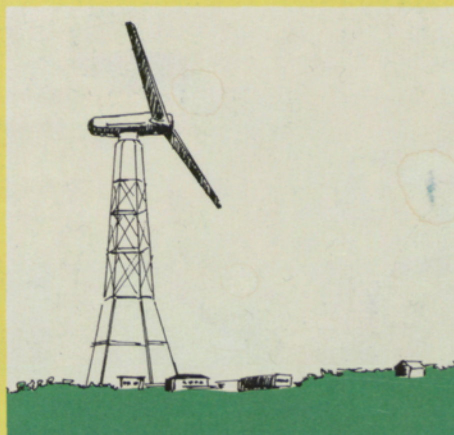
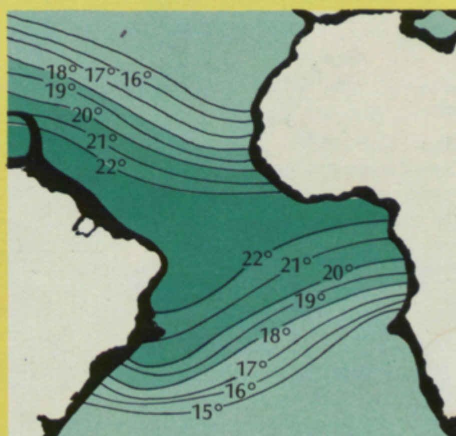
ENGINEERING

CORNELL QUARTERLY





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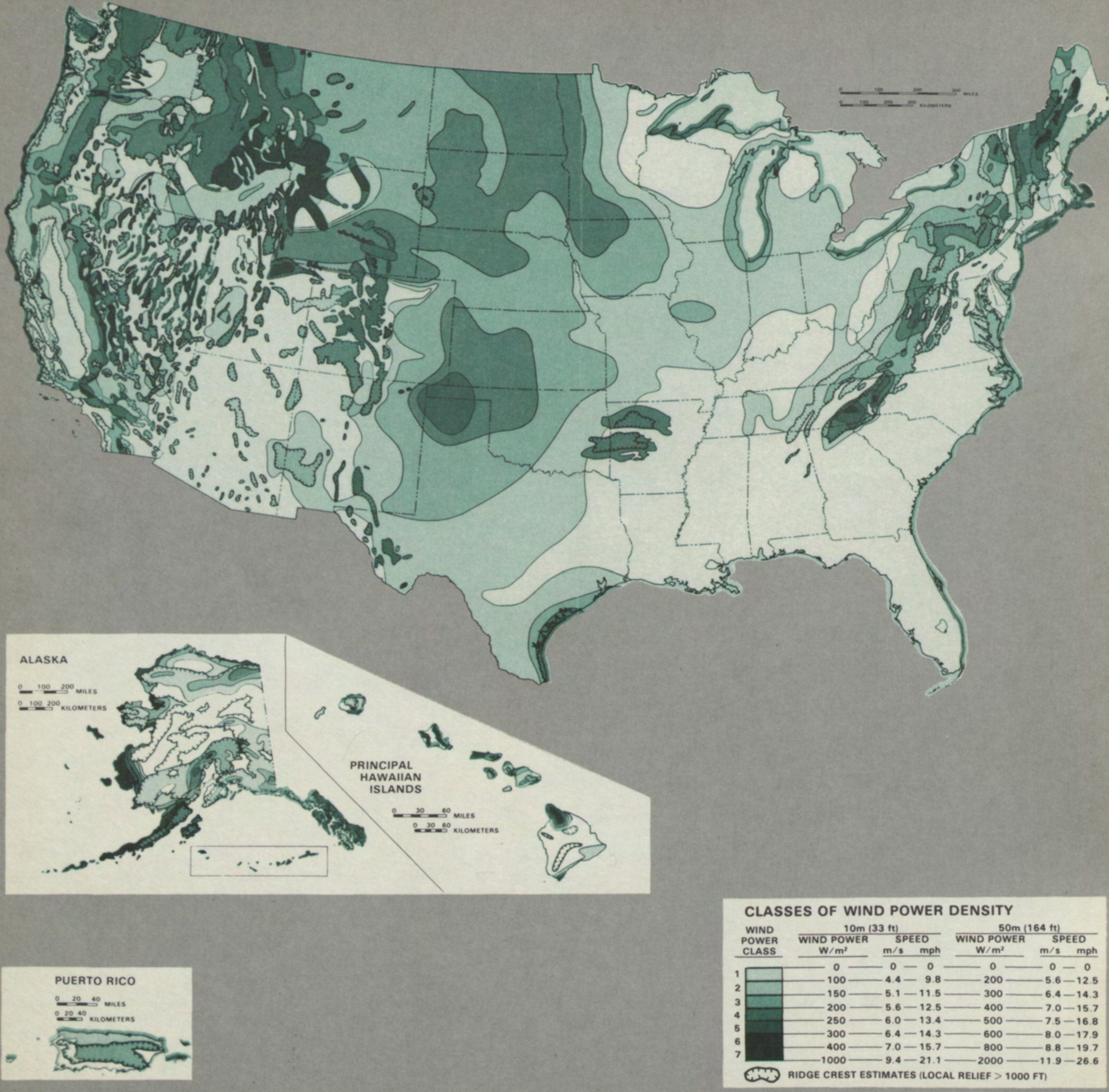
SUMMER 1982

SOLAR ENERGY PROJECTS IN JEOPARDY



CLASSES OF WIND POWER DENSITY

WIND POWER CLASS	10m (33 ft) WIND POWER W/m²	10m SPEED m/s	10m SPEED mph	50m (164 ft) WIND POWER W/m²	50m SPEED m/s	50m SPEED mph
	0	0	0	0	0	0
1	100	4.4	9.8	200	5.6	12.5
2	150	5.1	11.5	300	6.4	14.3
3	200	5.6	12.5	400	7.0	15.7
4	250	6.0	13.4	500	7.5	16.8
5	300	6.4	14.3	600	8.0	17.9
6	400	7.0	15.7	800	8.8	19.7
7	1000	9.4	21.1	2000	11.9	26.6

RIDGE CREST ESTIMATES (LOCAL RELIEF > 1000 FT)

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Opposite: A wind resource map produced by Pacific Northwest Laboratory for the U.S. Department of Energy. It is based on a synthesis of twelve regional assessments. Local terrain may cause variations of as much as 100 percent. Outside cover: Illustrations by Sue Bloodgood representing solar-derived energy sources: wind power, crop residues, and ocean thermal energy conversion.

