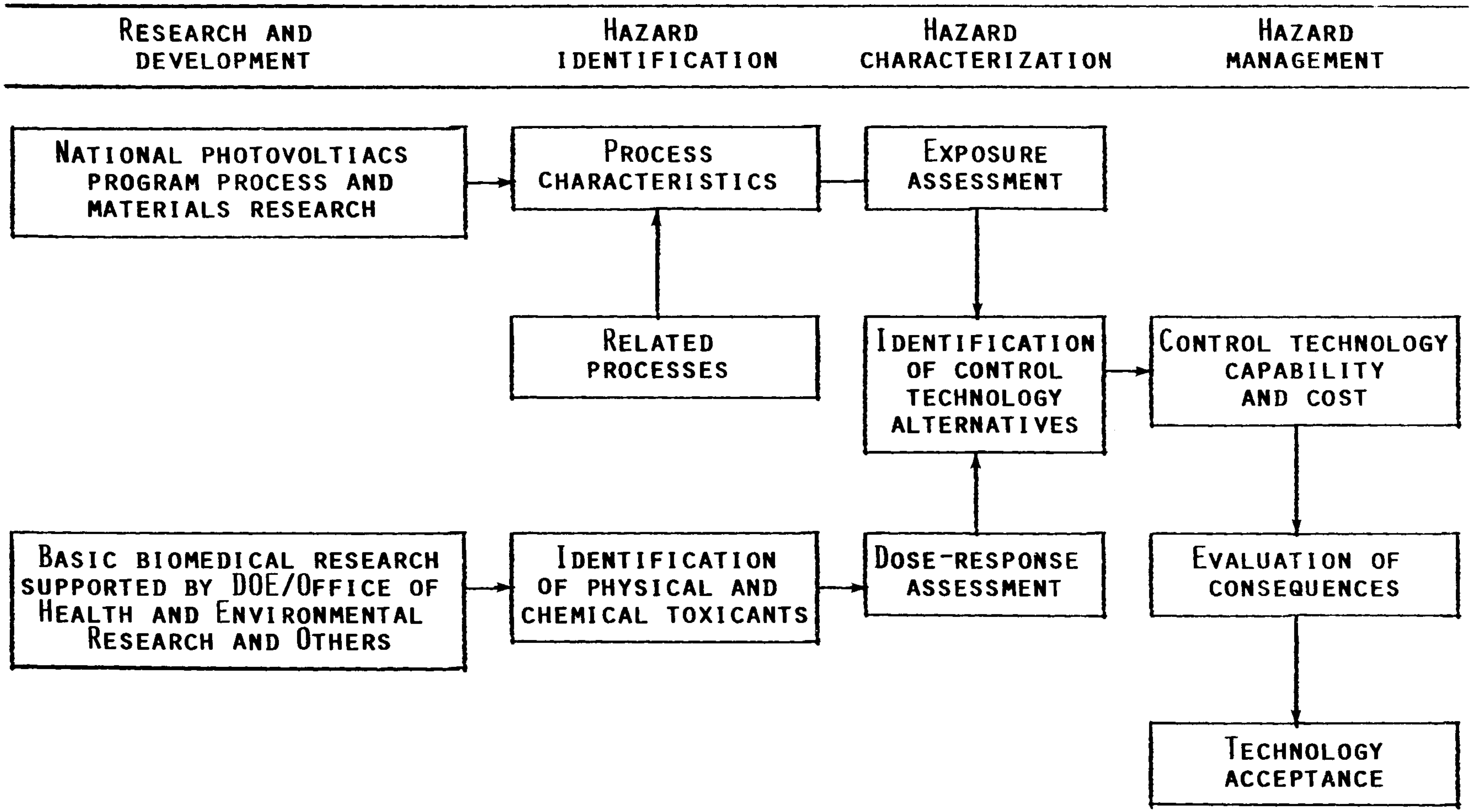
Selected Publications

- ELECTRIC SHOCKS: HEALTH HAZARDS ASSOCIATED WITH A RESIDENTIAL PHTOVOLTAIC ENERGY SYSTEM

- ESTIMATES OF OCCUPATIONAL SAFETY AND HEALTH EFFECTS RESULTING FROM LARGE-SCALE PRODUCTION OF MAJOR PHOTOVOLTAIC TECHNOLOGIES

- MANUFACTURE OF AMORPHOUS SILICON AND GALLIUM ARSENIDE THIN-FILM SOLAR CELLS: AN IDENTIFICATION OF POTENTIAL HEALTH AND SAFETY HAZARDS

- PHOTOVOLTAIC ENERGY SYSTEMS: ENVIRONMENTAL CONCERNS AND CONTROL TECHNOLOGY NEEDS



ELEMENTS OF PHOTOVOLTAIC HEALTH AND SAFETY HAZARD ASSESSMENT ACTIVITIES

PHYSIOLOGICAL EFFECTS AT A NOMINAL AMBIENT TEMPERATURE (82°F)

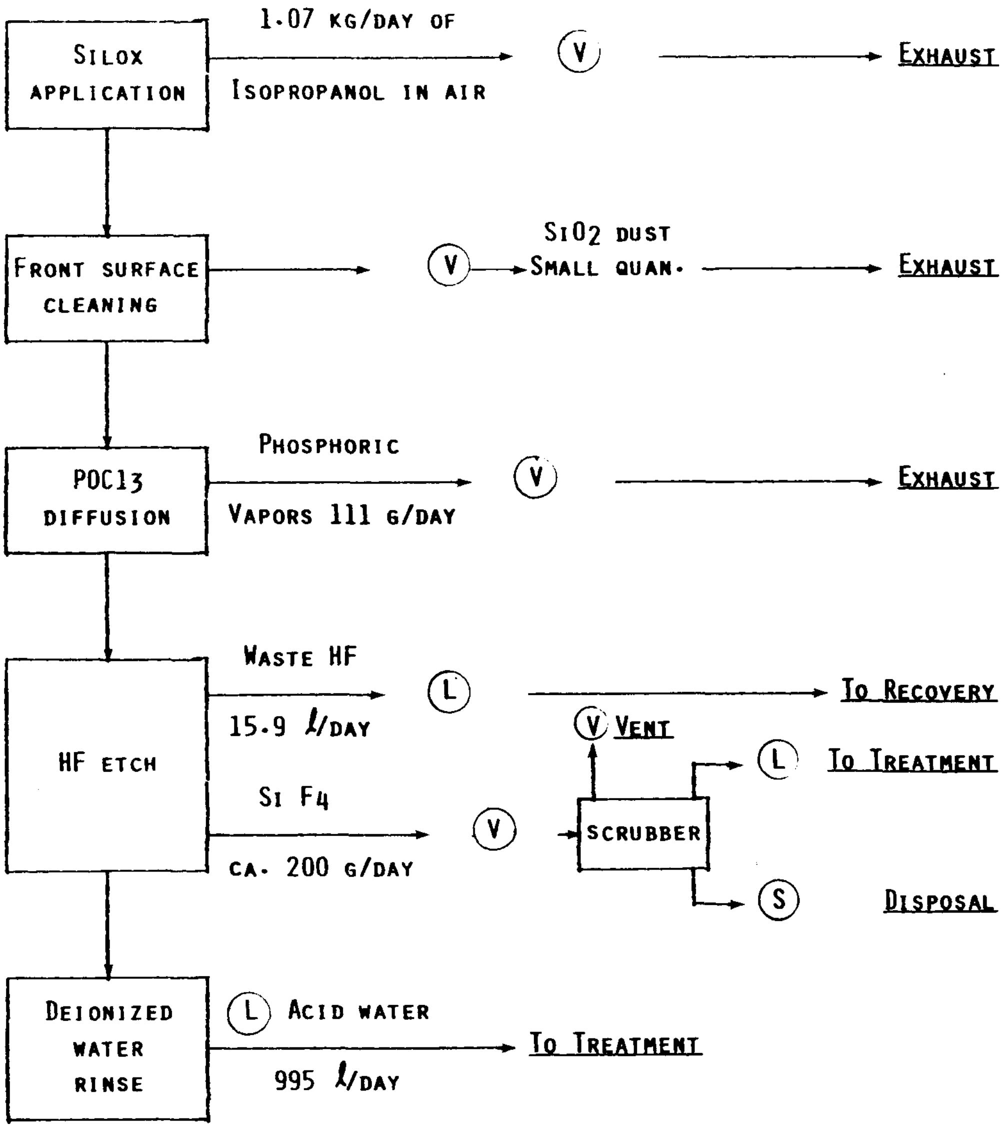
NUMBER OF MODULES IN SERIES	OPEN CURRENT VOLTAGE (VOLTS)	TOTAL BODY IMPEDANCE (OHMS)	CURRENT PASSING THROUGH BODY (MA)	PHYSIOLOGICAL EFFECT
1	17.6	500	35.2	PAINFUL SHOCK, MINOR CONTACT BURNS.
3	52.8	500	105.6	PAINFUL SHOCK, TEMPORARY RESPIRATORY ARREST.
5	88.0	500	176.0	CARDIAC ARREST, UNCONSCIOUSNESS.
7	123.2	500	246.4	CARDIAC ARREST, UNCONSCIOUSNESS, DEATH.

