had begun asking pointed questions about the relevance of oceanography to national goals, and the ICO, which was composed mostly of the heads of federal marine science programs, found itself in the unusual and embarrassing position of being "unable to rationalize further growth," the oceanography budget having risen to $135 million by 1964.

Wenk had left the FCST for the Library of Congress, but returned to the Executive Office in 1966 to head the newly formed marine council under Vice President Humphrey. As Wenk saw the council's role, it was to be a vigorous advocate for marine science, and most definitely not a neutral arbiter of policy. His objectives were to soothe rivalries among government oceanographers that could harm them all, to apply pressure on Congress and the budget bureau to keep the money flowing, and, of course, to rationalize growth. "If putting fuel in the oceanography tank was the name of the game," Wenk writes, "what purposes would justify that addition."

In its quest for rationale, the coun-

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RESEARCH NEWS

Photovoltaic Cells: Direct Conversion of Solar Energy

ENERGY

Solar cells that generate electricity by means of photovoltaic processes are the predominant source of power for space satellites. Because such cells convert sunlight directly into electricity without an intermediate thermodynamic cycle, and because sunlight is a large and inexhaustible resource, this technology is an inherently attractive source of power. At present, solar cells are not competitive with other means of generating electricity for terrestrial use, but their long-run potential has attracted increasing attention. Recent improvements in cell fabrication and manufacturing methods have stimulated novel proposals for utilizing solar energy on a large scale. Among the applications being studied are the solar-powered house—which some proponents believe could be a reality within 10 years—centralized generating station, and, as a more distant possibility, large orbiting power stations that would transmit energy back to earth.

Of the difficulties that stand in the way of terrestrial applications, the key problems are those of reducing the cost of solar cell arrays more than a hundredfold, increasing their useful lifetimes, and developing methods for the storage of energy. The relatively small numbers of cells produced for spacecraft are manufactured by costly batch processes and assembled by hand. Radiation damage in space or corrosion by humidity and other environmental agents on earth typically degrades the performance of unprotected cells well before the 20 to 30 years expected of power plants, and there is general agreement that encapsulation of cells in glass or plastic will be necessary. For terrestrial applications, the rotation of the earth and the uncertainties of cloud cover make solar energy an intermittent resource, and, as a result, some must be stored for use when the sun doesn't shine. Space power stations do not suffer from the intermittent availability of sunlight, but for them to become feasible, the cost of transporting the components into orbit will have to be greatly reduced.

Nonetheless, there is considerable optimism among those working on direct conversion of solar energy, which has the advantage, they point out, of avoiding virtually all of the environmental contamination problems associated with other sources of power. New and unfamiliar technologies are not required—photovoltaic cells were among the first semiconductor devices to be developed. But in recent years, according to a report by the National Academy of Sciences (*1*), there has been very little support for research aimed at improving solar cells and also no financial incentive for major industrial development efforts. The report concludes that the efficiency with which existing silicon solar cells convert sunlight to electricity, about 13 percent, might well be increased to 20 percent.

Silicon cells have been the mainstay of space power systems, but cadmium sulfide and gallium arsenide cells have also been developed and tested. In operation, positive and negative charges are generated within the cells by the absorption of solar photons. The charges diffuse across the cell until they either recombine or are separated and collected by an electrical inhomogeneity, typically a p-n junction between two semiconductor regions. Existing silicon cells develop about 0.5 volt, so that large numbers of cells must be arranged in series to achieve high voltages. The output is direct current, which in a practical power system would have to be inverted to alternating current before distribution to the consumer.

Silicon solar cells are made from single crystals of the material, and production of these crystals has always been a costly and awkward process. In a promising development, however, continuous ribbons of silicon have been grown at Tyco Laboratories in Waltham, Massachusetts. In the Tyco process, which was originally developed for continuously growing single crystals of sapphire, the ribbon is formed from a die that controls the shape of the emerging crystal. According to A. I. Mlavsky of Tyco, the process can already produce crystals at the rate of more than 2 centimeters per minute and could easily be automated to produce 100 crystals simultaneously. Although the process works well for sapphire and has produced silicon crystals with very few dislocations, the silicon is not yet of high enough quality for solar cells. The problem is that molten silicon is a highly reactive substance, very nearly a universal solvent, and it appears to be dissolving part of the die and thus introducing impurities into the silicon. A search for better die materials is continuing, and, if successful, could effectively lower the cost of silicon solar cells.

A second significant factor in the cost of silicon solar cells is that of the raw material. Although silicon is an abundant element and is available in metallurgical grade at $600 per ton, the cost of the extremely pure material needed for cell manufacture is 100 times higher, and its production consumes large amounts of energy. Assembling of solar cells into large arrays is also expensive and not easily automated. Although some have speculated that costs of silicon solar cell assemblies may rapidly be reduced to less than the $400 per kilowatt typical of nuclear power plants, others believe that additional breakthroughs in manufacturing and materials will be necessary to reach that goal.