WIND POWER FOR ELECTRIC UTILITY SYSTEMS

by Robert J. Thomas

On October 10, 1941, on Grandpa's Knob near Rutland, Vermont, a large wind turbine was synchronized with the Central Vermont Public Service Corporation network, and the world's first megawatt-sized windmill to supply an electric utility grid came on line.

Since then, in the manner of the wind itself, the promise of wind power has died down and picked up again. The 1.25-megawatt (MW) Smith-Putnam unit on Grandpa's Knob established the basic design configuration most likely to be cost-effective and demonstrated that large wind turbines can be integrated into electric utilities as power plants. Also in the early forties, the Federal Power Commission was sufficiently interested in wind power to initiate a study, which concluded that wind could be a stable and reliable source of utility power if operated on a large scale in conjunction with interconnected steam and hydro systems. But then, with the discovery and development of cheap oil reserves in the United States and elsewhere, especially in the Arab countries, the efforts to utilize wind power for utility applications were abandoned. Subsequent developments, beginning with the oil embargo of 1973, renewed the interest in wind; the federal Department of Energy (DOE) initiated a new effort as part of its program to advance the use of renewable energy sources, and other agencies and a number of private companies supported or undertook projects in wind power. Whether development activity will rise or diminish in the near future is uncertain in view of the current federal budget situation.

Still, the technology is now the most advanced in concept and demonstration of any of the solar-derived energy systems, and it seems inevitable that wind-generated energy will be integrated at some level into existing power grids during this decade.

THE U.S. POTENTIAL FOR WIND ENERGY GENERATION

The Federal Power Commission report on the potential of electricity generation from wind energy envisioned the supply of very low-cost wind power up to perhaps 20 percent of the nation's total aggregate capacity. Fluctuations in wind velocity, the report suggested, might be compensated for by wide dispersion of turbine sites and the use of hydro storage systems.

To consider the implications of such a prospect, we need an idea of the magnitude of this electrical power. Approximately 30 percent of all the energy used in the United States is in the form of electricity; in 1977 this amounted to 22.6 quads of energy, produced from coal, oil, gas, nuclear fuels, and hydro sources. One quad is one quadrillion or 10^{15} BTUs, a vast quantity difficult to imagine; it is equivalent to 172 million barrels of oil or to the amount of coal that would be contained in a train of cars stretching 3,700 miles, as from Seattle to Key West and beyond.

Does the nation have sufficient wind resources to make an impact on electricity supply of this magnitude? In particular, could it significantly reduce the consumption of oil? Detailed resource data are available in the form of twelve regional assessments conducted by Pacific Northwest Labora-

Figure 1

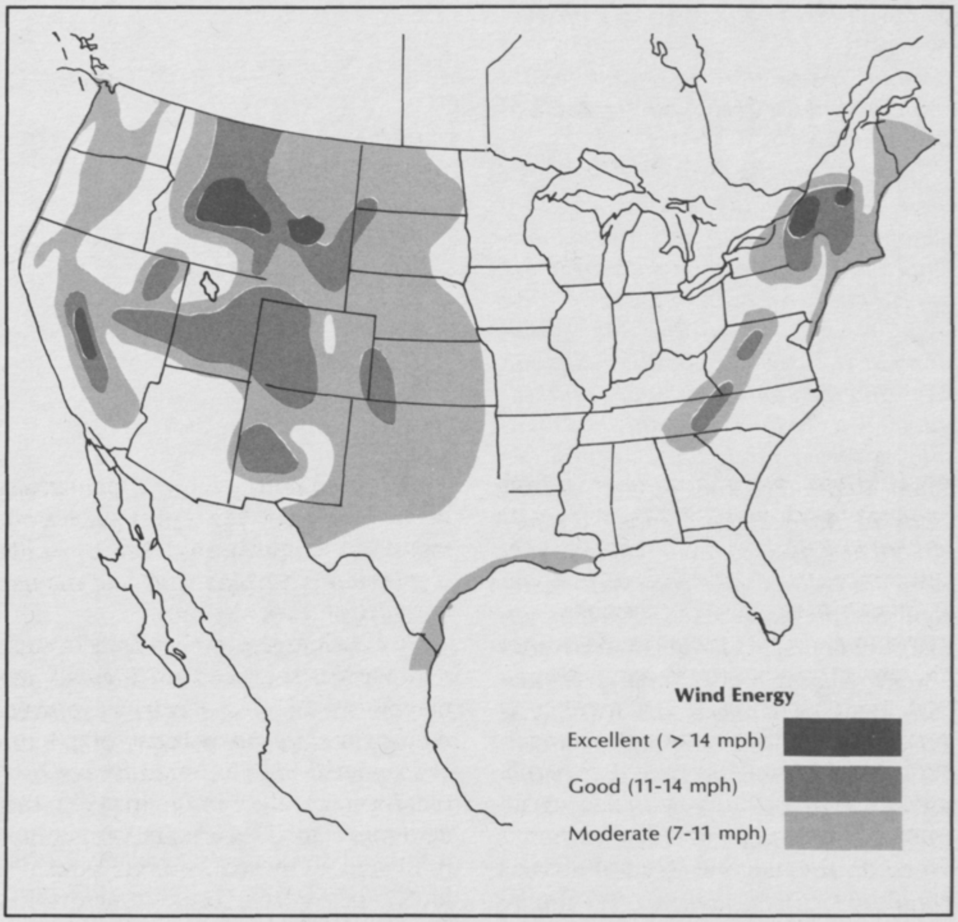


Figure 1. United States land area suitable for siting wind turbines, as assessed by the General Electric Company's Space Division. The table lists the total areas of land assessed as excellent, good, *and* moderate, *and the numbers of square miles in each category that are thought to be actually available.*

MAXIMUM POTENTIAL OF WIND POWER FOR GENERATING ELECTRICITY

Site Assessment	Useable Area	Number of Mod-2s	Electricity Produced*	Energy Saved*
Excellent	3,000	4,800	0.2	.6
Good	54,000	86,000	2.0	6.0
Moderate	157,000	250,000	2.7	8.1
TOTAL	214,000	340,800	4.9	14.7

**Production and savings are measured in quads per year. One quad equals 10^{15} BTU, the equivalent of 300 billion kWh of electricity or 172 million barrels of oil.*

tory; various atlases present the information in graphic, tabular, and narrative form. On the basis of these assessments, DOE has prepared a wind-resource map displaying annual average wind power throughout the United States and its territories (see the inside front cover). The General Electric Company's Space Division also conducted a survey for DOE (see Figure 1), and found approximately 1,574,000 square miles of United States territory that experiences average wind speeds above 7 mph. Of this, about 214,000 square miles were estimated as actually available. In the study, potential wind sites were defined as *moderately good* (7-11 mph average wind velocity), *good* (11-14 mph), and *excellent* (greater than 14 mph). (It should be noted, however, that wind speed alone does not determine the desirability of a site. High winds alternating with periods of calm might produce an excellent average, but nevertheless a poor site; steady winds are much better.)