Summary of types of potential chemical and physical hazards

Technology Manufacturing step Process	Chemical		Physical		
	Gas	Solid	Electrical	Electro-magnetic	Thermal
Amorphous Si					
α-Si deposition					
RF glow discharge	X	X	X	X	X
DC proximity glow discharge	X	X	X		X
Reactive RF glow discharge sputtering	X	X	X	X	X
Reactive ion beam sputtering	X	X	X		
CVD	X	X			X

ENVIRONMENTAL CONTROL COSTS FOR GASEOUS POLLUTANTS

GAS	SOURCE	CONTROL TECHNOLOGY	RESIDUALS (KG/10 MWP)		COSTS($)	
			UNCONTROLLED	CONTROLLED	CAPITAL	O&M
ARSINE	GaAs HALIDE CVD	$KMnO_4$ SCRUBBER, FLARE STACK	14,670	<770	15,000	102,000



SILOX APPLICATION AND FRONT JUNCTION FORMATION

Workshop Discussion Topics

- DOE/BNL ROLES AND RESPONSIBILITIES.
- INDUSTRIAL HYGIENE CONTROL PROGRAMS.
- ENVIRONMENTAL POLLUTION CONTROL PROGRAMS.
- ENVIRONMENTAL, HEALTH AND SAFETY ISSUES FOR CENTRALIZED AND DECENTRALIZED APPLICATIONS.
- RESEARCH PRIORITIES AND NEEDS.

FY 1984 Tasks

- HAZARD IDENTIFICATION (AMORPHOUS SILICON, COPPER INDIUM DISELENIDE, CADMIUM TELLURIDE, ZINC PHOSPHIDE)

- HAZARD CHARACTERIZATION (GALLIUM ARSENIDE, SILANE, AND NON-IONIZING RADIATION)

- HAZARD MANAGEMENT (GALLIUM ARSENIDE AND SILANE)

- WORKSHOP (ENVIRONMENTAL, HEALTH AND SAFETY ISSUES AND RESEARCH NEEDS)

NOTES

NATIONAL PHOTOVOLTAIC PROGRAM ANNUAL REVIEW MEETING
April 30, 1984
Kissimmee, Florida

Agenda

7:00 a.m. Registration (Coffee available)

8:30 a.m. Welcome and Opening Remarks: Robert Annan, U.S. Department of Energy

9:00 a.m. Introduction of Keynote Speaker: Robert San Martin, U.S. Department of Energy

9:15 a.m. Keynote Address: Don Fuqua, U.S. House of Representatives

10.00 a.m. Break

10:30 a.m. "Status of the Japanese Sunshine Project Photovoltaic Program," Yoshihiro Hamakawa, Osaka University

11:00 a.m. "Status of the Commission of European Communities PV Programs," Roger Van Overstraeten, Catholic University-Leuven, Belgium

11:30 a.m. Luncheon (by reservation)

1:30 p.m. Solar Energy Research Institute
Chairman: Lloyd Herwig. U.S. Department of Energy
"SERI Photovoltaics Research." Don Ritchie
"Recent Developments in the Subcontract Photovoltaic AR&D Research," Tom Surek

2:45 p.m. Sandia Laboratories
Chairman: Andrew Krantz, U.S. Department of Energy
"Systems" Ed Burgess
"Concentrators," Eldon Boes

3:45 p.m. Break

4:15 p.m. Jet Propulsion Laboratory
Chairman: Morton Prince, U.S. Department of Energy
"Project Analysis and Integration," William Callaghan
"Materials and Devices Research," Marty Leipold
"Process Development," Don Bickler
"Reliability and Engineering Sciences," Ron Ross

5:15 p.m. "Environmental Health and Safety in Photovoltaics," Paul Moskowitz, Brookhaven National Laboratory

NATIONAL PHOTOVOLTAIC PROGRAM ANNUAL REVIEW MEETING

April 30, 1984
Kissimmee, Florida

LIST OF ATTENDEES

A

ABERGER, NORBERT
WACKER CHEMITRONIC GMBH
Joh Hess-Strobe 29
Burghausen, West Germany 08263
0049-8677-833693

ABOU-ELFOTOUH, FOUAD
SERI
1617 Cole Blvd., 16/3
Golden, CO 80401
303/231-1020, FTS 327-1020

ADKINSON, DONALD
LENBROOK INDUSTRIES
1145 Bellamy Road
Scarborough, Ontario, Canada M1H 1H5
416/438-4610

AKIRA, USAMI
NAGOYA INSTITUTE OF TECHNOLOGY
Gokiso-Cho, Showa-Ku
Nagoya, Aichi-Ken, Japan 466
052/732-2111 X462

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ARMY FOREIGN SCI. & TECH. CENTER
220 Seventh Street
Charlottesville, VA 22901
804/296-5171 X671

ANDERSON, D. A.
SILONEX INC.
331 Cornelia Street
Plattsburgh, NY 12901
518/561-3160

ANNAN, ROBERT
U. S. DEPARTMENT OF ENERGY
1000 Independence Ave., S. W.
Washington, D.C. 20585
202/252-1720

ARNETT, JAMES
ARCO SOLAR INDUSTRIES
Engineering Department
PO Box 4400
Woodland Hills, CA 91365
818/700-7227

ARVIZU, DAN
SANDIA NATIONAL LABORATORIES
Box 5800, Div 6224
Albuquerque, NM 87185
505/846-0387

ASANO, TAKUSHI
TERASAKI ELECTRIC CO., LTD.
7-2-10, Hannancho, Abeno-ku
Osaka-shi, Japan 545
06/692-1131

ASHIDA, YOSHINORI
MITSUI TOATSU CHEMICALS, INC.
Research Scientist
3-2-5, Kasumigaseki, Chiyoda-ku
Tokyo, Japan 100
03/593-7364

ASHTON, GARY
3M
3M Center Bldg. 201-1E-16
St. Paul, MN 55144
612/733-8425

AULICH, HUBERT
SIEMENS RESEARCH LABORATORIES
Otto-Hahn-Ring 6
8 Munchen 83
089/636-44683

AYER, JOHN
NATIONAL RESEARCH COUNCIL
Montreal R D M50-348
Ottawa, Ontario, Canada K1A0R8
613/993-9278

B

BARLAUD, MICHAEL
AFME
Route des Lucioles
06560 Valbonne France
93/747979

BARNETT, ALLEN M.
UNIVERSITY OF DELAWARE
Electrical Engineering Department
140 Evans Hall
Newark, DE 19716
302/451-8784/2405

BARUCH, PIERRE
UNIVERSITY OF PARIS 7
G.P.S. - 2 Place Jussieu
F-75251 Paris-CEDEX-5, France
33-1/336.25.25 X46.8g

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SERI
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Golden, CO 80401
303/231-7035, FTS 327-7035

