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Advances in Materials Technology: MONITOR

Issue Number 9 1987/2

Dear Reader,

This is the ninth issue of UNIDO's state-of-the-art series in the field of materials entitled Advances in Materials Technology: Monitor. This issue is devoted to SOLAR CELLS MATERIALS and is addressed to a select target audience of policy makers, scientists, technologists and industrialists in developing countries.

In each issue of this series, a selected material or group of materials will be featured and an expert assessment made on the technological trends in those fields. In addition, other relevant information of interest to developing countries will be provided. In this manner, over a cycle of several issues, materials relevant to developing countries could be covered and a state-of-the-art assessment made.

This issue on SOLAR CELLS MATERIALS contains information on UNIDO's workshop on the establishment of a Consultative Group on Solar Energy Research and Applications (COSERA). Several papers on SOLAR CELLS MATERIALS were prepared for that workshop. An overview of these articles is provided in an article "Solar Cells - Materials and Production" speciallly written for this Monitor by Mr. T.J. Coutts, Principal Scientist of the Solar Energy Research Institute in Golden, Colorado, USA. In addition, his paper on "A Review of Economic and Technological Requirements of Solar Cells: Status and Research Directions of Polycrystalline Thin-Film Devices" is also published.

The other articles in this Monitor are "State-of-the-Art in Photovoltaic Research and Application", which gives a review of the state-of-the-art of single and polycrystalline solar cells and "Volts from the Blue" referring to the development and cost of thin-film photovoltaic cells.

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The current awareness section includes again information on new products, new processes and applications. This is followed by information on marketing. Readers will also find useful lists of Solar-Photovoltaics and Solar Materials Research Institutes in developing and developed countries and of United Nations and other organizations which are active in the field of Solar-Photovoltaics.

The "face" of our Monitor will change in the future, which hopefully will help our readers to distinguish more easily the Advances in Materials Technology: Monitor from our other Monitors. Our "Dear Reader" will then move on to the second page, together with comments and suggestions from readers. Already with our last issue we have omitted the date and instead put the year and the number of the quarter.

At this point we would like to emphasize our appreciation for all your comments and suggestions that we receive from our readers. We always welcome them and your news on developments of new materials.

Department for Industrial Promotion,
Consultations and Technology

CONTENTS

STATE-OF-THE-ART IN PHOTOVOLTAIC RESEARCH AND APPLICATION

1. Introduction

The photovoltaic effect, known in semiconductors for more than a century [1], became of interest for commercial solar energy conversion with the invention of the higher efficiency (6 per cent) Si and CdS/Cu_2S solar cells [2,3] in 1954 and their first successful deployment in satellites, starting with Vanguard I in 1957. This was followed in rapid succession with larger and larger multi kW-panels, made mostly from Si single crystals with typically ~10 per cent panel efficiency, which was reached in 1963 and maintained for the next decade with best cell efficiencies near 12 per cent and production cost [4] dropping from > \$500 W^{-1} in 1958 to ~100\$ W^{-1} in 1971.

At that time there was little commercial interest except for a modest space programme market of < 100 kWy^{-1}. The only other solar cell materials with promise were single crystal GaAs of slightly higher efficiency flown by some USSR space crafts and the CdS/Cu_2S polycrystalline thin-film cell, further developed by the Clevite-group [5]. A more extensive commericial use except for use in concentrators of GaAs was impeded since it is substantially more expensive than Si. The initial development of CdS/Cu_2S was discontinued because of incomplete understanding of cell degradation and suspected efficiency limitation near 10 per cent.

As a result of comprehensive studies sponsored by NSF and NASA and by the National Academy of Science, it became evident in 1972 that a substantial reduction in production cost to approach \$1 W^{-1} and an increase of efficiencies beyond 10 per cent for thin-film and beyond 20 per cent for single crystal cells were feasible [6]. With significant government support mainly in the USA, Japan and Western Europe, rapid progress was made and essentially all technical goals set in 1972 have been achieved and surpassed (thin-film efficiency 12 per cent, single crystal AM1 efficiency 21 per cent for Si and AlGaAs) [7]. The economic goal seems to be within reach and large quantity solar panels currently sell for ~ \$5 W^{-1}. Life expectancies of better Si-panels are well in excess of 10 years.

Further conservative projections suggest single crystal efficiencies in excess of 25 per cent, thin-film efficiencies > 15 per cent, life expectancies > 25 years (for single crystal cells) and production cost well below \$2 W^{-1} for single crystal panels and well below \$1 W^{-1} for thin-film panels in 1985 dollars.

This gives photovoltaic large-scale terrestrial solar energy conversion a realistic potential beyond the presently already available markets, which have absorbed in excess of 50 MW and produced revenues in excess of \$1 billion during the last five years.

In the following sections we will list the recent achievements in R&D for the different types of solar cells and panels, review present production methods, and give a short overview of deployment experience and future markets.

2. Solar cell types and materials

The photovoltaic effect in modern solar cells is based on the separation of excess carriers in the built-in field of a junction within a semi-conductor. The excess (over thermal equilibrium) carriers are created by absorbed sunlight. Their separation creates a photo-emf which makes the solar cell act like a battery and permits, through an external circuit, the extraction of almost all of these excess carriers (the collection efficiency approaches 1 in better cells).

Different cell types can be distinguished by:

(i) How the built-in field is established (homo- or heterojunctions, or Schottky barriers);

(ii) How the light is absorbed (direct or indirect band gap materials);

(iii) The type of the cell design (front- or back-wall, or multijunction cells); and

(iv) The crystal state of the device (single or polycrystalline, or amorphous).

Presently there is no clear-cut preference of the large variety of possible devices, except for properly chosen band gap 1/ (see figure 1), since there are economic trade-offs and new candidates may be found with promising futures. Examples are the $CdS/CuInSe_2$ cell, which now shows best efficiencies near 12 per cent, and the CdTe cell with efficiencies in excess of 10 per cent; yet both cells were unknown 2/ only a decade ago. However, the large amount of material research necessary before one can hope to optimize material treatment and cell design is in essence an economic barrier for rapid expansion. Therefore the first promising candidate, single crystal Si, is still the forerunner in technology development and has the largest market share.

2.1 Single crystal Si solar cells

Silicon is an indirect band-gap material requiring a relatively thick (typically 0.2 mm) cell to absorb most of the active light in the solar spectrum. The geometry and band model of a typical n^+pp^+-Si solar cells is shown in figure 2. By increasing the minority carrier diffusion length to values well in excess of the cell thickness and reducing recombination at the back contact by using a back surface field (using an Al back contact with Al-diffusion into a thin layer during a 15 minute heat treatment at 500-800°C) one obtains cells efficiences of typically 14 per cent [12]. By reducing the thickness of the front n^+-layer and the density of recombination centers there and in the p-n junction, the blue/violet response was raised and the efficiency improved beyond 15 per cent [13]. Further substantial improvements of the current were achieved by etching the front surface to reduce reflectivity (velvet effect [14]) with efficiencies in excess of 17 per cent. After almost a decade with little further progress, Green and co-workers [15] have pushed the efficiency of the single crystal Si-cell well above 20 per cent by further reducing the recombination at the front surface (by introducing a thermally grown SiO_2 layer

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1/ It should be noted that the presently achieved highest efficiency of Si solar cells is substantially higher than the 19 per cent predicted from an obviously too conservative model by Loferski in 1956. Better recent estimates by Wolf [9] put this maximum efficiency for Si to 22 per cent and efficiencies in excess of 28 per cent for AM1 have been suggested more recently [10].

2/ A forerunner of this cell, the $CdTe/Cu_2Te$ cell, however, was already noted by Cusano [22] in 1963 and achieved efficiencies in excess of 7 per cent at that time.

(figure 3A)], by separating the front electrode through a thin SiO_2 layer (figure 3B), or by reducing the contact surface through such a layer (figure 3C), thereby increasing the open circuit voltage to 694 mV (AMO, 25°C). When surface etching is also applied to reduce reflection, Green [15] achieved 20.9 per cent efficiency at AM1 with indication that still higher efficiencies can be expected realistically.

2.1.1 Si-material [8]. Presently there are two trends discernible: to develop and produce low-cost raw Si material which is useful for cells with modest efficiency (in the 10-16 per cent range), and to develop ultra-high efficiency devices irrespective of the present cost of the raw material; however, assuming that a reasonable modification of the material production process could yield the necessary material without adding significantly to the cost.

At this time semiconductor-grade Si is used to produce Si-solar cells. This Si is made by the Siemens process in a quantity of a few thousand metric tons y 1/ at a price in excess of \$70 kg^{-1}. Several alternative processes have been studied, capable of producing solar grade Si (a material with slightly higher impurity concentration, but capable of yielding modest efficiency solar cells) at a cost of less than \$20 kg^{-1}.

One of the processes is based on Silane rectification and is already developed through pilot (100 mt y^{-1}) and production plant (1200 mt y^{-1}) by the Union Carbide Corp. Another 1200 mt y^{-1} plant is in construction and a 3000 mt y^{-1} plant is in design. The flow diagram of the Silane process is shown in figure 2; it is capable of producing solar cell grade silicon at a cost below \$20 kg^{-1}.

The rationale behind the development of solar grade silicon is the insensitivity of medium efficiency solar cells ('baseline' cell) in respect to some typical impurities. Figure 3 indicates that certain impurities, e.g. Cu and Al in n-type and P and Cu in p-type material, can be tolerated in excess of 1 ppm without major cell degradation. Other elements have to be avoided more carefully (e.g. transition metals).

It is expected that solar grade Si will become available in the near future and, because of the lower production cost, price flexibility can be expected in due course.

2.1.2 Si crystal/sheet growth. 2/ Substantial reduction in production cost can be achieved by improving the single crystal growth process. For instance, in an advanced Czochralski growth system of the Hamco Division of the Kayex Corporation, automated growth from 150 kg ingot/crucible with 2.2 kg h^{-1} throughput 15 cm rods can be produced, yielding 15 per cent efficient solar cells. A further cost reduction can be achieved by using polycrystalline Si for solar cells, which show moderate efficiencies in the 8-15 per cent range (typical 10 per cent for large quantities) when the grain size exceeds a few mm diameter and grain boundaries are appropriately passivated (usually by H_2 treatment). Examples are the ingot casting by Semix, Inc. and the ingot-casting-by-a-heat-exchanger method of Crystal Systems, Inc. Both methods are capable of producing up to 15 per cent efficient solar cells. The Semix process presently produces 20 x 20 x 15 cm^3 semicrystalline blocks with 83 per cent ingot yield at 2.3 kg h^{-1}. The Crystal Systems process produces slightly larger blocks of 34x34x17 cm^3 which are $>$ 95 per cent single crystal at 1.9 kg h^{-1} with $>$95 per cent yield.

Process variability, non-uniformity of grains, and non-uniformity of impurities still influence adversely the yield of cells with acceptable efficiencies from polycrystalline material.

All of these rods or blocks needs to be sawed into thin wafers. Several methods are presently being developed. The best present achievements are a slicing of 17 wafers from a 15 cm rod and 20 wafers from a 10 x 10 cm^2 cast block per cm length at a rate of 0.4 and 1.2 wafer min^{-1} respectively at 95 per cent yield. The finished wafer area per kilogram of ingot is 0.7 and 1.0 m^2 kg^{-1} respectively. Surface damage and resulting losses from the necessary etching to remove these damaged layers are additional cost factors which present a handicap to the above listed methods.

Major advances can be achieved by direct growth of Si-sheets. Several methods to produce such sheets are being developed; some results are available in the open literature and are listed below. The edge-defined film-fed ribbon growth developed by the Mobil Solar Energy Corp. has achieved a respectable 40 cm^2 min^{-1} growth of 10 cm wide ribbon. Simultaneous multi-ribbon growth of three ribbons at 10 cm width or five ribbons at 5 cm width with 0.15 mm ribbon thickness and yield 80 per cent cells with $>$12 per cent efficiency. More recently a nonagon growth technique was developed in which a hollow, polygonal shaped tube of 150 mm diameter is grown with nine flat sides, each one 50 mm wide and 0.3 mm thick, and later cut into rectangular blanks.

The dendritic web growth developed by the Westinghouse Corp. can produce 13 cm^3 min^{-1} for short ribbon lengths, which yield somewhat higher efficiencies (best achieved: 16.9 per cent).

A Si-on-ceramic pick-up from a liquid surface developed by Honeywell produces 60 cm^3 min^{-1} growth rate with sheets of $<$0.1 mm thickness and cell efficiencies of 10.5 per cent.

Still another method is being developed by the Energy Materials Corp., in which a crystal sheet is picked up from the meniscus of a Si melt and which has achieved a much larger throughput of 450 cm^2 min^{-1}, but at a larger ribbon thickness of 0.64 mm (pull speed 85 cm min^{-1}) and ribbon width of 15 cm. Best cell efficiency is 12.9 per cent.

Other methods are vigorously being developed and judged promising by the involved industry. It can be expected that with further research and development an improved production reliability (acceptable yield) can be achieved and increased efficiencies in the 17(+) per cent range can be obtained.

2.1.3 Cell and panel production. Cell and panel production contains a large number of steps which add costs and reduce overall yields. Streamlining (reduction in steps) and automation are being developed. A typical example is given in figure 4 for the conventional and a more advanced production sequence containing some cost estimates in 1980 dollars.

Recent advances are related to the goal of improving the metallization and overall process yield. They also include further improvement in liquid-dopant processing and thermal pulse diffusion

1/ At an estimated use of 5 metric tons MW^{-1}, a substantial fraction of this production would be needed for solar cells in 1986 with a projected production rate of 50 MWy^{-1} world wide.

2/ Examples listed here contain only material available in the open literature.

to produce simultaneously the n-p and $p-p^+$ junctions. Laser annealing of ion implanted dopants and microwave powered plasma systems are used, the latter to passivate (SiO_2) and to produce antireflective coating (SiN). New means to produce the top electrode, including laser pyrolysis of metallo-organic liquid films at the cell surface and printing with newly developed inks (e.g. Mo-Sn) are being developed (narrowest linewidth 3μm). New interconnecting automatic equipment using ultrasound is employed. Double chamber vacuum lamination is used. Further development of automation in cell production is in progress.

A 'Strawman' process analysis predicts feasibility of a \$2 W^{-1} low-cost cell and module fabrication, and, when fully automated, a possible \$0.70 W^{-1} cost (in 1985 dollars).

The updated goals established in 1983 of high efficiency 15 per cent Si modules at a cost of \$90 m^{-2} with 30 years deployed panel life seem to be realistic, although not without additional substantial effort in research and development, but not requiring a technology breakthrough.

The trend in the development of commercially available Si-solar cell panels is shown in figure 5 which clearly show the major advances achieved during the last decade, most significantly in sales price from an average of \$30 W^{-1} in 1975 to \$5 W^{-1} in 1985 (all in 1980 dollars), module efficiency (edge to edge) from 6 to 10 per cent average, and packing factor from 55 to 85 per cent. Significant further progress is expected when high efficiency cells will be used for production units, boosting the present average 11 per cent encapsulated cell efficiency potentially well above 15 per cent.

2.2 The amorphous Si-cell

A substantial improvement of the cost efficiency of solar cells is expected by using amorphous, hydrogenated, or fluorinated Si as the active cell material [20,21]. It has a much steeper optical absorption edge (behaving like a direct band-gap material) at an energy ($\sim$1.4 eV) better matched to the optical spectrum of sunlight, as shown in figure 6.

The material can be easily deposited on a large variety of material acting as the base electrode. The deposition is done in a gas discharge and permits via changes in the gas composition a rather simple change in doping and chemical composition of the deposited layer. It requires typical deposition temperatures of 200-300°C, i.e. temperatures which are low enough for the use of inexpensive substrates. The band gap can be changed between $\sim$1 and 2.8 eV by changing the host material from Si to SiC, SiGe or SiSn, using mixtures of silane and methane, GeH_4 or $Sn(CH_3)_4$, or similar fluorinated compounds with possibilities to produce stacked cells or window layers with relative ease.

Only 10 years ago the use of amorphous Si of efficient ($>$6 per cent) solar cells was shown by Carlson and Wronski [23]. Consequently, the development of such cells proceeded rapidly (figure 7).

The material can be made n- and p-type by doping similarly to crystalline Si. However, the α-Si solar cell is distinguished by several principal features from the crystalline Si cell:

(i) It is about 1000 times thinner since its absorption coefficient is substantially higher;

(ii) Its main region of generating minority carriers contains a substantial electric field ($\sim 10^4$ V cm^{-1}) to assist collection;

(iii) Its band gap lies closer to the optimum value (near 1.5 eV) for solar energy conversion;

(iv) The carrier mobility is $\lesssim 1$ cm^2 Vs^{-1}, i.e. only $\sim$1/1000 of the carrier mobility in crystalline Si; and

(v) There is cell degradation which requires careful development of commercially viable solar cell panels.

2.2.1 Production of α-Si cells, economical aspects.

The production of the α-Si cell as a thin-film cell is insensitive to substrate structure and can be fully automated. A typical cell cross-section is shown in figure 8.

Using a variety of substrates, from stainless steel to polymide films [36] to hybridization on already formed units such as roof shingles, has the potential to reduce the balance of system cost to highly attractive levels.

Present operation of production lines in several companies has entered a learning curve which promises a high probablity for full-scale commercialization after freezing of an attractive long-life-expectancy cell design with a reasonable efficiency ($\sim$10 per cent).

It is therefore expected that the α-Si cell production line will swiftly expand from the present consumer application market to the larger scale solar market which is presently dominated by the crystalline Si solar panels.

It is also expected that the production cost of these solar cells can be reduced to below \$0.55 W^{-1} (1985 dollars).

2.3 Other promising solar cells

It is too early to judge whether the inherent limitation in the present generation of Si crystalline and amorphous Si cells justifies vigorous further development of alternative materials. These limitations relate to:

(i) A too-low band gap in Si, limiting its maximum efficiency;

(ii) The indirect gap optical absorption, requiring a rather thick crystal sheet of Si;

(iii) The low mobility of both carriers in α-Si; and

(iv) Photochemical reactions at room temperature in α-Si.

Other materials, such as GaAs and CdTe, have advantages in respect to the above listed limitations, suggesting the potential of higher efficiencies and extensive life expectancy. However, both compounds contain elements of very limited supply (Ga and Te).

Present development of GaAs is justified since it can be operated at higher temperatures and high light intensity, making the cell attractive as a receiver in concentrators with concentration ratios up to 1000 (Varian). A cost comparison [38] shows that such GaAs cells with an efficiency of 25 per cent can cost between \$3.50 and \$10 per cm^2 to support an array cost of \$1.30 W^{-1}, while for the same array cost the price of Si concentrator cells of 20 per cent efficiency must be reduced by a factor of 12 below the above-projected cost for GaAs. The present state of the art permits an installed array field subsystem, cost near \$7/W with approximately 17 per cent of the subsystem cost allocated for the solar cell [38].

The highest presently achieved efficiency for single Mg-doped AlGaAs/GaAs cell is reported by Hamaker et al. [39] at 26 per cent in a concentrator deployment.

The development of thin-film GaAs is another possibility if surface and grain boundary passivation can be achieved. A high recombination velocity at these surfaces is a major drawback of the GaAs which is circumnavigated by using an AlGaAs window in highly efficient single crystal cells. Presently the thin-film polycrystalline cell has a disappointingly low efficiency while thin film single crystal cells still require GaAs substrate (epitaxy), yielding 20 per cent efficient cells or, being thinned by etching, require a thickness of $\sim 70 \mu m$ with efficiencies in the 16 per cent range.

A potentially interesting approach is a process known as CLEFT (cleavage for lateral epitaxial film transfer). Here lateral growth on a properly oriented, mostly masked GaAs substrate can be used to form GaAs single crystal sheets which can easily be cleaved from the substrate (figure 9) after it is bonded to glass, and cells of 17 per cent efficiency with only $5 \mu m$ thickness have been produced [40].

As a direct band-gap material with a high electron mobility, the material has sufficient potential to warrant further research and development (see Proceedings of the 18th IEEE Photovoltaic Specialist Conference).

The CdTe solar cell is another, potentially highly efficient cell which, as a single crystal cell, has already shown in excess of 13 per cent efficiency. The Kodak group has reported 10.9 per cent efficiency for a polycrystalline thin-film CdS/CdTe device at AM2 while, for a slightly thicker, sintered CdS/CdTe, heterojunction cell, the Matsushita group [44] reports an active area efficiency of 12.8 per cent.

Problems with a rapid development of this cell relate to difficulties to make a highly p-type material and to produce good ohmic contacts on the p-CdTe.

Other possibilities include heterojunction cells, such as $CdS/CuInSe_2$. Such a cell was developed by Michelson et al. at Boeing Aerospace Co. and yielded 11 per cent conversion efficiency. It is deposited by evaporation of the components in a multi-layer thin-film structure (figure 10).

This structure has the potential of obtaining cell efficiencies in excess of 15 per cent and excellent long-term stability [42].

Finally, the trend to develop higher efficient cells has sparked several research efforts to stack cells of different band gaps on top of each other with the goal of approaching 30 per cent conversion efficiencies. Even though the net benefit from the added cell is expected to be of the order of only 10 per cent, savings in the deployment structure could make the effort cost-effective. Careful matching of currents limit a two terminal device in material selection. Four terminal devices are more flexible in design and may be more promising to surpass single cell efficiences.

Stacking of AlGaAs/GaAs on top of Si has resulted in 22 per cent conversion efficiency. The progress is slow as the combination of two cells poses many technological problems due to interrelation of treatments [43].

2.4 Commercial markets of solar panels

As the first introduced commercially available solar panels, the Si panels have become the panels with by far the largest share of present deployment. Below we will list a number of examples of such deployment.

The market developed rapidly from only a few kW deployed in 1974 to shipments of more than 25 MW in 1984 with the following distributions:

Remote deployment	8 MW
Consumer products	7 MW
Utility grid power	5 MW
Off-grid power	3 MW
Government use	2 MW

Presently a total in excess of 100 MW of Si-solar cell panels are installed, providing ample experience of marketability and performance and offering the basis for a broader public awareness.

Most economical today is the use in remote areas where previously batteries or diesel-powered generators were employed.

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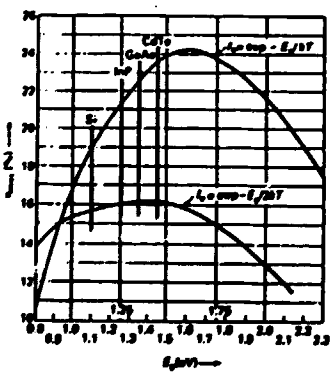


Fig. 1. Theoretical maximum solar cell efficiency as function of the band gap after Loferski [8].

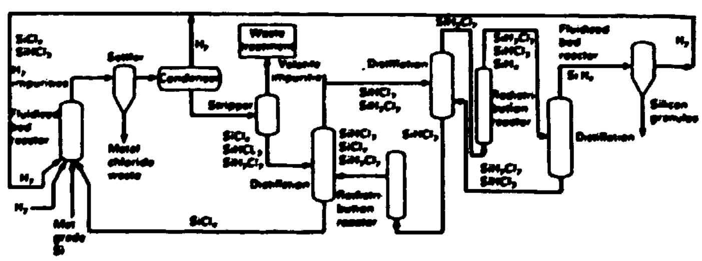


Fig. 2. Union Carbide silane process flow diagram.

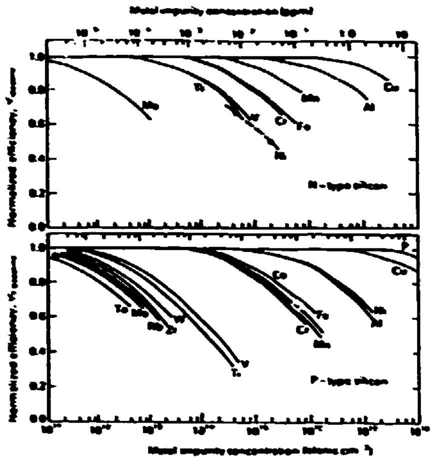


Fig. 3 Sensitivity of the relative cell efficiency in respect to concentration of typical impurities in n- and p-type materials used in cell production.

