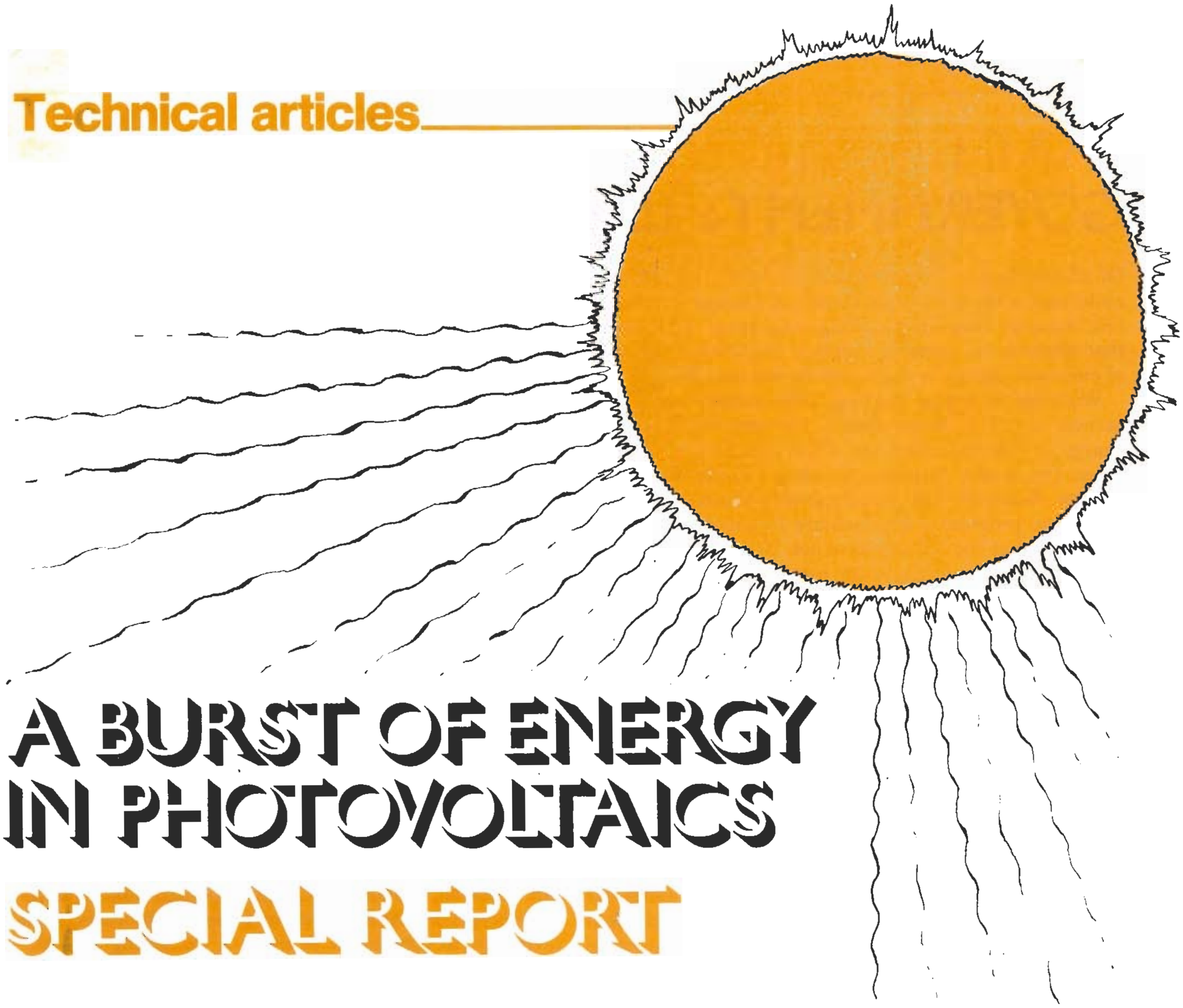


A BURST OF ENERGY IN PHOTOVOLTAICS

SPECIAL REPORT

by John Javetski, *Consumer and Industrial Editor*

☐ Solar cells seem more and more likely to supply part of the world's future energy needs—and to open up a major new electronics market as well. Ever since 1973, when the Arab oil embargo underscored the world's dependence on petroleum, researchers have redoubled their efforts to build a photovoltaic device that can extract electricity from sunlight more cheaply than conventional generators produce it from fossil fuels. Although that goal has yet to be achieved, except for applications in remote locations, photovoltaic cells today are more efficient and inexpensive than ever and promise to become even more so in the future.

To summarize the progress of the last six years:

- The price of a typical commercial solar-cell array has been halved. In 1973, a module that produced 1 watt of electricity under peak illumination at noon cost \$20 to \$30. Today, a module with identical performance and better reliability sells for about \$10 to \$15.
- Conversion efficiencies of cells based on "mature" technologies—single-crystal and polycrystalline silicon, cadmium sulfide, gallium arsenide, and concentrators—have risen dramatically and are now nearing their theoretical maximum.
- The U. S. and other governments have stepped up funding for research programs aimed both at reducing the production cost of today's cells and at identifying new technologies that could eventually become the bases of even cheaper arrays.

Thanks to falling costs, the worldwide market for photovoltaics is beginning to expand. Estimates of its growth rate vary widely, but experts generally agree that annual installed capacity will slowly gather steam and rise from last year's level of about 1 megawatt to at least 5,000 MW by 2000. There is absolutely no argument, however, that, when the market becomes large enough to justify automated mass production of cells, costs will really plummet. That will open up new markets, accelerate sales, and drive prices even lower.

Despite the progress to date, solar cells still have a long way to go before they can begin to satisfy more than a trivial percentage of the world's appetite for electricity. This report will survey the work being done today by researchers in the U. S. and around the world. Their efforts are as diverse as estimates of photovoltaics' potential viability as an alternate energy source, but they do have a common denominator—hope.

PART I

GOVERNMENTS LOOK TO THE SUN

Of all the programs of solar cell development, the most ambitious is the U. S. Department of Energy's Photovoltaic Systems Program. Its long-range goal is to ensure that photovoltaic systems supply a "significant" amount of electrical energy to the nation by the year 2000.

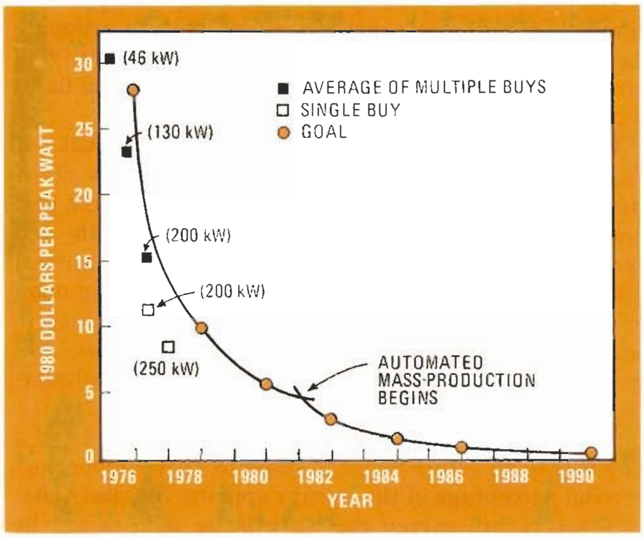
Washington began funding solar-energy research in earnest in 1973. Since then, although the agency in charge of administering the work has changed several times (from the National Science Foundation to the Energy Research and Development Administration to DOE), the program's intermediate targets between now and the end of the century have not.

Figure 1 shows these DOE targets in 1980 constant dollars, namely, to lower the price of solar-cell modules to $2.80 per watt by 1982, 70¢/W by 1986, and 15¢ to 50¢/W by 1990. At those prices in those years, DOE expects photovoltaics to put large dents in the stand-alone, residential, and utility markets, successively.

Ahead of schedule

What are the chances that the goals will be achieved? In Washington, bureaucratic "cautious optimism" is running high. "There's a better probability than ever of meeting the 1982 and 1986 goals," reports Paul Maycock, who has headed the energy technology program since 1977. "In fact," he adds, "we're about one year ahead of schedule," estimating that several soon-to-be-announced Federal buys of arrays should cost an average $5.50/W.

Besides being pleased with this technical progress, Maycock, who formerly handled marketing and product development for Texas Instruments Inc., is also elated that DOE recently recognized the importance of other aspects of photo-voltaic cell technology. First, it added price goals for systems ($6 to $13/W, $1.60 to $2.20/W and $1.10 to $1.30/W, respectively) to its 1982, 1986, and 1990, prices for arrays. Then, late last year, it assigned to its Conservation and Solar Applications branch responsibility for assuring that photovoltaic systems penetrate the various sections of the power market as they become cost-effective.



1. Racing with the sun. DOE hopes to cut the cost of solar-cell arrays to $2.80 by 1982 and 15¢ to 50¢ by 1990. Besides technical progress, the timetable assumes annual photovoltaics sales will grow to 20 MW by 1982, 500 MW by 1986 and 5,000 MW by 2000.

The Conservation and Solar Applications branch is initially authorized to spend $98 million over the next three years on administering the Federal Photovoltaics Utilization Program, which is totally separate from the Photovoltaic Systems Program. FPUP has two immediate goals: to develop the Federal market by encouraging Government agencies to buy photovoltaic systems, and to provide marketing support to commercial solar-cell manufacturers, whose growth is crucial to the ultimate success of photovoltaics.

Those manufacturers, in particular the growing number of wealthy oil companies that now own or subsidize cell manufacturing plants, were undoubtedly in mind when Congress passed Public Law 95-590 last year. The National Photovoltaics Act authorized expenditure of $1.5 billion over the next 10 years for photovoltaic research, development, and demonstration—a long-term program that is viewed by industry observers as an invitation to companies to make a marketing commitment to photovoltaics by investing in much-needed mass-production capacity.

Funding through the act, which becomes the authorizing legislation for the Photovoltaic Systems Program, will heavily favor the development of technology for the next few years and then gradually shift to emphasize demonstration projects in the field. Although that weighting irks commercial suppliers a bit, it delights research workers.

Small-scale integration

Whatever the act's eventual implementation, its philosophy parallels DOE's recent administrative decentralization of its photovoltaic effort—the creation in effect of a new middle level of management that will be responsible for integrating related parts of the program. Figure 2 shows the result: the inclusion in the organization of two supervisory, or lead, centers, the Solar Research Institute (SERI) in Golden, Calif., and the Jet Propulsion Laboratory (JPL) in Pasadena, Calif.

Roughly speaking, SERI oversees program elements involving advanced (and on occasion esoteric) R&D, while JPL is in charge of developing mature technologies. Day-to-day management of the program elements will continue under research organizations like Sandia Laboratories, Albuquerque, N. M., the National Aeronautics and Space Administration's Lewis Research Center in

Foreign governments are banking on sun power, too

The expenditures of overseas governments for photovoltaics development look like small-scale versions of Washington's—with one important difference. Until the passage last year of the 10-year National Photovoltaics Act, the U. S. was the only country with a long-range solar-energy plan not backed by a multiyear funding authorization.

The following list provides an update of the directions and financial support that various nations are giving to photovoltaics activities:

The European Economic Community. Beginning this month, the Commission of the European Economic Community will spend about $24 million over a period of four years on promoting the development of solar cells in its nine member countries. In accordance with usual EEC policy, that sum will be matched by funding from local sources, mainly national governments.

The $24 million will sustain projects now supported by the $10 million injected into photovoltaics by EEC during the last 20 months. That work includes 50 contracts for research and development of technologies that range from placing single-crystal silicon on graphite ribbons to raising the efficiencies and lowering the costs of cadmium-sulfide, cadmium-telluride, and amorphous-silicon cells, as well as cells used in concentrator systems.

More pragmatically, between now and 1983 the commission hopes to build three or four generating plants that will produce 300 to 400 kilowatts of electricity each. Wolfgang Palz, the commission's director-general, sees France and Italy as strong candidates for the new plants, but hopes a northern EEC member like the UK, West Germany, or Denmark will get a shot at one, too.

France. At mid-year, planners at the year-old French Commissariat à l'Energie Solaire (COMES) were busy putting together a long-range program aimed at reducing the costs of solar cells to $1.60 to $2.50/W by 1985, a less ambitious target than the U. S. Department of Energy's. Although the path to that goal has yet to be plotted, the commissariat already has a rough idea of what it will cost to get there. It estimates total funding—including government money, private investment, and help from the European Economic Community—at $115 million. Still to be decided is how much of that sum the French government will contribute.

This year, COMES is spending $4.7 million on photovoltaics, almost triple the $1.7 million it distributed during 1978. And it is not the only French government agency interested in power from sunlight; the Centre National de la Recherche Scientifique (CNRS) and others have budgeted another $4.5 million for 1979.

Over the last three years, the French have shifted their R&D emphasis from programs with long-range goals to those that show greater practical potential in the next few years. These short-term programs include systems studies and work on single-crystal-silicon cells and concentrators. Not to be overlooked, however, is their continued development of less mature cell technologies and low-cost production of silicon ribbons and cast crystals.