The table summarizes findings and conclusions of the General Electric

A Historical Note about the Windmill on Grandpa's Knob

Two men associated with Cornell took part in the development of the historic Smith-Putnam windmill, the world's first wind turbine of megawatt size to generate electricity for a utility system. They were William R. Sears, who founded and directed Cornell's Graduate School of Aerospace Engineering and since 1975 has been at the University of Arizona; and the late Theodore von Kármán, who was the 1953 Messenger Lecturer at Cornell and in 1959 spent the spring term at the University as the Victor Emanuel Distinguished Professor. Von Kármán was director of the Guggenheim Aeronautics Laboratory at the California Institute of Technology (GALCIT) from its founding in the late 1920s until 1942, and later founded and directed NATO's Advisory Group for Aeronautical Research and Development (AGARD) in Paris. Sears was von Kármán's student at Cal Tech.

The windmill project was described by von Kármán in his autobiography, *The Wind and Beyond* (written with Lee Edson and published by Little, Brown, copyright 1967):

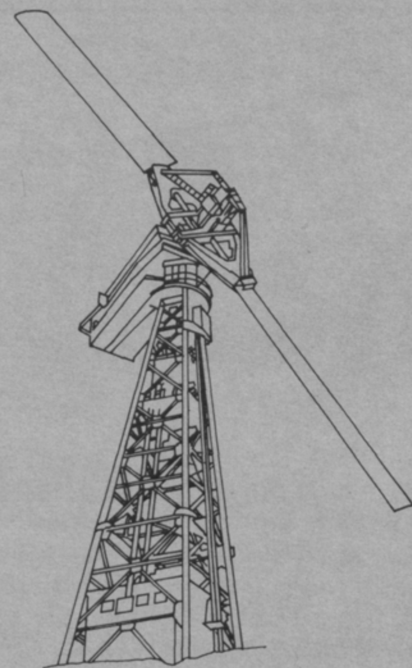
One day in 1939, Palmer C. Putnam, an energetic New England promoter, approached me for advice on what turned out to be the most unusual wind project of my Cal Tech days—a windmill to generate electricity. Putnam had managed to persuade a number of electrical utilities to back him financially. . . . To advise on design, Putnam got together a group of consultants. . . . Dr. William Sears, then an instructor at Cal Tech, Duncan Rannie, a graduate assistant, and I soon formed the aerodynamics team of the project.

In laying out the project I discovered there was actually no theory from which to design windmills, only empirical rules. So in keeping with my usual approach I suggested that we first build models illustrating the conditions at the various possible windmill sites and then make a number of wind-tunnel tests to determine the best location. After we made our selection, we could determine the proper dimensions of the windmill, make a scale model, and thus gradually and soundly we would develop a satisfactory design. But the sponsors were in a hurry. They wanted to plunge directly into design without model tests. I argued with Putnam. I asked him whether it was wise to skip important steps. "Could the Wright brothers have gone directly into the design of the DC-4 from their first flight at Kitty Hawk?" I asked. Putnam only nodded at me and continued with his idea. . . . We finally agreed on a single design [and] *the windmill was completed in August 1941. It was the largest of its type ever built. . . . On its first operational trial it generated enough electricity to light up a small town. The promoters were delighted.*

However, a problem soon arose because of the new engineering features, mainly the coning, in that the blades were too flexible. . . . We had to put in damping devices, and these introduced new loads when the blades rotated. Some of the structures soon started to loosen. One winter the shaft had to be sent out for repairs . . . and finally one of the blades tore loose and broke.

After that the backers lost heart. They had second thoughts about the costs. Moreover, we were at war [and] *materials were growing scarce.*

I was sorry to see the windmill abandoned. . . . I think if we had taken the job step by step we would have learned about the coning in time. . . .



The Smith-Putnam wind turbine, situated on 2,000-foot Grandpa's Knob in Vermont, was mounted on a 110-foot tower and had rotor blades measuring 175 feet from tip to tip. It generated 1.25 MW of power in winds of 30 mph or more, and was in intermittent operation between 1941 and 1945. The project was conceived by Palmer C. Putnam and funded by the S. Morgan Smith Company of York, Pennsylvania, a manufacturer of hydraulic turbines.

Left: The first wind-turbine generator built as part of the Federal Wind Energy Program was the 100-kW Mod-0. It has been in operation at NASA's Plum Brook station near Sandusky, Ohio, since 1975.

Right: This 200-kW generator on Block Island, Rhode Island, was the third Mod-0A built under the federal program. Professor Thomas went to Block Island to study the utility and its operation; his conclusions, "A Report on the Block Island Power Company MOD-0A Wind Turbine Project," were published recently by NASA.

Four machines of this type have been built in different kinds of environments. The first, installed at Clayton, New Mexico, began operating in early 1978 (the system was described by T. Reddoch and J. Klein in an article that appeared in Spectrum *in 1979). The other two Mod-0As were installed on the island of Culebra, Puerto Rico, and at Kahuka, Hawaii.*

survey. If all the available land were used to site Mod-2 wind turbines (the most technologically up-to-date federally-funded machines), hundreds of thousands of the huge machines clustered at sites across the nation could produce almost one-fourth of the nation's electricity. This would save a much larger amount of energy in the form of fuel for electricity-generating plants; the savings would amount to about seven million barrels of oil a day.

For this and other reasons, electric utility companies are greatly interested in exploiting wind power. In 1980 an Electric Power Research Institute (EPRI) survey showed that fifty-one United States utilities were conducting eighty-three wind projects. These programs, along with a concerted effort by DOE and NASA, have created a solid engineering foundation, including theoretical development and demonstration results. Machines suitable for commercial use appear ready for mass production.

THE MOD SERIES OF WIND TURBINES

Several large wind turbines are currently being designed and constructed by public and private concerns in this country. (A *large* wind-turbine generator is defined arbitrarily as one with a maximum output power greater than 100 kilowatts [kW] electric.) The horizontal-axis designs developed under the Federal Wind Energy Program will be discussed here because they are representative of the type and because information about them is readily available.

When the federal program was reestablished in 1973 as an element of the solar-energy program, it was decided to engineer and test a wind turbine of reasonably large size in order to provide an engineering database. NASA's Lewis Research Center was delegated to design, build, and test a 100-kW machine with a rotor 125 feet in diameter. The Mod-0, as it was named, became operational in 1975 and has served as a test-bed for the subsequent machines of the Mod series. It is still in operation at NASA's Plum Brook station near Sandusky, Ohio.