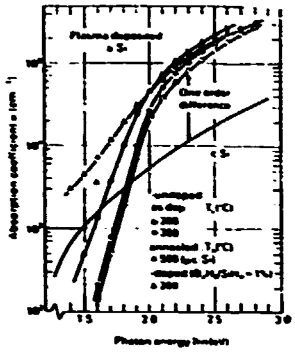
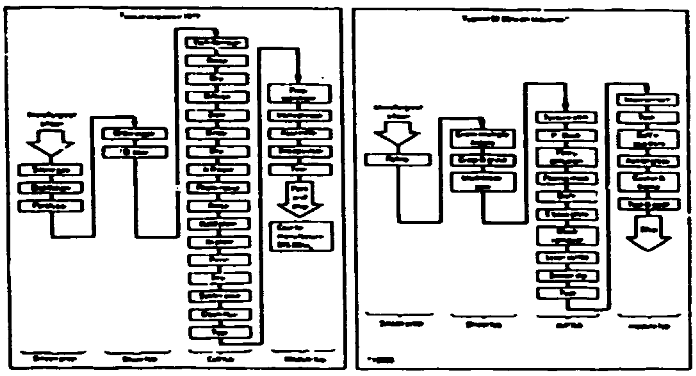


Fig. 6 Optical absorption coefficient of a-Si in comparison with microcrystalline and single crystal Si after Hamakawa [19]



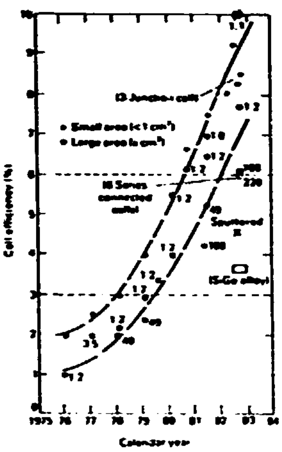


Fig. 7 Development of the a-Si solar cell during the last 10 years

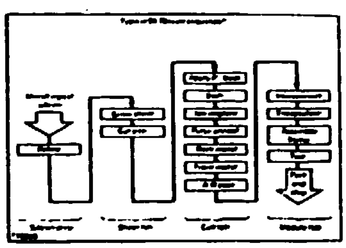


Fig. 4 Solar cell and module production process sequences.

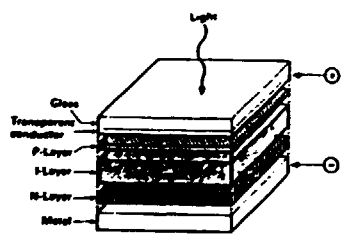


Fig. 8 Cross-section through a typical a-Si solar cell

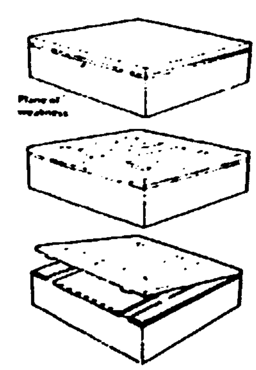


Fig. 9 Schematic diagram of the CLEFT process illustrating the separation of the thin top all from its reusable substrate after Fan et al [20]

State-of-the-art in photovoltaic research

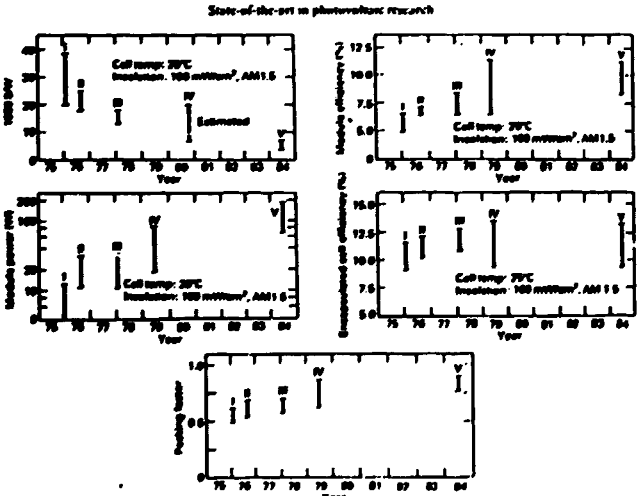


Fig. 5 Development trend of commercial Si solar cell panels during the last decade

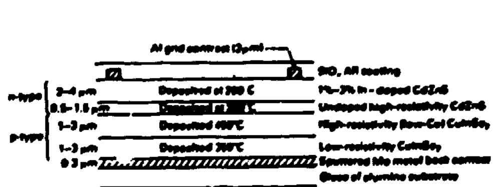


Fig. 10 CdS-CuInSe solar cell structure developed by Boeing

Consultative group on solar energy research to be set up by UNIDO

Eleven experts representing developed and developing countries met at UNIDO from 8-10 December 1986 to consider the establishment of a Consultative Group on Solar Energy Research and Application (COSERA).

COSERA is being set up to promote the effectiveness of solar energy research in developing countries and the transfer of research results into industrial production, commercialization and widespread use. The experts met at a workshop intended as a preliminary activity to widen consultations with donor agencies and institutions in developing countries.

In a world where energy resources are fast becoming scarce, solar energy is renewable, abundant and widely available in developing and developed countries.

Several initiatives have been made at the regional level, and there has been some measure of international co-operation, a good deal of it by other international bodies, but there is still a lack of concerted effort at the global level, in particular in strengthening the technological capabilities of developing countries for energy research and applications, eventually leading to local manufacture. It is for this reason that the Consultative Group is to be established.

Recommendations. The experts envisage COSERA as an institutional group of scientific establishments, donor organizations and financing agencies interested in harnessing solar energy for development needs in various parts of the world. COSERA would act as the catalyst that will co-ordinate the efforts of the many institutions throughout the world.

As part of its first phase of operation, the expert meeting recommended that COSERA should:

- Assist in setting up and strengthening links between the interested parties, such as donor agencies, Governments, industry, scientists and citizen groups;
- Ensure the smooth flow of funds and mobilize more funds for the most promising activities in the field;
- Promote closer integration of the results of solar energy research, development and applications in the energy plans of countries or regions;
- Strengthen national capabilities at all levels (e.g. decision makers, planners, scientists, industrialists, the public) in harnessing solar energy effectively for specific national needs.

The meeting stressed that it was important, at the present stage, for COSERA to be project-oriented. It should consider proposals for recommendation to funding agencies as well as propose projects that it considers to have high priority to interested parties.

Once COSERA has been established, it could move into other phases, the experts pointed out. These could include:

- Supporting training and labour development;
- Setting up and strengthening mechanisms to exchange experiences and information;
- Providing support for the publication of directories, guidebooks and information on commercially exploitable technologies;
- Setting up and strengthening existing centres at regional and international levels.

The experts pointed out that COSERA would not be an intergovernmental body, nor would it "dictate" what needs to be done. Its main purpose would be to harmonize action on solar energy and to function with a minimum of legal or bureaucratic constraints.

The experts recommended that UNIDO should take the necessary follow-up action through a task force and organize a meeting before the end of 1987 in order to establish COSERA.

Finally, the experts stressed that the widespread use of solar thermal technologies will enable developing countries to reduce their dependence on imported fossil fuels, to improve their balance-of-trade situation substantially and to maintain the health of their environment.

* * *

The following article on solar cells materials and production was prepared by Mr. T.J. Coutts* specially for this issue of the Advances in Materials Technology: Monitor. We publish it together with the paper written by the same author: "A review of economic and technological requirements of solar cells: status and research directions of polycrystalline thin film devices". This paper as well as two more** discussed in Mr. T.J. Coutts' article were used as the background material for the UNIDO Workshop on the Establishment of a Consultative Group on Solar Energy Research and Applications/COSERA. Due to limited space we are not in a position to publish these documents but hope that Mr. Coutts' article will provide you with some information on their gist. Copies of the two documents may, however, be obtained on request.

Solar cells - materials and production

At present, the group IV semiconductor Si is by far the most widely researched material in the electronics industry. It is also the material with which by far the most experience has been gained in the field of photovoltaics. However, there are sound fundamental reasons to suppose that Si would not be an ideal material for photovoltaic (PV) conversion. That it is so widely used is due solely to the fact that such a wealth of experience and knowledge from the electronics industry is available. The extremely

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"A review of economic and technological requirements of solar cells: status and research directions of polycrystalline thin film devices", Doc. No.: UNIDO/IPCT.16(SPEC.)

** "Solar cell materials and fabrication technologies" by K.W. Böer, Professor, University of Delaware, Newark, DE 19716, USA.
Doc. No.: UNIDO/IPCT.19(SPEC.) Please also refer to Mr. Böhr's article "State-of-the-art in photovoltaic research and application" on pages 3-6.

"Study on amorphous silicon solar cells" by Arun Madan, GlastechSolar Inc., 12441 W. 49th Avenue, Wheat Ridge, CO. 80033, USA.
Doc. No.: UNIDO/IPCT.18(SPEC.)

high purity and crystalline perfection of modern Si mean that solar cells based on Si are still amongst the highest efficiency converters of any material used. All of this explains why more operating experience has been gained with single crystal Si than with all other solar cell materials combined.

In addition to all of this, it is a plentiful material and the reserves for its refinement are never likely to become exhausted. However, it is not without problems. From the perspective of a developed country, it is obvious that the driving force behind the development of any alternative means of generating electricity is cost competitiveness. Although there are many rural or remote environments in which Si-based PV generators are economically attractive in comparison with diesel generators or grid line extensions, for expansion into the potentially larger domestic market it is necessary that the price drops to around \$40-75/m^2. For modules with a conversion efficiency of optical to electrical energy around 13-17 per cent this would imply and electricity cost of about 6.5¢/kWh (expressed in 1982 dollars). It is highly improbable that modules based on single crystal Si solar cells will ever achieve the target cost, so despite their attributes, it follows that the future of PV in the industrialized countries must depend on alternative cheaper materials and lower cost production techniques. In the three key papers in this issue (by Coutts, Böer and Madan), these aspects are discussed in greater detail.

From the perspective of a developing country, the driving force is still essentially economic but is more subtle. Shortage of capital can, in many cases, introduce an extra option beyond simple cost comparisons; that is, not to purchase any electricity generating system. Since this would mean tolerating a lower quality of life than would be the case with electrification, it is clearly an undesirable option.

We shall see that the alternative materials are all to be used in thin film form. For the developed countries, this implies lower materials and production costs than for single crystal Si. For the developing countries, although these factors are important, an additional consideration is that the production of these devices relies on relatively low-level technology which implies that the need to import is obviated. Hence, if PV is to be used extensively in these countries, one would expect those devices based on thin films to have the greatest potential. It is these which will be the subject of this edition. In the first paper, Böer reviews the properties required of solar cell materials from a physical basis. In the second, Coutts discusses in more detail the economic arguments in favour of thin film polycrystalline solar cells, reviews fabrication methods and their technical status, and indicates problem areas and research directions for the future. In the third paper, Madan presents the case for α-Si:H based solar cells, the third key option of the thin film devices. For the reader who does not wish to proceed beyond this introduction, I shall now try to present a précis of each of these three papers.

Böer's paper begins with an historical background of solar cells which commercially begins with their use in satellites. Although the devices have been used in this context very successfully for many years the problems with regard to terrestrial application are much more severe. Although a solar cell is simply a large area diode and elementary solid state theory is capable of explaining many key features of performance, more elegant theories are required to explain certain non-intuitive aspects of their behaviour. Professor Böer spends some time in discussing the numerical techniques he has developed to solve the transport, continuity and Poisson equations which, at the fundamental level, truly explain the underlying physics. The non-specialist reader may be somewhat overawed by this approach and may wish to concentrate on the sections preceeding and following the theoretical section. The performance of the modern generation of single crystal Si cells is then discussed, and the value of modern efficiency-enhancing techniques such as minority carrier mirrors, surface texturing and shaped collector grids, is explained. The sequence of processes in the preparation of semiconductor grade single crystal Si is then presented. As already indicated, it may be that cells based on single crystal Si will be too expensive for large-scale utilization in developing countries (a point made by all three contributors to this special issue). Böer discusses briefly the potential of cells based on amorphous Si which should probably be of much greater interest to developing countries. There are, however, problems of degradation of efficiency (the well-known Staebler-Wronski effect) and these must be solved before α-Si cells are used in large volume. To date, this problem has proven somewhat obdurate. Of special interest to a number of readers will be Böer's information on US Government-sponsored research, and on various partnerships between Government and industry. The author then touches briefly on cells based on GaAs (less relevant to developing countries), CdTe and $CuInSe_2$. The latter two of these are discussed in greater detail in the second of these three papers. Finally, Professor Böer gives details of markets and break-even costs in the USA. Although this information may be of general interest to the reader, as pointed out earlier, simple economics are not relevant in the context of developing countries.

In the next paper, Coutts discusses the two polycrystalline solar cells based on $CuInSe_2$ and CdTe. These are two of the thin film cells (the third being α-Si:H) which are being vigorously pursued in the USA. The paper begins with a discussion of the economic arguments relating to these devices but the author concludes that there are too many uncertain inputs to the cost/benefit formulations to lend the results real credence. International and political changes alone can radically affect these calculations. However, the general feeling regarding the attainment of cost targets is optimistic for thin film cells. It is also pointed out that minerals limitations may be the most severe constraint on the large-scale production of $CuInSe_2$ and CdTe cells. This of course will never be the problem with α-Si:H cells. In general, however, the author concludes that the most important aspects of economics are cell efficiency, large area high throughput manufacturing capability, and cell stability. Each of the subsequent sections of the paper considers these in some detail. The requirements for efficient photovoltaic conversion are discussed in general terms, and the non-specialist may find this easier to follow than Böer's detailed analysis. This section of the paper also relates to the final section in which problems and future research directions are indicated. It should be remembered that the materials properties required of the semiconductors are rather specific and demanding. That they must be achieved over large areas at a high throughput is even more demanding. Problems of pinholes, non-uniformities in thickness or composition, and structural (i.e., crystallographic) variations, must all be solved. Unfortunately, investigation of these issues requires considerable capital investment which is not available during the present times of budget restrictions. The third area, that of device stability is better understood and, with the two materials considered in this paper, is not an intrinsic problem. Rather, the problems arise due to degradation of external contacts and of the cell encapsulation. Hence, more attention must be paid to these technological, as opposed to fundamental aspects. This will be particularly true for application in developing countries where environmental conditions can be extreme. Finally the author discusses the major research areas which will be followed in the future.

The final paper of the three deals with the amorphous silicon solar cell which, internationally, probably receives more attention and funding than the other devices. Since these papers have been written independently and have not been collectively edited, there is inevitably some duplication. For example Dr. Madan again stresses the value of thin film cells, and α-Si:H in particular over single crystal Si. However, the points readily bear repetition. A potentially useful feature of this article is the listing of companies actually marketing opto-electronic devices; solar cells in particular.

The basic physics of amorphous semiconductors is discussed at an elementary level, which will probably be appreciated by the non-specialist. The concepts of "mobility edge" and dangling bonds are introduced; these are fundamental concepts of immediate relevance. Dangling bonds reduce the quality of α-Si and the realization that the incorporation of hydrogen can ameliorate the problem, represents one of the major advances in this area. In fact, so much hydrogen is needed that the films are regarded as a Si:H alloy. Films of the latter are usually, but not always, produced by glow discharge decomposition of SiH_4 (Silane) and the two conductivity types achieved by adding PH_3 (phosphine, for n-type) or B_2H_6 (diborane, for p-type). In this way p-n junctions can be fabricated. However, the physics of these devices is still more complicated than crystalline silicon and there is still a severe lack of knowledge regarding loss mechanisms, and this makes predictions of maximum efficiency somewhat uncertain. However, a probable upper limit would seem to be about 18 per cent. Although the incorporation of hydrogen greatly improves the materials properties, these are still poor by comparison with crystalline Si. This means that p-n junctions with good diode behaviour (we remind the reader that a solar cell is merely a photo-active diode) cannot be made. Hence it is necessary to incorporate an intrinsic layer (i-layer) between the p- and n- layers. This realization is central to the achievement of efficiencies greater than 10 per cent, now routine at laboratories throughout the world. Madan then discusses the possible increases in efficiency which may result from tandem or cascade cells. In these, two or more cells are stacked upon each other. Each cell responds best to particular parts of the spectrum and, in principle, high efficiencies can result. For example, 18 per cent conversion efficiency is anticipated within the next three years. As regards fundamental issues, that of device stability is of predominant importance. This aspect is being vigorously addressed worldwide and it may be that the entire future of these devices depends upon solving the degradation problem. Madan then discusses various mass production techniques and gives illustrations of these. To the credit of the industry module efficiencies greater than 6 per cent have now been achieved.

Future trends are finally indicated and the number of novel ideas suggests that this topic will remain lively for many years.

Conclusion

The three papers reviewed here should be sufficient to convince even the most cursory reader that the field of photovoltaics has the widest possible range of subject interests. Aspects from fundamental solid state physics and chemistry, to the economics and politics of mineral reserves need to be considered. This diversity has ensured my continued interest over 15 years and I see the future as being, if anything, even more interesting and challenging. It is hoped that this review will stimulate a similar enthusiasm amongst non-specialist readers, who may well be able to influence future research, development and applications of photovoltaics.

The comments and opinions expressed in this article are those of the author and do not necessarily represent the views of his employers (The Solar Energy Research Institute), The Midwest Research Institute, nor the US Department of Energy.

A review of economic and technological requirements of solar cells: status and research directions of polycrystalline thin-film devices

For solar cells to make a large impact on the provision of electricity for terrestrial consumption, it seems inevitable that the thin-film device will need to be successfully developed. The relatively high cost of single crystal silicon mitigates against its ever achieving cost competitiveness with conventionally generated electricity, except perhaps in remote areas where the comparison would be with diesel generators. In the medium-term future, it is also possible that systems based on optical concentration of the solar flux onto highly efficient cascade cells utilizing sophisticated ternary and/or quaternary III-V alloy semiconductors will have a substantial impact. Indeed, such systems may well prove to be the long-term preferred option provided that satisfactory solutions can be found to the many fundamental and engineering problems. However, the possible success of the concentrator systems does not exclude other photovoltaic generators unless they prove to have a significant economic advantage. Since we are certainly not presently in a position to demonstrate with any degree of certainty whatsoever that this will prove to be the case, the sensible strategy, for the time being, is to pursue all practicable options. Thin-film polycrystalline solar cells have made significant progress in recent years and three materials combinations have exceeded conversion efficiencies (whenever this term is used, it can be presumed that measurements have been made at 28°C, using the Aml.5 direct spectrum, normalized to $100.mWcm^{-2}$; and under the atmospheric conditions defined in NASA TM 73702 (1) of 10 per cent. The three devices are $CdS/Cu_{2-x}S$, $CdS/CuInSe_2$ and CdS/CdTe; and of these research on the first (at least in the USA) has largely been discontinued because of obdurate problems of stability. Of course, the efficiency of cells based on α-Si:H has also exceeded 10 per cent (2) but these will not be discussed here since it is the intention to concentrate on polycrystalline devices and, in particular, on those based on $CdS/CuInSe_2$ and on CdS/CdTe. In fact, we shall be examining the various criteria for viability of thin-film cells in general but will attempt to illustrate the points by reference to these particular devices. Firstly, we shall examine the overall case for the expenditure of large sums of money on the development of thin-film solar cells in terms of their economic prospects; next we shall discuss what properties are required of the materials and devices; thirdly we shall discuss the present status of $CdS/CuInSe_2$ and CdS/CdTe cells; and finally, we shall point out those problems which presently appear to be the limiting factors and the research directions which are being followed in the hope of overcoming the problems and realizing the objective of technically and economically viable polycrystalline solar cells for large-scale terrestrial utilization.

The economics thin-film solar cells

Thin-film solar cells have several economic strengths and weaknesses which are generally balanced against each other in a costs/benefits analysis to show that the technology either is, or is not, likely to achieve cost-competitiveness with either methods of generating electricity. We shall briefly examine these arguments.

The arguments are usually based on a comparison with the costs associated with the production of single crystal cells. The actual cost of an individual cell depends on a number of factors, some of which can be estimated with reasonable accuracy. For example, having decided on the particular fabrication technique, one might then estimate the throughput of cells (meters^2, per year), the capital cost and lifetime of the equipment, the efficiency of the cells, the labour cost, and whether single or double shift operation would be required. In addition to these more less well-known numbers, would be less tangible factors such as the prevailing discount rate (which is subject to large fluctuations), whether or not the capital was to be borrowed and the duration of the loan, maintenance costs, and the cost of the factory (and whether it would be rented or purchased). Furthermore, the total size of the market and the estimated share likely to be acquired by an individual company, plus their required return on investment, would affect the decision whether or not to compete in the field. Despite these many complicated factors, the claim is usually made that thin-film production techniques are capable of yielding devices at a cost which will ultimately under-cut the cost of electricity generated by silicon solar cells. More important is whether or not the thin-film cells will under-cut the cost of conventionally- or diesel-generated electricity and, again, to predict the cost of energy from these sources at some date in the future is impossible. Previous calculations have often assumed a different rate of inflation of energy to that of money (3), usually the former being assumed greater than the latter. In recent years, the reverse has been the case, and this quirk of international economic forces alone would have been sufficient to spoil many a hitherto promising looking costs/benefits analysis. Possibly even more important than all the above vagaries is the influence of political policy; i.e., grants, tax-credits etc. These can change not only the cost projections but may have the effect of stimulating a market. Although it is perfectly reasonable for a utility company or a consumer to specify what the unit costs should be (because if that figure is not attained, the product, i.e., the electricity, will remain non-competitive) it is much more difficult for a manufacturer, potential or otherwise, to predict with any certainty whether (or when) that target will

Table 1. Principal solar cells under development

Semiconductor(s) involved	Type of cell	Rare element	Density (Kgm m^{-3})	Approximate maximum efficiency	Mass of rare element required per GWp per m thickness (tonnes)	Mode of Operation
Si	single crystal		2200	20	20.7	Flat plate or low concentration
	amorphous thin-film			11	12.0	
CdS/Cu_2S	thin-film	Cd	8650	10	60.6	Flat plat
CdS/InP	single crystal	Cd and InP	8650	15	62.8	Only feasible with concentration
	all thin film	In	7310	5	57.6	
ITO*/InP	single crystal InP, thin film ITO	In	7310	16	50.4	Only feasible with concentration
$CdS/CuInSe_2$	thin-film	Cd In Se	8650 7310	11	36.7 13.6 12.3	Flat plate
CdS/CdTe	thin-film	Cd Te	8650 6240	11	58.8 18.1	Flat plate
$GaAs/Ga_xAl_{1-x}As$**	single crystal thin-film	Ga	6095	23 5	37.1	Very high concentration flat plate

* ITO = Indium tin oxide (0.2 m thickness film, 200 m thickness crystal assumed).

** x taken as 0.2.

be achieved. Despite these cautionary comments, there are many examples of low-cost, large volume thin-film production lines, and it seems more likely than not that the target figures based on the economic constraints will be achieved. If there is a limitation, it is the obvious one of achieving a sufficiently high efficiency coincident with low production costs. Previous studies have shown that unless a particular minimum efficiency is exceeded (the absolute value of which varies from time-to-time) the cells themselves could be zero cost but the system as a whole would remain non-viable because of excessive, area related, balance-of-system costs.

In the above list of parameters influencing cell costs, we have not included a contribution from the cost of the materials. Generally, we utilize films which are only of the order of one or two micrometers thick so that even very large areas, which would be required to generate significant amounts of electricity, do not represent a large part of the total cost. Possibly more important, however, is the actual availability of some of the materials used. In Table 1, we show an assessment of several types of solar cell, including the two we have cited as being of special interest here, and have calculated the mass of the mineralogically scarce element required, per unit generating capacity, per micrometer thickness. The calculation is based, very simply, on the approximate maximum efficiency of the particular device, observed to date at the laboratory level (4).

In Table 2 we show a summary of mineral reserves, resources and refinery capacity for the various scarce elements itemized in Table 1. Although the techniques of predicting the extent of reserves are notoriously prone to inaccuracies (much less those of predicting resources), these data at least give us an idea of potential problem areas. Clearly, the estimates of the total world reserves of indium and tellurium suggest that the limited availability of these together, with a fairly restricted refinery capacity, may well constitute a problem if the $CdS/CuInSe_2$ and CdS/CdTe cells are ever to be produced in large volume. With tellurium, the problem is less severe because much of the resources could be converted into reserves, given the necessary economic stimulus. With indium, however, we have a much more severe problem since both the resources and the annual world refinery capacity are extremely limited.

There is considerable contention in the photovoltaic community about the accuracy of these estimates and it is not our purpose here to comment on this. As with the financial arguments presented earlier, they are intended to be cautionary only. If indeed they were proved in time to be accurate, then undoubtedly they would constitute a most important economic argument for some and against other cells. Hence, the cost of the elements involved in the two most successful polycrystalline solar cells may well be limited to 1-2 per cent of the total cell cost, but their availability may prove the dominant decisive factor in the long term.

In terms of material costs, that of the substrates would be expected to dominate over that of the semiconductors (8). If, for example, we consider an array generating 1 GWp with a conversion efficiency of 10 per cent, then the required area would be $10^7 m^2$. Clearly, if the substrates for this were to be glass, the cost and production problems would be severe. Hence there is an active effort to develop low-cost substrates. However, encapsulation will inevitably be required and since glass has been the most successful material used to date for this purpose, it may be difficult to find a replacement. Possibly, thin glass films could prove to be successful in this context, and these have been successfully deposited by RF sputtering in the past.

Table 2. World mineral statistics (5)

Material	Reserves (tons x 10^3)	Other Resources (tons x 10^3)	Annual Production Capacity (1980) tons
Si	unlimited	unlimited	2479*
Cd	754**	18 142	29510
Se	168	461	2547
Te	39	109	406
In	2	2	65
Ga	110	55	29

* This figure is the actual 1980 production level of polycrystalline silicon (Source: Monegon (6)). The remaining values in column 4 of the table are the predicted 1980 refinery capacities, the data being extracted from several articles in (5).