West Germany. Bonn's Ministry for Research and Technology, which began supporting the development of terrestrial photovoltaics in 1974, is today aiming the lion's share of its support in one direction, the Bavarian town of Burghausen. There, Wacker-Chemitronic GmbH and AEG-Telefunken are together developing a polysilicon crystallization process that they hope will reach the stage of yielding large quantities of cheap efficient solar cells by the year 1985.

Two years ago, the ministry was so impressed with the cells' export potential that it decided to pick up 80% of the cost of refining the process and building production facilities. Its eight-year bill will be $76 million, a sum that dwarfs its expenditures on other ongoing R&D projects.

Although insignificant by comparison, the German government's funding for other than polysilicon research covers a broad spectrum, including work on amorphous silicon, cadmium-sulfide cells, cadmium-selenide thin films, and cadmium-telluride concentrator cells. Reportedly, Bonn is now considering a post-1985 program of yet unspecified proportions.

Japan. "Mysterious," as in the phrase, "the mysterious East," aptly describes Japan's Sunshine Project, a comprehensive, multibillion-dollar program begun in 1974. For today, the Ministry of International Trade and Industry (MITI), which shepherds the project, will not say how things are going and essentially forbids its contractors to publicize their efforts.

Observers interpret this silence as a sign that the project is progressing slowly. They note that Sunshine's photovoltaics program began in 1974 with the vague goal of "reducing costs to one hundredth or less" and an equally vague timetable: basic research through 1980, design of a pilot production facility from 1981 to 1985, and low-cost power generation sometime during 1986–90. As a result, profit-motivated companies not participating in the project are today considered ahead of the MITI-industry team.

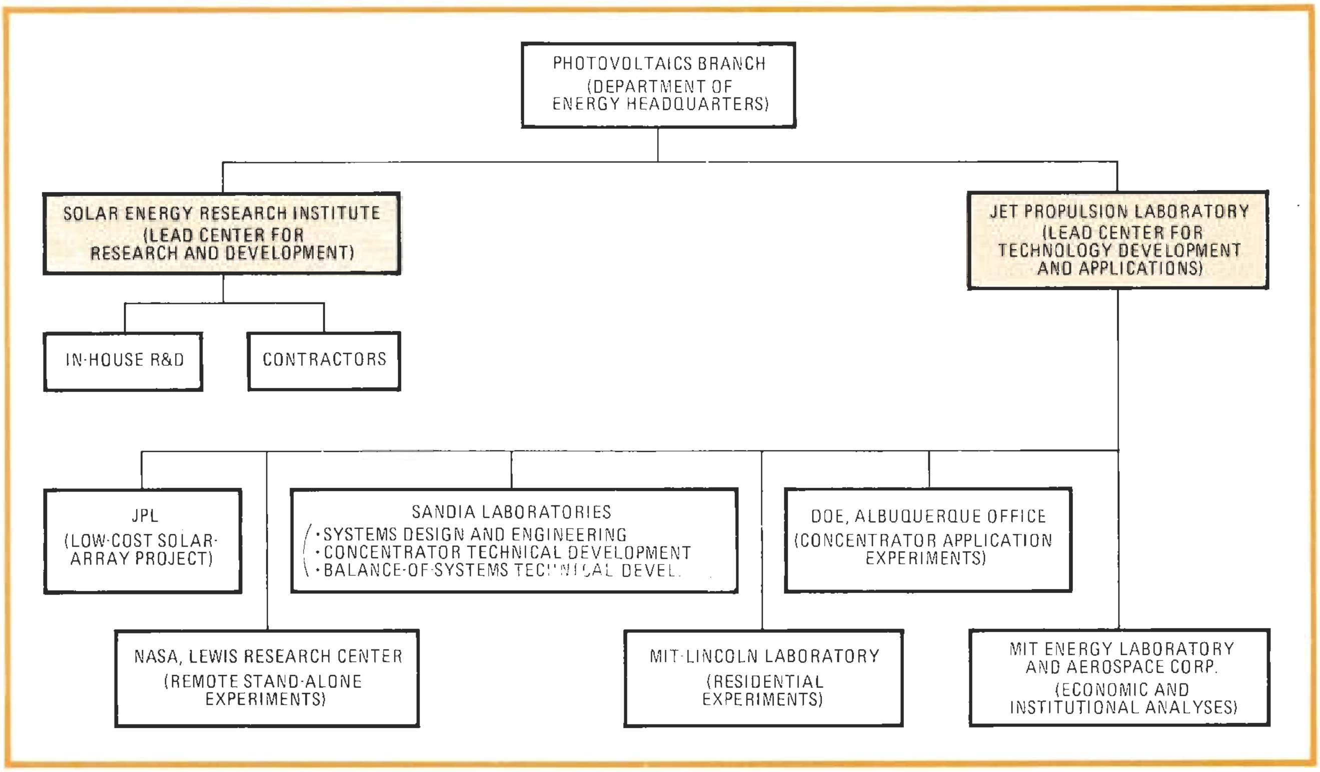
All Sunshine spokesmen will say is that they plan to model a 3-kW station with a mock power source and begin studying its static characteristics this year. Dynamic studies, with real cells, will follow in 1980.

Italy. Rome has been characteristically slow to move on a national solar-energy scheme. Now awaiting the reconvening of parliament is a modest plan, drawn up by the Ministry of Industry, that calls for the total subsidy of rural photovoltaic installations that would not be tied to an electrical grid. According to the plan, 80% of the cost of any such project would be picked up by the government, the remainder being paid for by ENEL, the state-owned utility company.

Great Britain. Unlike Italy, the government of the UK at least has the excuse of perennially clouded skies for its lack of a significant photovoltaics program to compare with DOE's. The British Department of Energy does have a $12 million solar program, but its chief aim is to develop thermal heat-exchange panels. Limited funding for solar-cell R&D in Britain also comes from the Department of Industry, the Science Research Council, and the European Economic Community.

Canada. Its northern latitude is the reason that Canada's solar-energy program is lukewarm toward photovoltaics. But, according to John Simpson of the National Research Council, federal spending for photovoltaic R&D this year amounts to about $1 million. Included in the latter is development of several cells based on polysilicon.

Like the U. S., Canada is now beginning to steer its funding toward more demonstration projects. By 1982, Simpson expects two or three types of polycrystalline cells to be in production. Two years later, with a viable industry in place, Canada should be better able to predict its future in photovoltaics.



2. Decentralization. Research-oriented institutions manage the various elements of the Photovoltaic Systems Program on a day-to-day basis. New to the hierarchy are the lead centers at JPL and SERI, which aim to integrate the work of the projects that they oversee.

Cleveland, Ohio, and the Lincoln and Energy Laboratories of Massachusetts Institute of Technology.

For fiscal year 1980, which begins this October, DOE needs a $130 million appropriation to allow the existing program to continue. But that amount, a modest increase over the $103.5 million being spent in fiscal 1979, is by no means certain to remain intact in next year's Federal budget, which is now in the process of being made final in Congress.

Regardless of the sum finally budgeted for next year, Uncle Sam's financial support for photovoltaics puts other governments' expenditures in the shade (see "Foreign governments are banking on sun power, too," p. 107). However, despite smaller Federal and private outlays overseas, foreign photovoltaic technology is considered serious competition by American solar experts. DOE's Maycock attributes the successes of the West Germans, for example, to their decision to put their eggs in fewer well-chosen technological baskets, a gamble that seems to be paying off, at least in promise.

But, in general, American cell technology still shines brightest internationally, especially in terms of diversity. A good example of that sophistication is the work being done at and for JPL to advance the state of the art of the oldest, most understood solar cell technology: single-crystal silicon.

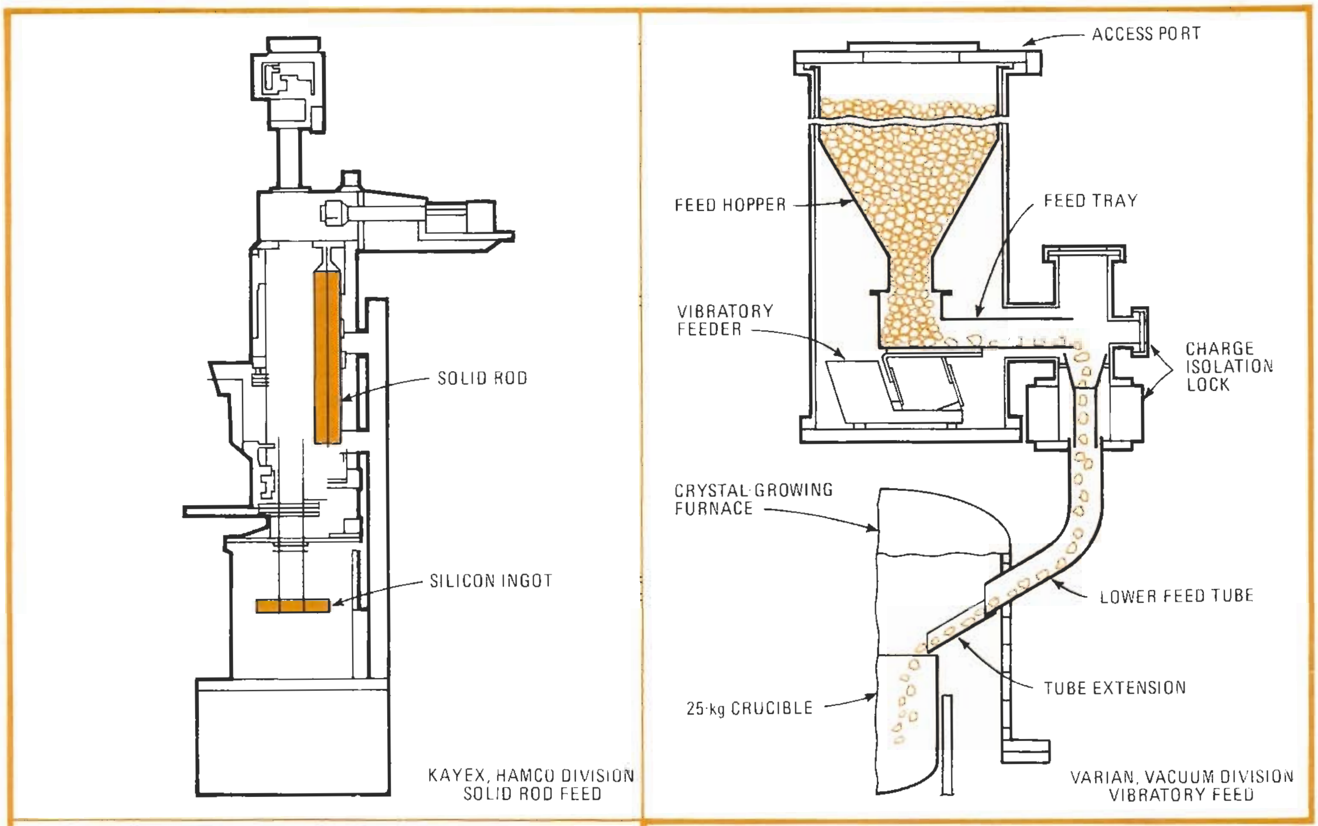
PART 2
THE PUSH TO PRODUCTION IN SILICON

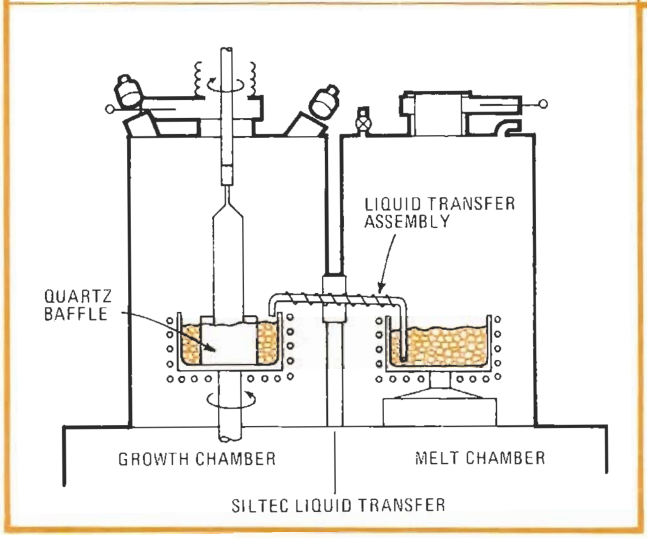
The obstacles to the large-scale manufacture of solar cells are being attacked on every level. The material, its shape, the transparent encapsulant, and the final module, complete with pn junctions and electrical contacts, are all undergoing intense development. In the U. S., the main focus is on conventional crystalline silicon. Elsewhere, amorphous silicon is also coming in for a lot of attention.