The Mod-0A project was initiated in 1975 in order to gain real utility operating experience. This turbine is similar in design to the Mod-0, but can provide a maximum output of 200 kW with its 125-foot-diameter blade. While the

Figure 2

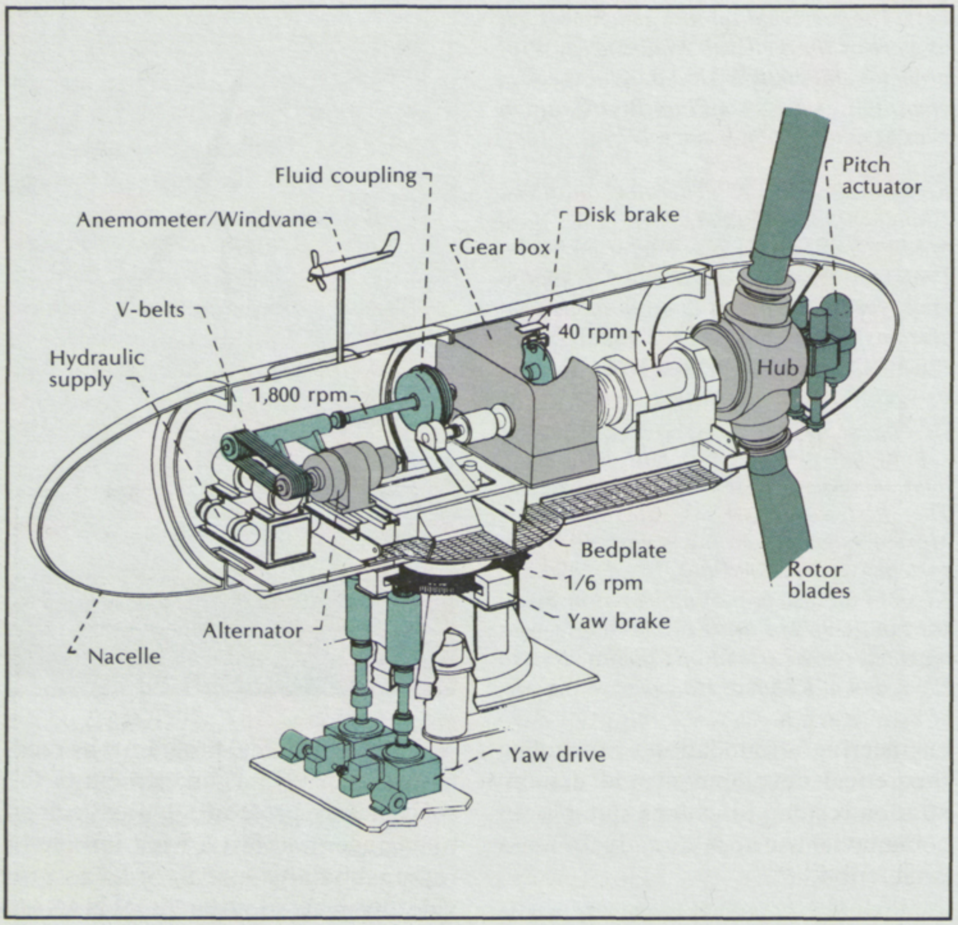


Figure 2. A schematic of the nacelle interior of a Mod-0A 200-kW wind-turbine generator.

Mod-0As were being designed, personnel in the Federal Wind Energy Program sent a request to utilities around the country for detailed information on possible sites; sixty-four companies responded and sixteen sites were selected. (So far, eight machines—four Mod-0A, one Mod-1, and three Mod-2—have been installed at six locations.)

The Mod-1 project was designed to develop a wind turbine in the megawatt range that would generate power for a utility system at costs competitive with conventional generation. General Electric's Space Division won the competitive contract in 1976 and in 1979 began operating the 2,000-kW Mod-1 on Howard's Knob in Boone, North Carolina.

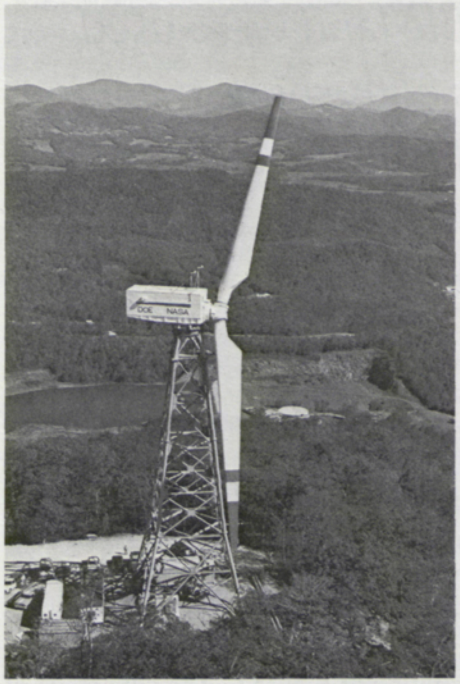
In 1977 the Boeing Company was awarded a contract to design, fabricate, and assemble three Mod-2 MW-range turbines with rotor diameters of 300 feet or more. The purpose was to test the potential cost-effectiveness of this size turbine in moderate wind regimes (14 mph mean wind speed) and to begin a limited study of dynamic interactions encountered with machines of this size. These three turbines are now being installed and tested at Goodnoe Hills, Washington.

Operating characteristics of the four Mod-series machines already built are shown in Figure 3. Conceptual design contracts have been awarded for a new generation of wind turbines, the Mod-5.

THE NEXT STEP IN IMPLEMENTING SYSTEMS

The stage is now set for the next major step toward implementation of wind-energy-conversion systems (WECS): the operation of hundreds of dispersed, intermittent wind turbines on utility systems. A single wind turbine cannot be relied upon as a firm or continuous source of power; this was recognized in the early Federal Power Commission studies and is still accepted. Now, as then, the object is to integrate large arrays, or clusters (fifty or more units) of wind-turbine generators into a utility.