** As an indication of the uncertainties in mineral forecasting see (7).

This concludes our discussion of the economic case for solar cells. It is apparent that the case is not as clear as some of the protagonists of this technology imply. Future fuel prices will determine what the proper targets should be for production costs, and production experience will determine whether they can be met. Since the long-term solution to enery shortage problems is likely to involve a mix of technologies, it is only prudent to continue development even of those which, like photovoltaics, are surrounded by economic uncertainties. To some extent, I believe, that the economics will take care of themselves; it is far more important, for the time, to concentrate on improving device efficiencies. This will be the subject of the next section.

What are the qualities required of thin-film solar cells?

To make this technology a success, there must be several requirements fulfilled which, in the last analysis, all amount to reducing the cost of the energy generated over the lifetime of the cells. In one sense this is simply a detailed extension of the economic discussion of the previous section but here we identify three key topics which are presently being attacked. These are cell efficiency, the ability to produce large areas with a high throughput, and cell stability. All the economics of the cells are inherent in these three factors but rather than discussing these, which as has already been explained involves much gazing into crystal balls, we shall concentrate on what is needed to ensure high efficiency and what the limitations are, on what development of high throughput techniques is being undertaken and what special problems need to be addressed, and finally on what practical experience is available of the stability of the two devices of interest.

Efficiency

The efficiency of a solar cell (9) is dependent on the properties of the absorber, of the window layer, of the junction between them, on losses at the external electrical contacts and on optical losses. Assuming that with careful design the latter two losses can be made very small, we shall concentrate on the properties required of the two semiconductors and on their interface.

In brief, the properties required of the absorber are that it should (10):

(i) Have a band-gap somewhere around 1.5 eV since this is near the optimum for photovoltaic conversion;

(ii) Have a large optical absorption coefficient for all wavelengths less than that corresponding to that of the band-gap; this ensures that minimal thicknesses are required which minimizes the materials requirement;

(iii) Have as long a minority carrier diffusion length as possible; this ensures that the photogenerated carriers diffuse to the junction and are swept across it by the internal field before recombination can occur.

Similarly, the properties of the window layer (assuming that we are dealing with heterojunctions) are that it should:

(i) Have as large a band-gap as possible so that it transmits freely across the solar spectrum. Typical window layers are indium tin oxide (with a band-gap of about 3.7 eV) and CdS (with a band-gap of about 2.42 eV). Clearly, the latter cuts off at a longer wavelength than desirable;

(ii) Have as low a resistivity as possible. This enables the thickness to be reduced without the film presenting a large resistance to the lateral flow of current to the grid lines. Also, the spacing of the grid lines can be increased for low resistivity window layers, which reduces the shading losses;

(iii) Be straightforward to form ohmic contacts;

(iv) Have large diameter, vertical grains, or have passive grain boundaries. In this way, it is possible that the performance of polycrystalline devices can approach that of single crystal cells.

Figures 1 and 2 show the absorption spectra of several semiconductors including those under special consideration here. As regards the interface, there are again several criteria which should be used to guide the choice of the two materials (11). These are as follows:

(i) There should not be a severe mismatch of the electron affinities of the window and absorber layers. Such a mismatch can lead to a discontinuity in the edges of the conduction and/or valence bands and this can impede the movement of photogenerated carriers across the junction;

(ii) There should not be a large crystallographic mismatch between the two films. The presence of mismatch causes recombination centres which lead to increased reverse saturation current, and a reduced fill-factor and open circuit voltage;

(iii) The coefficients of thermal expansion of the two materials should be as nearly equal as possible. Since deposition of one semiconductor onto the other is at elevated temperature (e.g. a substrate temperature of about 220°C is used for the deposition of CdS onto $CuInSe_2$) strain can be caused upon cooling, and this again causes interface states which increase the reverse saturation current;

(iv) The two materials should ideally be non-reactive. This means that they should not react chemically, and should not interdiffuse. Although such effects are nearly impossible to avoid on an atomic scale, they are actually undesirable because they negate, or at least reduce, the value of design criteria.

In principle, there are many materials combinations which meet these criteria both individually and as a combination but in practice, very few yield efficient devices. Other guidelines can be used to define the necessary optical and electrical properties of the components of a window layer heterojunction solar cell. The monochromatic photocurrent of such a device can readily be shown to be (to a good first approximation)

$$J_L = K\left[1 - \frac{\exp(-\alpha W)}{1 + \alpha L}\right] \qquad (1)$$

where K is constant dependent on the photon flux at the junction, α is the optical absorption coefficient for the particular wavelength radiation, W is the width of the depletion region between the two semiconductors, and L is the minority carrier diffusion length (in general, for electrons, since we virtually always consider p-type absorbers and n-type window layers). To ensure $n=1$, we simply require that the products αW and/or αL are large for the absorber. Since the flux generates excess electron/hole pairs in the absorber, it follows that we wish as much of the depletion field to be located therein as possible. Hence, a further design requirement is that the absorber be much less heavily doped than the window layer. The actual width of the depletion layer (and hence the required doping of the absorber) should be of the order of $1/\alpha$. For typical absorbers and useful wavelengths this quantity is $\sim 0.3\,\mu m$; and to obtain values of W of this magnitude or greater requires the doping density of the absorber to be 10^{16}-10^{17} cm^{-3}. Although values less than this range lead to larger values of W and, theoretically, higher collection efficiency, in practice they can also lead to the problem of excessive series resistance losses. Since we wish most of the depletion field to appear across the absorber, to increase the drift component of the collected photocurrent, we can also specify the impurity concentration of the window layer. It is also possible to improve the design by creating graded impurity profiles which have the effect of extending the depletion region (11).

Assuming that the simple photo-diode equation can be applied, the open-circuit voltage of a solar cell can be written, to a good approximation, as

$$V_{oc} = \frac{AkT}{e} \ln\left(\frac{J_L}{J_o}\right) \qquad (2)$$

where A is the diode ideality factor, k, T and e are respectively Boltzmann's constant, absolute temperature and electronic charge, and J_o is the reverse saturation current. It follows from this equation that the ratio (J_L/J_o) should be as large as possible. The efficiency of a cell is given by

$$\eta = J_L \cdot V_{oc} \cdot F \qquad (3)$$

where F is the fill-factor of the cell. F also depends on maximizing (J_L/J_o), in the absence of losses due to series and shunt resistance, and hence on minimizing J_o. Thus, the latter quantity closely influences two of the three parameters governing device efficiency. Since for many devices J_L approaches the theoretical limit for the particular absorber/window layer combination, much of the remaining potential for efficiency improvement lies in reducing J_o. There are nine possible contributions to J_o (11) but, for heterojunctions, the most significant is often found to be due to recombination via interface states. In fact, the reverse saturation current (or rather its reduction) is probably the single most important target for device improvement. To minimize J_o requires that the volume of the films is free of an excessive density of recombination centres, that the interface is as free of defect states as possible, and that the contacts are not problematic. Also, it is necessary to ensure that interdiffusion and chemical reactions at the interface are minimal. A large variety of analytical techniques is used to investigate these problems and these will be discussed in the next paper.

Production of large area thin-film solar cells

So far we have discussed considerations relating to the possible competitiveness of solar cells, the availability of materials, and the fundamental physical design criteria. In this section we shall return partly to the economic aspects in the sense that we shall consider what means are being examined for large-scale production of devices. However, the need to deposit large areas of film with very specific properties, very quickly, raises a number of separate problems which are not of an economic nature. CdS/$CuInSe_2$ cells are usually fabricated entirely by vacuum deposition, the most well tried having been developed by the Boeing Corporation (12). This technique consists of three-source deposition of the $CuInSe_2$ and a single source for the CdS, as seen in figure 3. The substrates are usually of very limited area and deposition is usually quite slow. The construction of a typical cell is shown in figure 4. Although efficiencies have reached 11 per cent for these small area cells, to commercialize them will require rapid throughput of large areas, whilst still maintaining high efficiencies. Exactly the same comments can be made of the CdS/CdTe cells; these have also exceeded 10 per cent conversion efficiency and show great potential.

We shall now consider what the requirements are of the large area processes and shall then mention a few of the techniques being examined.

Production rates

For photovoltaics to make a significant impact on electricity supply in the USA it would appear that they eventually need to be introduced at a rate of around 10 GW of generating capacity per year. This means that there should probably be around 20 such machines each with a capacity of about 50 MW (13). For a device efficiency of 15 per cent and an area utilization of 80 per cent, this would require an output of 4.2×10^5 m^2 per year. Assuming 5000 hours of operation per year, this corresponds to 80 m^2 per hour, or 2.2cm/sec. for a width of 1 m. If the length of the deposition region is 100 cm (assuming a batch coater), then the coating duration will be about 50 seconds, so that if the required thickness of the absorber is 5000 A, the deposition rate will be about 5,500 A/min. Although this is readily attainable, it must be remembered that all the required film properties must be maintained throughout the production schedule.

Potential problems

(i) Pinholes

The films must be pinhole-free otherwise shorts will be formed which can severely degrade device performance. The origin of pinholes is usually particulate matter and this can be due to inadequate substrate cleaning or to falling debris from within the deposition system. Hence, great care will need to be paid to the cleanliness of the substrates and the interior of the deposition systems and this will need to be incorporated on a routine basis to avoid loss of yield.

(ii) Thickness non-uniformities

Whatever the method of deposition used, there is inevitably a distribution of the material emitted from the source(s) and hence of film thickness. For the absorber layer this could be an important consideration since it is not only necessary to ensure the thickness is greater than some minimum value, but also that it is not excessively thick which would result in materials wastage and loss of time.

(iii) Compositional non-uniformities

For compound semiconductors it is necessary to maintain the required composition across the entire substrate area to ensure consistency of electrical and optical properties. When two or more elements are being evaporated, it may be possible to reduce departures from stoichiometry by using several carefully distributed sources of each material. In the case of sputter deposition, the problem may be lessened by using large area targets.

(iv) Angle of incidence effects

It is known for evaporation that the grains of a polycrystalline film tend to align themselves towards the vapour stream. In the case of evaporation from several spatially distributed sources, the problem can be expected to be more complicated. It is not difficult to see that the properties of films of varying grain alignment and surface texture would be very unpredictable. In all the above cases, the effects would be to lead to a distribution of film and, hence, of cell properties. It is not difficult to show that the effect of this is to degrade the overall performance to that of the poorest areas. Virtually nothing is known about these effects in large-scale production. Although the above comments have been aimed specifically at vacuum deposition, it is certain that the same problems will arise in all methods.

Methods presently under investigation

The problem of large area rapid deposition, is already being investigated and several methods are being considered. For evaporation of $CuInSe_2$, (using open boats and Knudsen effusion cells) thorough studies have been made of the problems arising in scaling up from laboratory scale. The problems are not simply ones of scale but involve non-linear differential equations (14). The difficulties of scale-up have been usefully illustrated by analogy with laboratory and production scale genetic engineering. Reactive magnetron sputtering is also under consideration (13). This method involves sputtering from two metal targets (copper and indium) in a partial pressure of H_2Se. Other methods with the potential for large area coating of $CuInSe_2$ include alloy plating, close spaced vapour transport, and electrodeposition. In the case of CdTe deposition the methods being investigated include chemical vapour transport, electrodeposition, and hot-wall evaporation. Although substantial progress has been made, research has been too limited to exploit the potential fully. In terms of area the largest successful $CdS/CuInSe_2$ cells fabricated so far are approximately 100 cm^2 with an efficiency of 6.2 per cent; for CdS/CdTe, devices of up to 4,000 cm^2 have been produced with an efficiency of 5 per cent. A summary of these is shown in figure 5. Although these results are extremely promising, much more effort needs to be made. Careful studies of the physics of growth of the films have in general not been made and certainly the relationship of the growth parameters to the device physics is an unexplored area.

Device stability

It is of great importance that solar cells maintain their electrical output, without degrading, for about twenty years, if the system economics are to stay competitive. Many mechanisms of degradation can occur. Since several interfaces are involved in the device structure, chemical reactions or interdiffusion can take place and these will certainly affect device performance. However, degradation of the external contacts appears to be the cause of such instabilities as have been observed. $CuInSe_2$ devices have shown excellent stability after exposure to simulated sunlight for over 9,000 hours in controlled environment. However, degradation of the front contacts of unencapsulated cells has been observed during outdoor testing, and this appears to be due to attack of the aluminium grids by water vapour and chlorine. The solution to this problem probably lies in the development of adequate encapsulation, or of more sophisticated grid structures. As yet, no studies on the stability of CdTe based cells have been sponsored by DOE/SERI. However, two of the companies involved in manufacturing devices (Kodak, Matsushita) have performed preliminary studies. The former has obtained some evidence of contact degradation whilst the latter has not observed any degradation of performance on their screen printed cells. We may conclude from this that problems of stability appear to be minimal compared with other cells, for example CdS/Cu_2S, and that such instability as is evident is due to degradation of aspects of the cell other than the two semiconductors. This is most encouraging, since the latter problems tend to be inherent, whilst the former are technological and do not present a fundamental limitation.

Problem areas and major research directions

(i) Low V_{oc} in $CdS/CuInSe_2$ cells

Empirically, it has usually been found that the open circuit voltage of cells is approximately 2/3 the energy gap of the absorber. This is the case for many absorbers, but the rule certainly does not apply to $CuInSe_2$ for which typically V_{oc} = 400-450 mV, i.e., less than 1/2 Eg. The reason for this is uncertain other than that it is due to excessively large values of J_o. However, as we have already pointed out, there are many possible causes of this and the particular contribution has never been isolated. Since it also limits the fill-factor to less than 70 per cent, it is vitally important that this problem be addressed. Recently, there has been considerable discussion about the nature and location of the active electrical interface in these cells. EBIC data imply that the devices are actually buried homojunctions (although the mechanism(s) by which type conversion occurs is (are) still very much under discussion). Spectral response data however tend to contradict this theory. If indeed the buried homojunction model is correct, then we would expect V_{oc} to be substantially lower than if the heterojunction model applies. Since improvement of the device efficiency largely depends on improving V_{oc}, it is critical that this issue be resolved. If V_{oc} could be improved to nearer 600 mV then an efficiency approaching 15 per cent could be achieved.

To resolve this problem will necessitate improving our knowledge of the defect chemistry and the role of extrinsic doping of $CuInSe_2$. These are fundamental issues which are arising at a time when the device is already being commercialized. That they have not been resolved already is probably due to two reasons. Firstly, straightforward technology enabled relatively high efficiencies to be achieved without there appearing to be a need to study the materials at the fundamental level. Secondly, $CuInSe_2$ is unusual as an electronic material, in that its only evident application is in solar cells. Hence the wealth of background information available for many materials does not exist for $CuInSe_2$. The future of this material probably depends on this situation being remedied.

(ii) Controlled contacting to and extrinsic doping of p-CdTe

Single crystals of CdTe can be doped n-type or p-type with an excess of Cd or Te respectively. Extrinsic n-type doping with indium of both single crystals and films is also possible. It is also possible to produce low resistivity p-type crystals, but extremely difficult to produce highly conductive p-type polycrystalline thin-films. In general, the impurities tend to segregate at the grain boundaries. It appears that oxygen incorporation during processing or after deposition improve the conductivity. This observation is rather similar to that of the effects of junction movement in $CdS/CuInSe_2$ cells. To produce p-type films reliably and reproducibly requires much more effort in this area.

The contacting problems to p-type CdTe can be summarized as follows:

- Low resistivity ($< 10\Omega$cm) n-type films of CdTe can be produced and these permit very thin tunnel junctions of low contact resistance to be made with certain metals. Such low resistivities cannot be achieved for p-type films;

- The electron affinity of n-type CdTe is about 4.3-4.5 eV which is almost equal to its work function for degenerate, low resistivity material. For p-type material, the work function is approximately 6.0 eV. Ohmic contact to n-type material requires metals with a work-function around 4.4 eV; for p-type material a metal with work function greater than about 5.8 eV is required. Many of the former are available, whilst there are none of the latter.

The contact resistance between a metal and a semiconductor is governed by the height and the width of the potential barrier between the two. As explained, it is difficult to make either small for p-type CdTe. Since there are quite severe losses associated with poor quality contacts, again this is an area which will certainly receive considerable attention.

(iii) Development of p-type window-layers

All window-layers presently available are n-type and certainly there is no p-type semiconductor with a band-gap approaching that of materials like ITO and ZnO. This is a somewhat limiting situation since it removes the possibility of exploring the potential of window-layer heterojunctions using n-type absorbers.

Both CdTe and $CuInSe_2$ are available in n-type form and may have advantages over the p-type absorbers. However, the materials which can be made p-type, highly conductive and transmissive have a band-gap less than even that of CdS (~2.5 eV) so that absorption losses near the maximum of the solar spectrum would be prohibitive. It is possible that materials such as $CuGaS_2$ with its band-gap of 2.8 eV may be suitable or, indeed, other alloy systems could be developed. However, to date little effort has been devoted to this topic.

(iv) Research into cascade cells

Thin film cells have just the same possibility of being grown in tandem or cascade form as do the ternary III-V alloy devices. Optimum devices, theoretically, would utilize a top-cell with an absorber band-gap of about 1.6-1.8 eV and a bottom cell with an absorber band-gap of 0.9-1.1 eV. This is shown diagrammatically in figure 6. Several materials possibilities exist including $CuInSe_2$, a-Si:H, HgCdTe, for the lower absorber, and a-Si:C:H, CdTe for the upper absorber. Also, the material $CuGaSe_2$ should be nearly ideal particularly from the point of view of compatibility in $CuInSe_2$. There are also other alloys based on CdTe which have great potential. With any of these systems the production problems are severe since it is necessary to maintain high-quality materials properties throughout the deposition of many layers and over fairly wide temperature ranges. However, the very high potential efficiencies are attractive and cascaded thin-film systems have much to offer. Research in this area is comparatively limited at present and efficiencies appear to be limited by poor quality contacts to CdTe (in a CdS/$CuInSe_2$:CdS/CdTe cell). A typical device construction is shown in figure 7 and, in this configuration, efficiencies of several per cent have been recorded (15).

(v) Advanced deposition research

The major obstacle to investigating large-scale production technologies is their cost. Hence, far more effort has been devoted to improving the efficiency of small area devices than to studying the host of problems associated with large area deposition. Presumably as the small area efficiencies and the prospects for commercialization improve, more attention will be given to scale-up problems. Perhaps the main point to be remembered is that the efficiency of large areas will always be less than that of small areas and so the materials quality must be superior for the former, if efficiencies are to be maintained. Virtually no research has been done on the nucleation and growth of the absorber films $CuInSe_2$ and CdTe and, not surprisingly, the films and cells tend to be somewhat ill-defined. This situation must change before large area deposition can be made practicable.

Conclusions

Although many economic studies have been made of the probable cost-competitiveness of solar cells, it is our belief that there are too many variables for these calculations to be reliable. If indeed there is an economic restriction, for the thin-film devices based on $CuInSe_2$ and CdTe, it would be the availability of In and Te.

Simple theoretical considerations indicate that the major improvements to be made with $CuInSe_2$ cells are with V_{oc} and the fill-factor, both of which depend on reducing J_o. With the CdTe cell much of the potential improvement in performance will rely on improving the contact to the p-type material.

For the cascade cells, operational devices have already been demonstrated but there are considerable problems. Contacting the CdTe is again problematic, but there is the additional difficulty of avoiding interdiffusion of the various films and of providing transparent tunnel junctions. Optimization of either the two or four contact technique must be achieved. Finally, much more detailed studies of film and device properties need to be made, even at the laboratory scale, if the large area high throughput production techniques are ever to be successful.

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Figure 1. Thin-Film Heterojunction Solar Cells: Optimal Use of the Solar Spectrum.
Shown are the absorption coefficients of CdTe and $CuInSe_2$; transmission curves for various heterojunction partners (window materials) under study; and photon flux density (linear in energy, eV) for the AM 1.5 Global Spectrum.

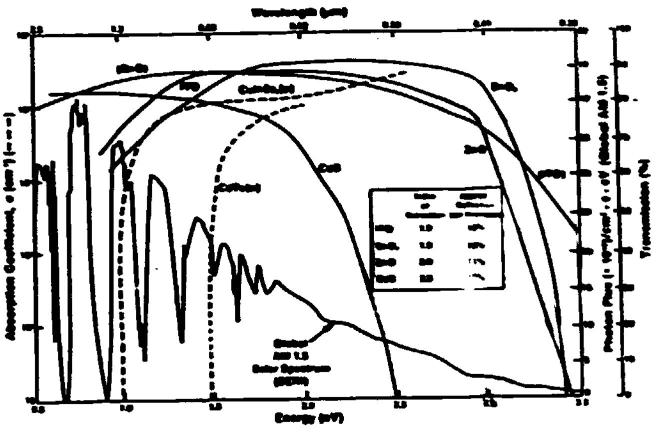


Figure 2. Absorption Coefficients of Various Thin-Film Semiconductors.

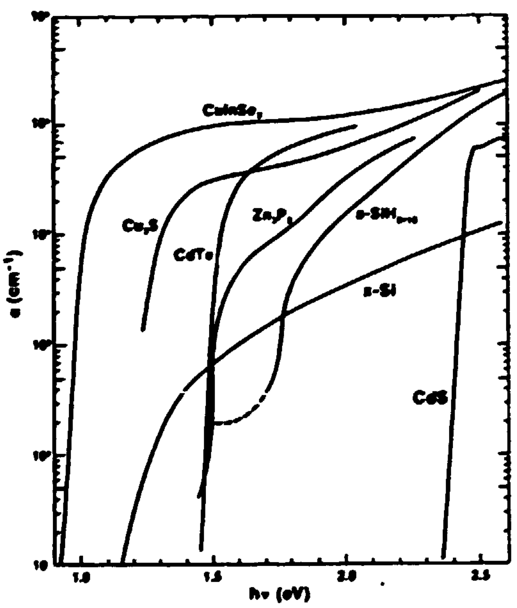


Figure 3. Three Source Deposition of $CuInSe_2$.

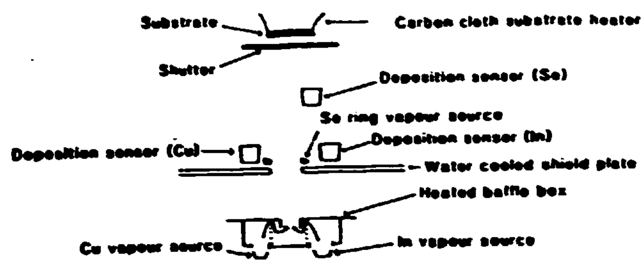


Figure 4. CdS/$CuInSe_2$ Cell Structure Showing Deposition Temperatures and the Relative Composition of Elements During Deposition (Boeing).

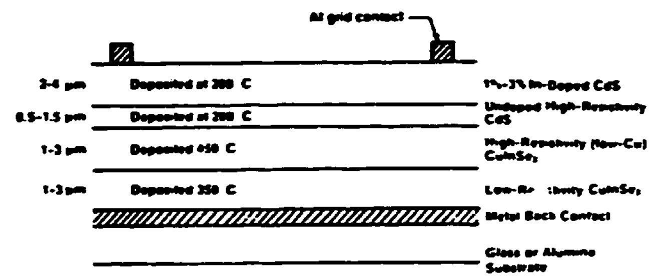


Figure 5. Large-Area Polycrystalline Thin-Film CdTe and $CuInSe_2$ Cells.

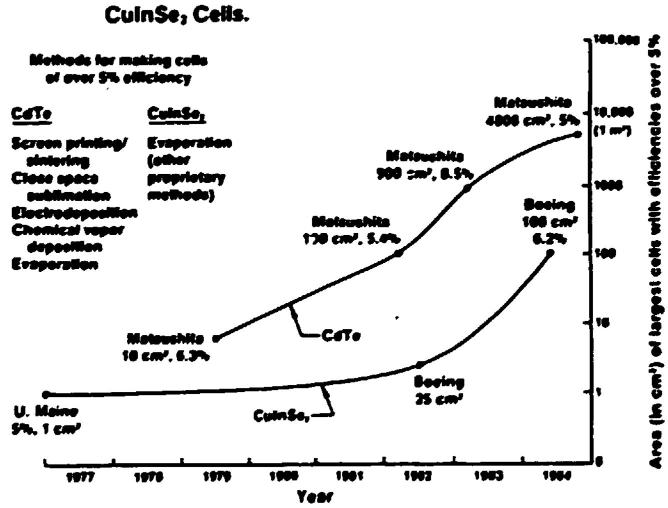


Figure 6. Iso-Efficiency Curves for Two-Cell, Four Terminal Cell.