The Jet Propulsion Laboratory in Pasadena, Calif., manages the Department of Energy's Low-Cost Solar Array (LSA) project. LSA is grooming one type of cell—single-crystal silicon—to meet the 1982 and 1986 price targets for modules. Since it began in 1975, the project has received consistently strong support from the Photovoltaic Systems Program, reflecting DOE's feeling that the well-understood silicon technology has the best chance of becoming cost-effective in the short term.

Like Gaul, LSA is divided into parts—four, to be exact. These parts, which JPL calls tasks, each aim to reduce the cost of one phase of the evolution of sand into sunlight converter. The four LSA tasks are: the production of polysilicon material, the formation of large crystalline sheets, cell encapsulation, and fabrication.

Task 1, reducing the cost of polysilicon, is considered a





3. Polish pullers. By making conventional Czochralski crystal-growing furnaces rechargeable with liquid or solid polysilicon, three LSA contractors now can pull more than one single-crystal-silicon ingot from a single crucible before it must be discarded.

crucial link in the production chain. Semiconductor-grade (99.999% pure) polysilicon, the feedstock for today's solar cells, now sells for about $65 per kilogram, or about $2.80 per watt in 1980 dollars. DOE hopes to cut that cost to $10/kg by 1982 and, along the way, discover whether so-called solar-grade polysilicon—polysilicon with impurity concentrations below the semiconductor but above the metallurgical grade—could be used to make cheaper cells with acceptable performance.

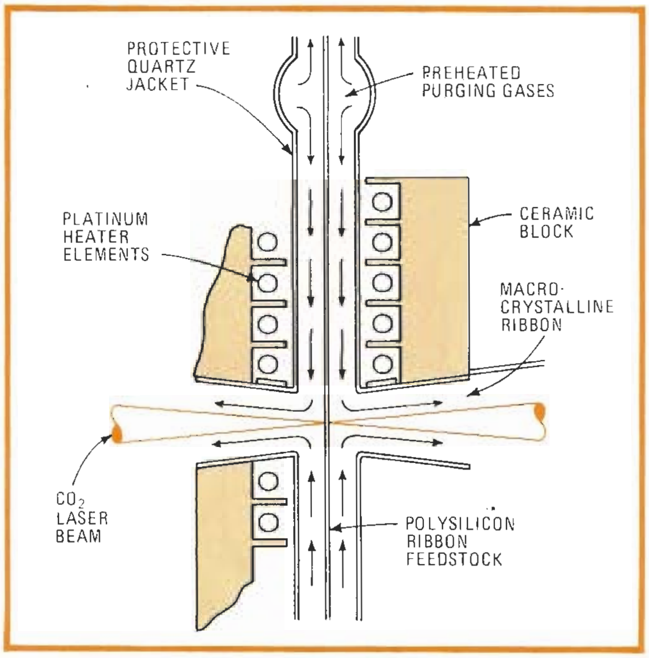
The price of polysilicon is not all that worries DOE. Industry observers say that today's tight market for the material may develop into shortages in the near future. That, they add, will hurt solar cell makers because polysilicon producers will be reluctant to invest $20 million to $40 million in a new plant just to serve a small customer like the fledgling photovoltaics industry.

With price and availability in mind, JPL is funding four low-cost polysilicon production processes (six others were dropped last October). Of these four, those of Battelle Laboratories, Columbus, Ohio, and Union Carbide Corp., Sisterville, Wis., are more advanced than those of Westinghouse Electric Corp., Pittsburgh, Pa., and SRI International Inc., Menlo Park, Calif.

Cutting poly's price

Battelle and Union Carbide both produce semiconductor-grade polysilicon—Battelle by zinc reduction of silicon tetrachloride in a fluidized-bed reactor, and Union Carbide by first producing silane from metallurgical-grade (98% pure) silicon and then depositing silicon from it. According to Lamar University of Beaumont, Texas, which JPL uses to evaluate the commercial feasibility of such processes, both approaches stand a good chance of meeting the $10/kg goal when scaled up into plants producing 50 to 100 metric tons a year.

Meanwhile, Westinghouse and SRI International are developing processes that yield solar-grade material. Both rely on sodium reduction of silicon halides and now show preliminary cost estimates of $9.40/kg and $6.20/kg, respectively. To get a better handle on the feasibility of using solar-grade polysilicon for cells, JPL has five contractors looking at the tradeoffs between purity and cell performance. They are: Aerospace Corp., Los Angeles; the National Bureau of Standards in



4. Ribbon to ribbon. Motorola converts fine-grained polysilicon feedstock into large-grained, macrocrystalline ribbons by heating and then recrystallizing them with a gas laser. This process requires no crucible or die and has a high throughput rate of 55 cm^2/min.

Gaithersburg, Md.; C. T. Sah Associates, Urbana, Ill.; Lawrence Livermore Laboratory in Lawrence, Calif.; and Solarex Corp., Rockville, Md.

Task 2 of the LSA project is to reduce the cost of transforming purified polysilicon into large sheets of single-crystal material suitable for cell fabrication. DOE sees this step as having great potential for cost reduction—from a whopping $5.85/W in 1976 to a hoped-for 94¢/W by 1982.

Ingots versus film

Today, JPL is funding several different processes [*Electronics*, Sept. 28, 1978, p. 97] that yield single-crystal silicon in one of three forms: ingots, shaped ribbons, or sheets. Although "pleasantly surprised" that Czochralski crystal growing—the technique used to make ingots for semiconductor manufacturers—continues to show progress, JPL expects that in the long run ingot technologies will cost a few cents more per watt than the newer ribbon and film processes.

The ingot growers—Kayex Corp.'s Hamco division in Rochester, N. Y., Siltec Corp. in Menlo Park, Calif., and Varian Associates' Lexington (Mass.) Vacuum division—are all modifying conventional Czochralski crystal-pulling furnaces to make them rechargeable with molten silicon (Fig. 3). That would allow extraction of more than one ingot before cooling the furnace, a procedure that inevitably cracks and destroys the expensive crucible in which the crystal grows.

Crystal Systems Inc., Salem, Mass., also makes ingots, but by casting them [*Electronics*, July 20, 1978, p. 44]. Its heat-exchanger method now yields 15%-efficient square ingots that, when sliced into cells, greatly improve the packing density of finished arrays. President Fred Schmid adds that their shape is not his ingots' only selling point: "Our process requires one third less power, material, and labor than Czochralski," he claims. Now producing 4-in.^{2} ingots, Schmid hopes eventually to increase their cross section to 12 in. on a side.

Crystal Systems also has a Task 2 contract to reduce the considerable (typically 50%) waste incurred in slicing ingots into wafers and then polishing or etching them to remove surface damage. It is using a multiwire sawing technique that yields up to 64 4-mil-thick wafers per linear inch of ingot and should eventually be able to reduce ingot waste to 33%. Other companies with ingot-wafering contracts are Varian, for multiblade slicing with an abrasive slurry, and Siltec Corp. and Silicon Technology Corp., Oakland, N. J., for inner-diameter sawing with fixed-diamond abrasives, today's prevalent sawing technique.

One way to eliminate the ingot-wafering step completely is to grow the crystalline silicon directly as thin ribbons or films. JPL is backing the work of four contractors in this promising area: Mobil Tyco Solar Energy Corp., Waltham, Mass.; Motorola Inc.'s Semiconductor Products group, Phoenix, Ariz.; Westinghouse Electric Corp.'s Research Center, Pittsburgh, Pa.; and Honeywell Inc.'s Corporate Technology Center, Bloomington, Minn.

Mobil Tyco, Motorola, and Westinghouse use different techniques to grow ribbons, but all three need to boost the throughput of their process and the conversion efficiency of their product before they can meet DOE's 1982 and 1986 cost goals. Last year, Westinghouse set a new record of 16% for ribbon efficiency with its dendritic-web process, while Motorola raised the growth rate of its ribbon-to-ribbon (RTR) process (Fig. 4) to 55 cm^2/min. Mobil Tyco, which already licenses its edge-defined film-fed growth (EFG) process to Japan Solar Energy Corp., can now pull five 2-in.-wide ribbons simultaneously from a single crucible.

Rather than make ribbons, Honeywell produces its films by dip-coating inexpensive carbon-coated ceramic substrates in molten polysilicon. Since its process consumes very little silicon, its target throughput rate for cost-effectiveness (0.15 cm/s) is lower than that for ribbon-growing techniques. To date, Honeywell has produced 2-cm^2 cells with an efficiency of 5.5%.

The crucible

As all of the processes described so far require either a refractory crucible to hold the molten silicon or a refractory die to shape it, JPL has also let several Task 2 contracts for the development of suitable die and container materials. These materials have to be: low-cost; mechanically stable at temperatures above 1,400°C, the melting point of silicon; not contaminating to silicon; and malleable with close tolerances. One material with all four of these properties is silicon nitride, so Battelle Labs, RCA Laboratories, Princeton, N. J., and Eagle-Picher Industries Inc., Miami, Okla., are working on it.

Unlike the solar cells used to power satellites in space, a relatively benign environment, terrestrial photovoltaics must survive moisture, salt spray, animals, vandals, ice, and snow. The objective of Task 3 of the LSA project is to develop a low-cost module-encapsulation system that can be expected to last for a period of at least 20 years.

JPL expects that the most difficult problem in this area will be protecting the module's sunlit side while maintaining transparency. It is keeping its options open as to what form the transparent element will take, but several candidate materials—glass and various polymers—already look promising. Nine contractors now are working on encapsulants, notably Motorola, on an antireflective coating for soda-lime glass, and MB Associates Inc., San Ramon, Calif., on development of glass-reinforced-concrete substrates.

Low-cost production

The final step in any solar cell's evolution is its conversion from wafer, ribbon, or film form into a finished multicell module that is ready for installation. That process, which includes creation of the photovoltaic pn junction, addition of electrical contacts, assembly and encapsulation, represents about 35% of the cost of a finished array and cost $8.36/W in 1976.

Today, JPL, backed by studies of mass-production techniques from Motorola, RCA, and Texas Instruments, thinks that this figure can be reduced to a mere 81¢/W by 1986 if plants can be built that can produce 5 to 30 MW of cells annually. Task 4 of the LSA project therefore aims to identify, develop, and demonstrate the feasibility of those processes that can be automated and incorporated into a mass-production sequence.

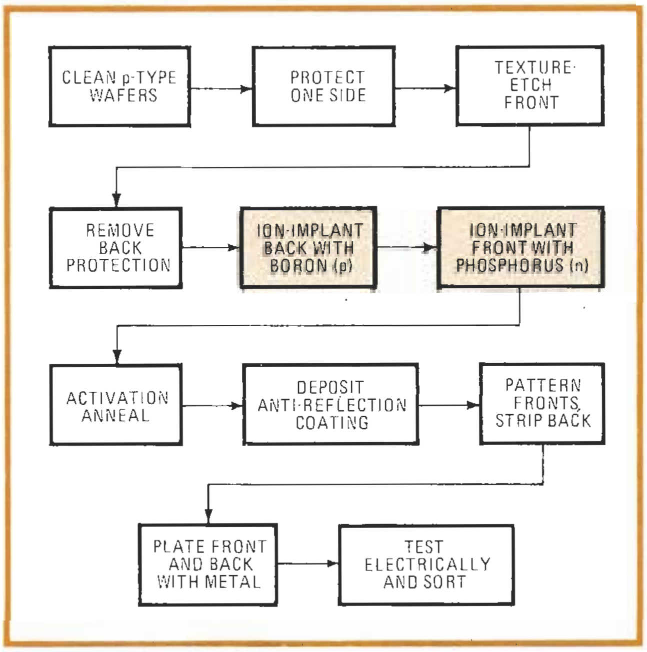
In September 1977, Task 4 went into phase 2, process development. Since then, nine firms have been busy refining their concepts of what the solar-cell production line of the future (Fig. 5) should look like. Included among them are such semiconductor giants as Motorola, RCA, and Texas Instruments, as well as commercial cell suppliers Solarex, Spectrolab Inc., Sylmar, Calif., and Sensor Technology Inc., Chatsworth, Calif.

All the phase 2 contractors report that JPL has made their difficult task a lot easier by developing Samics, the Solar Array Manufacturing Industry Costing Standards computer program. To use it, they phone in their preliminary cost estimate for any step in the process and receive back a detailed analysis, in cents per watt, of what the computer thinks that step will add to the price of a finished array.

JPL itself has used Samics to model a factory of the future, which it calls a "strawman" factory. Results indicate that solar cells with 12% to 14% efficiencies and priced at 56¢ to 69¢/W could be manufactured in such a factory having a capacity of 50 to 250 MW annually.

In the future, Task 4 work will focus on replacing two techniques used to form semiconductor junctions: diffusion of impurities and furnace annealing. Their replacements, ion implantation and laser- or electron-beam annealing, seem promising ways of cutting manufacturing costs, but only if their throughputs can be scaled up. Spire Corp., Bedford, Mass., has already developed a 100-milliampere ion implanter that, according to Samics, should add no more than a penny to the cost of a 1-watt cell.