The cadmium sulfide cell appears to be a more likely candidate for low-cost photovoltaic cells within the near future, although it has the disadvantage of considerably lower efficiency in that it converts only about 6 percent of the incident light to electricity. The main advantage of the cadmium sulfide cell is that it can be made from microcrystalline thin films, rather than from single crystals. Thus these cells can be produced by vacuum-depositing materials on plastic, a process that lends itself to continuous mass-production methods. Several estimates suggest that cells cheap enough to be commercially competitive with other sources of electricity could be manufactured with existing techniques. A major problem with cadmium sulfide cells, however, has been their lack of reliability, since they degrade easily in the presence of moisture, at elevated temperatures, and possibly under the influence of light.

Gallium arsenide cells have been proposed as a possible substitute for silicon cells, in part because of their resistance to radiation damage. Small gallium arsenide cells with efficiencies claimed to be as high as 18 percent have been tested at one laboratory. There is some question, however, as to whether gallium can be found in sufficient quantities to permit large-scale use of such cells, and it seems likely that they will be more costly to make than either silicon or cadmium sulfide cells.

Even if low-cost, high-efficiency solar cells can be produced, however, their effective utilization in an energy system will not automatically come to pass. A particularly difficult problem is that of energy storage. Electrochemical storage is one possibility, but batteries of adequate capacity that can also withstand frequent charging and discharging for many years have yet to be developed. Hydrostorage of the type now used by some utility systems is limited, for large facilities, to a few regions of the country. Mechanical storage in high-speed flywheels is considered by some observers to be a realistic possibility, although little work on practical systems has been done. Another attractive proposal is that of storing energy in the form of hydrogen, which could be reconverted to electricity in fuel cells; the low-voltage, direct-current output of solar cells is ideal for electrolysis of water (from whence the hydrogen), but potential safety problems, the difficulties of storing gaseous hydrogen, and a source of long-lasting and inexpensive catalysts for the fuel cells need to be resolved.

Because practical large-scale energy storage is not yet available, most proposals for photovoltaic power systems have been designed to do without more than limited storage. A prototype solar house being developed by Karl Boer and his colleagues at the University of Delaware in Newark, for example, will be interconnected with the existing utility system in a tandem arrangement. In the proposed system, sunlight would be a supplemental source of energy, providing electricity and heat to the house and to a small conventional storage battery during daylight hours and in essence supplying excess power to the utility network; in emergencies and during the hours of peak demand, the utility company could switch the house to the storage battery, thus lightening its load. Conventional power plants would provide the bulk of the electricity for the utility system. Because peak hours of sunlight coincide to some extent with the hours of maximum use of electricity, Boer believes that as much as 20 percent of a utility's power could be supplied by solar energy without the use of major storage facilities—in effect, solar cells on houses and commercial buildings would provide reserve capacity for the utility.

Design for a Solar House

The solar cells in the Delaware design would be cadmium sulfide cells encapsulated in plastic panels that would replace normal roofing materials. Because of the low efficiency of the cadmium sulfide cells, essentially the entire roof of an ordinary house would be needed to provide adequate power, Boer estimates. In addition to generating electricity, the roof panels absorb heat that is collected and stored in compact thermal reservoirs of frozen salts. An electrically driven heat pump connected to one of the reservoirs heats and cools the house, and other reservoirs provide hot water.

Although the cost of the prototype house will be considerably more than for conventional systems, Boer believes that mass production of the solar panels, with only slight improvements of existing techniques, could bring the cost of power from the system to within range of commercial feasibility. Utilities, he believes, might be willing to partially subsidize the extra cost of a solar house and to maintain the solar panels in return for use of the excess power from the unit. Although costs and the technical feasibility of an interconnected system on a large scale remain to be demonstrated, the advantages of a distributed system and its potential for rapid development have attracted considerable notice.

A more long-range system that would also avoid the need for major storage of power is a space power station in synchronous orbit around the earth. As proposed by Peter Glaser of Arthur D. Little, Inc. in Cambridge, Massachusetts, large steerable arrays of silicon cells would generate electricity that would be converted to microwave power, transmitted back to antennae on earth, and converted back to electricity (*2*). Large antennae, about 1 kilometer in diameter in space and at least 7 kilometers in diameter on earth, would be needed to transmit and receive the microwave beam efficiently. Although such a system could provide large amounts of power, questions about the endurance of the components, the control of large structures in space, and the safety of the microwave radiation have still to be answered. Demonstration of such a system will be difficult and costly, since it is dependent on the existence of an inexpensive space shuttle.

Consideration of photovoltaic cells for terrestrial power systems has only just begun, and more proposals for practical systems can be expected. It seems likely that efficiencies of silicon solar cells can be improved to around 20 percent, comparable to the efficiencies expected from large solar-thermal power plants, and that mass production techniques will eventually lower the costs of these semiconductor devices significantly; low-cost cadmium sulfide cells may be available even sooner. Although large amounts of photovoltaic power are not likely to be available in the near future, and although the development of this technology will undoubtedly require major federal funding, the potential resource is large. There appears, in the opinion of many scientists in the field, to be no basic reason why direct conversion cannot become a reality.

—Allen L. Hammond

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