Plans for this integration are already taking shape within many utilities throughout the country. The Hawaiian Electric Company, for example, intends to buy power from a private developer who intends to install an 80-MW cluster on Oahu by 1985. Southern California Edison hopes to be generating 3 percent of its energy with the wind by the year 2000. Pacific Gas and Electric has agreed to buy power from a 350-MW cluster that a

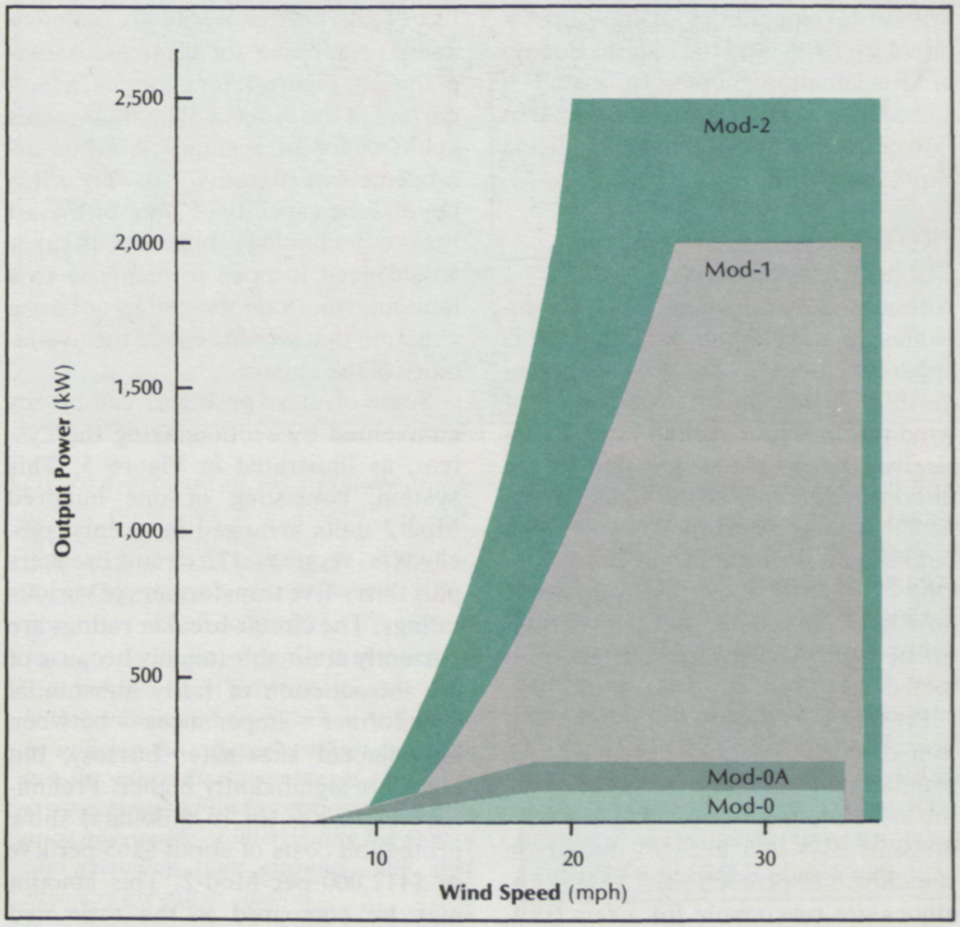


Left: The 2,000-kW Mod-1 on Howard's Knob in Boone, North Carolina, has a rotor 200 feet in diameter and a tower 131 feet high. This machine, situated on a hillside overlooking the town, is the only one tested so far that has had acoustical noise problems.

Left below: This 2-MW machine is one of three Mod-2s now being installed at Goodnoe Hills, Washington, and tested on the Bonneville Power Adminstration system.

Figure 3. Operating characteristics for four wind turbines of the Mod series. An additional machine, the Mod-5, is planned.

Figure 3



"If all the available land were used . . . hundreds of thousands of the huge machines . . . could produce almost one-fourth of the nation's electricity."

private developer hopes to have operational by 1989. And the federal Bureau of Reclamation hopes to install a 150-MW cluster on the Western Area Power Authority system at Medicine Bow, Wyoming.

PROTECTING BOTH CLUSTER AND GRID

Although the interest of private companies in developing wind power is apparent, there are, of course, potential difficulties in integrating clusters of wind turbines into utility systems. Basically, the problems are due to the intermittent nature of the wind and the fact that large wind turbines have no counterpart in established hardware. One of the concerns, for example, is how both the cluster and the conventional utility hardware can be protected.

Present approaches to the assimilation of clusters are centered on two standard interfacing configurations—the T-bus and the ring-bus arrangements—with security based on standard bus protection. These techniques are reasonable for a few (say, five or six) machines, but are economically prohibitive for clusters. As explained in Figure 4, for example, a fault current of the order of 300,000 amperes could occur in a standard T-bus arrangement of 101 units. Not only is this beyond the capacity of state-of-the-art breaker technology, but every breaker would need to open in response to a fault anywhere on the collector bus, a situation that would reduce the availability of the cluster.

Some of these problems can be circumvented by sectionalizing the system, as illustrated in Figure 5. This system, consisting of one hundred Mod-2 units arranged in twenty subclusters, requires 172 circuit breakers plus thirty-five transformers of various ratings. The circuit-breaker ratings are currently attainable (mainly because of the introduction of fairly substantial transformer impedances between nonadjacent subcluster busses), but costs are significantly higher. Preliminary estimates (in 1976 dollars) show protection costs of about $165 per kW or $412,000 per Mod-2. This amount may be compared to the estimated fabrication and installation cost of $1.6 million (in 1976 dollars) for a Mod-2 machine.

Another bus arrangement that has been suggested for large clusters of wind machines is the ring-bus configuration of Figure 6. The advantage of this arrangement is that a machine bus fault can be isolated by opening two circuit breakers, a capability that enhances the operating reliability of the cluster. Like the T-bus, however, this configuration has the disadvantage of requiring that each circuit breaker be capable of interrupting a very large fault current, a function that is beyond the capability of state-of-the-art breakers. The ring-bus could be sectionalized, as shown for the T-bus in Figure 5, but again the cost of protection would be higher.

THE CORNELL DESIGN FOR A SPECIAL INTERFACE

These economic and technical problems of integrating a wind-turbine cluster into a utility grid are obviated by use of an AC/DC/AC interface specifically designed for intermittent sources

Wind-energy-conversion systems (WECS) require arrangements for the protection of both the turbines and the power grid. Protection schemes based on standard interfacing configurations are unsatisfactory for WECS, however, as shown in Figures 4, 5, and 6.