Meanwhile, overseas cell producers are improving their production processes. In France, the Centre de Recherches Nucléaires in Strasbourg has been working



5. Factory of the future? Once the size of the market for photovoltaics justifies it, companies will begin to mass-produce solar-cell arrays. This typical processing sequence employs ion implantation, rather than diffusion, of impurities to form the cell junctions.

with RTC-La Radiotechnique Compélec, which is based in Paris and is a leading European supplier of single-crystal arrays. Together they are developing a technique that uses pulsed lasers to improve the diffusion of phosphorus into p-type substrates.

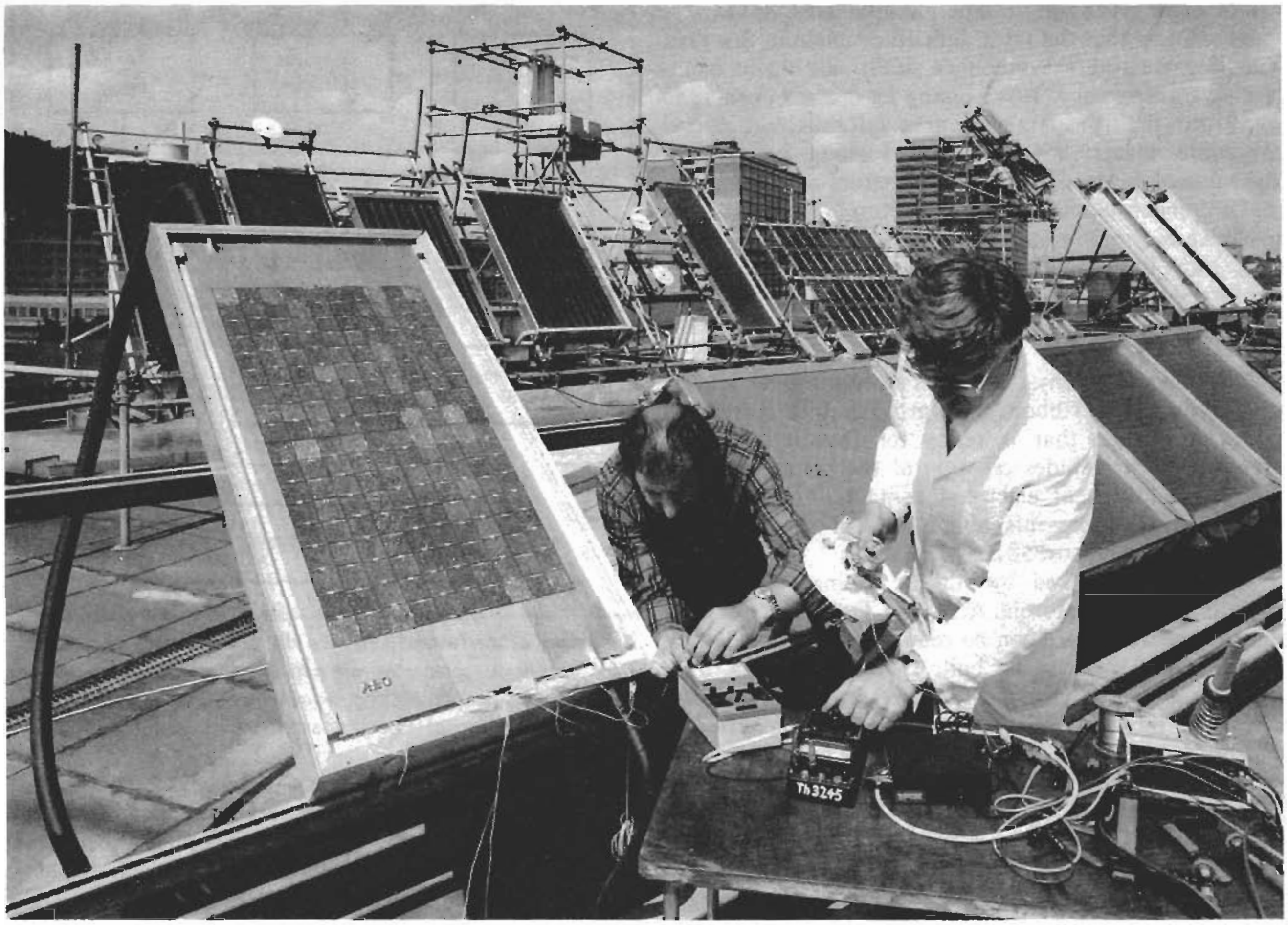
Another French supplier looking into low-cost diffusion techniques is Laboratoires d'Electronique et de Physique Appliquée (LEP), based in Limeil-Brévannes. LEP is depositing indium-tin-oxide (ITO) layers on wafers, and then forming pn junctions with a high-temperature diffusion process. The ITO layers then serve as both electrodes and antireflective coatings.

Poly looks promising

Rather than grow expensive, 0.1-to-0.2 mm-thick single-crystal silicon sheets for solar cells, several companies are investigating placing 20-to-30-micrometer-thick films of polycrystalline silicon on low-cost substrates like graphite. Today, research efforts are focusing on increasing the efficiency of such cells by orienting their crystalline grains vertically, perpendicular to the substrate. This minimizes recombination losses of photogenerated charge carriers, but requires that the grains be at least 100 μm on a side to maximize absorption.

Two firms that seem to have solved the problem are Solarex Corp. and Heliotronic GmbH [*Electronics*, Oct. 26, 1978, p. 68]. Both cast the material for their cells into bricks, a technique that requires less energy than Czochralski crystal growth, has a higher throughput, and lends itself better to automation.

Solarex, which also produces single-crystal silicon arrays, has already set up a production subsidiary, Semix Inc., near its headquarters in Rockville, Md. Within a year, Semix should be ready to make 15%-efficient, 10-by-10-cm semicrystalline cells for $4 to $6/W.



6. Poly panel. German technicians check the performance of an array of polysilicon solar cells. The finished array, made by AEG-Telefunken from semicrystalline wafers cast by Wacker-Chemitronic's Heliotronic subsidiary, comprises 180 5-by-5-cm cells that are 10%-efficient.

Heliotronic, the Burghausen subsidiary of Wacker-Chemitronic GmbH, will produce an inexpensive, fibrous polycrystalline material called Silso, which AEG-Telefunken, Europe's leading supplier of solar cells for space vehicles, will then turn into finished arrays (Fig. 6). Now supplying samples of 10-by-10-cm wafers with efficiencies greater than 10%, Heliotronic hopes to cut prices to 25¢/W within five to eight years by boosting volume.

Elsewhere, work on polysilicon cells remains still in the research stage:

- At Southern Methodist University in Dallas, Texas, chemical-vapor deposition has been used to grow thin films of silicon on recrystallized metallurgical-grade polysilicon substrates. To date, this process has yielded 9-cm^2 cells with efficiencies of 9.5%.
- Motorola in Phoenix uses electron beams to deposit thin polysilicon films on temporary substrates of molybdenum and tungsten. By thermal-shear techniques, it then separates large-area (3.8-by-4.5-cm) films from the substrates and recrystallizes them using lasers.
- In France, LEP deposits polycrystalline-silicon layers on carbon ribbons by pulling the ribbons through zones of molten silicon. However, it is still unsure whether this process will be feasible on an industrial scale.

If single-crystal and polycrystalline silicon are favorites in the solar-cell materials derby, amorphous silicon, which has no crystalline structure at all, is a sleeper. That is because, in the words of Donald Feucht, manager of SERI's Photovoltaic Program office, "amorphous silicon might in the long run be the ultimate low-cost photovoltaic material."

Crystallizing the amorphous future

A relatively new semiconductor material, amorphous silicon has optical and electrical properties that are far different from those of crystalline silicon. For one, amorphous silicon is a strong absorber of light. Cells made from it need be only 1 μm thick, which spells savings in material costs and processing times. And its amorphous structure makes it insensitive to the substrate on which it is deposited, allowing the use of inexpensive materials like glass or plastic.

But, unfortunately, today's amorphous-silicon cells are notoriously inefficient. Despite estimates that conversion efficiencies as high as 15% are possible, the highest reported to date is 6%, by RCA Labs in Princeton, N. J.

RCA produces its amorphous cells, which include metal Schottky barriers on their tops, by using a glow-discharge technique and introducing hydrogen during deposition. Although details of the mechanism are not well understood, the hydrogen atoms apparently attach themselves to the silicon atoms' broken covalent bonds, which are characteristic of any amorphous substance. Thus they reduce recombination of photogenerated carriers that would otherwise occur at those sites.

Today, amorphous-silicon researchers are focusing on two ways to boost conversion efficiency. One is the addition of gases other than hydrogen during deposition to further reduce entrapment of carriers by dangling bonds. A notable proponent of this approach is Stanford Ovshinsky of Energy Conversion Devices Inc., who has used fluorine as a process modifier. Incidentally, Ovshinsky's work recently attracted the attention of Arco Solar Inc., Chatsworth, Calif., an oil-company–backed supplier of single-crystal silicon arrays. Arco Solar has agreed to pay $3.3 million to the Troy, Mich., firm for a nonexclusive license to develop Ovshinsky's technology into a marketable product.

The other efficiency-raising technique is rf sputtering, an alternative to glow-discharge that is well understood and adaptable to automation. Among the researchers in this camp is the Department of Electrical Engineering at the University of Sheffield in Great Britain.

The UK has another proponent of amorphous silicon in Walter E. Spear of Dundee University. Spear's group is now achieving efficiencies of 5%, but he cautions that their work should still be considered experimental because scaling up has yet to be tackled.

Spear also has his own idea of why RCA's progress has not been equalled by other laboratories. "RCA's Schottky-barrier diodes are but a fraction of a square millimeter in size," he says. He also argues that the metal electrodes in Schottky-barrier diodes absorb 75% of the incident light, so such devices can never attain maximum theoretical efficiencies.

Work in Japan

However, low efficiency is not stopping the Japanese from getting on the amorphous bandwagon. Sanyo Electric Co., for example, intends to put amorphous-silicon cells in consumer products like digital clocks and desktop calculators by the spring of 1980. Although its parts convert only 2.5% of the energy from a fluorescent lamp into electricity, the Osaka City–based firm claims that they already are on a par with single-crystal-silicon cells for cost-effectiveness. Eventually, Sanyo hopes to slash production costs to 1% of what it now costs to make a single-crystal cell.

A second Japanese company high on amorphous silicon is Fuji Electric Co., another nonparticipant in its country's Sunshine project. Fuji has developed 7-by-7-cm amorphous-silicon cells that are four times the area of Sanyo's, but comparable in efficiency (2%). Its Schottky-barrier prototypes contain two layers of amorphous silicon, with different percentages of impurities, that rest on a stainless-steel substrate.

PART 3
ALTERNATIVES TO SILICON

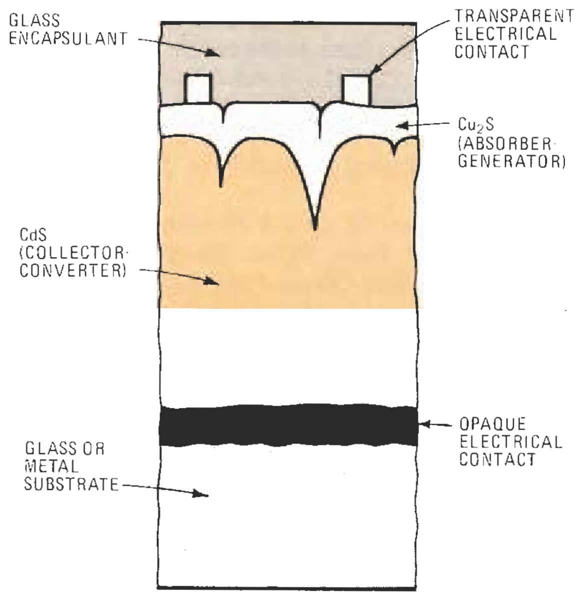
Silicon is not the sole source of solar cells. Many combinations of dissimilar materials, called heterojunctions, and even differently doped layers of the same material, called homojunctions, also exhibit the photovoltaic effect to varying degrees.

Cadmium-sulfide (CdS), for instance, when joined to one of several other materials, forms a solar cell with a theoretical conversion efficiency as high as 16%—and with the potential for low-cost production. Like amorphous silicon, CdS is a strong absorber of light, so that productive cells as thin as 8 micrometers can be made from very little material. But, also like amorphous silicon, most of today's CdS cells generally fall far short of theoretical conversion efficiencies.