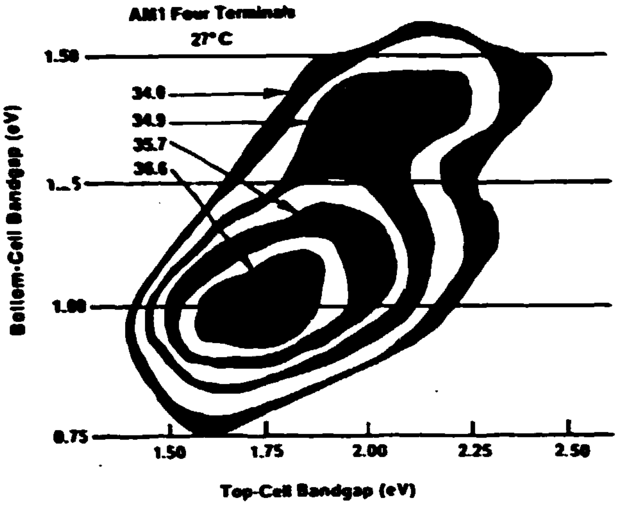
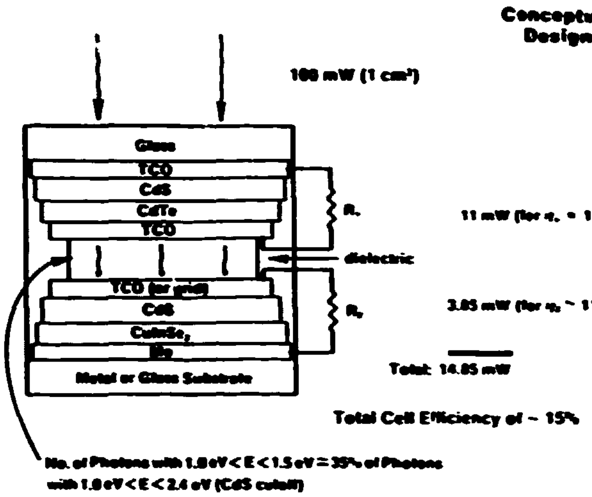


Figure 7. Two-Junction, Four-Terminal Optically Stacked Polycrystalline CdTe/CuInSe$_2$ Solar Cell.



VOLTS FROM THE BLUE

The idea of turning sunlight into electricity inspires visions of a world freed from dependence on scarce and polluting fuels. But although solar cells - also called photovoltaic (PV) devices because they generate a voltage when exposed to light - have existed for more than three decades, their high cost has until recently restricted them mainly to such exotic uses as powering spacecraft. Commercial success is now coming, but in less dramatic form than was once imagined. The Japanese, recognizing that there is more money in consumer products than in spaceships, are turning out millions of PV-equipped watches and calculators a month, and solar cells will soon appear on larger products, such as battery chargers, TVs, and automobile sunroofs.

Solar electricity is still expensive. PV cells cost roughly \$10 per watt of generating capacity, several times more than a conventional power plant. But in contrast to other power sources, the "fuel" costs nothing and there are no moving parts to break down. Moreover, PV technology works well on any scale, so capacity can be expanded step by step.

The cost of PV cells has dropped enough so that they can now compete with diesel generators for power at remote sites - such as communications relays and water pumps - that are not hooked up to a utility grid. Solar cells are especially attractive in third world countries, where there are fewer central generating plants and where fuel prices can be exorbitant. In India, for example, diesel costs \$4 a gallon.

Solar power's drop in cost - a tenfold reduction over the past decade - stems from a radical shift in photovoltaic technology. Invented at Bell Laboratories in 1954, solar cells were for many years made almost exclusively of the same ultrapure and expensive form of silicon crystals so ubiquitous in microelectronics (where the quantity of material per device is much smaller). But the Japanese have demonstrated that for many applications, especially where it is not that important to generate large amounts of power per square foot, cheaper and less refined materials are perfectly adequate. They can go onto less expensive substrates, be churned out more rapidly at looser tolerances, and cover areas much larger than those feasible for crystalline silicon devices. Furthermore, they can be manufactured with straightforward, highly controllable processes that are easily integrated into a continuous production line. Although the performance of these lower-cost PV devices does not yet approach that of the best commercial crystalline devices - which transform into electric power up to 15 per cent of the solar energy that strikes them - some are coming close, and improvements are occurring steadily.

The leading low-cost approach involves thin films of semiconductor that are only 0.5-50 microns thick; "bulk" crystal devices, by contrast, measure 150-250 microns. Thin films soak up light as much as 100 times better than bulk crystals, thereby reducing the amount of material needed, and they offer less electrical resistance, simply because the electrons pass through less material on their way to the contact.

Thin-film PVs can be made from a variety of materials, such as cadmium telluride and gallium arsenide. But the favorite, which drives virtually all the solar-powered watches and calculators now on the market, is amorphous (non-crystalline) silicon. In 1985, over 8 megawatts worth of amorphous silicon PV devices were produced, according to Edward S. Sabisky, manager of the amorphous silicon programme at the Solar Energy Research Institute (Golden, Colo.). Utilities are showing interest as well. Alabama Power, for example, plans to build an experimental power plant in which amorphous silicon solar cells generate 100 kilowatts.

Amorphous silicon is 40 times more light-absorbent than crystalline silicon; hence far less material is needed to produce useful power. But commercial amorphous devices are only 4-6 per cent efficient. While several laboratories in the US and Japan have reported small amorphous cells rated at 10-12 per cent, this is still only about half as efficient as the best single-crystal silicon cells.

Much of the work on raising amorphous silicon's performance involves alloying with other materials. In any solar cell, electricity is generated only by those photons with enough energy to lift an electron from the valence band (in which state it is tightly linked to the atomic nucleus) into the conductive band; photons with energy lower than this "bandgap" value pass through the material with no effect. Amorphous silicon has a relatively high bandgap - 1.7 electron-volts (eV) - resulting in a higher voltage. A crucial disadvantage, however, is that the cell produces a low current, since it responds only to high-energy photons (that is, photons toward the blue end of the spectrum). The much more abundant red and yellow photons lack the energy to make the electrons conductive.

Alloying amorphous silicon with another material can change its bandgap and thus broaden its response to cover more of the solar spectrum. In one particularly promising approach, two or three cells are stacked one on top of another, each alloyed to "tune" it to a different portion of the spectrum. The top cell may contain an element such as carbon that increases the bandgap, and the bottom layers could contain band-gap-reducing substances such as germanium. The silicon-carbon alloy intercepts the high-energy (blue and violet) photons; the remainder of the sunlight passes through to be absorbed in the silicon-germanium zone.

Such "multijunctions" can be produced either by passing the substrate from one deposition chamber to the next (the monolithic technique) or by fabricating individual cells separately and then stacking them mechanically. Monolithic cells lend themselves better to continuous mass production, but suffer from a severe constraint: with present fabrication techniques, a monolithic multijunction is limited to a single pair of electrical contacts, one at the top and one at the bottom. The problem with such a series hookup is that the ouptput of the stack cannot exceed the smallest current produced by an individual cell. Designers must therefore adjust layer thicknesses so that each cell produces roughly the same current when exposed to typical sunlight conditions; any extra current will simply be wasted as heat.

Mechanically stacked cells can each carry their own set of contacts, avoiding the need for current matching. The additional contacts block some sunlight, however, and also complicate assembly because they render the device more fragile. These problems could be solved with the use of more transparent contact materials and with refinements in assembly techniques.

Multijunctions are responsible for the high performances of several laboratory devices. Energy Conversion Devices (ECD - Troy, Mich.), for example, has reported a 13 per cent unit comprising a stack of three cells. The top two cells, consisting of unalloyed amorphous silicon, trap most of the blue light. The lower-energy red photons pass downward unimpeded and are absorbed in a bottom region of silicon-germanium alloy. ECD's next step will be to add yet another layer below the germanium alloy, with a still lower bandgap to catch more of the long-wavelength light.

There are also ways to soup up devices without using multijunctions. Sanyo, for example, has attained 11.5 per cent efficiency in a single-junction PV by texturing the top layer of the cell to make it more absorbent, and by making the bottom contact reflective; as a result, incident light is trapped. In the US, Solarex (Rockville, Md.), a subsidiary of Amoco, has reported a 10.4 per cent device using a "superlattice"; two materials with different bandgaps are deposited in extremely thin alternating layers near the top surface of the cell. Although high-quality American and Japanese prototypes are generally no larger than a square centimeter, several US companies are now reporting square-foot prototypes in the 7-8 per cent range.

But there is a dark cloud in the picture: amorphous devices lose up to half their efficiency after a few weeks or months of exposure to the sun. After this plunge, efficiency appears to remain constant indefinitely. This effect has not hampered the most common use of amorphous silicon cells, because watches and calculators draw very little power; even the output of a degraded cell is enough. Yet the material's instability has been the main obstacle to its use in remote areas, where a spent cell could be hard to replace.

Opinions differ as to the cause of amorphous silicon's instability, but the prevailing view blames the fundamental character of the material. In crystalline silicon, every atom is strongly bonded to four other atoms to form an ordered, diamond-shaped lattice. In the amorphous state, by contrast, the silicon-silicon bonds are weaker, and the atoms assume a more jumbled arrangement, with many dangling bonds. These defective bonds trap electrons, reducing the current that reaches the cell's contacts. The problem gets worse over time, it is thought, because sun-energized electrons break more bonds. Meanwhile, however, sunlight heats the material, accelerating the formation of bonds. Efficiency eventually reaches equilibrium when this thermal healing balances the bond-breaking effect.

Happily, multijunction cells seem somewhat more stable than single-junction cells. One reason is that the introduction of alloys or dopants to form the different layers apparently relieves stresses that would otherwise break weak bonds. Also because multijunction devices use thinner layers of material, electrons are less apt to encounter a dangling bond on their short journey to the circuit contact. And when they do, the electrons are less likely to be trapped, thanks to the more intense electric field that develops in a thinner layer than in a thicker slice at the same voltage. Consequently, the gradual increase in broken bonds has a comparatively small effect on the cell's output. ECD recently reported a triple-junction cell that retained 95 per cent of its original 11 per cent efficiency after several months of testing.

Another problem is manufacturing: production of all amorphous silicon cells, whether multijunction or not, is still a bottleneck. In the conventional process, silane gas (SiH_4) is decomposed by heat and radio-frequency discharge in the presence of a substrate. This "glow discharge" technique is slow, however, as well as subject to defects. While several alternatives are being studied, none seems capable of solving the speed and quality problems at once.

It is possible, for example, to accelerate the process by using disilane (Si_2H_6), which contains twice as much silicon as silane does; unfortunately, commercially available disilane is of uneven quality, besides being more expensive than silane. ECD claims that a 20-fold increase in deposition rate, to 0.01 micron per second, is possible by boosting the discharge frequency into the microwave régime. The microwave technique is experimental, however, and still has a relatively high defect rate. Other companies may scrap glow discharge altogether. Sanyo and Chronar (Princeton, N.J.) are investigating photochemical vapour deposition, using the energy of light to excite atoms and molecules. This gentler method has been shown to give higher-quality material, but it is still slow.

Such problems have spurred interest in alternatives to amorphous silicon. The strongest competitor is copper indium diselenide ($CuInSe_2$), first developed as a PV material in 1980 at Boeing. In addition to being extremely stable, it is the most light-absorbent PV material known; nearly 99 per cent of incident visible light is absorbed within the first half micron. Another advantage is that the electrons in $CuInSe_2$, when energized by falling photons, remain conductive a relatively long time before returning to the valence band. Thus, large proportions of light-generated charge carriers reach the contacts and contribute to the electrical output.

Although capable of generating fairly large currents, copper indium diselenide is hampered by low voltage owing to a bandgap of ony 1.0 eV. Largely because of the low voltage, efficiency gains have been slow in coming. Recent reports indicate that the material will be most useful in conjunction with other, higher-bandgap materials. Arco Solar (Chattsworth, Cal.), for example, has demonstrated a 12.5 per cent device by stacking amorphous silicon on $CuInSe_2$. Cadmium sulfide could also serve as a high-bandgap companion.

It may be possible, however, to increase the bandgap (hence the voltage) of copper indium diselenide itself. According to one theory, the cause of the material's low bandgap is a lopsided bonding arrangement; the copper-selenium bond is shorter than the indium-selenium one. This asymmetry may be lowering the bandgap by up to half an electron-volt. Laboratories at Boeing and elsewhere are working on alloying the material with gallium in the hope of evening out the bonds and thus raising the bandgap to 1.3-1.4 eV.

The second major problem with copper indium diselenide is its complicated fabrication process. At least three different gases are needed to form the compound. The process must be repeated many times, adjusting the proportion of copper and selenium to match the function of the layer being deposited. Boeing has reported little progress in scaling up its five-year-old chemical vapour deposition system, but promising alternatives are emerging. In a process called reactive sputtering, a stream of high-energy particles jars copper and indium atoms loose from a target. The ejected atoms pass through hydrogen selenide gas, where they react to form $CuInSe_2$ on a substrate. Arco Solar is thought to be using this technique, which is well suited to continuous production of large-area cells.

Another alternative, electrodeposition, is already well established in battery production and other industries. Copper is electroplated onto a substrate, followed by indium; finally, the mix is exposed to hydrogen selenide. The virtue is extreme control: "You can literally count atoms," says Vijay Kapur, whose year-old firm, International Solar Electric Technologies (Inglewood, Cal.), is now trying to commercialize the process. After only a few months of work, the company produced $CuInSe_2$ cells with a respectable 7 per cent efficiency.

The leader in $CuInSe_2$ research is now Arco Solar, which has reported efficiencies of 13.1 per cent for small laboratory devices and has built square-foot prototypes working at 7.1 per cent. These modules contain 18 amorphous silicon cells laid out on a single large copper indium diselenide device. Innovations include electrodes of zinc oxide that are more transparent and conductive than the tin oxides used in other cells, and a gel - placed between the amorphous silicon and the copper indium diselenide - with a refractive index that compensates for light-bending that originates elsewhere in the device. These features allow more light to reach the bottom cell, boosting power output. Ultimately, Arco Solar expects to achieve efficiencies of 20-24 per cent, says research vice-president Charles Gay.

Of the other materials attracting interest for PV applications, the leading contender is cadmium telluride (CdTe), which has neither the instability of amorphous silicon nor the low voltages of copper indium diselenide. Its bandgap of 1.4 eV makes it sensitive to most of the solar spectrum; in fact, efficiencies of almost 11 per cent have been reported.

But producing CdTe is a major challenge. One problem is that deposition requires high temperatures (600-700° C), ruling out the use of some less rugged (and less expensive) substrate materials. Other difficulties stem from the need for precise control over the proportions of the two elements. A deviation of merely 1 per cent in the ratio of cadmium to tellurium changes the material from n-type, where electrons (negatively charged) are the dominant current carriers, to p-type, where electron vacancies, or holes (positively charged), are in the majority. A PV cell needs both n and p regions in order to produce electricity (see "A solar cell primer"); CdTe is usually made p-type, while a transparent top layer of cadmium sulfide serves as the n-type region. Unfortunately, control over the ratio is hampered by a large difference in vapour pressure between tellurium and cadmium.

One way around some of these fabrication problems is to use external dopants such as phosphorus and arsenic to create the n and p zones; the Cd/Te ratio can then be adjusted solely to minimize electrical resistivity. Some success with this method has been achieved by researchers at Arco Solar and by Ting Chu, professor of electrical engineering at Southern Methodist University (SMU) in Dallas. Arco Solar has produced small CdTe cells with 9.1 per cent efficiency, and claims it can reach 15 per cent. While the company has no immediate plans for commercialization, a spinoff does. Yerkes Electric Solar (Chatsworth, Cal.), recently started by Arco Solar alumnus William Yerkes, is developing a deposition process that Yerkes claims could run at temperatures well below 500° C. He hopes to start up a small pilot line this summer, supplying 4 x 6-inch custom cells for specialty products.

Another thin-film candidate, gallium arsenide (GaAs), is better known to the solar cell industry for its high performance in bulk crystalline form. Indeed, the highest efficiency ever attained by a PV device, 23 per cent, came from a GaAs cell. The material's bandgap of 1.45 eV is optimal - allowing sensitivity to most of the solar spectrum while producing a reasonably high output voltage. Whereas amorphous silicon and $CuInSe_2$ probably will not exceed 15 per cent efficiencies for single junctions, thin films of GaAs could top 20 per cent.

Once more, however, the obstacle is fabrication. United Technologies (East Hartford, Conn.) tried growing single thin crystals of gallium arsenide on a low-cost, disposable substrate - ordinary table salt. But this process was still batch-oriented and slow. In another project, SMU tried depositing polycrystalline gallium arsenide onto graphite-coated tungsten. Unfortunately, the process required temperatures of over 1,100° C, hot enough to melt away part of the substrate. Such failures have left GaAs as the darkest horse in the thin-film race.

For the near future, then, amorphous silicon will likely continue to rule the world of thin-film PV cells, despite the material's questionable stability and relatively low efficiency. Some solar-industry watchers predict that the Japanese, with their focus on supplying cells for mass-produced consumer products, will achieve such economies of scale that amorphous silicon devices will be only slightly more expensive than the glass or steel substrates on which they sit.

In the US, Arco Solar, ECD, and Chronar have each opened plants that can turn out a megawatt worth of amorphous cells per year. Solarex is operating a pilot facility, but parent company Amoco has not given the go-ahead for full-scale production. Meanwhile, Sanyo alone has an annual production capacity of 5 megawatts. Earlier Japanese efforts in amorphous silicon, together with the additional factories scheduled to come on line soon, will give Japan a strong advantage in the low end of the market for at least the next few years.

RESOURCES

Contacts

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Solar Energy Industries Assn., 1156 15th St., NW, Suite 520, Wash., DC 20005, (202) 293-2981.

Electric Power Research Institute (EPRI), 3412 Hillview AVe., Palo Alto, CA 94304, (415) 855-2000.

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A solar cell primer

The photovoltaic effect, which underlies all solar cells, involves a semiconductor atom's outermost electrons. Silicon, the most common PV material, has four such "valence" electrons, which can be shared with neighbouring atoms to form bonds. Heat or light can loosen the electrons so that they become mobile, and hence able to conduct. When that happens, the electron moves away from its parent atom, leaving a "hole" at its former position. In untreated materials, a freed electron would soon lose energy and fall back into this hole without any useful effect. To prevent such recombination, PV cells consist of junctions much like those in transistors and other electronic components.

Junctions are formed by doping - adding impurities - to change the electrical characteristics of the host material. One side of the device is made "n-type" by introducing atoms that contain one more valence electron than do the atoms of the host semiconductor; the other side is made "p-type" by doping with atoms having one fewer electron than the host. After doping, excess electrons on the n side spontaneously move across the junction to fill vacant sites on the p side, giving that region a net negative charge; excess holes move in the opposite direction, making the n side positively charged. The resulting charge imbalance creates an electric potential that the PV device needs in order to produce electricity.

The key to the photovoltaic effect is the action of the electrons that have spilled over to the p side. When made conductive by absorbing light, electrons move across the junction toward the positively charged n side. There, electrical contacts can draw them off as usable current.

By far the major limitation on solar cell efficiency is poor matching with the solar spectrum. Sunlight consists of photons that carry a wide range of frequencies and hence a wide range of energies. A PV device, however, responds only to those photons with enough energy to lift a valence electron into the conductive band. Photons below this "bandgap" threshold pass through without effect. With higher-frequency photons, meanwhile, energy that exceeds the bandgap is wasted as heat.

The ability of a 1-micron thin film to soak up as much light as a 100-micron slab of crystalline silicon, and thus generate a comparable electrical output, comes from another factor; the type of bandgap, direct versus indirect. Crystalline silicon has an indirect bandgap; this means that when an electron absorbs a photon and jumps from the valence to the conduction band, it changes not only energy but also momentum. In order for overall momentum to be conserved, an electron can absorb a photon only when an additional particle, called a phonon, is formed in the crystal. By contrast, amorphous silicon and the other thin-film PV materials have direct bandgaps, in which electrons move between bands without changing momentum. Because they do not depend on phonon formation, these direct-bandgap materials are 100 to 1,000 times as light-absorbent as bulk silicon.

Solar cell performance can be rated with values other than efficiency. One useful yardstick is the "fill factor". If a wire connects the cell's two terminals, maximum current flows (it is called short-circuit current). If the wire is cut, the voltage between the two terminals goes to its maximum value (open-circuit voltage). Drawing lines at these two values on a current/voltage plot forms a box. Because current times voltage equals power output, designers would like both values to remain high under all circuit conditions. The fill factor represents the portion of this theoretical box that is filled by the cell's actual performance curve. Thus a fill factor of 100 per cent is ideal. In reality, however, current falls off as voltage rises to its open-circuit value; a fill factor of 80 per cent is considered excellent. (Source: High Technology, July 1986, p. 28)

CURRENT AWARENESS

1. Silicon

1.1 Amorphous silicon

Amorphous solar cell sets efficiency record

An unprecedented energy conversion efficiency of 12.2 per cent in solar cells made of proprietary amorphous-material alloys has been reported by Stanford R. Ovshinsky, president of Energy Conversion Devices Inc.

The efficiency high was achieved in a cell consisting of three extremely thin, vertically stacked subcells made of proprietary fluorinated amorphous materials, each subcell sensitive to a different colour in the spectrum. The cells were produced by Sovonics Solar Systems, a partnership of ECD and Standard Oil Co. (Ohio).

A major advantage of multilayer cells is excellent stability, says Ovshinsky. "The triple-cell design has proven in our laboratories to retain over 90 per cent of its efficiency over a 20-year period. Other high-efficiency amorphous solar cells lose as much as half of their efficiency after only 24 hours of illumination."

ECD, in its joint venture with Sohio, is already manufacturing 1-ft-wide by up to 1,000-ft-long continuous-strip solar cells with efficiencies in the 8 per cent range, Ovshinsky continues. This is achieved with two-layer cells.

Looking to the future, Ovshinsky says that "from the start of our work in photovoltaics, we have consistently been able to duplicate laboratory results in our large-area operations. For this reason, we expect to continue achieving higher efficiency." (Source: Machine Design, 10 October 1985, p. 2)

Stainless steel coil for a-Si PV

Japan's firm Takasago Tekko has developed a way to mass-produce stainless steel coils used in making amorphous silicon photovoltaic cells. A new surface processing technique is used to give the cells a surface roughness of less than 1,000 angstrom.

The new method makes it easier and more practical to use the new substrate material, the company says. The material will be for SUS-430 and SUS-304 in thicknesses of 0.1-0.2 mm and 0.2-0.5 mm, with a standard maximum width of 200 mm. Other widths of 400 mm and 760 mm are also available.

To supply material in coil form, PV cell production processes were speeded up, and included vapour deposition and coiling by continuous processing. The domestic price per metric ton is about 2,000,000 yen ($11,100). (Source: Solar Energy Intelligence Report, 25 February 1986, p. 63)

Amorphous superlattice solar cells by optical CVD

Amorphous silicon (a-Si) is the most likely candidate for low-cost, large surface area solar cells. However, a major drawback is their low photoelectric conversion rate.

The Research Centre of Sanyo Electric has developed a laminate moulding method for making solar cells with alternating 2.5 nm layers of a-Si and amorphous silicon carbide (a-SiC). In this method, a substrate is first placed in a vacuum chamber and heated to 200-300°C, then, disilane gas, the raw material for the a-Si layers, and a mixture of disilane gas and acetylene gas, the raw material for the a-SiC layers are alternately introduced. An optochemical reaction is induced on the substrate by ultraviolet light from a low pressure mercury vapour lamp outside the chamber.

The finished film has a definite 2.5 nm periodic structure, and has been confirmed to be a high quality superlattice film with few surface defects.

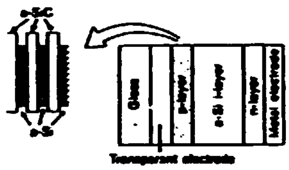
Although the solar cells produced using this superlattice film moulding technology have the same p-i-n structure as ordinary a-Si solar cells made as six-layer superlattice films, the n and i layers are made by plasma chemical vapour deposition (CVD) and only the window-side p-layer is made by optical CVD (Figure).

As a result, this solar cell can utilize the 300-500 nm short wavelength band of light which is absorbed by the p-layer of ordinary a-Si solar cells, and has a photoelectric conversion ratio of 10.5 per cent even with a surface area of only 1 cm^2.

Sanyo is the world's leader in the application of superlattice films for solar cells. The company has chosen this approach because by making amorphous materials into superlattice film, the electrical properties of the interface conditions can be greatly improved and also because amorphous materials have a high degree of structural freedom which accommodates non-uniformities in the lattice structure, allowing superlattices to be made easily.

The problem is whether the photoelectric conversion rate can be increased to near that of stacked or other solar cells and even if it can, whether manufacturing costs can be kept below those for single-crystal silicon.

Superlattice structure p-layer



Structure of the p-layer Superlattice Solar Cell

(Source: JETRO, January/March 1987)

* * *

The Research Centre of Sanyo Electric has further developed a new automobile sunroof that incorporates an amorphous silicon solar battery. The Amorton Sunroof produces 10-20 W of power, enough to run the car's ventilator. Any extra power can be used to charge the battery. The solar cell is sandwiched between a protective film and reinforced glass. The sliding sunroof was introduced in early 1986.

* * *

An experimental car running on amorphous silicon solar cells has also been unveiled by Sanyo Electric. The car, under development for 5 years, can run for 22.5 miles when fully charged and has a 330 lb load capacity, a 15 mph maximum speed and recharges in six years.