BENNER, JOHN
SERI
1617 Cole Blvd, 17/1
Golden, CO 80401
303/231-1396, FTS 327-1396

BERRY, WILLIAM B.
UNIVERSITY OF NOTRE DAME
402 E. Pokagon
South Bend, IN 46617
219/239-5532

BHARGAVA, BHARAT
CENTRAL ELECTRONICS LIMITED
Industrial Area 4
Sanibabad, U.P., India
20/3557

BICKLER, DONALD B.
JET PROPULSION LABORATORY
4800 Oak Grove Drive
Pasadena, CA 91109
818/577-9219

BILGER, G.
UNIVERSITY OF STUTTGART
Inst. f. Physikalische Elektronik
Pfaffenwaldring 47
D-7000 Stutgart 80
West Germany
07 11/685-1

BISHOP, CHARLES J.
A. D. SMITH
Box 584
Milwaukee, WI 53201
414/447-4226

BLAKERS, ANDREW
UNIVERSITY OF NEW SOUTH WALES
School of Electrical Engineering
PO Box 1, Kensington, 2033, Australia
02/6622811

BLEIL, CARL
132 Chalmers Drive
Rochester, MI 48063
313/652-3881

BOES, ELDON
SANDIA NATIONAL LABORATORIES
Division 6226, PO Box 5800
Albuquerque, NM 87185
505/844-5634

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Troy, NY 12181
518/266-6684

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PO Box 4400
Woodland Hills, CA 91365
818/700-7163

BOYD, HERBERT M.
ALABAMA POWER COMPANY
1609 Celinda Lane
Birmingham, AL 35238
205/250-2388

BRANDHORST, HENRY W. JR.
NASA-LEWIS - MAIL STOP 302-1
21000 Brookpark Road
Cleveland, OH 44017
216-433-4000 Ext. 786

BRAWLEY, THOMAS
APPLIED SOLAR ENERGY CORP.
15251 E. Don Julian Road
City of Industry, CA 91749
818/968-6581

BRUTON, TIMOTHY M.
BRITISH PETROLEUM RESEARCH
CENTRE
Chertsey Road
Sunbury-on-Thames, Middlesex
England TW167LN
09327/63667

BUCHANAN, MARGARET
NATIONAL RESEARCH COUNCIL
Montreal Road
Ottawa, Ontario, Canada K1AOR6
613/993-2730

BULAWKA, ALEC O.
U.S. DEPARTMENT OF ENERGY
1000 Independence Avenue, S.W.
Washington, D.C. 20585
202/252-1719

BURGESS, ED
SANDIA NATIONAL LABORATORIES
Div 6221
Albuquerque, NM 87185
505/844-2178

BURGELMAN, MARC
GHENT STATE UNIVERSITY
St. Pietersnieuwsiruub 41 B-4000 Gent,
Belgium
92/23 38 22

BYRON, STANLEY
MATHEMATICAL SCIENCES NW
Spectra Physics
2755 Northup Way
Bellevue, WA 98004
206/827-0460

C

CALLAGHAN, WILLIAM
JET PROPULSION LABORATORIES
4800 Oak Grove Drive
Pasadena, CA 91103
818/577-9517

CAMMERER, FRITZ
SIEMENS
Delpstr 15
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SERI
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CHAMBOULEYRON, IVAN
INSTITUTE OF PHYSICS - UNICAMP
PO Box 6165
Campinas, S. P. Brazil 13100
192/391232 (Brazil)

CHAMPNESS, CLIFFORD HARRY
MCGILL UNIVERSITY
Electrical Engineering Dept.
3480 University Street
Montreal, Quebec, Canada H3A 2A7
514/392-4208

CHANDRA, SURESH
BHARAT HEAVY ELECTRICALS LTD.
18-20 Kasturba Gandhi Marg,
Hindustan Times House,
New Delhi, India 110001
5717459

CHEEK, GARY C.
K. V. LEUVEN/ESAT LABORATORY
Kardinaal Mercierlaan 94
Heverlee, Belgium 3030
016/220931

CHEN, CHERN P.
JET PROPULSION LAB
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Pasadena, CA 91109
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Clarksburg, MD 20731
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PV SYSTEMS
8251 Roanne Drive
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305/678-2470

COUTTS, TIM
NEWCASTLE POLYTECHNIC
Ellison Place
Newcastle, England
011 44 670 55119

CULL, RONALD
STANDARD OIL CO.
4440 Warrensville Court Rd.
Cleveland, OH 44128
216/581-5266

CURRY, RICHARD
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214/942-5248

CURTIS, HENRY
NASA/LEWIS
21000 Brookpark Road
Cleveland, OH 44125
216/433-4000 X309, FTS 294-6309

D

D'AIRO, JOSEPH
DYTEK LABORATORIES
Airport International Plaza
Bohemia, NY 11716
516/467-5553

DALACU, NICK
A. D. PLATING & ELECTROFORMING
110 Aikman Ave.
Hamilton, Ontario, Canada L8M1P9
416/523-4636

DANIEL, RON
JET PROPULSION LABORTORY
4800 Oak Grove 506-316
Pasadena, CA 91109
818/577-9189

DAVIS, CLARA
CLEMSON UNIVERSITY
ECE Department, 102 Riggs Hall
Clemson, SC 29631
803/656-3377

DAVIS, H. JOHN
NORANDA RESEARCH CENTRE
240 Hymus Blvd.
Pointe Claire
Quebec, Canada M9R 1G5
514/677-6640

DAY, JOHN
STRATEGIES UNLIMITED
201 San Antonio Circle, Suite 205
Mountain View, CA 94040
415/941-3438

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VACTRONIC LABS EQUIPMENT
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East Northport, NY 11733
516/261-2660

DELOMBARD, RICHARD
NASA LEWIS R.C.
21000 Brookpark
Cleveland, OH 44135
216/433-4000

DEL VALLE, JUAN
CIEA-IPN
Av. Ipn. 2508
Mexico, D.F. 14-740
7-54-68-03

DEVANEY, WALTER E.
BOEING AEROSPACE COMPANY
P.O. Box 3999 M/S 88-43
Seattle, WA 98199
206/773-1249

DHERE, NEELKANTH
INSTITUTO MILITAR DE ENG
MATERIALS SCI
Pca Gen. Tiburcio, 80, Praia Vermelha
Rio De Janeiro, RJ, Brazil 22231
021/551-0700

DONON, JEROME
PHOTOWATT INTERNATIONAL S.A.
131 Route de l'Empereur
Rueil-Malmaison, France 92500
1/7080505

DROUOT, LOUIS PAUL
AFME
Route des Lucioles - Sophia Antipous
06560 Valbonne, France
93/747979

DUMAS, KATHERINE
JET PROPULSION LABORATORY
4800 Oak Grove Drive
Pasadena, CA 91109
818/354-6546

DUNLOP, ANDREW
DOW CORNING CORPORATION
PO Box 1767, CO2430
Midland, MI 48640
517/496-4224

E

EBERSPACHER, CHRIS
ARCC SOLAR, INC.
PO Box 4400
Woodland Hills, CA 91365
818/700-7312

EDENBURN, MICHAEL W.
SANDIA NATIONAL LABORATORIES
Box 5800, Div 6224
Albuquerque, NM 87185
505/844-4003

EGUREN, JAVIER
ISOFOTON S.A.
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Malaga, Spain
52/340900

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LUZ INTERNATIONAL
P.O. Box 7929
Jerusalem, Israel
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ELLIS, JIM
SOLAVOLT INTERNATIONAL
4036 E. Atlanta Ave
Phoenix AZ
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EPSTEIN, BARBARA
DYNAMIC SOLAR PRODUCTS
91631 Overseas Highway
Tavernier, FL 33070
305/852-9683

EPSTEIN, ROBERT
DYNAMIC SOLAR PRODUCTS
91631 Overseas Highway
Tavernier, FL 33070
305/852-9683

ESKENAZI, DEBORAH
MERIDIAN CORPORATION
5113 Leesburg Pike, Suite 700
Falls Church, VA 22041
703/998-0922