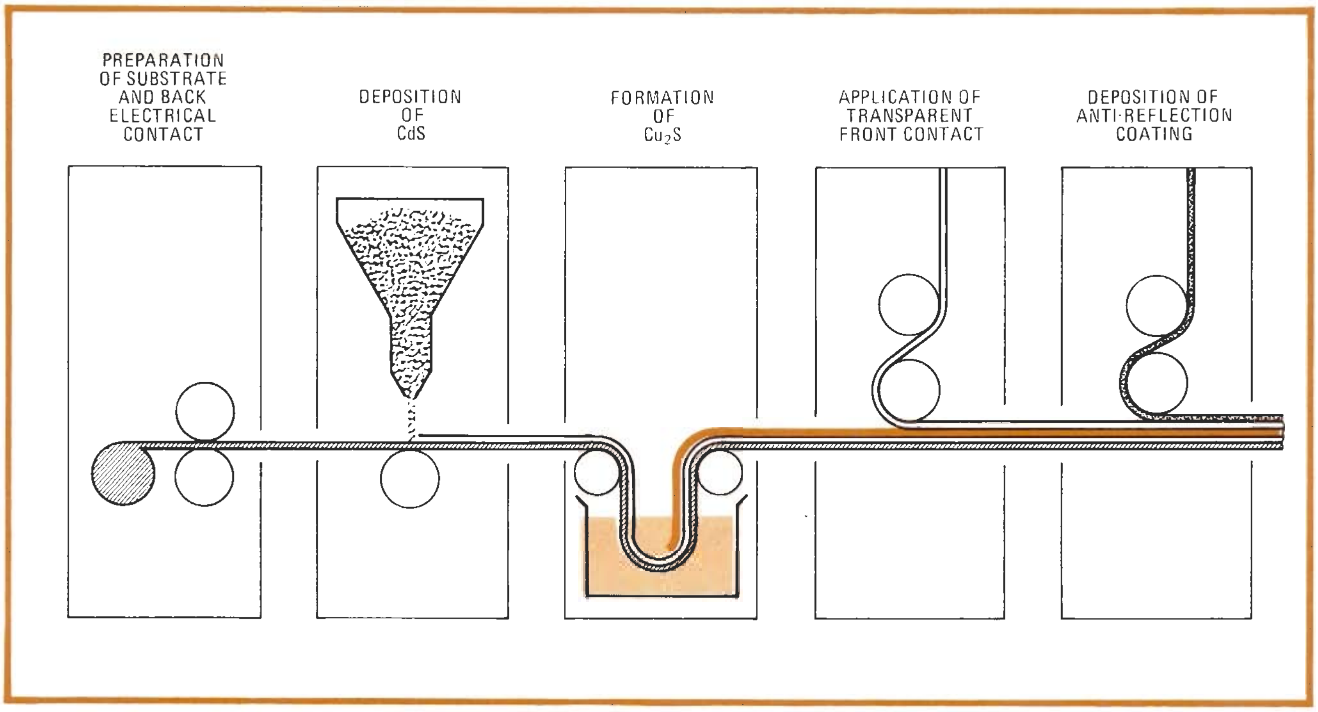
An exception is a cell based on cadmium sulfide and cuprous sulfide (Fig. 7). CdS/Cu_2S cells have attained efficiencies greater than 9%, and several organizations say 14% to 16% looks possible. What's more, these same researchers predict that techniques borrowed from the chemical process industry will make it possible to produce such cells for 10¢ to 30¢/W by 1990.

The two organizations that continue to do the best work with cadmium sulfide are the Institute of Energy Conversion, an independent development group set up at the University of Delaware at Newark, and the University of Stuttgart in West Germany.

Last June, IEC director Allan M. Barnett announced he had reached 9.15% efficiency. He also shocked some



7. Two in one. This cadmium-sulfide/cuprous-sulfide heterojunction is typical of thin-film photovoltaic cells. It is made up of two active layers: an absorber-generator, and a collector-converter that have a matching lattice structure but opposite conductivity.



8. Continuous CdS. Pilot production process for CdS/Cu_2S solar cells includes five basic steps that build the device from bottom to top. Analyses show continuous production of 10%-efficient cells becomes cheaper than batch processing once annual output exceeds 20 MW.

silicon specialists by predicting that thin-film CdS/Cu_2S cells could be selling for 35¢/W as early as 1982, easily beating DOE's 1986 price goal of 70¢/W [*Electronics*, June 22, 1978, p. 42]. Barnett expects to pass 10% "within a year" by adding zinc, in concentrations of about 25%, to the cadmium sublattice. The zinc reduces the mismatch between the CdS and Cu_2S lattices and raises the cell's open-circuit voltage.

Meanwhile, the Institute is slowly lining up five independent companies to license its CdS technology and set up pilot-production plants based on the process shown in Fig. 8. SES Inc., a Shell Oil subsidiary also located in Newark, Del., already reports limited production of 6.5%-efficient CdS/Cu_2S cells from a plant, still under construction, scheduled eventually to produce 1 MW of cells per year.

Another firm setting up a CdS pilot plant is Photon Power Inc. of El Paso, Texas. Photon Power is also working with Libbey-Owens-Ford on ways to feed a glass-manufacturing plant's output directly into the cell production line as the CdS cell substrate, in order to slash prices to 5¢ to 15¢/W. Its major challenge is to speed up cell production from its present 2-cm/min rate to the 20 cm/min of the float-glass facility.

The University of Stuttgart also has set up a small production line and now makes 7-by-7-cm CdS/Cu_2S cells that are 6.7%-efficient. Stuttgart produces its cells by evaporating a CdS film onto a glass substrate, dipping the film in a cuprous-chloride solution for a few seconds, and then encapsulating the cell between glass plates. (In contrast, IEC creates its junctions on a metal substrate by reacting evaporated CuCl with CdS.) German scientists are now investigating the use of reactive-sputtering techniques to improve control of the CdS and Cu_2S depositions, as are groups in California at Lockheed's Palo Alto Research Laboratories and Lawrence Livermore Laboratories.

One other CdS-based cell that shows promise is the heterojunction of cadmium sulfide and copper indium selenium. With SERI funding, Sperry Univac's Defense Systems division in St. Paul, Minn., and Boeing Aerospace Corp. in Seattle, Wash., are both trying to develop a CdS/$CuInSe_2$ cell that is at least 4 cm^2 in area and has a minimum conversion efficiency of 8%.

Market acceptance of any CdS-based cell will require careful attention to its handling and encapsulation, since cadmium is a toxic substance that could contaminate personnel and the environment. That is not seen as an insurmountable problem, however, nor is the fact that cadmium is not as abundant as silicon. Domestic supplies of cadmium will be sufficient to supply annual production rates greater than several thousand megawatts through the end of the century, but production beyond that level could cause shortages.

Concentrating on gallium arsenide

Another promising type of solar cell utilizes gallium arsenide. GaAs devices are more expensive to manufacture than single-crystal silicon cells, and they also contain a toxic substance (arsenic), but they absorb light even better. Single-crystal GaAs cells hold the record for photovoltaic efficiency—26%, with single-crystal silicon in second place at 22%.

One way to offset gallium arsenide's high cost is to use small cells and concentrate sunlight on them through lenses and mirrors. Unlike silicon cells, whose efficiencies deteriorate rapidly at the high temperatures produced by concentration, the theoretical maximum conversion efficiency of gallium-arsenide cells remains fairly constant as temperatures rise: it is still 20% at

100°C. This property of gallium arsenide makes it the focus of research into the use of concentrated-sunlight conversion systems (see p. 117) at central power stations, which would be better equipped to maintain them than ordinary consumers.

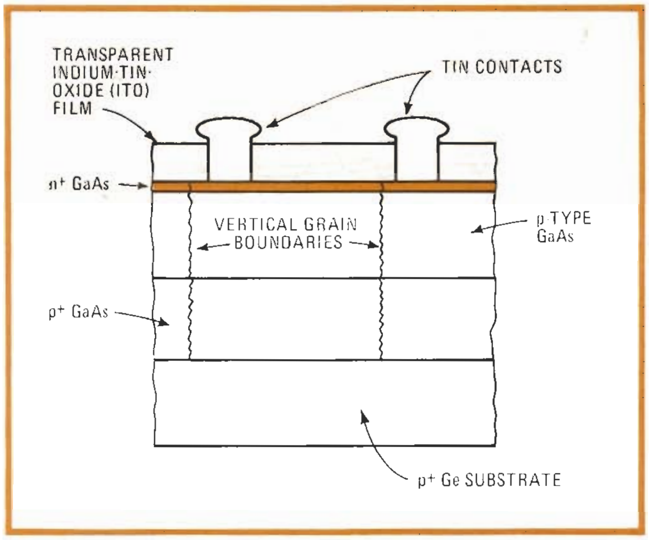
An alternative approach is to make GaAs cells cheap and efficient enough to use in direct sunlight. Virtually all research in this area is on thin-film polycrystalline GaAs cells that, although only 1 or 2 μm thick, have a theoretical conversion efficiency of 16%. Three types are currently being developed: GaAs metal-insulator-semiconductor (MIS), or Schottky-barrier, cells; GaAs homojunctions topped by a window of gallium aluminum arsenide; and GaAs shallow homojunctions. All have the same aim: to raise conversion efficiency by reducing the heavy losses of light-generated charge carriers that are caused by recombination at dangling covalent bonds in the thin molecular layer at the top of the cell where photons are absorbed.

Research into GaAs MIS cells is being conducted at JPL, at Southern Methodist University in Dallas, and at Rockwell International Corp.'s Science Research Center in Thousand Oaks, Calif. JPL, shooting for goals of 15% and 70¢/W, is growing p-type GaAs thin films epitaxially on substrates made by vapor-depositing germanium layers on coated steel and then recrystallizing those layers with a laser beam. At SMU, large-area (9-cm^2) thin films of GaAs deposited on cheap graphite substrates have demonstrated efficiencies of 6.7%. Rockwell is concentrating on developing liquid-phase molecular-beam epitaxy growth of thin GaAs films, also on low-cost substrates. Funding for Rockwell's efforts comes largely from a year-old DOE contract for $1 million that allows the firm to subcontract a portion of its laboratory work to four universities [*Electronics*, May 11, 1978, p. 50].

Rockwell is also looking into heterojunctions of GaAs topped by a thin layer of p-type gallium aluminum arsenide (GaAlAs). Transparent to virtually the entire solar spectrum, the GaAlAs layer has a lattice structure that closely matches that of GaAs and so reduces recombination losses. Although single-crystal cells of this type have shown efficiencies as high as 22%, the thinness of polycrystalline structures permits dopants to diffuse so rapidly through the cell that they soon short-circuit it. The search for slower-diffusing dopants, alternative cell structures, and new deposition techniques is continuing both at Rockwell's Science Center and at its headquarters in Anaheim, Calif.

Shallow GaAs homojunctions are the subject of development work at the Massachusetts Institute of Technology's Lincoln Laboratory in Lexington. There, researchers dope three layers of GaAs with different impurity levels (Fig. 9). This structure has demonstrated efficiencies as high as 20%. It has low losses because photons bypass the many recombination centers in the shallow (0.1-μm-thick) n^+ upper layer and instead are absorbed in the p-type layer beneath it.

MIT's shallow-homojunction structure has a transparent top layer of indium tin oxide (ITO) that reduces both resistance and reflectance losses. One organization bent on improving ITO growth techniques is the Engineering Center at Rensselaer Polytechnic Institute in Troy, N. Y. Researchers at RPI are now comparing two ways to grow ITO layers: chemical-vapor deposition and rf sputtering. Also rumored to be working on development of GaAs cells are researchers in the Soviet Union.



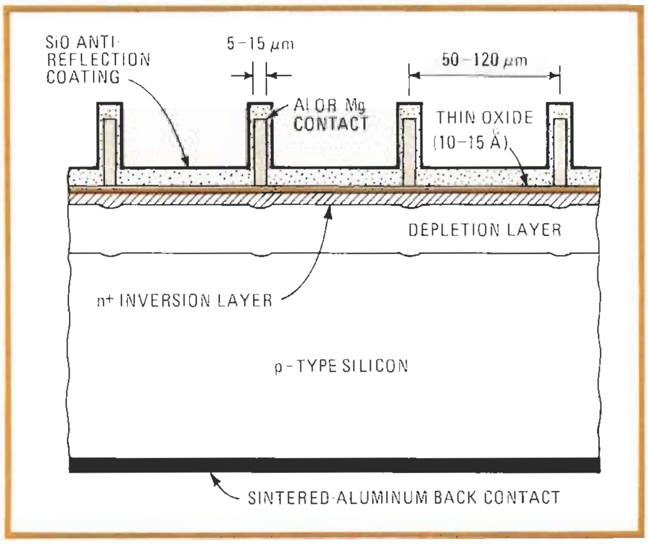
9. Fooling photons. This 20%-efficient shallow-homojunction cell comprises three layers of GaAs that are doped at different impurity levels. Photons pass through the thin top layer so quickly that few are lost; instead, they are absorbed in the thicker layer beneath it.

Advancing the frontiers of solar technology

One aspect of photovoltaic development on which all experts agree is the need for diversity. Although advanced cells based on single-crystal, polycrystalline, and amorphous silicon, cadmium sulfide, and gallium arsenide now can be considered the front runners in the race to meet short-term goals, long-term planners stress that simultaneous exploration of virgin technical territory is vital, to identify options that could be turned to should unforseen roadblocks halt progress in a thus-far promising technology.