* * *

Matsushita Battery Industrial and Showa Aluminium (both Osaka, Japan) have successfully mounted an amorphous silicon photovoltaic cell on an aluminium substrate, offering a possible lighter weight, lower cost module. In work done at Matsushita's Technology Laboratory, a 0.3-mm thick aluminium substrate was developed for a-Si, forming the PIN structure via plasma chemical vapour deposition. The new cell has electrical features like cells with stainless steel or glass substrates. The aluminium substrate is anode-oxidized, forming a 6-10 micron alumina film, after which chrome electrodes are formed on the film's surface using electron beam evaporation. PIN structure a-Si cells are next made on the aluminium plate using plasma CVD. A protective transparent conductive oxide film applied to the surface completes the cell. Because aluminium radiates more readily than the polyimide resin of other cells, the new cell is less prone to reduced efficiency from heat buildup in outdoor use. (Source: SolarIntel, 6 January 1987, p. 6)

Amorphous silicon germanium for solar cell

The Electronic Technology General Research Institute has developed a material enabling the efficiency of an amorphous solar cell to be greatly improved, together with Mitsui Toatsu Chemicals, Nippon Glass, Central Glass, Hattori Seiko, and Shimazu Seisakusho. By combining the conventional amorphous silicon with this new material called amorphous silicon germanium, it will be possible to realize a revolutionary amorphous solar cell, which can convert more than 15 per cent of optical energy into electricity. The new material is an amorphous thin film alloy made of silicon and germanium. Utilizing its OES (optical emission system), it is possible to precisely control plasma and to produce thin film alloy at a speed as high as 2 A per second. By accumulating the amorphous silicon thin film and the amorphous silicon germanium thin film, it is possible to produce a high-efficiency cell, in which short-wavelength light is converted into electricity at the amorphous silicon layer, and long wavelength light at the amorphous silicon germanium layer. (Source: Chem. Economy & Eng. Review, January/February 1986, Vol. 18, No. 1-2 (195))

High conversion efficiency amorphous solar cell

Mitsubishi Electric Corporation has succeeded in manufacturing a prototype large area (100 cm^2) amorphous solar cell with a three-layered tandem construction that has a photoelectric conversion efficiency as high as 9.6 per cent. It was manufactured as part of the Photovoltaic Power System Technology R&D Project under the Sunshine Project, implemented by the Agency of Industrial Science and Technology of the Ministry of International Trade and Industry.

The three-phase tandem construction solar cell consists of three laminated solar cells having different wavelength areas, thereby utilizing the sunlight's wide spectrum of light most effectively. It is characterized by a high photoelectric conversion efficiency and minimal cell deterioration by optical irradiation, and while its construction is complicated, it features excellent productivity when manufactured by the plasma chemical vapour deposition (CVD) process.

Conventional types of solar cells fail to utilize the long wavelength portion of solar energy, making them incapable of using their full potential, but this amorphous solar cell features a high photoelectric energy conversion efficiency because of the use of an improved amorphous silicon-germanium (a-SiGe:H) material that absorbs long wavelength optical energy.

Besides this solar cell technology, the company is also engaged in the trial production of a power system amorphous solar cell module. (Mitsubishi Electric Corporation Public Relations Dept., 2-3 Marunouchi 2-chome, Chiyoda-ku, Tokyo)

(Source: JETRO, April 1986, p.8)

Fuji develops enhancement for amorphous silicon cells

Fuji Electric Co., Tokyo, says it has developed a way to make more efficient amorphous silicon photovoltaic cells. The technology employs plasma chemical vapour deposition to apply germanium in the I layer of a solar cell's P-I-N structure to lower the energy band gap of the layer to 1.4 electron volts.

Fuji says it produced an 11.5 per cent efficient, 1-sq-cm test cell last year using this "radial separation plasma CVD" process and is seeking to better this to 14 per cent on a module measuring 30-cm x 40-cm. The company has not said when such a module might be available, but it is expected to reach 12-13 per cent perhaps by this autumn. Marketing could start in late 1987.

The company now is upgrading the technology in manufacturing a 10-cm x 10-cm amorphous silicon cell. Officials are confident they can produce a high-efficiency device of this size using the new process. (Source: Solar Energy Intelligence Report, 5 August 1986, p.250)

Indian researchers to achieve 7-8 per cent in a-silicon by 1990: DNES

Indian researchers will develop the technology for making large-area amorphous silicon photovoltaic cells by 1990, at the end of the Seventh Plan, predicts Maheshwar Dayal, secretary of the Department of Non-Conventional Energy Sources (DNES) in an article in The Hindu newspaper of Madras, India.

At a meeting organized by the Indian Science Writers Association, A. K. Barua of Calcutta's Indian Association for Cultivation of Science (IACS) noted research will soon yield a-Si efficiencies of 7-8 per cent on cell surfaces measuring 1 ft. sq., up from the current 4-5 per cent on 1 cm x 1 cm. Efficiencies elsewhere around the world are higher - Energy Conversion Devices, Troy, Mich., and the Solar Energy Research Institute, Golden, Colo., are stable at 8-9 per cent.

The IACS work is part of a multi-institutional programme of DNES and includes the National Physical Laboratory, New Dehli; University of Poona, Pune; the Indian Institute of Science, Bandalore; and IIT Dehli. Some Rs8-10 crores of the total Rs27 crores allocated to DNES will be spent on R&D of a-Si photovoltaic cells, say Dayal.

Meanwhile, the newspaper reports, a 1-megawatt-per-year pilot plant will soon be ready. The design and process technology was developed in India, although the equipment and some of the sophisticated components will be imported. Dayal pointed out that development of a-Si technology has been accepted as one of the national technology missions, but is not clear whether DNES will receive additional funds to complete the project. (Source: Solar Energy Intelligence Report, 14 October 1986, p. 323)

France and Germany to co-operate in amorphous silicon research

French and West German researchers will co-operate in designing a system to produce amorphous silicon material for photovoltaic cells, and display and sensing devices. The effort is being conducted as part of the European Eureka high-technology research programme.

The researchers say they hope to design and build a system able to create enough cells in one year to produce a cumulative 1 peak megawatt of power. The work will be performed by France's Solems and West Germany's Messerschmitt-Bolkow-Blohm (MBB).

At present, Solems - a joint subsidiary of Total Oil, a petroleum corporation, and Saint Gobain, a glass manufacturer - is the only company in Europe working on amorphous silicon for use in solar cells. MBB has expertise in the manufacturing of crystalline silicon photovoltaics. (Source: Solar Energy Intelligence Report, 5 August 1986, p. 250)

Chronar dedicates its 100-KWP a-Si PV plant for Alabama Power

Chronar Corp., Princeton, N.J., USA, has officially dedicated the world's first amorphous silicon photovoltaic power plant, a 33,762 sq. ft, 100-kilowatt (peak) generator located at Alabama Power Co.'s Alabaster, Ala., general services complex. Construction of the plant required approximately six months. It is capable of generating enough power to service the average needs of 25 homes, Chronar says.

The 3.5 acre installation is arranged in eight rows of panels connected in series to produce 250-500 volts. Each row is composed of 22 modules connected together in 11 panel junction boxes. Each module contains 16 of the company's 3-ft x 4-ft solar panels in parallel which produce up to 45 amperes. The panels, manufactured at Chronar's U.S factory in Port Jervis, N.Y., are fixed at a tilt appropriate for top output during the summer peaking time.

The unit automatically turns on at sunrise and off at sundown. The AC-output voltage of the 480-V, three-phase inverter - a 12-pulse utility-interactive unit with a computer monitoring and maximum power tracking system - is transformed to 12,000 V for distribution to the utility grid. The field can produce over 0.5 megawatt-hours per day, Chronar says. (Source: Solar Energy Intelligence Report, 1 July 1986, p. 206)

Amorphous solar cell by laser processing

The Semiconductor Energy Research Institute has developed a laser processing technology for cutting only the outermost layer of a thin metal film formed on the glass substrate. By utilizing this technique, it will be possible to produce an amorphous solar cell with a large area of 40 cm x 60 mm. (Source: Chem. Economy & Eng. Review, October 1985, p. 35)

A-silicon may trigger boom in solar cells

Solar cell technology might dramatically change, a University of Utah physicist believes, if cells were made out of amorphous silicon instead of pure silicon crystals.

In the sun-drenched west, for example, says P. Craig Taylor, solar cells "could become a reliable, economical alternative to energy derived from coal or oil, with the potential of creating a multi-billion-dollar-a-year industry". He feels that "the technological importance of this research ... from the development of sophisticated solar cells to thin film transistors and lasers, should be great".

Silicon is already used in semiconductors and small-diameter solar cells to conduct electricity, he notes. Although amorphous silicon isn't as good as pure crystals in many respects, it can be made thinner, in larger pieces, in fewer steps and cheaper.

"Smaller is better for solid state devices," said Taylor, "but if you're not concerned with miniature electronic circuits and fast switching times, then large areas may have important implications." In the case of solar cells, larger would be better, he feels. But intensive production methods and prohibitive costs have kept the devices small, limiting their use to the recreational market. Many scientists are working to make solar cell devices from amorphous silicon. By evaporating the substance on glass or stainless steel, the product can be divided into any size needed. Amorphous silicon absorbs light better than crystalline silicon, Taylor says, and its efficiency is a "respectable" 6 per cent.

Market captured at 15% efficiency

"If we could increase that efficiency to about 15 per cent, then it's clear that amorphous silicon would capture an important fraction of the solar cell power market. It could amount to many billions of dollars a year if it turns out to be a viable alternative to coal, oil or other forms of energy."

But there are roadblocks. Amorphous silicon displays several unstable qualities, "which appear to be a generic property of the material". For example, exposure to light tends to degrade the material, changing its physical properties and reducing its efficiency. The structural changes are subtle and difficult to find.

Researchers are using the latest techniques of electron spin resonance, nuclear magnetic resonance and laser light to probe the atomic structure. "To get rid of these instabilities," Taylor said, "we have to understand what they are and why they occur. We know 'why' in general, but we don't know enough of the details to answer the question of how to get rid of them."

The 1977 Nobel Prize in physics was given to Philip W. Anderson and Nevill F. Mott for describing disorder in crystalline solids. "But this research," Taylor said, "only gave us a partial solution to the problem of instabilities in a-Si. In a very simple sense the problem is understood, but not in a way that relates to real materials. Nor are the instabilities understood." Taylor's research is supported by the National Science Foundation, the Solar Energy Research Institute and the Office of Naval Research. (Source: Solar Energy Intelligence Report, 15 April 1986, p. 120)

1.2 Polycrystalline silicon

A better way to build efficient solar cells: development of the University of Erlangen-Nürnberg, FRG

A new breed of photovoltaic cell (whose cost will eventually be half that of conventional devices) makes a quantum leap in conversion efficiency and promises a drastic improvement in price-per-watt performance. Using inexpensive polycrystalline silicon as its base material, the cell is about 14 per cent efficient - some 4 per cent better than conventional polysilicon solar cells.

The cell consists of a 1.5-nm layer of silicon dioxide grown onto a p-doped silicon substrate, onto which a grid of aluminium contacts is deposited. An aluminium back contact covers the cell's entire bottom. The key step is the plasma chemical-vapour deposition of an 80-nm-thick silicon nitride film. A mechanical mask, rather than an expensive photolithographic mask, is used to create the metal contacts, which at just 8 μm wide permit current densities as high as 35 mA/cm^2.

Keeping cool. In ordinary solar cells, temperatures of more than 800°C are required for a diffusion process that takes over an hour to make the p-n junction. Moreover, if ion implantation is used with a conventional cell, a high-temperature step is again required - this time to activate the dopants and to anneal damage that ion bombardment causes to the crystal lattice. These processes ultimately have a negative effect on the cell's efficiency.

Thanks to its silicon nitride film, the new cell requires no such steps. For operation, the film must have a high concentration of positive charges at its bottom - the side facing the substrate. These charges set up a depletion region in the substrate as well as a region with a high electron concentration near the substrate surface.

To achieve the high concentration of positive charges, the researchers dip the cell into a solution containing cesium. The region with the high electron concentration, about 10 to 50 nm thick, forms an induced p-n junction.

This region changes, or inverts, the cell's type of conduction - say, from hole to electron conduction - hence it is called the inversion layer. The positive cesium ions greatly increase electron density in the inversion layer, thereby enhancing the layer's conductivity.

The nitride film also protects the delicate silicon surface and the metal contacts from corrosion, contamination, and scratches. Moreover, the film retards reflection, ensuring that as much light as possible reaches the silicon. A textured pyramid surface collects scattered light and further cuts down reflection.

Light penetrating the cell between the contacts produces hole-electron pairs, which are separated by the depletion region's electric field. The holes diffuse toward the back contact while the electrons travel through the high-conductivity inversion layer to the contacts above. Current then flows through the external circuit, its strength depending on the light's intensity.

Continuing development work on the silicon-nitride inversion-layer cell could lead to polysilicon versions with efficiencies up to 17 per cent and single-crystalline types with 19 per cent efficiencies. (Extracted from Electronics, 7 August 1986, pp. 38 and 42)

Polycrystal silicon for solar cell

Osaka Titanium Co. Ltd. has test-manufactured polycrystal silicon with a conversion efficiency of 12.9 per cent (10 cm^2) as a material for a solar cell. It has improved the conversion efficiency by about 3 points by bundling small single crystals to a polycrystal and by removing impurities. (Source: Chem. Economy & Eng. Review, October 1985, p. 35)

Polycrystal type solar cells

The Agency of Industrial Science and Technology will set about development work on production technology for polycrystal type solar cells with high efficiency in fiscal 1987 under the Sunshine Project. The agency will commission Hokusan to develop sheet shape substrate production technology and Hitachi, Sharp Corporation and Kyocera Corporation to develop high-efficienct cell technology. Intermediate evaluation of the development and research will be made at the end of fiscal 1988.

Under the Sunshine Project, amorphous type and crystal type solar cells are being developed with the object of reducing the power generation cost of solar cells to that of the existing power generation systems. The production cost of the present crystal silicon solar cell is ¥1,100-1,300/W, because of a difficulty in reducing the crystal production cost. The production of the amorphous silicon solar cell, which cost is lower than the crystal type, has been given priority in recent years. However, the amorphous type is inferior to the crystal type in light-electricity conversion rate. So, the agency has decided to develop the polycrystal silicon solar cell which has a higher conversion rate than that of the amorphous one.

If the conversion rate is improved by 1 per cent, the cost of the solar cell will lower by ¥70/W. Accordingly, if the conversion rate of the polycrystal type is set at 15 per cent or higher, the cost can be reduced by ¥20/W or more. Since studies on mass-production effects and panel production have been continued with respect to the crystal silicon solar cell, the production cost will drop to ¥550/W or lower, so even with improvement of the conversion efficiency, its cost competitiveness with the existing electric power sources can be raised. (Source: Chem. Economy & Eng. Review, June 1986, p. 32)

2. Other photovoltaic materials

2.1 Gallium arsenide

Soviet GaAs research

A study recently released from Kiser Research Inc., Washington, D.C., USA, titled "The Guide to Soviet Gallium Arsenide Technology", reports that the Soviet Union has developed an extensive theoretical and experimental foundation for the applications of GaAs.

Some of the best research today, says the report, takes place at the Joffe Institute in Leningrad. There, the late D. N. Nasledov, the Soviet father of GaAs, and his associates first investigated the electrical, optical, magnetic and other physical properties of GaAs crystals.

Particularly important past Soviet developments include a method of laser pulse annealing of semiconductor wafers, which was adopted by U.S. manufacturers, and an early appreciation of the optoelectronic properties of GaInAsP. (Extracted from Semiconductor International, February 1987, p. 24)

Thin, lightweight GaAlAs solar cell for satellites

Sharp Corporation has developed a new gallium-aluminium-arsenide solar cell that is extremely thin and light.

GaAlAs solar cells have a high conversion efficiency of 17.6 per cent, much higher than that of the 13.5 per cent of single crystal silicon solar cells. However, since the specific gravity of GaAlAs is more than double that of silicon, electricity generation per gram is only 0.14 Wp, compared with 1.03 Wp for single crystal silicon.

Based on the fact that only the surface of the GaAlAs wafer plays a part in electricity generation, the company attempted to reduce the weight of the wafer by making it thinner.

A solar cell with a wafer consisting of layers of gallium, aluminium and arsenic was fabricated and the wafer side etched with an etching agent consisting of hydrogen peroxide and an aqueous ammonia solution. In about 16 minutes, the thickness of a 2 cm solar cell was reduced from 300 microns to 50 microns. The thickness tolerance was kept within 5 microns. The solar cell side was not etched since it was coated with wax.

The solar cell's conversion efficiency was confirmed to be exactly the same as that of an ordinary GaAs wafer, considerably increasing output per gram from 0.14 Wp to 0.74.

While this performance still falls short of the performance of silicon crystal wafers, it none the less marks a very high conversion rate per unit area, making it highly promising for use in satellites. (Sharp Corporation Public Relations Sect., 22-22, Nagaike, Abeno-ku, Osaka)

(Source: JETRO, February 1986)

Gallium arsenide solar cell nears maximum theoretical efficiency:

A world record for photovoltaic efficiency - 23.7 per cent - has been recorded for one-sun gallium arsenide solar cells produced by Spire Corp. The previous record was 22.2 per cent. One-sun solar cells, which do not require lenses to concentrate sunlight, are useful for supplying electricity to power repeater stations, navigational buoys, pumps for deep wells, and remotely-located refrigeration units for medical supplies. Currently, gallium arsenide solar cells are too expensive for commercial markets, but improved efficiency over silicon solar cells may expand their use beyond current space-based applications.

The flat-plate, 0.5 cm^2 cells are layered with gallium arsenide by metalorganic chemical vapour deposition. Spire, under funding by the Department of Energy, will continue to work toward reaching the maximum theoretical efficiency of 28 per cent to 31 per cent conversion of sunlight energy to electricity. Spire is also investigating high efficiency, radiation resistant indium phosphide solar cells under NASA funding. Various aspects of the design of both types of cells are patentable, and Spire is interested in licensing arrangements.

Spire also offers ion implantation services for gallium arsenide and indium phosphide wafers. Like doping, ion implantation activates semiconductors - but ion implantation offers advantages of more uniform, controllable layering. Available ion species include hydrogen, magnesium, zinc, selenium, titanium and others. Special high-dose, low temperature, and large-area implants are also offered.

(Solar Cells: Electronic Materials Div., Spire Corp., Patriots Park, Bedford, MA 01730. Ion Implantation: Ion Implantation Div., same address.) (Source: Inside R&D, 25 February 1987, p.7)

2.2 Indium phosphorus

Solar cell for satellites

The Nippon Telegraph and Telephone Public Corporation's Ibaraki Telecommunications Research Institute has developed a photovoltaic cell which is highly resistant to radiation and has a high capacity to convert solar energy into electricity.

The cell is made of indium-phosphorus compound semi-conductors. The material is being highlighted as the next generation semiconductor stuff to replace silicon.

The newly developed semiconductor is capable of converting 18 per cent of solar energy into electricity - a world record conversion rate. It is also highly resistant to radiation and has a longer life than the gallium arsenide cells now in use, according to the Institute.

It is expected that the semiconductor will become the power source of a large communications satellite with a life expectancy of 10 years or more. (Source: Asia-Pacific Tech Monitor, January-February 1985, p. 35)

3. New materials and technologies

New materials boost photovoltaic cell efficiency:

Lumeloid, a plastic, and Lepcon, a glass designed by researchers at Phototherm could turn 70 per cent to 80 per cent of the energy from sunlight they receive into electricity. Most photovoltaic cells produce only 15 per cent efficiency. It's this sort of high efficiency that may help push photovoltaics into head-on competition with conventional means of electricity production.

Lumeloid consists of cheap filmlike sheets of plastic covered with conductive polymers. The company won't reveal names of chemicals used to produce Lumeloid, but here's how Lumeloid works: When sunlight hits sheets of the polymer, energy in the light transfers to electrons in the polymer, which escape at one end in the form of electricity. Although the plastic will have to be replaced every year, it's so inexpensive that electricity would still cost only three or four cents/kWh. Commercielly generated electric power runs about 10 cents/kWh. And most photovoltaic cells produce energy for about $1/kWh. Lumeloid will be developed and licensed by Phototherm.

Lepcon, which was a preliminary design to Lumeloid, consists of glass panels covered with array of millions of Al or Cu strips, each less than a micron wide. It works on the same premise as Lumeloid, but Lepcon never has to be replaced. (Source: Inside R&D, 24 September 1986, pp. 6 and 7)

An efficient thermal energy storage material is being developed at the Solar Energy Research Institute (SERI, Golden, Colo.). The polyalcohol-based material absorbs large amounts of solar energy during the day and releases it into a building at night. It has the unusual property of being able to store more energy below its melting point than at its melting point, obviating the need to melt and freeze material for an energy storage cycle. SERI scientist David Benson says that the material has a heat storage capacity that is many times greater than that of masonry or concrete. As a result, a much smaller weight is needed to store solar heat. Until now, storage has been the weak link in the use of solar energy. (Source: Environmental Sci-Technol., Vol. 21, No. 3, 1987, p. 223)

New-type solar cell

A group headed by Professor Tsubomura at Osaka University has developed a basic technique for a wet type photocell which can convert solar light energy into electric energy by immersing semiconductor matter in liquid. This technique provides a possibility of producing a cell with an energy conversion efficiency comparable to that of the current silicon solar cell. The group will start the development of a new process solar cell. (Source: Chem. Economy & Eng. Review, October 1985, p. 35)

Faster, cheaper photovoltaic silicon

An argon inductive plasma melting technique, developed at Electricité de France, allows ultrapure photovoltaic silicon to be obtained 100 times faster than by the present zone melting methods. Bars of metallurgical-grade silicon move at 8,000-9,000° K through a plasmagenic fluid containing oxygen. The layer of slag formed on the surface and which contains the impurities - mainly boron - "migrates" to the ends of the bar. The purification factor reaches 20,000 in just four runs and can be controlled by the amount of oxygen in the plasmagenic fluid. Present zone melting techniques require silicon bars which are already highly purified: up to 99.9 per cent in certain cases. Here, a 98 per cent prepurification is enough. An overall yield of 80 per cent is attained, versus only 20 per cent with chemical techniques. Per kilogram of photovoltaic silicon, energy consumption is four times less (50 to 100 kWh). The process being tested in the laboratory purifies silicon bars having a cross-section of 10 cm^2. A 100-kW plant would allow treatment of 20 metric tons of silicon per year. This technique would offer photocell manufacturers the chance to use metallurgical-grade silicon directly as raw material. (Source: Sciences and Techniques in French, February 1984, p. 66)

4. Applications

Soviet solar central receiver begins generating electricity

The 5-megawatt (electric) Soviet solar power plant being built in the Crimea has started to feed electricity to the national grid. So far, half of the 1,600 heliostats, each measuring 25 m^2, and computer-controlled to track the sun, have been installed.

The complete plant will have 20 circles of mirrors covering 40,000 m^2 to focus the sun's rays on a boiler 80 m above the ground on a tower. Water in the boiler will be heated to 256°C (493°F), producing steam to drive a conventional turbine. Surplus hot water is kept in insulated vessels under pressure for release as steam on cloudy days.

The plant, on the shores of the Sea of Azov near the village of Mysovoye has some 2,300 hours of sunlight per year. The cost of electricity from the plant is expected to be approximately twice the average, but this is seen as acceptable for a project designed to test new technology.

Plans are already under way to build a bigger plant rated at some 300 MWe in Uzbekistan, where sunlight totals 3,000 hours yearly. This generator will have 72,000 heliostats and a boiler placed on a 200-m tower. The unit will produce just 100 MWe at first, with a 200-MWe fossil fuel backup system. Elsewhere in Uzbekistan, a solar-powered metallurgical works is being built near Tashkent. (Source: Solar Energy Intelligence Report, 25 November 1986, p. 372, written by Judith Perera)

Russians look to space for solar power plants

Russian experts calculate that it is possible to build solar power stations in space to provide electricity for the Soviet national grid. They believe they can design a medium-sized station with a capacity of 100,000 to 500,000 kilowatts.

The stations would convert the sun's energy into electricity in the way most spacecraft do today. But it would then be converted to radiowaves and transmitted to ground-based receiving stations, which in turn would reconvert it to electricity. The idea was first proposed by an American scientist.

According to Yuri Zaitsev, the departmental head in the Space Research Institute of the Soviet Academy of Sciences, one quarter-metre of solar panel battery produces between 140 to 170 watts.

He estimates that an orbital power station capable of generating 500,000 kilowatts would have a mass equal to tens of thousands of tons. It could be built by arranging solar batteries in panels of about five square kilometres each. The development of continuous strips of solar cells are reducing that mass and the costs; further technical progress would make the economics even more attractive.

Another project under study in the Soviet Union relies on turbo-generators to convert solar energy into electricity. Giant mirrors in space would trap solar rays, beam them to a helium boiler on earth, heating the gas, which would then turn the blades of a generator to produce electricity.

Both those methods require conversion of energy into a form capable of transmission from space to Earth. That, according to the Russians, could be done in two ways: by laser beams or super-high-frequency (SHF) radiation.