Figure 4

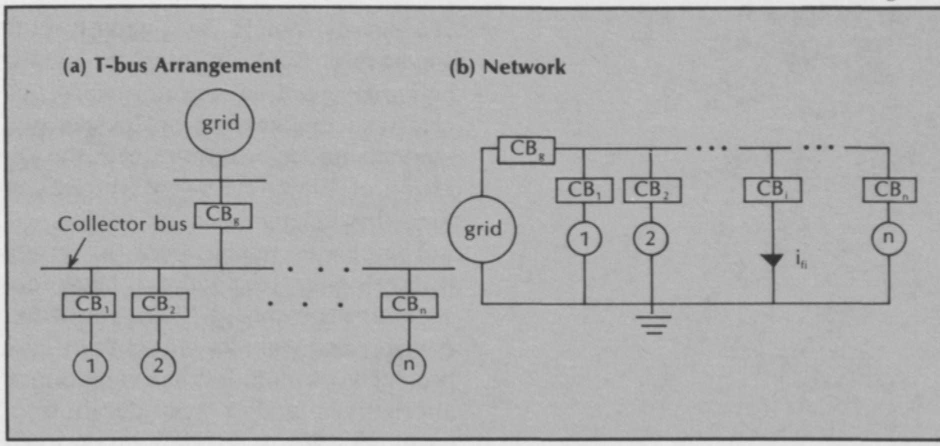


Figure 4. A suggested T-bus arrangement (a) and the equivalent network (b) for a cluster of n *wind-turbine generators. The reason that such an arrangement is unsatisfactory is that circuit breakers (CB) must be capable of interrupting the largest fault current that could flow, and this is much too high for state-of-the-art breakers.*

The explanation is that the maximum flow would occur whenever there was an internal machine fault anywhere in the system. In diagram (b), the fault current i_{fi} *for machine* i *includes the sum of all the fault-current components of the remaining* (n-1) *machines, plus the grid current. Even if a very large grid impendance (due to, say, a significant transmission-line distance and a step-up transformer) is assumed, and therefore the contribution of the grid current is neglected, the magnitude of* i_{fi} *can be appreciable. For example, if the collector bus is at generator voltage (4.16 for a Mod-2) and there are 101 machines, standard circuit calculations give a rated full-load current of 350 amperes per machine. The short-circuit current is therefore likely to be 3,360 amperes per machine, which implies a rating for this configuration of 336,000 amperes per breaker. In effect, with such a cluster arrangement* each *2.5-MW Mod-2 must be protected as though it were a 250-MW or greater generating plant.*

Figure 5

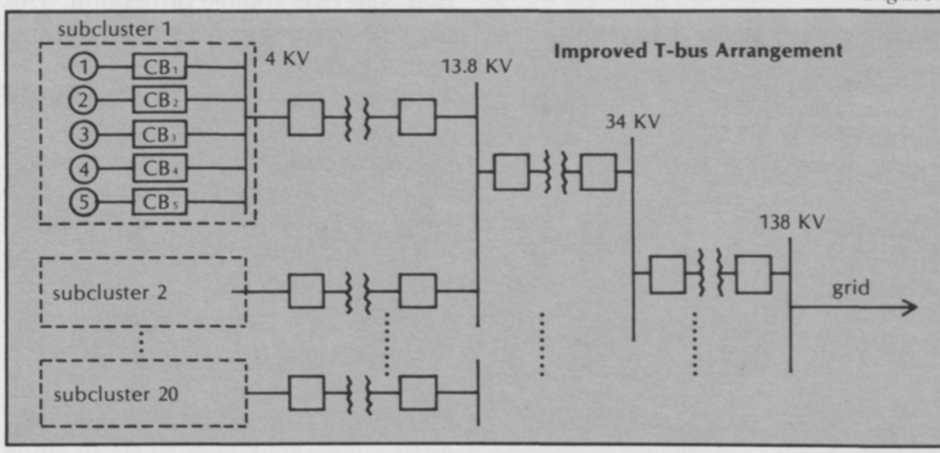


Figure 5. An improved T-bus arrangement incorporating subclusters and step-up transformers. Such a sectionalized system is preferable to the one represented in Figure 4 because of the adequate transformer protection and because all the circuit-breaker ratings can be achieved with present technology, but it would be expensive.

Figure 6

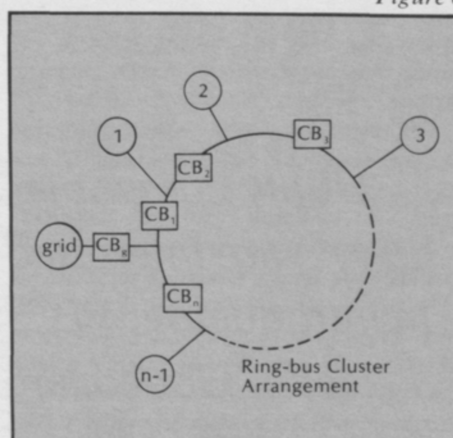


Figure 6. A ring-bus cluster arrangement. This configuration provides greater reliability because it allows a fault to be isolated by opening the adjacent current breakers, but the other disadvantage of the T-bus arrangement of Figure 4 remains: breakers must be capable of interrupting the sum of the maximum fault currents, and such breakers are not available.

"Utility companies are interested in introducing WECS and, indeed, are beginning to do so."

of energy such as wind-turbine generators. Such an interface is now being designed by a group of Cornell electrical engineering professors and students under a contract with the Division of Electric Energy Systems of the federal Department of Energy.

The cluster arrangement this group is developing (see Figure 7) takes into account problems of fault protection, control, and stability. In addition, the project work includes the evaluation of alternatives and a consideration of harmonic effects, insulation coordination, and overvoltage protection. This Cornell design has a number of inherent advantages:

- Interactions among generators are eliminated.
- Resynchronization is unnecessary.
- Individual generator speeds may vary widely.
- The output of the cluster can be centrally controlled.
- The system is economically attractive.

The cost projections for this arrangement (excluding wire and grid interconnection equipment) are about five dollars per kW for the rectifiers and fifty dollars per kW for the inverter, or about one-third the protection costs for a conventional AC system.

The point about generator speed is particularly significant. If each generator could run asynchronously, the cluster would be able to capture significantly more wind. However, virtually all recent wind-turbine designs are for constant-speed synchronous machines, sized variously for different average-velocity wind regimes. In the early (1940) Federal Power Commission study it was recognized that for optimum performance a set of turbines should operate at a natural speed dependent on the velocity of the wind, but that the energy must be delivered at constant frequency. The suggestion then, as now in the Cornell proposal, is for DC/AC conversion, permitting turbine operation at the most advantageous speed in order to extract "a materially larger amount of total energy from the wind." (The Power Commission study, however, suggested DC machines operating in parallel with individual inverters, the use of automatic tap-changing transformers, and field regulation.)

THE PROSPECTS OF WIND POWER FOR UTILITY SYSTEMS

The assimilation of wind-turbine clusters into standard power networks—the subject of the Cornell research—is one of the most important current technical problems in the development of wind-power systems for utilities. So far, research and development efforts applicable to large wind-turbine generators have been concerned with stand-alone machines or, at most, two or three machines. Little is yet known about the compatibility between an existing power network and a wind-turbine cluster supplying a substantial portion of the system load and, consequently, little is known about the expected operation of wind-energy-conversion systems, or WECS. Specific problems to be addressed include the protection of turbines and power grids, which I have discussed. Also, the siting of clusters must be studied in terms of the anticipated penetration level, and aggregate dynamic models must be developed.