Indicative of American commitment to this philosophy is the dramatic increase in the budget of SERI's advanced R&D program—from $6 million to $7 million in fiscal 1978, to $13.5 million in fiscal 1979, to a requested $47 million for fiscal 1980. In addition, in May 1978 President Carter infused another $22 million into advanced R&D during fiscal 1979. According to Donald Feucht, who heads DOE's advanced R&D lead center at SERI, the bulk of the $22 million is supporting additional projects on amorphous silicon and new solar cell materials that he labels high-risk—those that may or may not develop into cost-effective technology. Scientists overseas are also pursuing new cells aggressively, as the following roundup of advanced R&D activities in the U. S. and outside it shows:

- Metal-insulator-semicondudtor (MIS) cells using silicon. MIS, or Schottky-barrier, solar cells have theoretically high conversion efficiencies because they lack a heavily doped surface layer where recombination losses can occur. Furthermore, they can be processed at temperatures below 500°C, which increases their long-term stability. Those characteristics give MIS cells based



10. Efficiency down under. To build this 17%-efficient MIS solar cell, Australian researchers first evaporate an aluminum contact onto the back of a p-type polysilicon wafer, then sinter the wafer in nitrogen. This produces the thin oxide layer on top of the wafer. The final steps are evaporations of the top contact and the antireflection coating. The latter step induces the n^+ inversion layer shown.

either on single-crystal or polycrystalline silicon the potential for low-cost manufacture.

Researchers at the School of Electrical Engineering at Australia's University of New South Wales in Kensington recently reported achieving 17.6% conversion efficiency from a 3-cm^2 polycrystalline-silicon cell with the structure shown in Fig. 10. Worth noting is the n^+ inversion layer, induced by the silicon-oxide coating, that improves carrier-collection efficiency. Also attractive is the cell's open-circuit voltage of 655 mV—the highest obtained from any silicon cell to date. The university's Martin A. Green expects to reach 20% efficiency by the end of the year.

Two other universities working on MIS silicon cells are Rutgers, in its electrical engineering department in Piscataway, N. J., and the University of Konstanz in West Germany. Rutgers reports having built both 12.5%-efficient single-crystal-silicon cells that are 2 centimeters square and 8.8%-efficient cells based on Wacker-Chemitronic's Silso semicrystalline silicon material. The University of Konstanz is now testing polycrystalline n- and p-type MIS silicon cells fabricated on several different metallic substrates.

■ Tin-oxide/silicon heterojunctions. At the Government Research Laboratories of Exxon Corp.'s Research and Engineering Co. in Linden, N. J., electron-beam and spray-deposition techniques are being used to make low-cost, high-efficiency heterostructures of tin oxide (SnO) and silicon and indium tin oxide (ITO) and silicon. Now reporting efficiencies of 12.24% for SnO_2/single-crystal silicon and 10% for ITO/single-crystal silicon and SnO_2/polycrystalline silicon, the Exxon group hopes to approach the theoretical efficiency of 20% and reduce production costs within DOE's timetable. Also investigating ITO/Si and oxide-semiconductor-on-silicon (OSOS) solar cells is a group at Colorado State University's electrical engineering department in Fort Collins.

■ Cadmium telluride. Among those studying deposition of CdTe solar cells are Monosolar Inc., Santa Monica, Calif., and Battelle Institut in Frankfurt, West Germany. Monosolar has produced 4%-efficient, 3-by-3-cm cells by electrochemically depositing CdTe films 0.1 to 0.2 μm thick on ITO-coated glass; its eventual goal is to produce 10%-efficient, foot-square cells for under 20¢/W. Battelle, aiming at concentrator applications, deposits layers of zinc telluride and cadmium-sulfide on slices of crystalline CdTe and is looking at alternate layers as well.

■ Cuprous oxide. Cu_2O solar cells could be very inexpensive to produce because they can be made by oxidizing copper, a cheap and abundant metal. They also have theoretical maximum efficiencies of 13%. Today, several groups are working to better their understanding of cuprous oxide's basic energy-conversion mechanism. For instance, at the University of Washington's Joint Center for Graduate Study in Seattle, Larry Olsen has extracted 1% efficiency from Cu/Cu_2O Schottky-barrier cells, while Kernforschungsanlage Jülich in West Germany reports similar performance from thin-film Cu_2O cells made by partially oxidizing copper foils. Also working with Cu_2O is a group at Wayne State University in Detroit, Mich.

■ Cadmium selenide. The Battelle Institut in Frankfurt hopes to double the 5% efficiency of its CdSe MIS cells to 10% and is also investigating alternatives to ZnSe as the insulating layer.

■ ITO/indium phosphide and ITO/GaAs. Researchers at Bell Laboratories in Murray Hill, N. J., have made 14.4%- and 12%-efficient solar cells by placing amorphous and polycrystalline ITO films on single-crystal InP and GaAs substrates, respectively. Deposition techniques that have been tried include ion-beam deposition, rf sputtering, and magnetron sputtering. Although such cells are still relatively inefficient, Bell Labs reports that they are easy to make and so potentially low-cost.

■ Zinc phosphide. The Institute of Energy Conversion at the University of Delaware in Newark has produced single-crystal and thin-film p-type Zn_3P_2 cells by vacuum evaporation techniques. IEC is now investigating ways to boost the efficiency of its magnesium-based Schottky-barrier Zn_3P_2 devices from their present 6%.

■ Electrochemical cells. A new program at SERI, electrochemical cell development, will soon begin at several of a dozen companies now negotiating contracts. Electrochemical cells with single-crystal-silicon electrodes immersed in an electrolyte have already demonstrated conversion efficiencies of 8% to 10%. Future work will investigate the use and stability of low-cost polycrystalline and amorphous-silicon electrodes.

One such system is now being developed by Texas Instruments Inc. Backed by DOE to the tune of $14 million over the next four years, the Dallas firm hopes to demonstrate the commercial feasibility of a photovoltaic fuel cell. The key to the system on which it is working is the immersion of inexpensive silicon droplets in the electrolyte. When sunlight hits the droplets, they generate a current that extracts hydrogen from the electrolyte; the hydrogen then is stored and used to charge a fuel cell that generates electricity when needed.

PART 4
CONCENTRATOR SYSTEMS

□ One way to reduce the cost of power from a photovoltaic system is to use fewer expensive solar cells in the array, but equip them with a low-cost optical system to focus and intensify the sunlight reaching them. Over the last few years, this idea has been refined until today's concentrator systems stand an excellent chance of beating flat-panel (nonconcentrating) arrays to the Department of Energy's goal of $2.80/W by 1982. In fact, DOE last year asked eight industrial firms for their cost estimates for such systems. Their replies were unanimous: each said that using today's technology—12%-efficient cells in a concentrator system with 10% overall efficiency—it could attain the 1982 goal now, if its sales were on the order of 10 MW per year.

Although market expansion alone should enable the technology to reach the 1982 goal, considerable technical advances are still needed before it can attain DOE's 1986 goal of 70¢/W. Today, several firms are under contract to Sandia Laboratories, which coordinates DOE's concentrator efforts. All are working to lower the cost and raise the efficiency of concentrators' two basic components: solar cells that can work under intense illumination and optical systems that concentrate sunlight on them.

The types of solar cells being considered for use in concentrators are: silicon, gallium arsenide, and so-called multi-bandgap cells. In all three cases, high efficiency breeds cost-effectiveness because an increase in performance—a greater output current for the same light intensity—leads directly to a reduction in the area that must be covered by the magnifying optics. Gallium-arsenide cells require few design changes to be efficient at high concentration ratios, but special fabrication techniques are needed to maintain the efficiency of silicon cells when they are irradiated by the equivalent of more than 100 suns (Fig. 11).

Concentrating on silicon

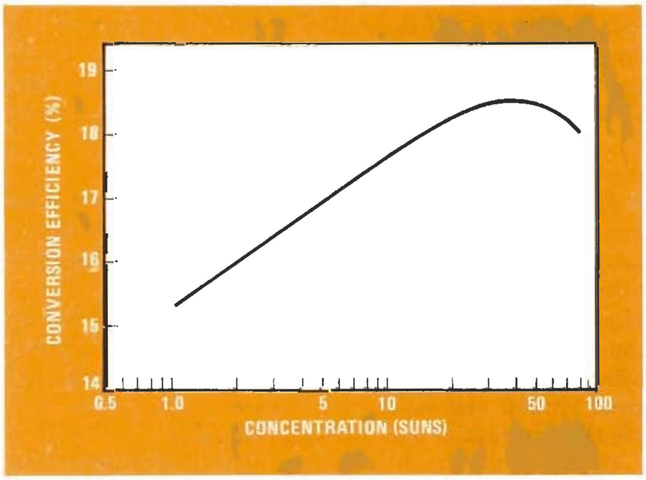
It was once thought that silicon cells would be ineffective at concentration ratios higher than 10 to 20 suns. Today, however, opinions have changed. Specially designed silicon cells have demonstrated conversion efficiencies as high as 14% at up to 1,000-sun intensities. Such silicon cells are quite different from those intended for flat-panel arrays. Their substrate resistivity is lower to minimize voltage drops at high temperatures, they have extra layers that are heavily doped to reduce ohmic losses, and their front-electrode grid patterns are finer, to enable them to handle the increased currents produced by concentrated sunlight.

Microwave Associates Inc., Burlington, Mass., now holds the record for conversion efficiency of a silicon cell operating under concentration: 20% at 600 suns. Several other firms also have designed silicon concentrator cells that have peak efficiencies ranging from 14% to 18% when illuminated at anywhere from 20 to 250 suns. Among the leaders in developing such cells are: Optical Coating Laboratory Inc.'s Photoelectronics division, City of Industry, Calif.; Motorola Inc.'s Solar Operations Group, Phoenix, Ariz.; Solarex Corp., Rockville, Md.; RCA Laboratories, Princeton, N. J.; Sandia Laboratories, Albuquerque, N. M.; General Electric Co.'s Space Systems Operations, Philadelphia, Pa.; and SGS-ATES Componenti Elettronici SpA, Milan, Italy. All produce large-area (typically 2-by-5-cm) cells that require cooling at high temperatures produced by concentration.

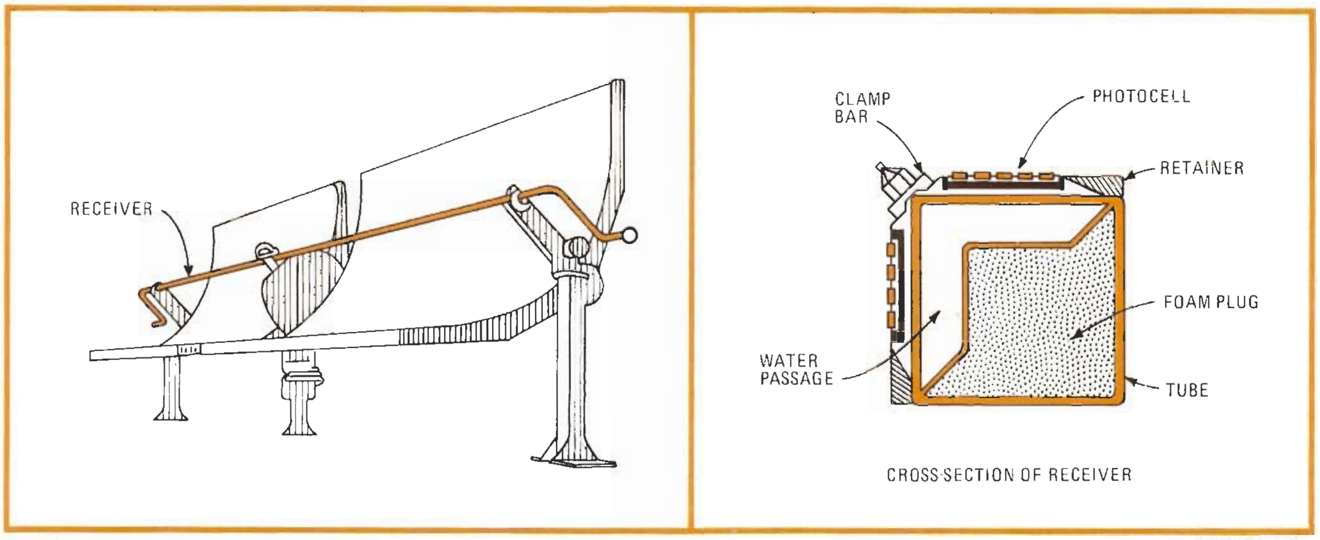
For gallium-arsenide cells, efficiency is not as much of a problem at high concentration ratios, since GaAs cells have a negative temperature coefficient of efficiency as small as 0.25% per °C increase in temperature. Especially promising for concentrator applications are heterojunctions of GaAs and GaAlAs. Those structures, which can be as small as 1 square centimeter, have demonstrated conversion efficiencies as high as 22% at concentration ratios of 1,000:1. Among the firms developing GaAs-based cells for concentrators are Hughes Aircraft Co.'s Research Laboratories in Malibu, Calif.; Varian Associates Inc. in Palo Alto, Calif.; Rockwell International Corp.'s Research Center in Thousand Oaks, Calif.; and Italy's SGS-ATES.