F

FAGNAN, DONALD
PHILADELPHIA ELECTRIC COMPANY
2301 Market Street
Philadelphia, PA 19101
215/841-4856

FAHRENBRUCH, ALAN L.
STANFORD UNIVERSITY
Stanford, CA 94305
415/497-2951

FAMELI, GIUSEPPE
ENEA
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Eau Claire, WI 54701
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HOUSE SCIENCE & TECHNOLOGY COMMITTEE
House of Representatives
B374 Rayburn
Washington, D.C. 20515
202/225-3975

FUENTES, MARTIN
SANDIA NATIONAL LABS
Box 5800
Albuquerque, NM 87109
505/846-4520

FULLMER, ROBERT G.
ECONOMISTA
Apartado 389
1250 Escazu
Costa Rica
28-28-19

FUQUA, DON
U. S. HOUSE OF REPRESENTATIVES
Rayburn House Office Building
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202/225-5235

G

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GILLETTE, ROGER
BOEING COMPANY
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Seattle, WA 98124
206/575-5474

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TRW
One Space Park R5/2182
Redondo Beach, CA 90278
213/536-2754

GORADIA, CHANDRA
CLEVELAND STATE UNIVERSITY
SH 305, 1983 E. 24th Street
Cleveland, OH 44115
216/687-3537

GORADIA, MANJU
CLEVELAND STATE UNIVERSITY
SH 305, 1983 E. 24th Street
Cleveland, OH 44115
216/687-3530

GRECO, GIOVANNI
PRAGMA SPA
Via P.O. 25/A
Italy 00100
06/9882246

GREEN, MARTIN A.
UNIVERSITY OF NEW SOUTH WALES
PO Box 1
Kensington, Australia 2033
61-2-662-2797

GROUMPOS, PETER P.
CLEVELAND STATE UNIVERSITY
Electrical Engineering Department
Cleveland, OH 44115
216/687-2592

H

HAAVIND, ROBERT
HIGH TECHNOLOGY MAGAZINE
38 Commercial Wharf
Boston, MA 02110
617/227-4700

HALACY, DAN
SERI
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HAMAKAWA, YOSHIHIRO
OSAKA UNIVERSITY
Dept. of Electrical Engineering
Toyonaka, Osaka, Japan 560
06/844-1151 X4588

HANAK, JOSEPH
ENERGY CONVERSION DEVICES, INC.
32400 Edwards Street
Madison Heights, MI 48071
313/585-7880

HANOKA, JACK
MOBIL SOLAR
16 Hickory Drive
Waltham, MA 02254
617/890-0909

HARRENSTIEN, HOWARD
UNIVERSITY OF MIAMI
Dept. of Civil & Arch Engr.
Coral Gables, FL 33124
305/284-3391

HARRISON, J. W.
RESEARCH TRIANGLE INSTITUTE
PO Box 12194
Research Triangle Park, NC 27709
919/541-5913

HATIC, LUCY
SOLAR COLLECTOR MFG.
P.O. Box 1609
Anna Maria, FL 33501
813/778-1271

HATIC, OSMAN
SOLAR COLLECTOR MFG.
P.O. Box 1609
Anna Maria, FL 33501
813/778-1271

HAWKINS, DEXTER C.
CLEMSON UNIVERSITY
102 Riggs Hall, ECE Department
Clemson, SC 29631
803/656-3377

HEALEY, HENRY M.
FLORIDA SOLAR ENERGY CENTER
300 State Road 401
Cape Canaveral, FL 32920
305/783-0300

HECHT, HANS
SIEMENS
Frankfurter Ring 152
D-8000 Munich 46 West Germany
089/3500781

HELLMUTH, NELSON
MORNING STAR
138 Industrial Corp.
Orange Park, FL 32073
907/264-2649

HELMREICH, DIETER
HELIOTRONIC GMBH.
Johannes-Hess - Str. 24
8263 Burghausen, West Germany
08677/83-2736

HENRY, PAUL
JET PROPULSION LAB.
4800 Oak Grove Drive
Pasadena, CA 91109

HERMANN, ALLEN
SERI
1617 Cole Blvd. 17/1
Golden, CO 80401
303/231-1311, FTS 327-1311

HERSCHITZ, ROMAN
RCA ASTROELECTRONICS
PO Box 800, MSTRGB
Princeton, NJ 08540
609/426-2135

HERWIG, LLOYD
U. S. DEPARTMENT OF ENERGY
1000 Independence Ave., S. W.
Washington, D.C. 20585
202/252-1692

HIDE, ICHIRO
HOXAN CORPORATION
2-3-12 Kikusui-Gojyo, Shiraishi-Ku
Sapporp-Shi, Hokkaido, Japan 003
011/8230252

HILL, ROBERT
NEWCASTLE POLYTECHNIC
School of Physics
Newcastle Upon Tyne, England NE18ST
0632/326002 X3650

HIMELREICH, LOUIS
DUPONT
2806 Kennedy Rd.
Wilmington, DE 19810
302/772-3286

HOELSCHER, JAMES F.
SOLAREX
1335 Piccard Dr.
Rockville, MD 20850
301/948-0202

HOFFMANN, WINFRIED
NUKEM GMBH
Postfach M0080, D-645 Hanau M
West Germany
06181-58-2773

HOGAN, JUDITH
MERIDIAN CORPORATION
5113 Leesburg Pike, Suite 700
Falls Church, VA 22041
703/998-0922

HOGAN, STEVE
SPIRE
Patriots Park
Bedford, MA 01730
617/275-6000

HOLLINGSWORTH, MICHAEL
SOLENERGY CORPORATION
26 1/2 Orue St.
Marblehead, MA 01945
617/639-0081

HOLLRICHER, OTFRIED
WACKER CHEMITRONIC
D-8263 Burghausen
West Germany
08677-830

HOLM, PAIGE
ARIZONA STATE UNIVERSITY
1748 W. Lindner
Mesa, AZ 85202
602/839-1746

HONG, CHUM-SAM
ENERGY RESEARCH LABS
3rd Fl., No.1, Sec. 1
Fu Shin South Rd.
Taipei, Taiwan
02/7219760

HOUKOM, ROLF S.
DERBY SECURITIES
29 Broadway
New York, NY 10006
212/425-2224

HOWE, ARTHUR
AMOCO RESEARCH CENTER
PO Box 400
Naperville, IL 60566
312/420-5271

HOWELL, BILL
INTERMETAL TECHNOLOGY, INC.
5951 Kentland Ave.
Woodland Hills, CA 91367
818/347-7775

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1617 Cole Blvd. 16/3
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303/231-1220, FTS 327-1220

HWANG, HUEY-LIANG
TSING HUA UNIVERSITY
Dept. of Electrical Eng.
Hsin-chu, Taiwan 300
035/715131

I

IIDA, HIDEYO
TAIYO YUDEN CO., LTD.
562, Hongotsukanaka, Harunamachi
Gumma-gun, Gumma-ken, Japan 370-33
0273/43-1115

INOUE, MICHAEL S.
KYOCERA INTERNATIONAL, INC.
8611 Balboa Ave.
San Diego, CA 92123
619/576-2684

ISAYAMA, TAKEHIKO
HITACHI ZOSEN CORPORATION
1-3-40, Sakurajima, Konohana-ku
Osaka, Japan 554
06/463-7111

J

JACKSON, JIM
GOVERNOR'S ENERGY OFFICE
301 Bryant Bldg.
Tallahassee, FL 32301
904/488-2475

JANOUSEK, BRUCE K.
THE AEROSPACE CORPORATION
PO Box 92957 M2/275
Los Angeles, CA 90009
213/647-1820

JARGELIUS, MIKAEL R.
INSTITUTE OF MICROWAVE TECH.
Box 70033
Stockholm, Sweden 10044
08/238320