The advantage of laser beams lies in the feasibility of developing a very narrow ray, which would need comparatively small transmitting and receiving equipment. But a great amount of energy would be lost during the conversion processes.

On the other hand, the SHF radiation, which the Russians prefer at this stage, has no problem passing through the atmosphere and conversion losses are much smaller.

But, to ensure the high efficiency of energy transfer in the SHF waveband, most of the energy flow would have to be concentrated in a narrow angle. That would require aerials in space at least 100 times bigger that existing ones on Earth which, in turn, would need to be as large as the power plant in space.

The Russians have worked out that the most efficient way of placing power stations in space would be to assemble them in a near-Earth orbit and then move them to a geostationary position. That would enable them to generate electricity round the clock.

Soviet scientists have calculated that space power stations would become economically viable only if the cost of placing one kilogram of cargo into orbit could be kept to below 50 roubles. That is about $50, and about one tenth of today's costs.

Other ideas on Soviet drawing boards include giant mirrors in a geostationary orbit to direct powerful light beams towards ground-based sensors and solar cells, which would convert solar energy into electricity. There is even a plan to use solar reflectors to light individual towns. (Source: The Times, p. 18, 9 December 1985, article written by Andrew Wiseman)

Jamaica to get solar test laboratory with help from US-based DSET

Jamaica has awarded a contract to DSET Laboratories Inc. - a New River, Ariz., solar exposure testing facility for solar components, systems and materials - to consult on the design and commissioning of a Solar Test Laboratory for the Jamaican Bureau of Standards.

The project is sponsored by the Jamaican Ministry of Mining, Energy and Tourism and funded in part by the United States Agency for International Development. Its objective is to provide technical support for the Jamaican solar industry and further explore the potential for solar energy applications in Jamaica and the Caribbean Basin.

The new facility, located in Kingston, will include an outdoor solar collector test stand and stagnation rack, indoor thermal systems test bench and data acquisition and reduction equipment. The laboratory is due for completion in mid-1986, DSET says. Personnel from the U.S. firm will supervise installation, train technical staff, and present a series of technical seminars for the Jamaican solar community on the design implications of the test data. (Source: Solar Energy Intelligence Report, 18 February 1986, p. 56)

Advanced low-energy housing

The Thermal Insulation Laboratory at Lygby, Denmark is involved in the International Energy Agency's Solar Heating and Cooling Programme. As part of the IEA work, the laboratory's Peder Pedersen has led an investigation of large site-built roof collectors. Using stock aluminium and designs that save on installation labour, his group has driven down the cost of roof-integrated collectors to the range of US$10 per square foot.

A 55-unit solar development is being monitored to test the thermal performance of various low-energy schemes, including heat-recovery ventilators, insulating and reflecting shutters, superinsulation, sunspaces and thermal mass. Testing a new thermosiphon solar water heater that blends with the skin of the building is also part of the low-energy house project. (Source: Asia-Pacific Tech. Monitor, March-April 1986, p. 42)

Solar power reviewed

The latest world developments in solar power technology were recently reviewed at an international two-day conference in the UK, attended by delegates from countries in Africa and Asia. The event, entitled Applications of Photovoltaics, was held on 12 and 13 September at Newcastle Polytechnic in north-east England, home of the Newcastle Photovoltaics Applications Centre.

Among the speakers was Mr. S. C. Bajpai, of the University of Sokoto, Nigeria, who discussed the cost-effectiveness of the photovoltaic energy plants which it is hoped to establish in Nigeria before the year 2000.

The conference, it was stated, intended to look at both terrestrial and space applications of the solar panel. Countries without a national electricity grid stand to gain substantially from using solar power. In some parts of the world, the point is now being reached where it is cheaper to use solar power than diesel engine generators. (Source: African Tech. Review, September 1985, p. 10)

Storing the scarce sun's heat

Finland's research has concentrated on assessing just how much solar radiation it gets and on storing it for use during the fierce winters. At Helsinki University of Technology, the Solar Energy Group has developed main-frame computer models to judge seasonal heat storage choices. Computer work suggests that seasonally stored solar energy might be delivered for as little as 6 cents to 7 cents per kWh - about the price of conventional fuel in Finland today.

The same group is analyzing performance results from the Kerava Solar Village, a prototype solar district heating project. (Source: Asia-Pacific Tech Monitor, March-April 1986, p. 44)

Salt ponds and PV concentrators

The Engineering Department at the University of Reading, not far from London, is working on small-scale photovoltaic systems and salt-gradient ponds. The aim is to lower the cost of PV systems so that they can be economically sensible for water pumping in the third world. They have tested conventional one-sun cells under focused sunlight and found it worth while to use concentration ratios of up to 10. New insights have been gained about the complex behaviour of salt gradient ponds. (Source: Asia-Pacific Tech. Monitor, March-April 1986, p. 43)

Matsushita has developed a new film-type solar cell that offers 6-9X more power in low light conditions than conventional solar cells. Sunceram II, produced using screen printing techniques, offers energy conversion efficiency of 12.8 per cent/0.8 cm^2, allowing it to power a pocket calculator with a light source as low as a match. It will also drive the calculator from an aircraft reading light, or the dome light of a car. Future applications include powering road signs, irrigation pumps and outdoor clocks. (Source: Fin Post, 12 April 1986, p. 19)

Remote village power

According to Ta-Noo Vicharangsan, chief of the Energy Industry Development Office at the Government's Ministry of Industry in Thailand, 10 500-watt photovoltaic arrays have already been installed as part of the effort. The idea is to give remote villages central power sources. In systems built so far, villagers bring their own batteries to a solar station - the PV array - for charging. Then they use the batteries to power fluorescent lights, radios, tape players or televisions. Each of 10 working stations has cost about US$5,000. (Source: Asia-Pacific Tech. Monitor, March-April 1986)

Solar thermal studies

In the remote town of Alice Springs, Australia, a private company, Australian Solar Ponds has produced electricity from solar ponds. The 1,600 m^2 pond is tied into a 20 kW Organic Rankine Cycle engine (ORC). Its output power: an air-conditioning shed, a nearby homestead, water pumps and irrigation for a vineyard in the parched countryside.

Australia's premier research group CSIRO's Harry Salt began working on a small rockbed for the group's test house and the experiments and computer modelling pointed to a 5-inch-thick slab over a 6-inch deep rockbed as a useful storage system for well-insulated houses in mild climates. (Source: Asia-Pacific Tech. Monitor, March-April 1986)

Thin film solar electric modules replace and charge batteries

Thin film silicon solar electric (photovoltaic) modules function as primary battery replacements in such products as radios, calculators, and smoke detectors. Other common applications include battery charging in remote controls, instruments, tools, and portable computers, as well as products with a liquid crystal display. Photovoltaics produce electricity from sunlight or normal indoor lighting. Power can be built into a product independent of electric cords or batteries. (Atlantic Solar Power Inc., 6455 Washington Blvd., Baltimore, MD 21227, USA) (Source: Machine Design, 6 March 1986, p. 240)

Solar power pack on wheels

With all the advancements and developments in modern technologies, energy needs of many remote rural areas, of even developed countries, away from the power grids are still not met satisfactorily. The main problems encountered are the heavy cost and difficulty in fuel transport over long distance and maintenance of diesel powered generators.

Solar systems have been used to a certain extent to meet the needs of villages and nomadic tribal areas. Here again, protecting the expensive photovoltaic systems from rain and dusty winds is of immense importance. Seriwa's Solar Research Centre in Perth, Australia, has done some work towards this end.

A prototype solar pack was developed for field trials and use by a rural community near Millstream. They already had an adequate water supply powered by windmill, so their Solar pack unit was able to provide extra refrigeration capacity. The basic power services for this aboriginal community were identified as:

- Communications: reliable power for very high frequency for flying doctor and other vital communications;

- Water: pumping for a potable water store;

- Refrigeration: chilled and frozen storage for bulk meat, vegetables and dairy products, and for medication and vaccines;

- Area lighting;

- Battery charging for vehicle use;

- TV/Video: power for a communal set.

The unit, called a 'survival package', is a low-maintenance, energy efficient solar pack housed in a second-hand, insulated cargo container. The container forms a robust, transportable shelter for the electrical equipment.

The photovoltaic array is fixed to the roof of the container and consists of 750 watts of Mobil Solar Corporation ribbon solar cells. The container also holds a 19 kWh battery bank, Dunlop lead-acid, tubular traction type. System voltage is 24 V DC.

An electronic controller prevents over-charging of the battery bank during periods of excess solar radiation, while also ensuring that non-essential loads are disconnected during periods of poor solar radiation. The design load for the system is 4 to 5 kWh per day.

The main power supply is provided in the DC form which the solar cells produce and the batteries store. Matching the demand and supply is thus made easier, as few readily available appliances run on DC. This avoids a repeated problem with communities' diesel generators, which tend to get overloaded in attempts to power many appliances.

The prototype has four chest-type refrigeration units with a total capacity of 600 litres. The equipment is highly efficient with its high level of insulation. It uses 1/4 of the energy than a domestic refrigerator takes to do the same job. The main storage battery and the refrigeration equipment are fixed permanently to the walls and floor of the container and hence can be transported without further modification. The internally mounted transceiver and inverter equipment are packaged separately and stored within the container for transport. The container is normally mounted on two 4.5 m lengths of 203 x 76 mm steel C-channels and bolted to the container sides to ensure stability in high wind speeds. During transport, these channels are stored within the container and are fixed to the floor. (Extracted from Asia-Pacific Tech. Monitor, March/April 1986).

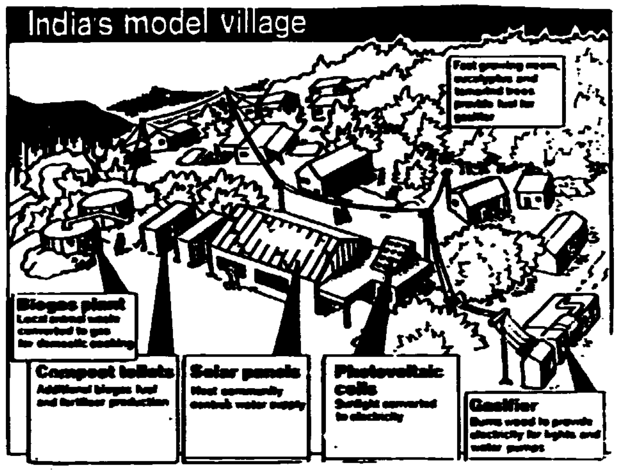
Indian village sets energy example

The little village of Khandia has shown that India could save millions of dollars in its campaign to provide energy to remote areas. To date, says Dr. Manubhai Amin, emphasis has been on large-scale energy projects that require heavy investments in mining, transportation and other development costs. Khandia, he argues, has shown that modest local schemes are just as efficient and much cheaper.

Amin is head of the Gujarat Energy Development Agency (GEDA). The agency was founded to help villages establish non-commercial sources of energy. It took its mandate a step further, creating an integrated system designed to provide all the village's energy by using a combination of small-scale collection methods.

Says Dr. Amin, an industrialist and electrical engineer, "Here is a case study of decentralization to be closely examined. Here production and utilization of energy based on locally available renewable resources of energy are in the hands of the village community itself and not in the hands of government. If the villagers of Khandia succeed, this experiment can change the face of India."

One of the sources of energy is solar energy. Khandia can now have its own public health centre. The centre has a refrigerator run on photovoltaic cells, a 250-litre solar hot water system and a solar still for distilled water. The village also now boasts a community centre with solar-powered television and radio sets.



(Extracted from Action for Development, November/December 1986, written by S. Muthiah)

Solar energy for district hospitals

Electrical power supply has always been a problem in Kissidougou, a district town in Guinea, 600 km east of Conakry. At most, there is power for a few hours in the evening. The fuel supply for diesel generators is also unreliable, apart from the maintenance problems for such generators. Thus the district hospital with 150 beds had to be run almost entirely without any power supply.

During 1984 the hospital was furnished with solar-powered equipment which was considered essential for the hospital. A photovoltaic solar generator with a maximum power output of 770 watts supplies energy for two operating theatre lamps, one refrigerator (45 litres) and twelve fluorescent lamps of 20 watts each. A sufficient battery capacity of 350 Ah permits the system to work continuously day and night. It has an emergency storage unit for 48 hours should there not be enough sunlight for two consecutive days.

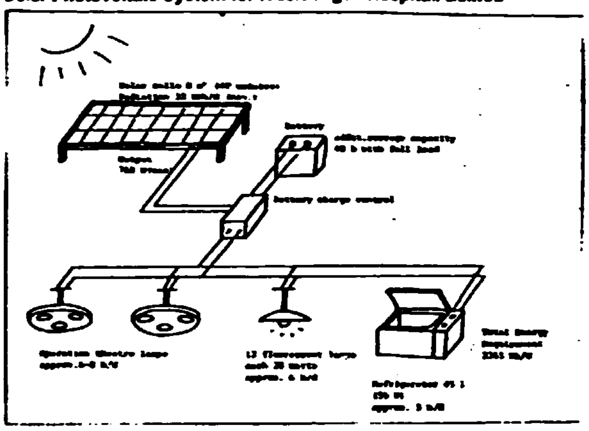
Instrument and dressing sterilisers are essential equipment for the operation unit. For this purpose a solar steam sterilizer (autoclave) was designed using solar vacuum tubes for steam generation. The design is unique and a first prototype was built for the hospital. A solar hot-air instrument sterilizer has also been designed and a prototype built to be tested at the hospital.

This equipment for the Kissidougou hospital and its test run is part of a project which is analysing the energy requirements for hospitals at isolated locations in developing countries and which is looking for ways to use renewable energy sources.

In May 1985 a first summary of the experience gained in Kissidougou was made. The photovoltaic power generation for light, operating theatre lamps and a refrigerator showed very satisfactory results and the system now ensures a 24-hour power supply for the operation unit at the hospital. The special low-powered bulbs for the operating theatre lamp with 3 x 15 watts proved sufficient in lighting strength.

The solar-powered autoclave with high-performance vacuum collectors is regularly used. A kerosene burner can be used should there not be enough sunlight. There is, however, still room for improvement. The distiller which provides the feed water is not efficient and operating the autoclave with several levers requires some experience. These deficiencies resulted in improvements which will be incorporated into the second prototype.

Solar Photovoltaic System for Kissidougou Hospital/Guinea



The hot-air sterilizer prototype went through several test runs and reached a temperature of 160°C under good sunlight conditions. The minimum sterilizing temperature should be 140°C. Except for minor improvements necessary for the handling of the sterilizer, the design can be recommended for use. The design is suitable for local manufacturing. (Extracted from GATE, 4/85, pp. 52-53, written by Walter Jahn, GTZ/GATE Sect. 213, resp. for R&D Projects)

Television runs with solar power

The time has come for the solar power to make inroads into the remote rural areas where it should rightly belong. Attempts to make solar photovoltaic power useful for many domestic requirements are being made throughout the world. A solar photovoltaic (SPV) powered television system has been developed as a result of one such attempt by the Central Electronics Limited (CEL) of India.

The CEL says that its solar television system is an ideal choice for remotely located and inaccessible unelectrified villages in most of the developing countries. The system is easy to install, operate and maintain.

The system consists of a 51 cm size black and white or colour television set, two or more matched solar photovoltaic modules, support frame structure, storage batteries and an electronic controller. The system is designed to operate the television set for a period of four hours every day, irrespective of the environmental conditions. It is claimed to operate successfully even for three consecutive totally sunless days. It is also possible to furnish special television systems receiving signals from satellites.

The SPV powered black and white television systems can be locally installed for about US$1200 to US$1,500/system. The system is ideally suited for mass education, entertainment, information dissemination on agriculture, weather forecast, etc., in remote and inaccessible areas. The technology of manufacturing the CEL SPV television systems is well proven by the fact that for the past several years, more than 250 such systems are operating successfully all over India. The SPV modules and the control electronics are available from all leading SPV manufacturers, including CEL. Television sets, batteries and other hardware are expected to be available locally. The technology of manufacturing the products is offered on license and the engineering, plant installation and start-up on a turnkey basis. (Source: Appropriate Technology Documentation Bulletin, Vol. XIII, No. 4, July-August 1986)

Lights go solar way

The Solar Light from the Thielsch Engineering Associates, Inc. of Rhode Island, USA, is a photovoltaic power lighting system that provides up to 15 hours of light without recharging. It works by collecting electricity from the sun during the day and storing it to provide 1,800 lumens of low pressure sodium light at night.

The standard model includes one 40-watt photovoltaic panel, one battery, controls and mounting hardware for one panel. The Solar Light can be set to turn itself on at night and automatically turn itself off at a pre-set time.

Other models feature two or three photovoltaic panels and additional batteries to provide more light between recharging or to accommodate operation up to three successive days of no sunlight. An optional lamp rated 35 watts at 4,800 lumens is also available. Another option provides power to an electrical outlet located 54 inches above the base. This model includes the standard light for all-night illumination, or reduced lighting hours combined with the operation of other electrical devices. (Source: Asia-Pacific Tech. Monitor, January-February 1985, p. 35)

Photovoltaic pumping unit

The first photovoltaic pumping unit in Greece has become operational on the remote island of Karpathos in the south Aegean Sea. The 10-kilowatt photovoltaic array powers a submersible centrifugal pump. Storage is provided in the form of two large tanks where water is fed to nearby fields for irrigation purposes.

The unit, owned by a local farming co-operative, was financed by the Hellenic Development Bank (ETBA) and the European Community. Total cost reached 50 million Greek drachmes ($375,000), of which 40 per cent was contributed by the EC as part of the demonstration programmes of the Energy Directorate (DG 17) and 60 per cent by ETBA.

System design and installation were handled by Ciceroi Hellas Industries, a unit of BP Greece. The solar field, consisting of 309 PV modules, each rated at 32 Wp, was manufactured by BP Solar Systems Ltd. of the United Kingdom for a cost of 13 million drachmes ($97,500) or $9.70/Wp.

The main system feeding the pump features 273 modules. Another 36 modules form the auxiliary system, which feeds the secondary circuits, including the measuring system, the computer, the controls and lights for the building.

The main system modules are arranged in sections containing seven modules connected in series. Three adjacent sections are connected in series to form a subarray of 21 modules, with a nominal terminal voltage of 330 VDC.

Each section is supported by a galvanized steel framework. The inclination of the modules is 35° towards south. The ground where the solar arrays are mounted is rocky and rough. This has been taken into consideration in the design of the supports, as well as in the way the foundation of the structure is built. The metallic structure is electrically grounded as a protection against lightning. (Source: International Solar Energy Intelligence Report, 3 March 1987)

The following article summarizes the current status, in terms of the technical performance and economic viability, of photovoltaic water pumping. This is based on eight years of practical experience. Technical problems have been largely overcome, although because photovoltaic pumps are not yet in widespread use there is a need for improved routine system selection and provision of maintenance back-up.

Solar pumping: an update

There has been a good deal of interest in solar water pumping for many years. The UNDP and the World Bank sponsored a major global solar pumping demonstration and evaluation programme from 1978 to 1983. (1) This included field trials, laboratory testing and economic analysis. The project assembled reliable technical and economic data from which the appropriateness and viability of solar pumping systems has been assessed. During the course of the project, and in major part as the direct result of it, small photovoltaic (PV) pumps have been developed to the stage where the best can meet all the technical and user prerequisites for wide-scale introduction. There are now many types of PV pumps commercially available and more than 3,000 PV pumps have been supplied worldwide in many successful demonstrations of the technology. The final output of the World Bank project was a Handbook on Solar Pumping. (2) The results reported below are based on an update report recently completed for the World Bank. (3)

Since the global solar pumping project, improvements have occurred, in terms of the performance, efficiency and cost of solar pumps. Photovoltaic pumps can be used in many applications where conventional pumping is generally employed. It is now important that information on the performance and costs of PV pumps is provided to decision makers and prospective institutional buyers of water pumping equipment. This is now happening, for example in the UNDP Photovoltaic Information Programme (4) and the US Department of Energy CORECT activities. (5) UNESCO has also sponsored an evaluation of photovoltaic system appliances for developing countries and the present paper has been prepared as part of on-going activities. (6)

The five principal configurations of PV pumps that are used at present are as follows:

(i) Submerged motor/pump unit, with centrifugal pump, often consisting of several impellers and then termed 'multi-stage'. The number of stages is a function of the lift required.

(ii) Submerged centrifugal pump (alternatively a rotating positive displacement pump of the progressive cavity type) driven by the shaft from a motor mounted at ground level.

(iii) Submerged reciprocating positive displacement pump (also known as a jack pump), driven by a shaft from a motor driven crank or beam ('nodding donkey') at ground level.

(iv) Floating motor/pump unit with centrifugal pump.

(v) Surface mounted motor pump unit, with a self-priming tank. The pump may be centrifugal or positive displacement. Positive displacement pumps have better self-priming properties but are generally less efficient for low head duties.

There are many ways of defining the size or rating of a PV pump. These include the peak photovoltaic array power and peak hydraulic power. Performance varies with solar input and it is the average volume of water delivered per day that is of most interest to potential users. The preferred method of referring to the capacity of a pump is therefore the daily volume of water delivered at the design head and design daily solar irradiation.

It is convenient to consider a daily hydraulic energy equivalent as the product of daily output and head, i.e. m^3/day x m head = m^4/day. Figure 1 presents the capacity range of a selection of PV pumps considered to be "off-the-shelf" systems based on a solar irradiation of 5 kWh/m^2/day. The information is based on data supplied by more than 40 of the principal suppliers. Of course it is possible to design a PV pump to meet any output and head requirements outside this range, but these become special designs, and, as discussed briefly later, high-capacity, high-power systems are mostly not economic. Commercially available systems range from systems with a daily output of as little as 10 m^3/day at three metres head (85 Wp array) to 100 m^3/day at 80 metres head (15 kWp PV array). The presentation used in Figure 1 includes the presentation of hydraulic energy equivalent lines (m^4/day) and also approximate array peak watts (Wp).

Although the donor agencies have financed the installation of a large number of PV systems worldwide, measured performance on systems in the field is still limited. In Mali where more than 80 PV pumps have been installed much experience has been gained. A standard evaluation methodology has been developed. (7) Initially problems were experienced with early installations but systems installed since 1982 have been found to be reliable. One significant factor given to the improved reliability has been the change from systems with surface mounted motors and submersed pumps to that of DC and AC submersible motor pumpsets. Shaft and head bearing maintenance was often a problem. Failures of components have almost always been pump, motor or power conditioning failures. Problems with the PV array have been few.

Statistical data on reliability (such as mean time between failures and percentage time operating) are almost non-existent, but the experience of established users has been that recent installations of equipment supplied by the more experienced manufacturers have been very reliable. Problems experienced with early electronics for brushless DC motors and AC motors are no longer present. Often the problems that have arisen could easily have been put right if someone with a little technical training had been available. Typical failures are not a problem of PV pumps as such, but they do illustrate the problems of introducing technical equipment into rural areas.

Consideration

One problem still not entirely overcome is that of pumps running dry. Some installations have been made where the peak pump output at noon can be greater than the borehole yield or recovery rate such that dry running occurs. Recent problems have also been experienced with very early installations in places where the water table has since dropped. Many systems are fitted with float switches or motor over-speed protection but these have not always proved effective and burning out of motors has then occurred. It should be emphasized that with proper consideration of the borehole or well characteristics such problems can easily be avoided.

The key technical factors emerging from field experience are the importance of reliable performance of the subsystem, and the frequent lack of accurate solar and water resource data, or improper use of such data when available. Many individual systems have exhibited poor performance resulting from errors in these basic data. Accurate information on the depth to the water table and its seasonal variation is particularly important. Fortunately, as experience with systems builds up in a country or a region, solar and water resource information will become more available and better understood.

The key institutional factors are the involvement of the end-user and the availability of technical support. The simplicity of the PV array and the standard technology of pumps has been shown to be easily understood by involved users and host-country technical organizations. Institutional barriers are primarily a function of lack of experience. Again, this problem will diminish as the number of systems in a country increases. The training and involvement of the end-user has been shown on many occasions to be the single most important factor in the maintenance, troubleshooting and management of a PV pumping system.

In addition to the field data much useful data have been collected on the performance of PV pumps from laboratory testing under controlled and reproducible test conditions.

Based on measured performance the efficiencies of [illegible] cal motor/pump subsystems used in solar pumps hav[illegible] n derived and are presented in Table 1.

The efficiency of the sub-system is an important parameter required for system sizing. The lower the system efficiency the larger the PV array size required for a specified application and location. Sub-system performance continues to improve with the introduction of new designs. Whereas the PV solar pumps of those tested in 1980 during Phase 1 the UNDP/World Bank project had average daily efficiencies of around 25 per cent at 7 m head, in 1985 good systems were typically 40 per cent efficient.

Based on the survey of commercially available systems (3) the PV array sizes specified by manufacturers are presented in Figure 2 as a function of pumped water demand.

References

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2. J. P. Kenna and W. B. Gillett "Solar Water Pumping: A Handbook". IT Publications, UK. (1985).