Splitting sunbeams

Rather than use its GaAs cells alone in a concentrator system, Varian instead teams them with silicon cells in what is called a multi-bandgap arrangement [*Electronics*, July 20, 1978, p. 42]. Since silicon and gallium-arsenide cells are most efficient when illuminated by light of different wavelengths, Varian uses a dichroic filter to



11. Some don't like it hot. Short-circuit current and conversion efficiency of silicon cells increase linearly at concentration ratios up to 40:1, but fall off at higher intensities. Reason: the currents induce internal voltage drops that lower cell output voltage.



12. Adaptable. Acurex Corp. has modified its parabolic-trough concentrator, normally used with solar heaters, to accommodate photovoltaics. The new receiver, which runs along the focus of the parabola, holds two adjacent rows of cells that are cooled by water.

split light of 165-sun intensity into high- and low-energy bands. The high-energy beam hits a 20%-efficient GaAlAs heterojunction and the low-energy beam strikes a 16%-efficient silicon cell, making total cell efficiency 31.4% and net system efficiency 28.5%, including optical losses. Varian hopes to boost the system's conversion efficiency to 35% and the concentration ratio to 500:1 by improving the cells and the optics.

Another firm with the same idea but a different approach is Research Triangle Institute, Research Triangle Park, N. C. RTI sandwiches two cells with different spectral sensitivities in a single package, eliminating the need for a filter. The top cell absorbs the high-energy photons in the concentrated light and transmits the photons with lower energies to the cell on the bottom. To date, RTI has exceeded 25% efficiency with this cell and sees 35% as an eventual goal.

It's all done with mirrors

Besides developing cheaper, more efficient concentrator cells, Sandia is funding several projects aimed at reducing the cost of the optical systems that concentrate sunlight on them. Their contractors are taking three approaches: adapting solar-heating concentrators, designing optical systems specifically for photovoltaics, and investigating any advanced concepts that seem to have low-cost potential.

Solar-thermal concentrator systems are now available commercially, and they are relatively simple to modify to accommodate photovoltaic cells, rather than thermal collectors. One such adaptation, by Acurex Corp., Mountain View, Calif., is shown in Fig. 12. Acurex changed the water-carrying receiver element of its parabolic-trough concentrator into a tube that is square in cross section and holds two rows of silicon cells. The 9%-efficient system uses 13%-efficient cells.

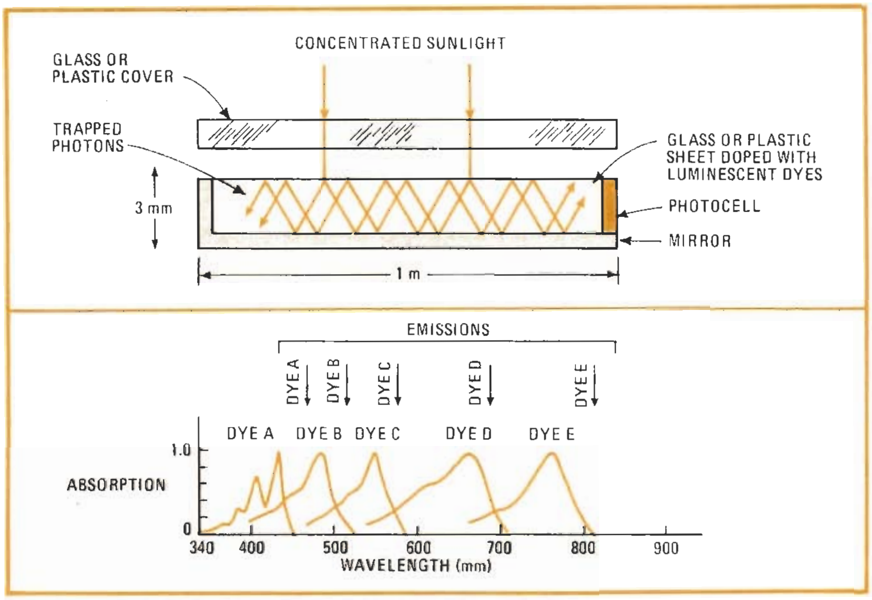
Of the optical-system designs that contractors have conceived from the ground up specifically for photovoltaic arrays, two look most promising: parabolic troughs and Fresnel lenses.

A parabolic trough focuses incident sunlight along a line parallel to its axis (Fig. 12). One 10-kW design, by Spectrolab Inc., Sylmar, Calif., comprises a number of troughs mounted in rows on a large turntable that permits azimuthal (horizontal) tracking of the sun. A single drive mechanism provides elevational tracking by pivoting all the troughs together about horizontal beams.

Martin-Marietta Corp., Denver, Colo., has built a 3.3-kW array that uses point-focusing, acrylic Fresnel lenses to concentrate 40-sun light on each of 272 silicon cells that are packaged as four-cell modules. Three of these arrays, which also track the sun about two axes, have been delivered to Sandia for evaluation. Other organizations working to reduce the cost of Fresnel-lens concentrators, and of the lenses themselves, are RCA's David Sarnoff Research Center, Princeton, N. J., and Swedlow Inc., Garden Grove, Calif.

Aware of the role that market expansion must play in reducing the cost of concentrators, Sandia and DOE's Albuquerque office have planned their deployment into the field to demonstrate their effectiveness and gain valuable operating experience. Phase 1 of the plan, which is called the Photovoltaic Concentrator Applications Experiments, ended this February. During Phase 1, 17 contractors were selected to submit detailed designs and budgets for proposed concentrator systems. Of these 17, five were chosen to continue into Phase 2, which is termed System Fabrication:

- General Electric Co.'s Space Systems Operation, Philadelphia, Pa., for a $3.4 million, 110-kW, parabolic-trough system that will ultimately be installed at Sea World in Orlando, Fla.
- Arizona Public Service Co., a Phoenix-based public utility, for a $6.5 million, 283-kW, Cassegrain-optics systems that will power that city's Sky Harbor International Airport.
- E-Systems Inc., Dallas, Texas, for a $650,000, 27-kW, Fresnel-lens system that will provide electricity and heat to Dallas-Fort Worth's airport.
- BDM Corp., Albuquerque, N. M., for a $1.1 million, 42-kW, reflective-trough system to power an office building in Albuquerque.



13. Glowing promise. This solar collector uses luminescent dyes that absorb sunlight in narrow frequency bands, then reradiate photons at different wavelengths. The system need not track the sun, as the dyes are sensitive to light incident at any angle.

■ Acurex Corp., Mountain View, Calif., for a $1.4 million reflective-glass dish system to be installed at a hospital in Kauai, Hawaii.

All of the above systems use silicon cells that are cooled by air or water. Installation should take about a year, so all five projects should be operational by mid-1980. Phase 3, Operation and Evaluation, will follow immediately and last up to two years. Significantly, Sandia hopes that all five systems will reduce purchases of electricity to the extent that they will pay for themselves by 1986.

Concentrators of the future

While Sandia expects market growth and applications experiments to help drive the costs of concentrator technology below $2.80/W by 1982, it recognizes that further reductions in cost will be difficult without the help of innovative technology. Therefore, it is also backing the development of four advanced concepts that hold promise for attaining DOE's 1986 goal of 70¢/W. They are a two-dimensional compound parabolic concentrator, a headlamp-type concentrator, an air-pressure-supported, a bubble-enclosed film concentrator, and a luminescent concentrator.

The two-dimensional concentrator under development at Sun Trac Corp., Wheeling, Ill., has two attractive features: a high concentration ratio (115:1), which allows the use of less efficient cells; and a high tolerance for tracking errors, which allows the use of a less expensive tracking system. The headlamp-type concentrator now being examined by Acurex Corp. could be inexpensive, as it could eventually roll off the high-volume assembly lines of automotive sealed-beam headlamps.

The air-pressure–supported, bubble-enclosed film concentrator now being developed by Boeing Co., Seattle, Wash., is both light and strong. Its concentrating reflector is a lightweight parabolic film formed in a vacuum and mounted on a lightweight tracking structure. The assembly is enclosed in an air-supported bubble that protects it from the environment.

Perhaps the most innovative of the four advanced concepts is the luminescent solar collector under joint development at Owens-Illinois Inc., Toledo, Ohio, and the California Institute of Technology, Pasadena, Calif. It comprises a glass or plastic sheet doped with luminescent dyes that are sensitive only to light in narrow frequency bands (Fig. 13). The dye molecules absorb sunlight and reradiate it at different wavelengths in many directions. Some of that light is reflected, becomes trapped within the sheet because the dyes cannot reabsorb it, and eventually bounces down the sheet to a photocell at its edge.

The most attractive feature of this system, aside from its 60% to 70% theoretical efficiency, is that it need not track the sun, since the dyes absorb light incident at any angle. At present, researchers are identifying dyes that have both long-term stability in sunlight and the correct absorption and reemission characteristics. Early results are promising, and projections are that this system may eventually cost as little as 63¢/W.

Thermophotovoltaics

Another advanced concept based on reradiation, but whose development is not supported by Sandia, is thermophotovoltaic conversion. This approach concentrates sunlight to heat a radiator to incandescence at about 2,000°C. The radiator then beams its own light, at longer wavelengths than those from the sun, onto a specially designed silicon cell that converts it into electricity at 40% efficiency. The cell also reflects unabsorbed light back to the radiator, maintaining its temperature.

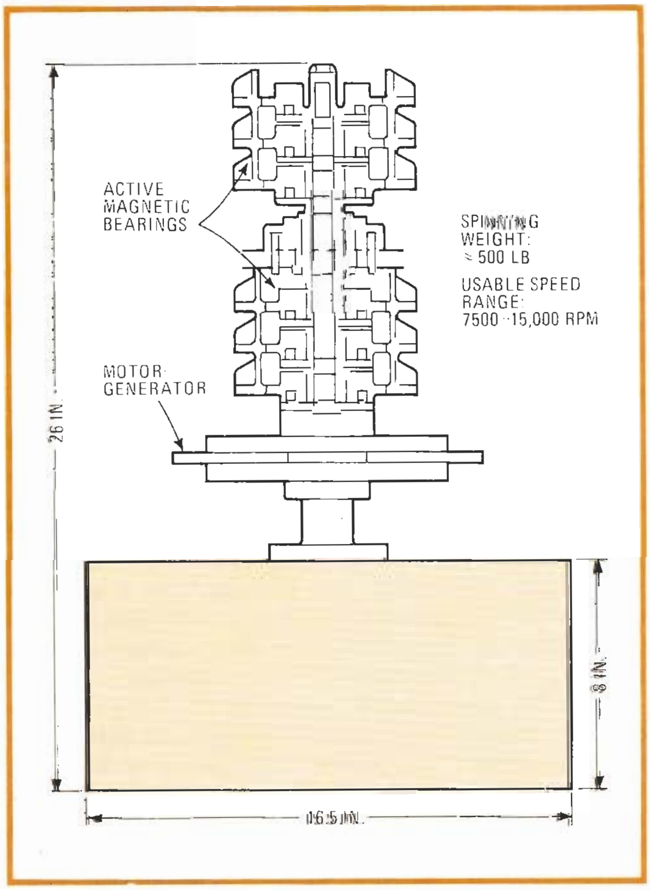
Assuming optical losses, such a system has a theoretical conversion efficiency of 35% to 40%. To date, Stanford University's Electronics Laboratories in Stanford, Calif., which is developing the concept with funding from the Electric Power Research Institute (EPRI) in Palo Alto, Calif., has achieved 26% efficiency, using an artificially heated radiator. By the end of the year, EPRI, which is totally funded by the U. S. utility industry, will have spent $650,000 over the last three years on cell development work at Stanford and $200,000 for optical and thermal R&D at various other contractors.

PART 5
SUBSYSTEMS AND APPLICATIONS

Despite the richness and diversity of Government-sponsored research and development on lower-cost of solar cells and concentrator systems, years will pass before those efforts begin to bear fruit. Only then will the market for photovoltaics expand beyond remote-power applications, in which they now serve, to larger markets like residences, commercial buildings, industrial plants, and utilities.

Before photovoltaic systems can begin to penetrate new markets, however, attention must be focused not only on reducing the cost of arrays but also on developing reliable, low-cost ancillary equipment to connect them to a wide variety of alternating-current loads. DOE recently recognized the eventual need for such equipment, which it calls balance-of-systems hardware, and now plans to devote a greater share of its 1980 budget to its development. Generally, balance-of-systems hardware comprises two categories of equipment: power-conditioning units and energy-storage devices.