JEFFREY, FRANK
3M
201 1E 3M Center
St. Paul, MN 55144
612/736-3168

JI, BINGHOU
HOHHOT INNER MONGOLIA UNIV.
Hohhot, Inner Mongolia
23241

JIAN NING, CHEN
TIANJIN INSTITUTE OF POWER
Tianjin Liqizhong, P.O. Box 277
Tianjin, China 300381
28851/28433

JINGXIAO, WANG
TIANJIN INSTITUTE OF POWER
SOURCES
P.O. Box 277, Tianjin Liqizhong
Tianjin, China 300381
28851/28433

JOHNSON, IRV
APPLIED SOLAR ENERGY CORP.
15251 E. Don Julian Rd.
City of Industry, CA 91749
818/968-6581

JOHNSON, ROBERT O.
STRATEGIES UNLIMITED
201 San Antonio Circle, Suite 205
Mountain View, CA 94046
415/941-3438

JONES, GARY
SANDIA LABORATORIES
Div 6223
Albuquerque, NM 87185
505/844-2433

K

KAMATH, G. S.
HUGHES RESEARCH LABORATORIES
3011 Malibu Canyon Road - MS RL63
Malibu, CA 90265
213/456-6411 X252

KARIUS, SIEGFRIED
NAT'L RES. COUNCIL OF CANADA
Montreal Road
Ottawa, Ontario, Canada K1AOR6
613/9932730

KAZMERSKI, LARRY
SERI
1617 Cole Blvd.
Golden, CO 80401
303/231-1115, FTS 327-1115

KESLER, MATT
SOLAVOLT INTERNATIONAL
3646 E. Atlanta
Phoenix, AZ
602/231-6434

KHATTAK, CHANDRA
CRYSTAL SYSTEMS, INC.
35 Congress Street
Salem, MA 01970
617/745-0088

KIDOKORO, MITSUHIRO
OPTOELECTRONIC IND. &
TECH. DEV. ASSN.
2-7-4, Nishi-shimbashi, Minatoku
Tokyo, Japan 105
03/508-2091

KING, DAVID L.
SANDIA NATIONAL LABORATORIES
Box 5800, Div 6224
Alburquerque, NM 87185
505/844-8220

KING, W. RAFFINGTON
SCIENCE APPLICATIONS, INC.
1710 Goodridge Drive
McLean, VA 22102
703/998-0931

KINGMAN, NANCY
3M
3M Center
St. Paul, MN 55144
612/733-0391

KITAMURA, SOTOYUKI
MATSUSHITA BATTERY INDUSTRIAL CO.
1, Matsushitacho, Moriguchi-shi
Osaka-fu, Japan 570
06/991-1141

KLEIN, ROBERT J.
IEEE STDS. DEPT.
345 E. 47th Street
New York, NY 10017
212/705-7774

KOLIWAD, KRIS
JET PROPULSION LABORATORIES
4800 Oak Grove Drive
Pasadena, CA 91103
818/354-5197

KONAGAI, MAKOTO
TOKYO INSTITUTE OF TECHNOLOGY
2-12-1, Ohokayama, Meguro-ku
Tokyo, Japan 152
03/726-1111 X2554

KRANTZ, ANDREW
U. S. DEPARTMENT OF ENERGY (CE 333)
1000 Independence Ave., S. W.
Washington, D. C. 20585
202/252-1724

KRAUSE, FRED
GEORGIA POWER COMPANY
7 Solar Circle
Shenandoah, GA 30265
404/253-0218

KREBS, KARLHEINZ
CEC-JOINT RESEARCH CENTRE
Ispra (Va), Italy 21020
0332/789902

KUBOI, OSAMU
KOMATSU ELECTRONIC
METALS CO., LTD.
2612, Shinomiya, Hiratsuka-shi
Kanagawa-ken, Japan 254
0463/23-1313

KUSS, GREGORY R.
KUSS OIL COMPANY
93 E. Riverglen Drive
Worthington, OH 43085
614/885-3051

L

LASSNIG, RUDOLPH
UNIVERSITY OF INNSBRUCK
Inst. of Exp. Physics
Schopfstr 41
6020 Innsbruck, Austria

LATHROP, JAY
CLEMSON UNIVERSITY
Clemson, SC 29631
803/656-3375

LAWSON, ALBERT
JET PROPULSION LABORATORY
4800 Oak Grove Drive M/S 507/228
Pasadena, CA 91109
818/577-9523

LECHEVALIER, ROBERT
U.S. DEPT. OF ENERGY
1333 Broadway
San Francisco, CA 94612
415/273-6362

LEE, Y. T.
UTL CORPORATION
4500 W. Mockingbird Lane
Dallas, TX 75209
214/350-7601

LEIPOLD, MARTIN H.
JET PROPULSION LABORATORY
4800 Oak Grove Drive
Pasadena, CA 91011
818/577-9267

LESK, I. ARNOLD
SOLAVOLT INTERNATIONAL
1750 E. Oregon Ave.
Phoenix, AZ 85016
602/231-6458

LEVY, SHELDON
BLACK & VEATCH
PO Box 8405
Kansas City, MO 64114
913/967-7119

LEWIS, IAN
ONTARIO MINISTRY OF ENERGY
56 Wellesley Street West, 10th Floor
Toronto, Canada M7A2B7
416/965-7037

LI CAUSI, SAVERIO
ENEA
Italian Nat. Energy Agency
c/o I.I.T. Research Institute
1825 K Street, N. W.
Washington, D.C. 20006
202/296-1610

LITTLE, ROGER
SPIRE CORPORATION
Patriot's Park
Bedford, MA 01730
617/275-6000

LING, KEN
APPLIED SOLAR ENERGY CORP.
15251 E. Don Julian Road
City of Industry, CA 91740
818/968-6581

LOFERSKI, JOSEPH J.
BROWN UNIVERSITY
Div. of Engineering
Providence, RI 02912
401/863-2870

LORENZ, JAMES H.
CONSULTANT
5331 E. Poinsettia Drive
Scottsdale, AZ 85254
602/951-0343

M

McCONNELL, ROBERT
SERI
1617 Cole Blvd. 17/1
Golden, CO 80401
303/231-1019, FTS 327-1019

McDANAL, A. J.
ENTECH, INC.
1015 Royal Lane
D/FW Airport, TX 75266
214/456-0900

McNEELY, JAMES B.
ASTROSYSTEMS, INC.
ASTROPOWER DIVISION
30 Lovett Avenue
Newark, DE 19711
302/366-0400

MACALEER, BRADLEY S.
MERIDIAN CORPORATION
5113 Leesburg Pike #700
Falls Church, VA 22041
203/998-0922

MACKAY, JOHN
UNITED ENERGY CORPORATION
420 Lincoln Centre Drive
Foster City, CA 94404
415/570-5011

MACOMBER, HAL
SOLAREX CORPORATION
1335 Piccard Drive
Rockville, MD 20850
301/948-0202

MAGID, LEONARD M.
PA CONSULTING SERVICE, INC.
707 Alexander Road
Princeton, NJ 08540
609/452-1734 X205

MAKIOS, VASILIOS
UNIVERSITY OF PATRAS
Patras, Greece
061/991-902

MAO, SHING
UTL CORPORATION
4500 W. Mockingbird Lane
Dallas, TX 75209
214/350-7601

MARIS, OLIVIER
SAINT-GOBAIN RECHERCHE
BP 135
93 304 Aubervilliers Cedex, France
1/834.92.19

MARTIN, STEVEN
A.S.U.
Tempe, AZ 85282
602/965-2924

MARUYA, SHIGEHISA
SEISHIN TRADING CO., LTD.
1-2-1, Sannomiyacho, Chuo-ku
Kobe-shi, Hyogo-ken, Japan 650
078/391-5391

MARUYAMA, KAZUMI
FUJI ELECTRIC CORP. RES. & DEV., LTD.
2-2-1, Nagasaka
Yokosuka City, Japan 240-01
0468-56-1191

MASAHIDE, TAKAKASHU
SIKOKU ELECTRIC POWER CO.
Takamatu-Chi, JAPAN

MATSUOKA, TSUGUFUMI
SANYO ELECTRIC CO., LTD.
1-18-13, Hashiridani, Hirakata-shi
Osaka-fu, Japan 573
0720/41-1161