Figure 7

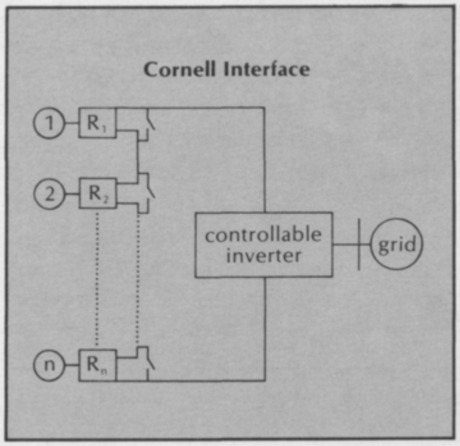
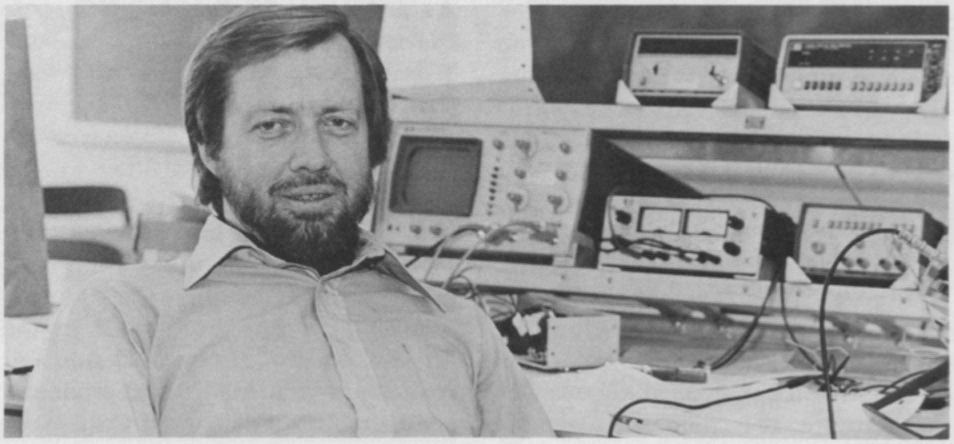


Figure 7. An interface under development at Cornell for integrating a wind-turbine cluster into a utility grid. The simplified diagram shows the arrangement of rectifiers (R_i) for the cluster and a controllable inverter unit that includes several inverters. The design provides fault protection, control, and stability.

Despite what needs to be done, however, the technology has an impressive record of successes. The Federal Wind Energy Program has encompassed more than just the design and installation of prototype machines. Economic and market analyses have been performed to provide program planners and potential users with information and forecasts. Several studies have been made of legal, social, and environmental issues. Meteorological work for site selection is ongoing, along with technical management of proposed new systems. Utility companies are interested in introducing WECS and, indeed, are beginning to do so.

All of this effort, and more, has gone into the development of a technology that may help offset our nation's dependence on foreign oil. It may be that the policies of the current administration will have the same effect on the national wind program as the discovery of cheap oil had some forty years ago. But if the momentum of development is sustained by continuing federal support, we may soon realize the promise of an abundant, renewable, environmentally clean energy resource.



Robert J. Thomas, an associate professor of electrical engineering at Cornell, specializes in system theory and control, with applications to problems in large-scale power systems. His recent research has included studies of potential problems associated with the integration of clusters of many large wind-turbine generators into utility systems. During 1979-80, he spent a sabbatical leave in Washington with the Office of Electric Energy Systems of the federal Department of Energy; as assistant program director, his major duties included the review of state-of-the art practices and problems in power-system control and integration, as well as critical review of ongoing research projects within the System Architecture and New Source Technology Integration programs. He is now a consultant to NASA on utility-related problems in wind technology.

Thomas came to Cornell in 1973 from Wayne State University, where he studied for bachelor's, master's, and doctoral degrees. He is a member of the Institute of Electrical & Electronics Engineers, Eta Kappa Nu, Tau Beta Pi, and Sigma Xi. He received the annual Excellence in Teaching award from the School of Electrical Engineering three times in recent years.

OCEAN THERMAL ENERGY TO FEED THE POWER GRIDS

by Robert Cohen

Huge collection and storage devices for solar energy are already present on Earth and could be used to generate electricity on a large scale. The collectors are the world's oceans, which absorb heat from the sun and develop thermal gradients between the surface and the depths. The conversion of such temperature differences to electricity is not complicated—essentially it is the reverse of a household refrigerator cycle—and does not require major new scientific or technological knowledge. Furthermore, it is potentially significant: ocean thermal energy conversion (OTEC) could eventually supply the world with a large fraction of the energy it needs.

OTEC is therefore an appealing potential source of clean, renewable energy. Whether commercial OTEC plants are feasible from the technical, economic, and environmental viewpoints remains to be demonstrated, however. A key question is the projected cost of OTEC in comparison with other renewable sources and with depletable fuels such as coal, oil, gas, and uranium.

A CENTURY-OLD CONCEPT COMING TO MATURITY

The concept of utilizing ocean temperature differences to generate electricity is not new. It was first proposed about one hundred years ago by Arsène d'Arsonval, a French physicist, who suggested using a substance with a low boiling point as the working fluid in a closed-cycle system. The first experimental studies were made by the French inventor Georges Claude and reported in 1930. In these experiments, conducted off the coast of Cuba, seawater was used as the working fluid in an open-cycle system.

Impending worldwide energy shortages spurred renewed interest in ocean thermal energy, and OTEC is now under development in a number of countries. The most ambitious program so far is the one conducted by the United States Department of Energy, with cumulative funding of about $200 million. (The program is currently operating at a reduced budget of $20 million a year.) In Hawaii a United States industrial consortium funded and successfully operated a small experimental pilot project, called Mini-OTEC, in conjunction with the state government (see the photograph on page 16). Other development programs are being carried out by the governments of France and Japan.

The basic requirement for an OTEC plant is access to ocean waters having sufficient temperature difference (typically about 20 degrees Celsius) between the surface and depths of about 1,000 meters. At certain locations, facilities could be built on shore, with the ocean water brought in by aqueducts, but in general, adequate thermal gradients are accessible only at sea, mainly at tropical and subtropical latitudes (see Figure 1). Electric power generated at sea can be transmitted to shore via submarine cable or used for manufacturing operations on the platform, with production of such energy-intensive, easily transported substances as aluminum, ammonia, hydrogen, chlorine, or magnesium.