3. I. T. Power. "Solar Powered Pumping Systems: Their Performance Costs and Economics". Contract Report to the World Bank, Washington DC, US. (July 1986).

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7. I. T. Power Inc. "Evaluating the Technical and Economic Performance of Photovoltaic Pumping Systems: A Methodology". Contract Report for USAID (May 1985).

(Much of the material presented in this paper is based on a report prepared by I. T. Power for the World Bank at the 7th European Photovoltaic Solar Energy Conference in Spain in October. Thanks are due to Richard Dosik and the World Bank Energy Department for their help in the preparation of this study, and for their permission to use material from it. The work on which the paper is based is not that of the author but that of his colleagues Anthony Derrick, Jeffrey Kenna, Sarah Lancashire and Matthew Buresch.)

(Source: African Technical Review, March 1987)

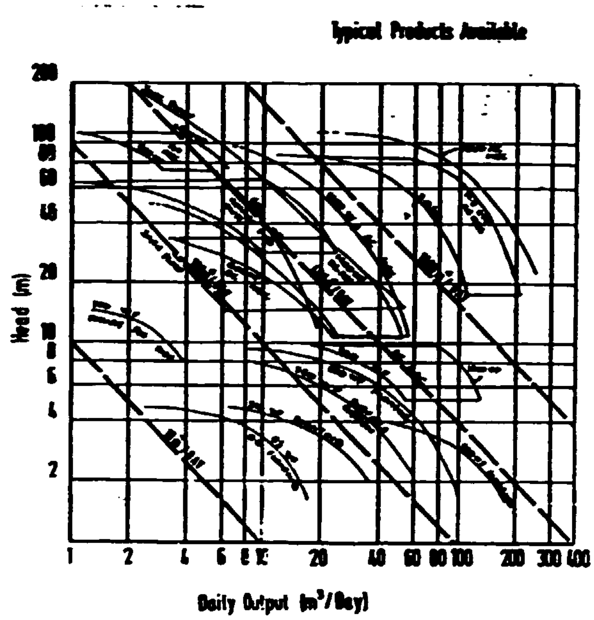


Figure 1. Commercially Available Solar Pumps

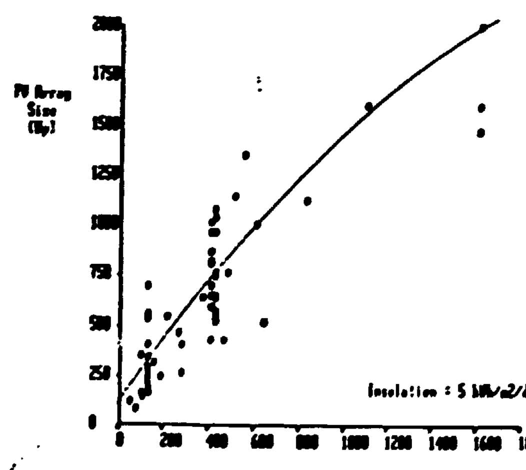


Figure 2. Photovoltaic Array Sizes vs Capacity

Table 1. Efficiency of Typical Motor/Pump Sub-systems (Based principally on test results of references 1 and 4).

Head (m)	Sub-system type	Typical sub-system daily energy efficiency		Typical sub-system peak power efficiency	
		average	good	average	good
2	Surface suction or floating unit with brushed or brushless DC motor and centrifugal pump	10625%	30%≥30%	40%	
7	Floating unit or submerged pump with surface mounted motor brushed or brushless DC motor and centrifugal pump	28%	40%	40%	60%
20	AC or DC submerged multi-stage centrifugal (MSC) pumpset, or positive displacement (reciprocating or rotary) with surface DC motor	32%	42%	35%	48%
50+	Positive displacement (reciprocating) or Positive displacement (rotary) with surface DC motor) and AC or DC MSC submersibles (but not normally ovr 100m)	36%	45%	40%	50%

MARKETING

Consumer goods power photovoltaics

The market for photovoltaic (PV) cells - devices that convert sunlight to electricity - is currently undergoing a shift in applications, technologies, and leading players. Multimegawatt installations that produce power for sale to utilities accounted for less than 10 per cent of last year's $170 million world market - down from 40 per cent in 1983, according to Paul Maycock of Photovoltaic Energy Systems (Casanova, Va.), a market analysis firm. About 60 per cent of the 1985 market went to communications relay stations, water pumping, remote residences, and other off-grid applications. Consumer electronics such as solar calculators, watches, and battery chargers accounted for 25 per cent of sales; this fast-growing segment could claim almost half of a projected $480 million world market by 1990.

In 1985, Japan had 44 per cent of the market, making it the leading producer of PV cells. The US claimed 35 per cent of the market. Atlantic Richfield's Arco Solar (Chatsworth, Cal.) is the world's largest PV manufacturer, with 20 per cent of the market. The other major producers are Sanyo and Fuji of Japan and Amoco's Solarex (Rockville, Md.), each with 10-15 per cent of the market. Other significant US manufacturers include Motorola and Shell's Solavolt International (Phoenix), Pilkington Group's Solec International (Hawthorne, Cal.), Chronar (Princeton, N.J.), Energy Conversion Devices (Troy, Mich.), Mobil Oil's Mobil Solar (Waltham, Mass.), and Spire (Bedford, Mass.), a producer of PV fabrication equipment.

A number of factors lie behind these changes. Growth in the utility-based PV market, located almost entirely in the US, peaked in 1983 and has been dropping ever since. At an average price of $9-$12 per peak watt, solar systems are several times more expensive than conventional power sources, according to Robert Stele of Strategies Unlimited (Mountain View, Cal.). He predicts that unless solar cells become more efficient and cheaper to make, large-scale PV energy will remain uncompetitive for some time. Another drawback is that federal solar tax credits, used to subsidize PV installations, expired at the end of 1985 and are unlikely to be renewed.

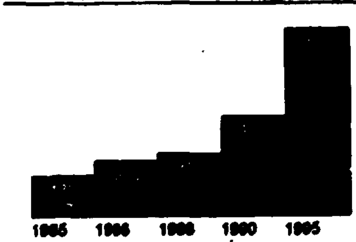
Looking farther down the road, James Caldwell, president of Arco Solar, believes that "within five years, PV manufacturers should be able to cut prices in half. That will lead to a ten-fold growth in the market, particularly for utility and off-grid applications." Zoltan Kiss, president of Chronar, is also optimistic about the current interest of utility companies, at least in research-scale PV plants. "Utilities are aware that photovoltaic power could become more economical in the late 1990s, especially as electricity rates continue to rise, so they want to maintain their experience with PV," he says. "Falling oil prices will not affect this picture, since only 8 per cent of US electricity is generated by oil." In 1985, Chronar sold a 100-kilowatt PV system to Alabama Power and Light, and Arco Solar sold a 300-kilowatt system to the Electric Utility Dept. of the City of Austin (Tex.).

Meanwhile, PV firms are turning to more commercially viable markets, particularly for consumer products. The growing importance of the consumer sector is triggering a shift from single-crystal silicon, the industry standard, to amorphous silicon. Single-crystal silicon devices are relatively efficient and durable, making them most suitable for the outdoor market for power plants, communications equipment, and off-grid locations. In 1985, this material captured 44 per cent of the world market, down from 50 per cent in 1983, according to Maycock.

Amorphous silicon cells are less efficient and have yet to prove their durability in outdoor applications, but their light weight and low cost make them suitable for consumer products. In 1985 amorphous silicon constituted 35 per cent of the market, up from 14 per cent in 1983. Japanese companies took an early lead in commercializing amorphous silicon, but such US firms as Chronar, Energy Conversion Devices, Arco Solar, and Solarex have also moved into this field. "The race now," says Stele, "is to develop new consumer product applications for this material as the market for solar calculators and watches becomes saturated."

Developing nations represent another potentially large, but problematic, market for PV systems. At villages and remote sites with no access to electrical grids, PV devices could power water pumps, refrigerators, communications facilities, and irrigation systems. But financial problems stand in the way of such third world applications. "The barrier here is not so much falling oil prices," says Arco Solar's Caldwell, "as lack of foreign exchange, high inflation, and uncertain availability of financing. When PV cell prices come down, international aid agencies may be more willing to finance PV imports."

World photovoltaic sales ($ millions)



(Excerpt from the article "VOLTS FROM THE BLUE" which appeared in High Technology, July 1986)

Eureka to include Europe-wide amorphous silicon project

Two British companies are supporting Messerschmitt-Bolkow Blohm of the Federal Republic of

Germany and Solems of France in a European-wide venture to make amorphous silicon, a "disordered" form of the element particularly useful in solar cells.

The venture is one of 10 technology projects announced at the end of 1985 under Eureka, the pan-European research programme backed by 18 West European countries.

Edwards High Vacuum of Crawley, Sussex, which is part of the BOC group, and Plasma Technology, based in Wrington near Bristol, have joined forces to develop a range of hardware to make amorphous silicon. The equipment will probably be used in Eureka.

The material is different from the monocrystalline silicon normally used in the semiconductor business. In the latter, atoms of silicon are arranged regularly in an ordered lattice framework. In amorphous silicon, in contrast, the atoms are spread unevenly throughout the material. Predicting the positions of individual atoms is therefore difficult, which increases the problems of turning it into integrated circuits.

In theory, however, amorphous silicon can be produced more easily and cheaply than the better known form of the element. To make the latter, crystals are deposited from molten silicon using expensive machines called crystal pullers.

To make the amorphous variety, atoms from a gas such as silane (silicon hydride) are deposited on to a substrate such as glass or stainless steel.

Companies in Japan and the US, for instance Nippon Steel and Energy Conversion Devisors, have pioneered applications of amorphous silicon.

In particular, this form of the material has become useful in photovoltaics, the conversion of sunlight to electricity in silicon solar cells. Cells made from the amorphous form of the material can be turned out cheaply.

So far, however, little activity in amorphous silicon production has taken place in Europe. This is in spite of the fact that many of the scientific principles behind production were first investigated at two British research centres: STL (the research laboratory of STC, the telecommunications company) and Dundee University.

The two UK companies may also help the European project by collaborating in further research, for instance in how to increase the efficiency of solar cells made from amorphous silicon. (Extracted from *Financial Times*, 23 December 1985)

Joint venture for solar cell

Showa Shell Oil has signed a contract with Arco Solar, a 100 per cent subsidiary of Atlantic Richfield, to introduce the amorphous solar cell technology developed by Arco Solar and to establish Showa-Arco Solar, a joint venture for producing and marketing solar cell products. Arco Solar, the world's largest solar cell manufacturer, has rich experience in large-scale thin-film solar cells. Showa Shell Oil intends to make the new cell available not only for consumer use but also for portable generators and large-scale power generation in the future.

A solar cell which converts solar light directly into electricity is now drawing much attention as a practical electric power source in remote areas. Arco Solar developed in 1984 a Jenesis module (30 x 30 cm) large-size thin film solar cell, and is the first to have opened the way to commercialisation of thin film technology. It is now constructing a fully automatic thin film solar cell commercial plant (10,000 kW) in Los Angeles. The plant is to be completed in 1988. There is a plan to introduce a plant of the same type into Japan after completion of the above.

Meanwhile, Showa Shell had tie-up relations with Arco Solar in 1980, and has manufactured and marketed products utilizing Japanese solar cells. The establishment of a new joint venture with Arco Solar is aimed to utilize its thin film technology and modules for large-scale electric power in Japan, and at the same time to unfold marketing activities in Asia and Oceania.

The market of solar cells last year is estimated at 6,000-7,000 kW, but a rapid increase in demand is anticipated, because their uses are expanding from consumer use to battery back-up power sources for yachts, motor boats, and private aircraft, and further to large-scale power generation plants. Responding to this trend, Arco Solar is developing a 30 x 120 cm thin film solar cell. The annual turnover of Showa Shell's amorphous solar cells last year was about ¥500 million, but sales are expected to greatly increase due to technology introduction and the establishment of joint ventures. The capital of the new company is ¥154 million, of which 75 per cent is borne by Showa Shell, and 25 per cent by Arco. (Source: Chem. Economy and Eng. Review, June 1986, p. 33)

American Cyanamid invests in solar cells

In a move to build up its electronic chemicals business, American Cyanamid has agreed to pay about $38 million for Chesebrough-Ponds' 75 per cent stake in Applied Solar Energy Corp. (ASEC), a $10 million/year producer of spacecraft solar cells and custom-designed photodetectors for medical products and industrial applications. The 75 per cent equity has been purchased in late 1984 by Stauffer Chemical, which - along with its ASEC holding - was acquired by Chesebrough-Ponds in March 1985. ASEC is based at City of Industry, Calif., and the remaining 25 per cent of its stock is publicly owned. It will augment Cyanamid's Electronic Chemicals Dept., which already makes organo-metallic dopants for semiconductors used in solar cells, medical electronic equipment and optoelectronic devices. Comments William L. Perry, president of Cyanamid's Venture Chemicals Div. (which was recently formed to develop growth opportunities in chemicals), "This acquisition represents both an exciting new area for our chemicals business and a significant growth opportunity for Cyanamid." (Source: Chem. Week, 2 April 1985, p. 5)

The Brazil Trade and Industry magazine reports that Heliodinamica put its revenues for photovoltaic exports in 1986 at nearly $3 million, almost double that of 1985. The company has signed contracts for transferring its single-crystal silicon technology to Argentina and India. India is buying 350,000 wafers for $1.05 million.

Five-year solar thermal goals

The US Department of Energy has set what it calls "highly ambitious" long-term goals for solar thermal electricity generating equipment in its five-year research and development plan for 1986-1990.... The plan covers: central receivers, parabolic dishes and parabolic troughs.

For central receivers, the five-year plan sets an annual system-efficiency goal of 20 per cent by 1990 and 22 per cent long-term; a system capital peak cost - including indirect costs, normalized to turbine or process capable of handling peak field thermal output - of $1,800 in 1990 and $1,000 long-term (both in 1984 dollars); a capacity factor of 0.5 both in 1990 and long-term; and a system energy cost (also in 1984 dollars) of 8¢/kWh in 1990 and 4¢/kWh long term.

For dishes, the goals are: system annual efficiency, 17 per cent in 1990 and 28 per cent long term; system capital cost of $2,100 in 1990 and $1,300 long term; capacity factor of 0.26 in 1990 and in the long term; and system energy cost of 7¢/kWh in 1990 and 5¢/kWh long term.

Goals for parabolic troughs, assuming a use only for thermal energy output, are: system annual efficiency, 35 per cent in 1990 and 56 per cent long term; system capital cost, $590/kWht in 1990 $370/KWht long term; capacity factor, 0.24 in 1990 and long term; and system energy cost, $23/mmBtu in 1990 and $9/mmBtu long term.

The Department of Energy adds that system goals are levelized in real dollars; long-term values levelized in nominal dollars, assuming 7 per cent inflation, are 11¢/kWhe and $14/mmBtu. The plan notes the $9/mmBtu process heat long-term target is the levelized cost of delivered energy in the 1990s and is derived from current fossil fuel costs of $5/mmBtu in 1984 dollars.

The goals are based on a number of assumptions: average peak insolation of 0.95kW/sq.m for both electric and thermal systems; average annual insolation, 2,690 kW/sq.m; plant construction time, three years; economic life, 30 years for electric and 20 years for thermal plants; depreciation time, 10 years electric and five years thermal, under the accelerated cost recovery service; investment tax credit, 10 per cent (both of these are covered and could change under the tax bill); real, after tax, discount rate, 3.15 per cent electric and 10 per cent thermal; 1984 base year for prices; 20 per cent of capital cost set aside for indirect cost and contingencies; and cost of land, $5,000/acre for electric, $12,000/acre for thermal.

A more detailed breakdown comparing current status and future goals (separated by a "::"), follows:

Current Technology::Long-Term Component Goals

	Electric(b)		Process Heat(b,c)	
	Annual Efficiency (%)	Cost (1984$)	Annual Efficiency (%)	Cost (1984$)
OPTICAL MATERIALS	88::92	20/sq.m::10/sq.m	88::92	20/sq.m::10/sq.m
CONCENTRATORS				
Central Receiver	55::64	150/sq.m(d)::40/sq.m(d)	55::64	150/sq.m::40/sq.m
Dish	70::78	160/sq.m::130/sq.m	70::78	160/sq.m::130/sq.m
Trough	(e)::(e)	-::-	64::65	200/sq.m::110/sq.m
RECEIVERS				
Central Receiver	90::90	80/sq.m::30/sq.m	90::90	80/sq.m::30/sq.m
Dish	87::90	40/sq.m::70/sq.m	87::95	40/sq.m::30/sq.m
Trough	-::-	-::-	75::90	40/sq.m::30/sq.m
TRANSPORT				
Central Receiver	99::99	45/sq.m::25/sq.m	99::99	45/sq.m::25/sq.m
Dish	93::99	70/sq.m::7/sq.m	93::94	70/sq.m::65/sq.m
Trough	-::-	-::-	98::98	40/sq.m::30/sq.m
STORAGE				
Central Receiver	98::98	25/kWht::20/kWht	98::98	25/kWht::20/kWht
Dish	-::-	-::-	-::98	-::20/kWht
Trough	-::-	-::-	-::98	-::20/kWht
CONVERSION(f)				
Central Receiver	36::39	600/kWe::350/kWe	99::99	50/kWt::40/kWt
Dish	23::41	380/kWe::300/kWe	99::99	50/kWt::40/kWt
Trough	-::-	-::-	99::99	50/kWt::40/kWt
BALANCE OF PLANT				
Central Receiver	NA(h)::NA(h)	65/sq.m::30/sq.m	NA::NA	65/sq.m::20/sq.m
Dish	NA::NA	35/sq.m::20/sq.m	NA::NA	35/sq.m::20/sq.m
Trough	-::-	-::-	NA::NA	35/sq.m::20/sq.m
SYSTEM(g)				
Central Receiver	17::22	2,900/kWe::1,000/kWe	48::56	800/kWt::270/kWt
Dish	13::28	3,400/kWe::1,200/kWe	56::68	780/kWt::430/kWt
Trough	-::-	-::-	32::56	760/kWt::370/kWt
OPERATIONS AND MAINT.				
Central Receiver	NA::NA	12/sq.m-yr::9/sq.m-yr	NA::NA	15/sq.m-yr::9/sq.m-yr
Dish	NA::NA	8/sq.m-yr::10/sq.m-yr	NA::NA	8/sq.m-yr::6/sq.m-yr
Trough	-::-	-::-	NA::NA	15/sq.m-yr::6/sq.m-yr
ENERGY COST(i)				
Central Receiver	NA::NA	0.13/kWhe::0.04/kWhe	NA::NA	21/mmBtu::7/mmBtu
Dish	NA::NA	0.13/kWhe::0.05/kWhe	NA::NA	17/mmBtu::9/mmBtu
Trough	-::-	-::-	NA::NA	30/mmBtu::9/mmBtu

(a) Central receivers use oil, dish near-term electric uses water/steam with sensible heat transport to central engine, dish long-term electric uses helium (high-temperature) with engine at each focal point and electric transport, and dish heat systems use water/steam. (b) Capacity factors are 0.5 central receiver electric, 0.26 dish electric, 0.9 central receiver thermal, 0.28 dish thermal and 0.24 trough thermal. (c) Includes production of fuels and chemicals. (d) Dollars per sq. m of concentrator aperture. (e) No goals for this option. (f) Electric conversion is with heat engines, thermal is with heat exchangers. (g) System costs normalized to turbine or process capable of handling peak field thermal output; includes direct and contingency costs for long term. (h) NA = not applicable. (i) Energy costs levelized in real dollars; last two lines are costs of electricity and heat in the 1990s; in nominal dollars (assuming 7 per cent inflation), the goals are $0.11/kWhe and $14/mmBtu.

(Extracted from Solar Intelligence Report, 1 July 1986)

UNIDO ACTIVITIES IN THE FIELD OF SOLAR-PHOTOVOLTA'

UNIDO reports:

IS.339 1982	Technological Information Profile on Solar Energy Applications by A. Takla
IS.340 1982	Directory of Solar Equipment Manufacturers/Volume 1
IS.341/ Rev.1 1984	Directory of Solar Research Institutes in Developing Countries
ID/WG. 401/5 1983	Responses of Developing Countries to Technological Advances. Some Basic Considerations with Reference to Biomass and Photovoltaics by O. A. El-Kholy

Documents from the Workshop on the Establishment of a Consultative Group on Solar Energy Research and Applications (COSERA), which was held in Vienna, Austria, from 8-10 December 1986.

ID/WG.464/1	Establishment of COSERA: Issue Paper
ID/WG.464/2	State of the Art of Research and Development of Solar Energy Technologies in India by T. K. Moulik
ID/WG.464/3	Solar Energy in Latin America by Ivan Chambouleyron
ID/WG.464/4	Report
IPCT.16 (SPEC.)	A Review of Economic and Technological Requirements of Solar Cells: Status and Research of Polycrystalline thin film devices by T. J. Coutts (Principal Scientist, Solar Energy Research Inst., 1617 Cole Blvd. Golden, Co. 80401, USA)
IPCT.17 (SPEC.)	Solar Thermal Conversion Technologies Trends in Research, Development and Commercialization by W. W. S. Charters (Professor, Mechanical Engineering Dept., University of Melbourne, Parkville, Victoria 3052, Australia)
IPCT.18 (SPEC.)	Study on Amorphous Silicon Solar Cells by Arun Madan (GlastechSolar Inc., 12441 W. 49th Ave., Wheat Ridge, Co.80033, USA
IPCT.19 (SPEC.)	Solar Cell Materials and Fabrication Technologies by K. W. Böer (Professor, University of Delaware, Newark, DE 19716, USA)

Development and Transfer of Technology Series No. 5: Technology for Solar Energy Utilization

* * *

LIST OF UNITED NATIONS AND OTHER ORGANIZATIONS ACTIVE IN THE FIELD OF SOLAR-PHOTOVOLTAICS

UNITED NATIONS ORGANIZATIONS

Division of Human Settlements and Socio-cultural Environment Division, Social Sciences and their Applications Sector, United Nations Educations, Scientific and Cultural Organization (UNESCO)
F-75700 Paris
France

Economic and Social Council, United Nations (ECOSOC)
United Nations Plaza
New York, NY 10017, USA

Energy Department, International Bank for Reconstruction and Development (World Bank) (IBRD)
1818 H Street NW
Washington, DC 20433
USA

Energy Development and Co-ordination Section, Division of Technological Research and Higher Education, Science Sector, United Nations Educational, Scientific and Cultural Organization (UNESCO)
F-75700 Paris
France

International Referral System for Sources of Environmental Information, Programme Activities Centre, United Nations Environment Programme (INFOTERRA)
P.O. Box 30552
Nairobi
Kenya

Library, Economic and Social Commission for Asia and the Pacific (ESCAP)
United Nations Building
Rajdamnern Avenue
Bangkok 10020
Thailand

Natural Resources and Energy Division, Department of Technical Co-operation for Development, United Nations (NRED/DTCD/UN)
United Nations Plaza
New York, NY 10017
USA

Natural Resources Division, Economic and Social Commission for Asia and the Pacific (NRD/ESCAP)
United Nations Building
Rajdamnern Avenue
Bangkok 10200
Thailand

Office of Development Research and Policy Analysis, Department of International Economic and Social Affairs, United Nations (DRPA/DIESA
United Nations Plaza
New York, NY 10017
USA

Pan-African Documentation and Information Service, Economic Commission for Africa (PADIS/ECA)
P.O. Box 3001
Addis Ababa
Ethiopia

Patent Information and Classification Division, World Intellectual Property Organization (WIPO)
34, Chemin des Colombettes
CH-1211 Geneva 20
Switzerland

Statistics Division, Economic Commission for Africa (ECA)
P.O. Box 3001
Addis Ababa
Ethiopia

United Nations Conference on Trade and Development (UNCTAD)
Palais des Nations
CH-1211 Geneva 10
Switzerland

Expanded Programme for Immunisation, World Health Organisation
20 Avenue Appia
CH-1211 Geneva 27

NON-UNITED NATIONS INTERNATIONAL ORGANIZATIONS

Commission of the European Communities (CEC)
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Committee on Data for Science and Technology, International Council of Scientific Unions (CODATA/ICSU)
51 Boulevard de Montmorency
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Council for Mutual Economic Assistance (CMEA) (Soviet Ekonomicheskoj Vzaimopomschi - SEV)
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Gulf Organization for Industrial Consulting (GOIC)
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Organization for Economic Co-operation and Development (OECD)
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75775 Paris Cedex 16
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South Pacific Commission (SPC)
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International Institute for Applied Systems Analysis (IIASA)
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Joint Research Centre, ISPRA Establishment, Commission of European Communities (JRC/ISPRA/CEC)
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(Source: UNESCO, Second edition 1986, "International Directory of New and Renewable Energy Information Sources and Research Centres")