MATSUTANI, TOSHINOBU
SHARP CORPORATION
282-1 Hajikami
Shinjocho, Nara 636-03
Japan

MAYCOCK, PAUL
PV ENERGY SYSTEMS INC.
2401 Childs Lane
Alexandria, VA 22308
703/780-9236

MEAKIN, JOHN D.
UNIVERSITY OF DELAWARE
INST. OF ENERGY CONVERSION
Wyoming Road
Newark, DE 19716
302/451-6243

MECKEL, BEN
DEPOSITION RESEARCH & DEV.
7670 Trade Street
San Diego, CA 92121
619/578-9400

MEGERLE, CLIFF
ARCO SOLAR INC.
PO Box 4400
Woodland Hills, CA 91365
818/700-7028

MIKHAIL, AMIR
SERI
1617 Cole Blvd.
Golden, CO 80401
303/231-1011, FTS 327-1011

MILSTEIN, JOE
SERI
1617 Cole Blvd.
Golden, CO 80401
303/231-7299, FTS 327-7299

MIMILA-ARROYO, JAIME
CENTRO DE INVESTIGACION Y EST.
AVANSADOS DEL IPN
Av. I.P.N. 2508 Mexio 14 D.F. Mexico
Mexico, Mexico
5/754-6803

MINAMINO, YASUYUKI
KYOCERA CORPORATION
1166-6, Nagatanino, Hebimizocho,
Yokkaichi-shi Shiga-ken, Japan 527
07482/3-6800

MISIAKOS, KONSTANTINOS
CLEMSON UNIVERSITY
102 Riggs Hall, ECE Department
Clemson, SC 29631
803/656-3377

MITCHELL, KIM
ARCO SOLAR INC.
PO Box 4400
Woodland Hills, CA 91365
818/700-7115

MITCHELL, WILLIAM
3M
Bldg. 201-35-01, 3M Center
St. Paul, MN 55144
612/633-9629

MITSUI, KOTARO
MITSUBISHI ELECTRIC CORPORATION
4-1, Mizuhara
Itami, Hyogo, Japan 664
0727/79-6200

MOACANIN, JOVAN
JET PROPULSION LAB
4800 Oak Grove Drive
Pasadena, CA 91109
818/354-3178

MOODIE, DUNCAN
STONE & WEBSTER ENGINEERING CORP.
PO Box 2325
Boston, MA 02107
617/589-8931

MORET, CASS L.
ETHYL CORPORATION
451 Florida Blvd.
Baton Rouge, Louisiana 70801
504/388-7806

MORRISON, ANDREW
JET PROPULSION LABORATORY
4800 Oak Grove Drive
Pasadena, CA 91109
213/354-7200

MOSKOWITZ, PAUL
BROOKHAVEN NATIONAL LAB.
Bldg. 475
Upton, NY 11973
516/282-2017, FTS 666-2017

MUI, JEFFREY Y. P.
SOLARELECTRONICS, INC.
21 Rita Lane, PO Box 141
Bellingham, MA 02019
617/966-1234

MULLEN, PAUL
MACOM-LASER DIODE
205 Forrest Street
Metuchen, NJ 08840
201/549-9222

MUNZ, PETER
UNIVERSITAET KONSTANZ
PF 5560
Konstanz, FR West Germany D-7750
07531/883644

MURFETT, ALAN
TELECOM AUSTRALIA
770 Blackburn Road
Clayton, Vic, Australia 3168
613/541-6621

N

NAKATANI, MITSUO
HITACHI LTD.
292, Yoshidacho, Totsuka-ku
Yokohama-shi, Kanagawa-ken, Japan 244
045/881-1241

NELL, MATTHIES
UNIVERSITY OF DELEWARE
113 West Park Place
Newark, DE 19711
302/451-6693

NELSON, MICHAEL
WASHINGTON ENERGY EXT. SERVICE
Box 1039
Republic, WA 99166
509/775-3865

NIJS, JOHON F.
K. U. LEIWEN LAB EAST
K. Mercierlaan 94
Heverlee, Belgium 3030
016/220931

NOBILE, FRED
SUNELCO CORPORATION
1619 S. Rancho Santa Ferd
San Marcos, CA 92069
619/471-0183

NOEL, GERALD T.
BATTELLE COLUMBUS LABORATORIES
505 King Avenue
Columbus, Ohio 43201
614/424-7481

NOONAN, TERENCE M.
1328 Chetworth Ct.
Alexandria, VA 22314
703/549-6547

O

O'CONNOR, WILLIAM H.
SOLAVOLT INTERNATIONAL
PO Box 2934
Phoenix, AZ 85062
602/231-6420

O'MARA, BRADLEY
BALANCE OF SYSTEMS SPECIALISTS, INC.
7745 E. Redfield Rd.
Scottsdale, AZ 85260
602/948-9809

OGAWA, TOMITARO
SUMITOMO PLASTICS AMERICA, INC.
345 Park Avenue
New York, NY 10154
212/207-0770

OTODA, MASASHI
MITSUBISHI ELECTRIC CORPORATION
4-1, Mizuhara, Itami-shi
Hyogo-ken, Japan 664
0727/82-5131

OTSUKA, MASAHIKO
OVERSEAS INDUSTRY RESEARCH
CENTER
Kojimachi Pacific Bldg. 4-4, Kojimachi,
Chigoda-ku, Tokyo, Japan 102
03/264-7693

P

PANAYOTATOS, PAUL
RUTGERS UNIVERSITY
PO Box 909
Piscataway, NJ 08854
201/932-3382

PANTON, AL
KYOCERA INTERNATIONAL
8611 Balboa Ave
San Diego, CA 92123
619/576-2600

PAPPAS, GEORGE N.
U. S. DEPARTMENT OF ENERGY
PO Box 5400
Albuquerque, NM 87115
505/846-5205

PARROTT, JOHN E.
UWIST
PO Box 25
Cardiff, Great Britain CF13XE
0222/42588

PATAPOFF, NICK
SOUTHERN CALIFORNIA EDISON R&D
P.O. Box 800
Rosemead, CA 91770
818/572-2961

PATEL, CHIMAN M.
SOLAR HIND ENERGY CO.
747 Sand Creek Drive
Carol Stream, IL 60188
312/690-1883

PEARSON, ANTHONY M.
JET PROPULSION LABORATORY
4800 Oak Grove Drive M/S 502/404
Pasadena, CA 91109
818/577-9415

PEREYRA, INES
UNIVERSITY OF SAO PAULO - BRASIL
L.M.E. - EPUSP - CAIXA Postal 8174
05508 Sao Paulo, S.P., Brasil
2112122 X256

PETER, FRANCIS A.
TOTAL C.F.P.
24 Rue Erlanger
Paris, France 75016
(33)(1)/743-7011

PETROU, PETROS
SILONEX INC.
331 Cornelia Street
Plattsburgh, NY 12901
518/561-3160

PETTY, TIM
SOUTHERN COMPANY SERVICES, INC.
P.O. Box 2625
Birmingham, AL 35202
205/870-6241

PFISTERER, F.
UNIVERSITY OF STUTTGART
Pfaffenwaldring 47
D-7000 Stuttgart 80, West Germany
07 11/685-1

PIZZINI, SERGIO
HELIOSIL S.P.A.
Via Franchetti 1/A
Milano, Italy 20124
02/6535759

PLAUCHE, FULTON M.
NASA/JSC
EP5
Houston, TX 77058
713/483-2594

PREVI, ALFREDO
ENEL
ENEL-CREL-Via A. Volta, 1 Cologno
Monzese (Milano) Italy
02/88475255

PRINCE, MORTON B.
U. S. DEPARTMENT OF ENERGY
1000 Independence Ave., S. W.
Washington, D. C. 20585
202/252-1725