All power-conditioning units contain an inverter, which converts the direct-current power from photovoltaic arrays into clean, alternating-current power required by ac loads. Although a wide range of inverters is available commercially today, most of them are inefficient when used with photovoltaic systems because the output voltage from solar-cell arrays varies significantly during normal operation.



14. Spinning reserve. MIT-Lincoln Lab's flywheel may someday make batteries and power conditioners obsolete in consumer applications. Now being built as a 1:10-scale model, the system, when scaled up, could store enough energy to power a home for a day.

Power-conditioning units also must control and distribute the output of the array. For stand-alone systems (those not backed up by a utility grid), control may involve connecting and disconnecting the array to and from the load at sunrise and sunset and during cloud cover. If the system includes a storage battery, the power-conditioning unit also must decide when to drive the load or charge the battery.

For grid-connected systems, the power-conditioning unit has additional duties. It must switch the load's input-power lines between the array and the incoming utility lines at the right times, matching impedances all the while, and it must also synchronize the array's output waveform with that of the utility when feeding power back into the grid.

Clearly, power conditioners are complex equipment. Recognizing this, Sandia Laboratories has funded the development of two such units: an industrial device designed by Westinghouse Electric Corp.'s Aerospace Electronics divison, Lima, Ohio; and one, destined for use in residences, that is now under development at Abacus Controls Inc., Somerville, N. J.

Westinghouse's power conditioner provides up to 62.5 kilowatt-amperes of three-phase power at 440 V ac. It includes a microprocessor that automatically synchronizes its output to utility lines and matches impedances precisely. During acceptance tests at Sandia, the unit succeeded in demonstrating an ac-dc conversion efficiency of 92% at full load.

Abacus Controls is at present developing a microprocessor-controlled, single-phase, split-110/220-V power conditioner that the firm says will have a conversion efficiency greater than 90%. It also says that the unit will be priced at $150 to $200/kW and that it will be sold commercially under the trade name Sunverter.

The storage story

In photovoltaic systems where no backup supply is available or desirable but where electricity is needed around the clock, some of the energy produced by the array during the day must be stored and then recovered to drive the load at night and on cloudy days. Today, conventional lead-acid and nickel-cadmium batteries are the only storage options. However, those batteries are expensive, inefficient, prone to rapid discharge, far from maintenance-free, and relatively short-lived. Therefore, DOE is now accelerating development of several advanced energy storage concepts that, in the long run,

Solar-power satellites to chase the clouds away?

If esoteric photovoltaic configurations like electrochemical fuel cells and dye-doped plastic sheets seem like technology borrowed from Buck Rogers, just wait. The Department of Energy and the National Aeronautics and Space Administration are together studying the feasibility of orbiting a series of massive, miles-long satellites bearing solar cells that would collect energy from the sun around the clock and beam it back to earth in microwave form.

With $20 million to spend over three years, the solar-power satellite (SPS) project office within DOE's Office of the Director of Energy Research is now identifying the technical, economic, environmental, and social implications of such a plan [*Electronics*, April 27, 1978, p. 96]. According to project head Frederick A. Koomanoff, the SPS concept as envisioned at present calls for 25 to 30 satellites to be launched and assembled in geosynchronous orbit by the end of the century.

Each satellite would measure about 18 by 5 kilometers and produce 5 gigawatts of electricity from silicon or gallium-arsenide cells, convert it into microwave energy, and beam it back to earth at 2.45 gigahertz. On earth, gigantic antennas 10 by 14 km in area would collect the microwave energy, convert it into 60-hertz power, and feed it into the nation's utility grid.

Koomanoff expects to have completed preliminary studies by June 1980. Then his group will publish their findings and recommend whether or not the concept warrants further detailed investigation. That next phase, he says, might be funded by legislation, now pending in Congress, that would appropriate $25 million for each year of subsequent research and development.

The SPS concept was first broached 10 years ago by Peter Glaser, a vice president of Arthur D. Little Inc., Cambridge, Mass., and since then has slowly gathered support not only in Congress, but in scientific circles as well. Undaunted by detractors who call SPS a boondoggle, Glaser maintains that the estimated $500 billion it would take to orbit the satellites "is not out of line with estimates of $1 trillion to develop alternative U. S. energy sources beyond oil and coal." As yet unanswered, however, are questions regarding defense of the satellites, the effects of concentrated microwave energy on the earth and its atmosphere, and what would happen if one of the satellites were to fall to earth.

may prove both technically and economically feasible.

DOE's energy storage and photovoltaic programs are separate, but they work closely together. Albert Landgrebe, who heads DOE's division of energy storage, reports that, although the agency is only at the stage of defining the program, it already has a pretty good idea of what it will be looking for.

According to Landgrebe, batteries designed to store photovoltaic electricity should respond quickly when called upon, have a long operating life, and, of course, be low-cost. Among the batteries with those characteristics that DOE is now looking at are improved versions of lead-acid batteries, reduction-oxidation (redox) batteries, and zinc-bromine batteries. Landgrebe sees the latter type as especially promising because they are fire-retardant and therefore a good choice for residential applications since consumers can not only use but also maintain them safely.

In fiscal year 1979, DOE is spending about $2.1 million on battery development and plans to boost funding to $5 million next year. But, despite those outlays, many solar-energy experts are skeptical that electrochemical batteries can ever develop into a viable piece of balance-of-systems hardware. Instead, they say, what is needed is an all-solid-state, maintenance-free unit that stores energy efficiently and at low cost.

Alan R. Millner of MIT's Lincoln Laboratory thinks that he knows how to build such a system. His idea: store energy in inertial rather than chemical form, in a flywheel spinning at high speed in a vacuum. The key to the system's potentially low price is not the flywheel itself, but rather its compatibility with power conditioners that are cheaper than inverters.

The system that Millner envisions is huge. It would include: a 6-foot-high, 14-foot-wide, 2-ton flywheel made of fiberglass or a similar material; a 95%-efficient dc motor–ac generator to accelerate the flywheel to 7,500 to 15,000 revolutions per minute during the day and produce 60-Hz power during deceleration at night; and electronically controlled active magnetic bearings to support the motor-generator and flywheel in a vacuum. Such a system, if installed in a pit beneath a garage, could store enough energy to power a typical home for at least one day, and last 20 years with little maintenance.

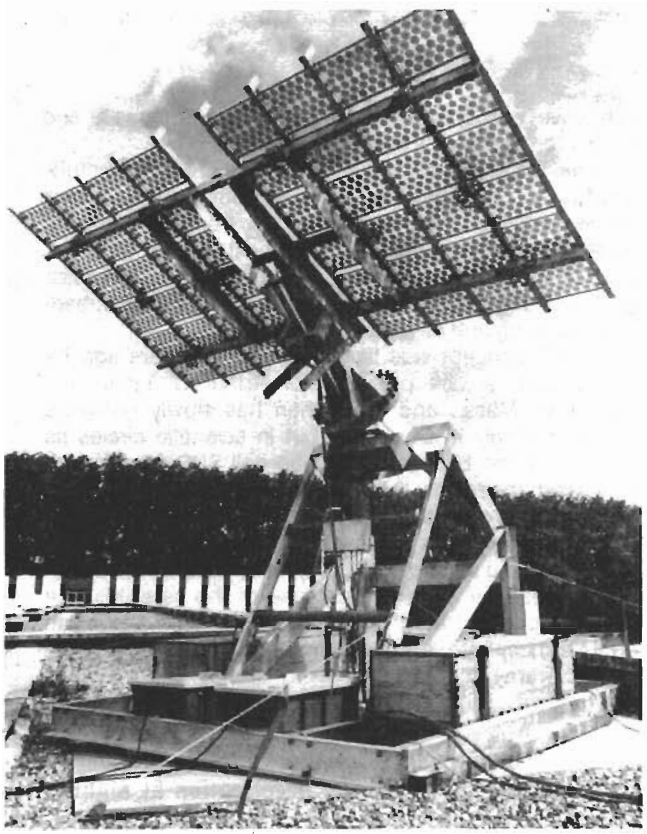
As to price, Millner claims that "on a life-cycle basis, flywheels will eventually cost less than today's batteries." He supports the prediction with preliminary cost analyses that show that, assuming reasonable reductions in the current high price of flywheel materials and the creation of mass-production facilities for all system components, the flywheel system could cost less than a combination battery-power conditioner as early as 1985.

Today, Millner is busy building an experimental model one tenth the size of his proposed system, which is shown schematically in Fig. 14. Assuming all goes well, he hopes to scale up to a full-size prototype that may even attract commercial interest.

Present and future applications

Clearly, there's an abundance of R&D into reducing the future costs of photovoltaic cells and related equipment. Even at today's prices of $10 to $15/W, however, solar cells are a growing business. More than a dozen companies now sell arrays of single-crystal-silicon cells for a wide variety of applications. Although those applications remain ones in which a conventional power source would be prohibitively expensive to install and run, there is growing evidence that the market for photovoltaics is beginning to expand.

To date, photovoltaics have served as reliable, maintenance-free, although small, power sources to remote equipment like satellites, mountaintop microwave repeaters, railroad signals, and navigational buoys. Some consumer products have been powered by solar cells, too,



15. Sun-powered pump. This experimental pumping station near Toulouse, France, moves 10 cubic meters of water each day. Built by Compagnie Industrielle des Piles Electriques, it is powered by a 500-watt array of solar cells from RTC-La Radiotechnique Compélec.

but they have chiefly been novelties like battery chargers for digital watches and calculators.

Now that array prices are falling below $10/W, however, photovoltaics are beginning to compete with diesel-electric generators for larger-sized (1-to-5kW), so-called intermediate-market applications—providing power to villages in less developed countries, as well as for outdoor lighting and rural pumps (Fig. 15). DOE, through the Federal Photovoltaics Utilization Program, is also helping to expand the intermediate market by encouraging Government agencies, including the armed forces, to buy photovoltaic arrays.

Three such Federally sponsored projects are notable for their size. One is a 60-kW installation that will power the U. S. Air Force's Mount Laguna radar station near San Diego, Calif. [*Electronics*, Jan. 19, 1978, p. 41]. This system was designed and built by Delta Electronics Corp., Irvine, Calif., a supplier of uninterruptible power supplies for computer, medical, and military applications. Today, the site is ready and the system is on its way from Irvine where it passed operational field tests with flying colors.

The remaining two sizable Federal photovoltaics installations are: a 360-kW concentrator system that will power and heat Mississippi County Community College in Blytheville, Ark., beginning this fall [*Electronics*, June 22, 1978, p. 44]; and a 100-kW setup that will power the visitors' center at Natural Bridges National Monument in southeastern Utah. This system, whose 260,000 silicon cells comprise the largest flat-plate array in the world, is scheduled to take over from the site's existing diesel engine late this year.

Eventually, when the cost of the photovoltaic systems falls below $1/W, solar power will become an attractive alternative to utility power purchased by consumers. Then, solar cells will begin to show up on small commercial buildings, industrial plants, and perhaps even on massive space satellites that would beam huge amounts of photovoltaic power back to earth in microwave form (see "Solar-power satellites to chase the clouds away?" p. 121). But the hopes for future cost reductions depend on continued international research and market expansion, and especially on timely achievement of the module-price goals that DOE is shooting for.

DOE's report card

Even assuming that some DOE contractors are reluctant to bite the hand that feeds them, a sampling of contractors' opinions of DOE's performance makes it clear that, in the words of Donald Feucht, manager of DOE's R&D lead center at SERI, the department is "charting a good course". Even Robert Willis, president of tiny Solenergy Corp., Wakefield, Mass., one of the few commercial solar-cell suppliers that receives no Federal money, agrees with DOE's philosophy of simultaneous R, D & D—research, development and demonstration.

Rather than fault DOE, many critics of the photovoltaics program instead blame the U. S. Congress, which holds the program's purse strings, for its one serious shortcoming—delays in funding. Those delays not only slow technical progress, they often force layoffs of hard-to-replace scientific and engineering specialists as well. Indicative of Congress' influence is the fact that many hold it responsible for stalling the growth of the entire solar-energy industry during the 18-month period between President Carter's unveiling of the National Energy Act and its enactment. During that period, 3 out of 10 solar-energy companies, many of them small, simply disappeared while potential customers waited for Congressional approval of promised tax credits against purchases of solar equipment.

Many also criticize the skimpiness of Federal support for photovoltaics development; in fact, America's annual budget for solar-cell R&D is roughly equal to what it now spends each day on imports of foreign oil. Recently, however, Washington has again begun to make louder noises about its commitment to photovoltaics and solar energy in general. Just last month, for example, President Carter announced the establishment of a financial development bank that would, among other things, provide low-interest loans for solar construction.

One remote possibility is a dramatic increase in funding for the photovoltaics program. Although far from a certainty at this point, such a crash program would envision solar cells supplying as much as 25% of U. S. electricity needs by the year 2000, a far cry from the present 5% goal. According to Paul Maycock, who heads the program, such a crash effort might accelerate DOE's timetable by two years. □

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