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National Society for Electricity and Gas (Societe Nationale d'Electricite et de Gaz - SONELGAZ)
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Photovoltaic Research Laboratory (Laboratoire de Recherches Photovoltaiques)
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Faculty of Science, University of Tandil (Facultad de Ciencias Exactas, Universidad de Tandil)
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7000 Tandil
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Institute of Solar Architecture (Instituto de Arquitectura Solar - IAS/FABA)
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Private Bag 0036
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Botswana Technical Information Service, Botswana Technology Centre (BTIS/BTC)
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Information Centre on Scientific and Technological Policy, National Council of Scientific and Technological Development, Secretariat for Planning (Centro de Information sobre Política Científica e Tecnológica, Conselho Nacional de Desenvolvimento Científico e tecnológico, Secretaria de Planejamento - CPO/CNPQ/SEPLAN)
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African Intellectual Property Organization (Organisation Africaine de la Propriete Intellectuelle - OAPI)
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National Commission for Scientific and Technological Research (Comision Nacional de Investigacion Cientifica y Tecnologica - CONICYT)
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Divisions of Scientific Research and Experimental Management, Colombian Society of Solar Energy and Non-Conventional Energies (Divisiones de Investigación Científica y de Gestion Experimental, Sociedad Colombiana de Energía Solar y Energias No Convencionales - SOCES)
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Standards and Industrial Research Institute of Malaysia (SIRIM)
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Selangor, Malaysia

University of Science, Malaysia (Universiti Sains Malaysia)
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Penang, Malaysia

Bamako Teacher Training College (Ecole Normale Superieure de Bamako)
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Bamako, Mali

Mali Aqua Viva
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A-San-B.P. 1, Mali

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Sonelec Inc. Hydraulics and Energy Authority (Societe Nationale d'Eau et D'Electricite, Commissariat Hydrologie et Energie)
B.P. 355
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Electric Research Institute, Federal Electricity Commission, Ministry of Energy, Mines and Industry (Instituto de Investigaciones Eléctricas, Comisión Federal de Electricidad, Secretaria de Energia, Minas e Industria Paraestatal - IIE)
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Vicente Guerrero y Escorza
Chihuahua, Chihuahua,
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Central Light and Power Co., Ministry of Energy, Mines and Industry (Compania de Luz y Fuerza del Centro, S.A., Secretariat de Energía, Minas e Industria Paraestatal - CLFC/SEMIP)
Melchor Ocampo 171, D.F. 17, Mexico, Mexico

Centre for Economic and Social Studies of the Third World (Centro de Estudios Economicos y Sociales del Tercer Mundo - CEESTEM)
Coronel Porfirio Diaz 50
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Division of Research and Technological Development, National Centre for Industrial and Technical Education (Division de Investigación y Desarrollo Tecnológico, Centro Nacional de Enseñanza Técnica Industrial)
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General Co-ordination Office, Mexican Petroleum, Ministry of Energy, Mines and Industry (Oficina de Coordinación General, Petroleos Mexícanos, Secretaria de Energia, Minas e Industria Paraestatal - PEMEX)
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Merida Institute of Technology (Instituto Tecnológico de Merida - ITM)
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Mexican Institute of Natural Renewable Resources (Instituto Mexícano de Recursos Naturales Renovables - IMRNR)
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(Source: UNESCO, second edition, 1986, "International Directory of New and Renewable Energy Information Sources and Research Centres")

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2540 Dole St.
Honolulu, HI 96822
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Information Services, Texas State Energy and Natural Resources Advisory Council
ERS Building, Room 509
200 E. 18th Street
Austin, TX 78704
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Lewis Research Center (LEWIS)
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Los Alamos National Scientific Laboratory,
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P.O. Box 176
Jefferson City, MO 65102
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National Academy of Sciences (NAS)
2101 Constitution Ave.
Washington, DC 20418
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National Technical Information Service
U.S. Department of Commerce (NTIS/DOC)
5285 Port Royal Road
Springfield, VA 22161
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New Mexico Solar Energy Institute, State of New Mexico
Box 3 SOL
Las Cruces, NM 88003
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Office of Scientific and Technical Information
U.S. Department of Energy (OSTI/DOE)
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Oak Ridge, TN 37831
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Portland General Electric Co. (PGE)
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Portland, OR 97204
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Power Information Center, Interagency Advanced Power Group, Franklin Research Center (PIC)
20th and Race Streets
Philadelphia, PA 19103
United States of America

Regional Energy/Environment Information Center, Denver State Public Library (DPL)
1357 Broadway
Denver, CO 80203
United States of America

Renewable Energy Institute (REI)
1516 King Street
Alexandria, VA 22314
United States of America

Solar Energy Center, Department of Architecture
University of Oregon
Eugene, OR 97403
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Solar Energy Collection, Library, Arizona State University
Tempe, AZ 85287
United States of America

South Dakota Energy Extension Service, South Dakota State Energy Office
Capitol Building
Pierre, S.D. 57501
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Sun Tech Library and Information Center, Sun Co.
P.O. Box 1135
Marcus Hook, PA 19061
United States of America

Technical Information Service, American Institute of Aeronautics and Astronautics (AIAA)
555 W. 57th Street
New York, NY 10019
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Tennessee Valley Authority (TVA)
400 West Summit Hill Drive
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420 Lincoln Center Drive
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Virgin Islands Energy Office, Virgin Islands Territory Governor's Executive Office
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Electronska Industrija Nis OOUR-RC, Yugoslavia

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Univerza Edvarda Kardelja V Ljubljani)
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Belgrade (Elektrotehnicki Fakultet. Univerzitet U
Beogradu)
Bulevar Revolucije 73
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Faculty of Physics, University 'Kiril I Metodij'
(Fakultet Za Fizika, Kiril I Metodij Univerzitet)
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for Coordination and Programme Orientation of
Development of New and Renewable Energy Sources
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Institute of Research into Pure Science Applications,
Faculty of Technical Sciences, University of Novi Sad
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Australian Solar Ponds
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Alice Springs NT 5750, Australia

Commonwealth Scientific and Industrial Research
Organization (CSIRO)
Box 225
Dickson
A.C.T. 2602, Australia

Solar Energy Research Institute of Western Australia
(SERIWA)
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Perth, Western Australia 6000

National Institute of the Extractive Industries
(Institut National des Industries
Extractives/Nationaal Instituut voor de
Extractiebedrijven - INIEX/NIER
200 rue du Chera
B-4000 Liège, Belgium

Nuclear Research Centre, Ministry for Economic
Affairs (Centre d'Etude de l'Energie Nucleaire,
Ministere des Affaires Economiques)
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Canadian Housing Information Centre,
Canada Mortgage and Housing Corp.
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(Source: UNESCO, Second edition, 1986, "International Directory of New and Renewable Energy Information Sources and Research Centres")

PUBLICATIONS

High-Efficiency Multiple Bandgap Solar Cell Research, L. D. Partain, L. M. Fraas, P. S. McLeod, J. A. Cape, Chevron Research Co., Richmond, Calif. 50 p., AD-A170 965/8/WDE. (Available from National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22161, USA)

Proceedings of MELECON '85 Mediterranean Electrotechnical Conference, Madrid, Spain, 8-10 October, 1985, Vol. 4, Solar Energy, Antonio Luque, A. R. Giguerias-Vadal, D. Nobill, Institute of Electrical and Electronic Engineers Inc., New York, N.Y., 239 p., are available as AD-A171 105/0 from Elsevier Science Publishing Co. Inc., 52 Vanderbilt Ave., New York, N.Y. 10017.

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The following two publications are available from American Solar Energy Society, 2030 17th St., Boulder, Colo. 80302:

Annual Meeting of the American Section of the International Solar Energy Society Proceedings, 1986, Boulder, Colo., K. W. Boer, Gregory Franta, B. H. Glenn, et. al., 541 p. 350 figs.

Eleventh Passive Solar Conference Proceedings, 1986, Boulder, Colo., 572 p.

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Research on Single-Crystal CdTe Solar Cells, Annual Subcontract Report, 1 February 1985 - 1 February 1986, J. M. Borrego, S. K. Ghandhi, Rensselaer Polytechnic Institute, Troy, N.Y., 17 p., DE86010719/WDE.

Les Generateurs Solaires Photovoltaiques: Du Satellite à la Station Spatiale (Photovoltaic Solar Generators: From Satellites to a Space Station), M. A. Ziliani, Societe Nationale Industrielle Aerospatiale, Cannes la Bocca, France, 21 p., text in French, N86-31993/6/WDE.

High-Temperature Composite Thermal Energy Storage for Solar Applications, Draft Final Report, E. T. Ong, R. J. Petri, D. S. Erickson, Institute of Gas Technology, Chicago, Ill., 59 p., DE86014161/WDE.

Potential High-Efficiency Solar Cells: Applications from Space Photovoltaic Research, D. J. Flood, National Aeronautics and Space Administration Lewis Research Center, Cleveland, Ohio, 15 p., N86-32627/9/WDE.

Photovoltaic System Design Assistance Center, Program Description, J. W. Stevens, G. J. Jones, H. N. Post, M. G. Thomas, Sandia National Laboratories, Albuquerque, N.M., 15 p., DE86013669/WDE.

Photovoltaic Membrane (PVM) Roof System, Second-Quarter Technical Progress Report, 1986, T. F. Francovitch, Single-Ply Institute of America Inc., Pasadena, Md., 21 p., DE86013244/WDE.

Materials Issues in Amorphous Semiconductor Technology. Proceedings of a symposium held last April as part of the Materials Research Society Spring Meeting in Palo Alto, Calif., presents controversial issues regarding the electronic structure of hydrogenated amorphous silicon (a-Si:H). Progress was reported in several areas of device technology, especially in increasing solar cell efficiency, in understanding a-Si interfaces and in developing flat-panel displays. The 107 papers cover the topics of solar cells, growth and structure of a-Si alloys, electronic structure and defects in a-Si:H and related alloys, photo-inducted defects, a-Si-Ge and a-Si-C alloys, interfaces, superlattices, thin-film transistors and displays, photoreceptors and image sensors, and optical data storage. Available in a 700-page book from MRS, 9800 McKnight Rd., Ste. 327, Pittsburgh, Pa. 15237, USA.

Heteroepitaxy on Silicon. Proceedings of the first symposium of its kind devoted to the subject, has been published by the Materials Research Society. The symposium, an international forum for this emerging, rapidly developing technology, was held last April as part of the MRS Spring Meeting in Palo Alto, Calif. The 29 papers are divided into topics on growth of gallium-arsenide on silicon, properties of GaAs on Si, heterostructures of semiconductors and insulators on Si, device properties of GaAs on Si and heterostructures of semiconductors and metals on Si. Copies of the 273-page hardbound book, edited by J. C. C. Fan and J. M. Poate, are available from Publications Department, Materials Research Society, 9800 McKnight Rd., Ste. 327, Pittsburgh, Pa. 15237, USA.

Low-energy hydrogen ion implants can help crystalline silicon PV

Low-energy hydrogen ion implants in the fabrication of high-efficiency crystalline silicon solar cells can result in hydrogen-caused effects in the emitter, space charge region and base of a solar cell, researchers at the Pennsylvania State University say.

University Park, Pa., scientists S. J. Fonash, R. Singh and X. C. Mu note that in web, Cz and Fz material, low-energy hydrogen ion implantation can reduce surface recombination velocity. They note that in these materials, the implants were found to passivate space charge region recombination centers. In web cells, hydrogen implants also passivated the base region. However, similar improvement was not seen in the base region of Cz or Fz cells.

Copies of the 60-page report, "Use of Low-Energy Ion Implants in High-Efficiency Crystalline Silicon Solar Cells, Final Report," DE86012364/WDE are available from the National Technical Information Service, 5285 Port Royal Rd., Springfield, Va. 22161, USA.

Development of a CdSe thin film solar cell by E. Rickus, Commission of the European Communities, Brussels, 1985, 64 p.

Holographic thin film systems for multijunction solar cells by W. H. Bloss, Commission of the European Communities, Brussels, 1985, 50 p.

Production of solar cells on the basis of low cost silicon by application of ion implantation and light-induced transient heating by A. N. Larsen, L. D. Nielsen, Commission of the European Communities, Brussels, 1985, 82 p.

Investigation on ion implantation as a technique suitable to fabricate high efficiency silicon solar cells, pt. 2, Ion implanted, laser annealed cell by G. Soncini, F. Zignani, Commission of the European Communities, Luxembourg, 1984, 81 p.

Solar cells for photovoltaic generation of electricity; materials, devices and applications by M. Sittig, Noyes Data Corporation, Park Ridge, N.J., 1979, 350 p.

Integrated thin film solar cell generators with higher output voltages by W. H. Bloss, H. Hewig, Commission of the European Communities, Brussels, 1982, 57 p.

Conversion and chemical storage of solar energy in a photoelectrochemical cell by G. Lepoutre, M. C. Richoux, M. De Backer, Commission of the European Communities, Brussels, 1981.

Alternative thin film solar cells by H. Pauwels, Commission of the European Communities, Brussels, 1982

Energie electrique et radiation solaire; possibilities d'application de cellules photo-voltaiques dans les regions en voie de développement, by Leuven, Atol, 1981, 73 p.

Solar cells, Institution of Electrical Engineers, London, 1978, 95 p.

Solar cells, edited by Charles C. Backus, New York, Institute of Electrical and Electronics Engineers, 1976, 504 p.

GAAS - (GAAL) as solar cells to be used under concentrated solar light conditions, Commission of the European Communities, Brussels, 1980, 29 p.

Directory of UK renewable energy suppliers and services; solar, wind, wave, biogas, biomass, small-scale hydro, geothermal, tidal; including energy recovery, University College, Cardiff. Formerly titled: Directory of UK suppliers and supplies in renewable energy, English, Nonconventional energy sources/United Kingdom/Directories 1986.

Directory of solar energy research projects in India, Tata Energy Research Institute, Bombay, 1978.

Solar Directory, edited by Carolyn Pesko, Ann Arbor, Mich., Ann Arbor Science, 1975.

PAST EVENTS AND FUTURE MEETINGS

1986

15 Nov. Passive Solar Adobe Construction Workshop and Solar Home Tour, Albuquerque, New Mexico, USA (New Mexico Solar Energy Institute, Box 3SOL, Las Cruces, N.M. 88003, USA)

9-11 Dec. Photovoltaic System Design Cape Canaveral, Florida (Florida Solar Energy Center, 300 State Road 401, Cape Canaveral, Fla. 32920, USA)

1987

16-17 Jan. Seri Photovoltaics Safety Conference, Lakewood, Co. USA (Solar Energy Research Inst., Golden, Co. USA)

28-30 Jan. International Conference on Stability of Amorphous Silicon Alloy Materials and Devices, Palo Alto, California. (Solar Energy Research Institute, 1617 Cole Blvd. Golden, Co. 80401-3393)

22-26 March Solar Energy Conference, Honolulu, HI (American Society of Mechanical Engineers, ASME Meetings Dept., 345 E. 47th St., New York, N.Y.10017)

4-8 May 19th Institute of Electrical and Electronic Engineers Photovoltaic Specialists Conferences, New Orleans, La. (Solar Energy Research Institute, 1617 Cole Blvd. Golden, Co. 80401-3393)

8-10 May SOLARMART: Indian Trade Mart for Solar Energy Products, New Delhi (Taj Trade and Technology Exchange, Sales and Marketing, Indian Hotels Co. Ltd., Majal Hotel, Apollo Bunder, Bombay 400039, India)

25-29 May Alternative Energy Sources, Dubrovnik, Yugoslavia (Inter-University Centre of Postgraduate Studies, Frana Bulica 4, YU-5000 Dubrovnik, Yugoslavia)

1-4 June Fifth Annual Renewable Energy Technologies Symposium and International Exposition/International Power Exhibition Conference (RETSIE/IPEC 87)

1-6 June New Materials Expo '87, Beijing, People's Republic of China (China Int. Convention Service Ltd., Harbour Crystal Centre, Suite 602, Tsimshatsui East, Kowloon, Hong Kong)

2-5 June Meeting of the European Materials Research Society, Strasbourg, France (MRS Europe '87, Centre de Recherches Nucleaires, Laboratoire PHASE 67037 Strasbourg Cedex, France)

2-5 June The Materials Engineering Exhibition, Olympia, London (Evan Steadman Services Ltd., The Hub, Emson Close, Saffron Walden, Essex CB10 1HL, UK)

10-12 June Fourth International Aluminium-lithium Conference, Paris, France (Société Français de Métallurgie)

14-18 June International Symposium-Workshop on Silicon Technology Development and its role in the sun belt countries. Pearl-Continental Hotel, Rawalpindi, Pakistan.

12-17 July American Solar Energy Society 1987 Annual Meeting, Portland, Ore. (American Solar Energy Society, 2030 17th Street, Boulder, Co. 80302)

14-17 July IPREX '87. The first Malaysian International Plastics and Rubber Exhibition at the Putra World Trade Centre in Kuala Lumpur. (Sponsored jointly by the Plastics and Rubber Inst. of Malaysia (PRIM) and the Rubber Research Inst. of Malaysia (RRIM).

15-16 July PRIM is also organizing: Developments in the Plastics and Rubber Products Industries; International Conference. (ISE Management Sdn Bhd, 3A Jalan SS 24/8, Taman Megah, 47301 Petaling Jaya, Selangor, Malaysia, TX: 37204 AKMISE MA)

20-25 July Sixth International Conference on Composite Materials and Second European Conference on Composite Materials, London, UK. (F.L. Matthews, ICCM-VI Director, Centre for Composite Materials, Imperial College of Science and Technology, Prince Consort Road, London SW7 2BY, UK)

27-30 July Fourth International Conference on Composite Structures, Paisley College of Technology, Paisley, Scotland. (Conference Dir., Paisley College of Technology, High St., Paisley, Renfrewshire, Scotland PA1 2BE)

29-30 July Twentieth Annual Technical Meeting of the International Metallographic Soc.: Metallography in the Development and Characterization of New Materials, Alloys and Processes, Sheraton Hotel, Monterey, California. (Lockheed Missiles & Space Co., Inc., 1111 Lockheed Way B/151, Dept. 48/93, Sunnyvale, California 90486)

12-14 Aug. Ninth University Conference on Glass Science, Rensselaer Polytechnic Inst., Troy, N.Y., USA. (Center for Glass Science and Technology Materials Research Center, Room 107, Rensselaer Polytechnic Inst., Troy, N.Y. 12180-3590, USA)

16-21 Aug. IUPAC International Symposium on Polymers for Advanced Technologies, Jerusalem, Israel. (Symposium Organizers and Secretariat Orta, Ltd., P.O. Box 50432, Tel Aviv 61500, Israel)

18-20 Aug. Conference on Emerging Technologies in Materials, Downtown Holiday Inn, Minneapolis, Minn., USA. (The Materials Engineering and Sciences Div. of AIChE, Meetings Dept. 345 E. 47th St., New York, N.Y. 10017)

24-27 Aug. Third Ceramics Technical Congress and Exhibition, Ataturk Cultural Center, Istanbul, Turkey. (Sponsored by the Chamber of Turkish Chemical Engineers. Technical Congress of Ceramics, General Secretary of KMO, Konur Sokak 4/1, Kizilay, Ankara, Turkey)

25-27 Aug. Conference on Nondestructive Testing of High Performance Ceramics, Boston, MA, USA. (Sponsored jointly by the American Ceramic Society, Inc., and the American Society for Nondestructive Testing)

26 Aug. - 18 Sept. Workshop on "Materials Science and Physics of Non-Conventional Energy Sources" in Miramara, Trieste, Italy (Prof. G. Furlan, P.O. Box 586, I-34100 Trieste, Italy)

2-6 Sept. SIMMEX 1987 - International Fair on Mining, Energy and Metallurgy, Poznan, Poland. (B. Zalewski, Poznan International Fiar, ul. Glogowska 14, Poznan 60-734, Poland)

7-8 Sept. Symposium on Advanced Materials and Processing Techniques for Structural Applications, Paris, France. (Sponsored by the European Council of ASM [American Soc. of Metals], 27 avenue Trudaine, 75009 Paris, France)

7-9 Sept. International Conference on Science of Ceramics, Canterbury, UK. (Sponsored by the Association Européene de Céramique and organized by the Institute of Ceramics, Science of Ceramics, 14 Shelton House, Stoke Road, Shelton, Stoke-on-Trent ST4 2DR, UK)

7-9 Sept. Third International Conference on Adhesion '87, York, UK. (Carole Franks, Plastics & Rubber Inst., 11 Hobart Place, London SW1W OHL)

9-12 Sept. Asiaplas '87 - Future Trends in Plastic and Rubber Technology, Singapore. (Plastics and Rubber Inst., 11 Hobart Place, London SW1W OHL, UK)

10-19 Sept. International Exhibition "CHEMISTRY" (Polymere), Moscow, USSR. (The USSR Chamber of Commerce and Industry, Sokoinicheski Val, 1-a Moscow 107113, USSR)

13-18 Sept. 1987 International Solar Energy Society Solar World Congress and Exhibition, Hamburg, FRG. (ISES Solar Weltkongress 1987 e.V., c/o Hanseatic Congress Management, Am Weiher 23, D-2000 Hamburg 20, Federal Republic of Germany. Telephone: (040) 40 76 23)

16-21 Sept. International Exhibition on Metallurgy, Foundry & Heat Treatment, Shanghai, China. (Adsale Exhibition Services, 21/F, Tung Wai Commercial Building, 109-111 Gloucester Road, Hong Kong)

22-25 Sept. Conference on New Materials and their Applications, University of Warwick, UK. (Institute of Physics, 47 Belgrave Square, London SW1, UK)

24-30 Sept. World Materials Congress, Chicago, Ill. (American Society of Metals, ASM, Metals Park, Ohio 44073, USA, co-sponsored and participated by scores of societies, associations, institutes, councils, federations, and other organizations from all over the world)

29 Sept. - 2 Oct. Polyurethanes World Congress, Eurogress Center, Aachen, FRG. (Soc. of Plastics Industry)

Oct. International Machinery and Technology Exhibition, Clay and Ceramic Industry, Rimini, Italy. (Ente Autonomo Fiere di Rimini, B.P. 300, I-47037 Rimini, Italy)

10-16 Oct. Materials Week 1987, Strain Hardening of Ordered Alloys, Cincinnati, Ohio, USA. (Sponsored by American Society of Metals (ASM))

13-15 Oct. Materials: Applications and Services Exposition, Cincinnati, Ohio, USA. (Conference and Expositions Dept., ASM, Int. Metals Park, OH 44073, USA)

27-28 Oct. Glass and Ceramics Developments, Hilton Int., Munich, FRG. (Industrial Minerals, Park House, Park Terrace, Worcester Park, Surrey KT4 7HY, UK)

2-6 Nov. International Plastics and Rubber Fair, Sarajevo, Yugoslavia. (Centre Skenderija, Ulica Mice Sokolovia bb, YU-71000 Sarajevo)

11-13 Nov. Sixth International Ferro Alloys Conference, Monte Carlo, Monaco. (Metal Bulletin Inc., 220 Fifth Ave., New York, N.Y. 10001)

15-18 Nov. Eight SERI Photovoltaicr Advanced Research and Development Project Review Meeting. Hyatt Regency Technical Institute, Denver, CO, USA. (Roland Hulstrom, Solar Energy Research Institute, Conference Co-ordination Section, 1617 Cole Boulevard, Golden, CO 80401-3393, USA. Telephone: (303) 231-1158)

15-20 Nov. Symposium on Performance of Composites in Severe Environments, New York. (Sponsored by American Society of Mechanical Engineers Applied Mechanics Division, Composite Committee and Materials Committee)

24-27 Nov. EXPERMAT '87 - International Symposium on Materials, Bordeaux, France. (Sponsored by the Centre d'Etudes des Systemes et des Technologies Avancèes, CESTA, 1 rue Descartes, 75005 Paris)

2-3 Dec. Specialisty Plastics Conference, Zurich, Switzerland. (Maach Business Services, Seestrasse 308, CH-8804 Au/Zurich)

7-10 Dec. Seventh Congress on Composites in Manufacturing, Long Beach, California. (Society of Manufacturing Engineers, P.O. Box 930, Dearborn, MI 48121, USA)

7-10 Dec. International Conference on Powder Metallurgy and Related High Temperature Materials, IIT Bombay, India. (P. Ramakrishnan, Conference Secretariat: Metallurgical Engineering Dept., IIT Bombay, Powai, Bombay - 400 076 India)

14-16 Dec. Eighth Miami International Conference on Alternative Energy Sources, Miami Beach, Florida. (Clean Energy Research Institute, College of Engineering, P.O. Box 248294, Coral Gables, Fl. 33124, USA)

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Advances in Materials Technology: Monitor
Reader Survey

The Advances in Materials Technology: Monitor has now been published since 1983. Although its mailing list is continuously updated as new requests for inclusion are received and changes of address are made as soon as notifications of such changes are received, I would be grateful if readers could reconfirm their interest in receiving this newsletter. Kindly, therefore, answer the questions below and mail this form to: The Editor, Advances in Materials Technology: Monitor, UNIDO Technology Programme at the above address.

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Readers' comments

We should appreciate it if readers could take the time to tell us in this space what they think of the ninth issue of *Advances in Materials Technology: Monitor*. Comments on the usefulness of the information and the way it has been organized will help us in preparing future issues of the *Monitor*. We thank you for your co-operation and look forward to hearing from you.