PULSCAK, MICHAEL W.
U. S. DEPARTMENT OF ENERGY
Ofc. of Conservation & Renewable Energy
1000 Independence Avenue S.W.
Washington, D.C. 20585
202/252-1726

R

RAEUBER, ARMIN
INSTITUT FUER SOLARE
ENERGIESYSTEME
Oltmannstrasse 22, D-7800 Freiburg
Fed. Rep. West Germany
0761/405046

RAJESWARAN, G.
BROOKHAVEN NATIONAL LAB.
Upton, NY 11973
516/331-5367

RALPH, E. L.
HAC
6445 N. Willard Ave.
San Gabriel, CA 91775
213/647-8855

RASCH, KLAUS-DIETER
TELEFUNKEN ELECTRONIC
Heilbronn, West Germany 7100
07131/882682

RICKUS, EDMUND
BATTELLE INSTITUTE
Am Roemerhof 35
D-6000 Frankfurt/Main, West Germany
0611/79082886

RISSER, V. VERNON
NEW MEXICO SOLAR ENERGY INST.
PO Box 3 SOL
Las Cruces, NM 88003
505/646-3944

RITCHIE, DONALD W.
SERI
1617 Cole Blvd.
Golden, CO 80401
303/231-1373, FTS 327-1373

ROBERTS, DONALD R.
WESTINGHOUSE ADVANCED ENERGY
SYSTEMS DIV
Box 10864
Pittsburgh, PA 15236
412/892-5600

ROBILLER, EDITH
SUN WORKS INTERNATIONAL
P.O. Box 442063
Del Ray Beach, FL 33444
305/276-2242

ROBILLER, GOTTFRIED
SUN WORKS INTERNATIONAL
P.O. Box 442063
Del Ray Beach, FL 33444
305/276-2242

ROMEO, NICOLA
DIPARTIMENTO DI FISICA
PARMA UNIVERSITY
Via M. D'Azeglio 85 43100
Parma, Italy
0521/46346

ROSE, BEN
SANDIA NATIONAL LABORATORIES
Box 5800
Albuquerque, NM 87185
505/846-4516

ROSS, RONALD G., JR.
JET PROPULSION LABORATORIES
4800 Oak Grove Drive
Pasadena, CA 91109
818/577-9111

ROTHBART, JAY N.
STANDARD OIL CO. (OHIO)
Midland Bldg.
Cleveland, OH 44115
216/575-8088

ROTHWARF, ALLEN
DREXEL UNIVERSITY
ECE Department
Philadelphia, PA 19104
215/895-2262

ROTUNDO, LOUIS
FLORIDA SOLAR ENERGY CENTER
300 St. Rd. 401
Cape Canaveral, FL 32920
305/783-0300

ROUX, MICHAEL
ONERA-CERT
2 Avenue Edonard Belin
31055 Toulouse, France
61/75-1109

RUCKTESCHLER, RAINER
OAK RIDGE NATIONAL LABORATORY
Solid State Division
Oak Ridge, TN 37830
615/576-5097

RUSSAK, MICHAEL
GRUMMAN AEROSPACE CORP.
M/S A01-26, R&D Center
Bethpage, NY 11714
516/575-8624

RUSSELL, MILES
MIT ENERGY LAB.-NE RES. EXP. STA.
711 Virginia Road
Concord, MA 01742
617/863-5770

RUSSELL, T. W. FRASER
UNIVERSITY OF DELAWARE
Institute Of Energy Conversion
Newark, DE 19716
302/451-6220

S

SABISKY, EDWARD
SERI
1617 Cole Blvd. 17/1
Golden, CO 80401
303/231-1483, FTS 327-1483

SALAZAR, CARLOS
OFFICE OF ENERGY - PUERTO RICO
Minillas Government Center
PO Box 41089 Minillas Station
Santurce, Puerto Rico 00940
809/726-8444

SAN MARTIN, ROBERT
U. S. DEPARTMENT OF ENERGY
1000 Independence Ave., S. W.
Washington, D.C. 20585
202/252-9275

SANDERSON, ROBERT
ARIZONA STATE UNIVERSITY
ERC 583
Tempe, AZ 85287
602/965-6145

SANO, SEIJIRO
KOMATSU LIMITED
2597, Shinomiya, Hiratsuka-shi
Kanagawa-ken, Japan 254
0463/23-1313

SARNO, ANGELO
ENEA
ENEA-CRIF, Via Nuova Delle Brecce 150
Napoli-Barra, Italy
081/611588

SCHAEFER, JOHN F.
NEW MEXICO SOLAR ENERGY INSTITUTE
Box 3-SOL, NMSU
Las Cruces, NM 88003
505/646-4240

SCHAUB, PETER E.
POTOMAC ELECTRIC POWER COMPANY
1900 Pennsylvania Ave., NW Room 804
Washington, D.C. 20068
202/872-3044

SCHMID, FREDERICK
CRYSTAL SYSTEMS, INC.
35 Congress Street
Salem, MA 01970
617/745-0088

SCHULER, DON
SANDIA LABS.
Dept. 6220
Albuquerque, NM 87185
505/844-4041

SCHWARTZ, RICHARD
PURDUE UNIVERSITY
Electrical Engineering
West Lafayette, IN 47907
317/494-3510

SCOLARO, TONY
U. S. DEPARTMENT OF ENERGY
1000 Independence Avenue., S. W.
Washington, D.C. 20585
202/252-5548

SELF, GEORGE
CHRONAR CORPORATION
P.O. Box 177
Princeton, NJ 08542
609/587-8000

SHEWCHUN, JOHN
SOLAR POWER DEVELOPMENTS LTD
3327 D. Mainway
Burlington, Ontario Canada L7P359
416/335-4713

SHIH, ISHIANG
McGILL UNIVERSITY
3480 University St.
Montreal, P.Q., Canada H3A2A7
514/392-4563

SHING, YUH - HAN
ARCO SOLAR, INC.
PO Box 4400
Woodland Hills, CA 91365
818/700-7104

SHIRASAWA, KATSUHIKO
JAPAN SOLAR ENERGY CO., LTD.
1166-6 Nagatanino
Yohkaicki, Shiga, Japan 527
07482/3-6088

SHUNICHI, YUYA
MITSUBISHI ELECTRIC CORP.
Amagazaki City
Osaka, Japan
06/491-8021

SINGH, PARAMJIT (P.J.)
ARCO SOLAR, INC.
PO Box 4400
Woodland Hills, CA 91365
818/700-7156

SINGH, RAJENDRA
UNIVERSITY OF OKLAHOMA
202 West Boyd, Room 219
Norman, OK 73019
405/325-4721

SIRTL, ERHARD
HELIOTRONIC GMBH.
Johannes-Hess-Str. 24
8263 Burghausen, West Germany
08677/83-2580

SMOKLER, MELVIN I.
JET PROPULSION LABORATORY
4800 Oak Grove Drive
Pasadena, CA 91109
818/577-0238

SOBAJIMA, SHIGENOBU
TEIJIN LIMITED
2-1-1, Uchisaiwaicho, Chiyoda-ku
Tokyo, Japan 100
03/506-4104

SPENCER, ROBERT
ACUREX CORPORATION
485 Clyde Ave.
Mt. View, CA 94042
415/964-3200

SRINIVAS, K. S.
BHARAT HEAVY ELECTRICALS LTD.
Bhel
Bangalore, India 560026

SPITZER, MARK
SPIRE CORP.
Patriot's Park
Bedford, MA 01730
617/275-6000

STATLER, RICHARD
NAVAL RESEARCH LABORATORY
Code 6612
Washington, D.C. 20375
202/767-2446

STEELE, ROBERT
STRATEGIES UNLIMITED
201 San Antonio Circle Suite 205
Mountain View, CA 94040
415/941-3438

STOIAKEN, LARRY
ALTER. SOURCES OF ENERGY
MAGAZINE
107 S. Central Ave.
Milaca, MN 56353
612/983-6892

STONE, JACK L.
SERI
1617 Cole Blvd.
Golden, CO 80401
303/231-1370, FTS 327-1370

SUREK, THOMAS
SERI
1617 Cole Blvd. 17/1
Golden, CO 80401
303/231-1371, FTS 327-1371

SUZUKI, KUNIO
SEMICONDUCTOR ENERGY LAB. CO.
3-11-1, Kamisoshigaya, Setagaya-ku,
Tokyo, Japan 157
03/482-2522

SZABO, LOUIS F.
STANDARD OIL CO. (OHIO)
4440 Warrensville Center Rd.
Cleveland, OH 44128
216/581-5269

SZOT, JOZEF
UNIVERSITY OF NEW SOUTH WALES
School of Physics
Kensington NSW, Australia 2023
02/662-2388

SZPITALAK, TED
UNIVERSITY OF NEW SOUTH WALES
PO Box 1, Kensington 2033
New South Wales, Australia

T

TANNER, DAVE
ARCO SOLAR INC.
PO Box 4400
Woodland Hills, CA 91365

TAYLOR, SAMUEL J.
U.S. DEPT. OF ENERGY
Photovoltaics Division
1000 Independence Avenue
Washington, D.C. 20585
202/252-1693

TENG, KAU-SHEN
ENERGY RESEARCH LABORATORY
3rd Floor, No. 1, Sec. 1, Fu-Shin So. Rd.
Taipei, R.O.C. China
036/966100

THEREZ, FRANCIS
LABORATOIRE D'AUTOMATIQUE ET
D'ANALYSE DES SYSTMAS
7 Avenue de Colonel Roche
31077 Toulouse, France
1661/252147

THOMPSON, WILLIAM
APPLIED SOLAR ENERGY CORP.
P.O. Box 1212
City of Industry, CA 91749
213/968-6581

TIBBETT, MICHAEL
CLIMATIC - SOLAR CORPORATION
1872 Commerce Ave.
Vero Beach, FL 32960
305/567-3104

TOMAR, MAHARAJ
ARIZONA STATE UNIVERSITY
Dept. Electrical & Computer Eng.
Tempe, AZ 85287
602/965-2565

TONG, BOK YIN
UNIVERSITY OF WESTERN ONTARIO
London, Ontario, Canada
519/672-2285

TREBLE, FREDERICK C.
CONSULTANT
43 Pierrefondes Avenue
Farnborough Hants, GU148PA,
United Kingdom
0252/542037

TSUGE, KAZUNORI
KANEGAFUCHI CHEMICAL IND. CO.
1-2-80, Yoskidacho, Hyogo-ku
Kobe-shi, Hyogo-ken, Japan 652
078/681-6551

TSUO, Y. SIMON
SERI
1617 Cole Blvd 17/1
Golden, CO 80401
303/231-7682, FTS 327-7682

TURKENBURG, WILLIAM C.
STATE UNIVERSITY UTRECHT
Princetonplein 5
Utrecht, The Netherlands
030/533171

TURNER, GARY B.
ARCO SOLAR, INC.
PO Box 4400
Woodland Hills, CA 91365
213/700-7159

TUSTIN, DAVID
JET PROPULSION LABORATORY
4800 Oak Grove Road
Pasadena, CA 91109
818/577-9597

TYAN, YUAN-SHENG
EASTMAN KODAK
Research Labs - Bldg. 82D
Rochester, NY 14650
716/477-3519

U

ULLAL, HARIN
ARCO SOLAR, INC.
21011 Warner Center Lane
Woodland Hills, CA 91365
818/700-7366

URQUHART, D. A. (DON)
SPECTRAL ENGINEERING LTD.
29 Poplar Plains Cr.
Toronto, Ontario, Canada M4V 1E9
416/967-1497

V

VAN HALEN, PAUL
SUNELCO
1619 S. Rancho Santa Fe Rd.
San Marcos, CA 92069
619/471-0183

VAN OVERSTRAETEN, ROGER
ESAT - KATH UNIVERSITEIT LEUVEN
Kard. Mercierlaan 94
Heverlee, Belgium B3030
016-22.09.31

VENTRE, GERARD G.
FLORIDA SOLAR ENERGY CENTER
300 State Road 401
Cape Canaveral, FL 32920
305/783-0300

VERIE, CHRISTIAN
LAB. PHYSIQUE DU SOLIDE
ET ENERGIE SOLAIRE
C.N.R.S., Parc De Sophia
Antipolis, Rue Bernard Gregory
Valbonne, France F-06560
33/93-745353

VIRSHUP, GARY
VARIAN ASSOCIATION
611 Hansen Way M/S K222
Palo Alto, CA 94303
415/424-6110

VOLKMER, K.
JET PROPULSION LABORATORY
4800 Oak Grove Drive, 511/311
Pasadena, CA 91109
818/577-9392

VOSS, BERNHARD
INSTITUT FUER SOLARE
ENERGIESYSTEME
Oltmannstrasse 22
D-7800 Freiburg, West Germany
0761/405046

W

WAHLICH, REINHOLD
WACKER-CHEMITRONIC
P.O. Box 1160
Burghausen, W. Germany 8263
08677/3010

WALKER, DELORES H.
NAVAL RESEARCH LABORATORY
CODE 6612
4555 Overlook Ave., SW
Washington, D.C. 20020
202/767-2446

WALLACE, WILLIAM L.
SERI
1617 Cole Blvd. 17/1
Golden, CO 80401
303/231-1380, FTS 327-1380

WANG, DONG CHENG
KUNMING TEACHERS COLLEGE
Kunming, Yunlong Yunnan, China
25050

WARFIELD, GEORGE
CONSULTANT
RD 2, Box 264
Vergennes, VT 05491
802/545-2410

WARNER, THOMAS
PVI INC.
P.O. Box 370
Boston, MA 02117
617/267-2325

WATANABE, HIROYUKI
JAPAN SOLAR ENERGY CO., LTD.
1166-6 Nagatanino
Yohkaichi, Shiga, Japan 527
07482/3-6088

WEINBERG, I.
NASA
21000 Brookpark Road
Cleveland, OH 44135
216/433-4000 X5295

WEINMEISTER, ROGER
SOLAVOLT INTERNATIONAL
3646 E. Atlanta
Phoenix, AZ 85040
602/231-6427

WENTZ, LARRY
STANDARD OIL COMPANY
1608 Midland Bldg.
Cleveland, OH 44115
216/575-4538

WEN-ZI, LI
TIANJIN INSTITUTE OF POWER SOURCES
P.O. Box 277
Tianjin, China P.R.C. 300381
28851/28433

WIESMANN, HAROLD
VACTRONIC LAB EQUIPMENT INC.
65 Brightside Ave.
E. Northport, NY 11731
516/261-2660

WILLIAMS, D. F.
NATIONAL RESEARCH COUNCIL OF CANADA
Sussex Drive
Ottawa, Ontario, Canada K1AOR6
613/992-5614

WILLISON, MICHAEL
UNIVERSITY OF NEW SOUTH WALES
School of Engineering, PO Box 1
Kensington, NSW, Australia 2033
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SPIRE CORPORATION
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WONG, KING S.
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PEKING UNIVERSITY
Beiging, China
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Y

YAMAYA, YOSHIAKI
OPTOELECTRONIC IND. & TECH. DEV. ASSN.
2-7-4, Nishi-Shimbashi, Minato-ku
Tokyo, Japan 105
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LABORATORY CO., LTD.
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Tokyo, Japan 157
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YASUHIRO, MAZDA
HOXAN RES. LABS, HOXAN CORPORATION
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Sapporo, Japan 003
011/823-0252

YATES, DOUGLAS
MOBIL SOLAR
16 Hickory Drive
Waltham, MA 02254
617/890-0909

YOKOHAMA, HIROSHI
THE JAPAN ELECTRICAL MANF. ASSN.
4-15, 2-chome, Nagatacho
Chiyoda-ku, Tokyo, Japan 100
03/581-0391

YUKIHIRO, TAKEDA
CENTRAL RES. INSTITUTE.
OF ELECT. POWER IND.
2-11-1, Iwato-kita, Komae-shi
Tokyo, Japan 201

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