The size of OTEC plants could readily be adjusted to match commercial applications. It is likely that the size would range from about 10 megawatts

Figure 1

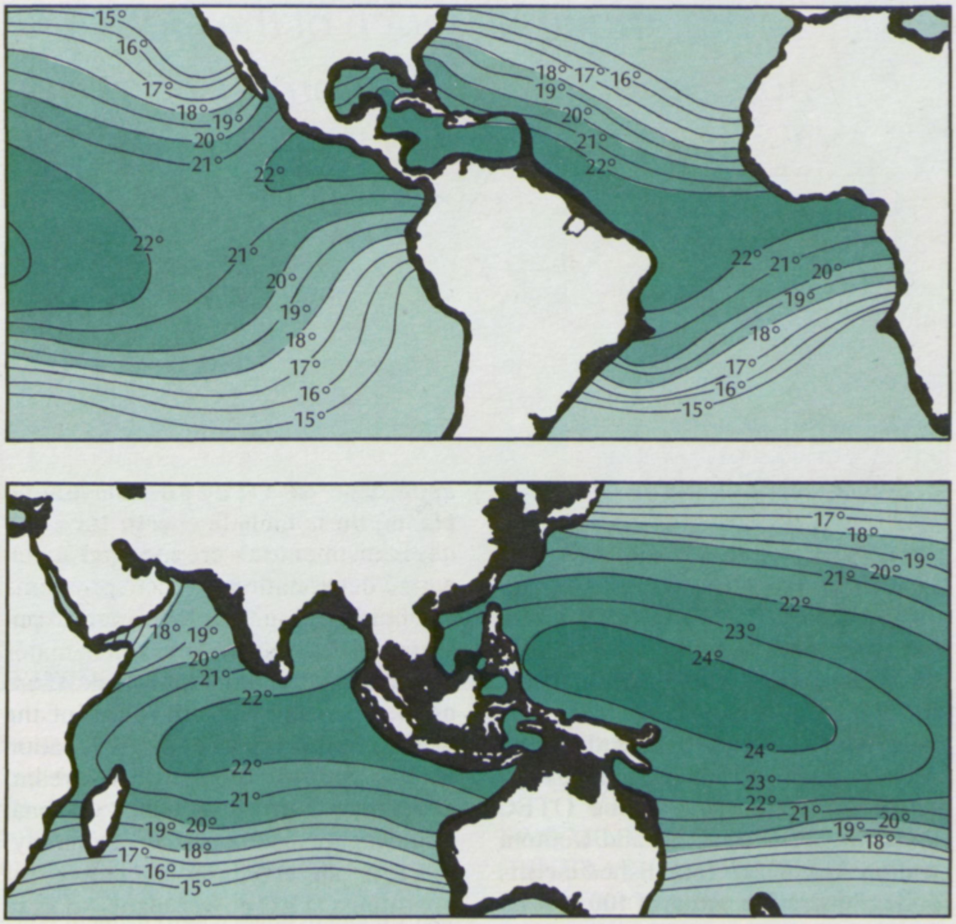


Figure 1. Ocean thermal gradients in tropical and subtropical ocean areas. The contours show the annual averages of monthly temperature difference (in degrees Celsius) between the ocean surface and depths of 1,000 meters. The shading shows areas ranging from those with temperature differences less than 18°C, to the most advantageous, with average monthly temperature differences greater than 24°C. The areas in black represent water depths less than 1,000 meters.

United States locations favorable for OTEC plants include the Gulf states, Puerto Rico, the Virgin Islands, Guam, and Hawaii. Many developing nations located in a band extending about 25 degrees in latitude on either side of the equator would offer early markets for cabled eelectricity.

(MW) to about 500 MW; the plants would be modular, and their limiting size would probably be determined by the ability to construct and deploy large ocean platforms cost-effectively.

OTEC AS A COMPETITIVE SOURCE OF POWER

OTEC power is one of the few solar-energy options (hydropower and biomass are others) that can provide a source of baseload electricity, available on a continuous basis. Accordingly, OTEC-derived electricity needs to be competitive in cost with electricity from other baseload sources, such as oil-fired, coal-fired, and nuclear power plants.

Since fuel is not required for plant operation, the major cost is for amortization of the capital investment. Capital costs for a 100- to 400-MW electricity-to-shore system installed 140 nautical miles west of Tampa, Florida, for example, are estimated in the range of \$3,000 to \$3,500 (1981 dollars) per kilowatt (kW), assuming that the plant is the eighth one constructed. (Initial plants will, of course, be more expensive.) Projected costs for electricity from such a plant are about 6 to 8 cents per kW-hour, comparable to costs projected for other baseload power sources in the Gulf Coast market for the years 1990 to 2000.

Fortunately, markets exist for electricity from the first OTEC plants: islands such as Puerto Rico and Hawaii, where most of the electricity is now derived from the combustion of oil. The capital costs for OTEC plants

"In principle, much of the electricity now produced by the combustion of oil could be replaced by OTEC power."

at such locations would be less than those for plants off Gulf Coast states, both because the ocean thermal resource is somewhat better and because the power cables would need to extend only 5 to 10 kilometers from shore. For these and many similar locations abroad, electricity from even the first commercial OTEC plant would probably be competitive with oil in 1990.

PROBLEMS OF COMMERCIAL OTEC DEVELOPMENT

Commercial development of OTEC technology requires demonstration of technical performance, reliability, and cost-effectiveness. The consideration that OTEC would be a domestic energy supply may also be a factor. Likely candidates for ownership and operation of OTEC plants include consortia of industries, utilities, and shipowners.

A major problem is financing the significant front-end capital investment that is required, especially for demonstration plants. Market penetration by OTEC will depend on its relative attractiveness as a commercial investment opportunity in an era in which the demand for capital will probably exceed its supply. In view of the technical and economic risks, federal incentives such as loan guarantees, low-interest loans, and investment tax credits will be needed for early OTEC plants.

Two OTEC-specific laws that provide an impetus for development were enacted in 1980. One is the OTEC Research, Development, and Demonstration Act, which established targets for demonstration plants of 100 MW by 1986 and 500 MW by 1989, and a target of 10,000 MW of United States commercial OTEC capacity by 1999. The other is the OTEC Act of 1980, which provides a streamlined, one-stop licensing procedure and extends to OTEC plants and plantships the mortgage loan guarantees already available to conventional ships. In particular, that law (as amended) authorizes $1.65 billion in loan guarantees for up to five OTEC demonstration plants and plantships. Other more general laws that have been enacted recently provide financial incentives potentially applicable to OTEC demonstration plants; these include energy tax credits, investment tax credits, and accelerated depreciation.

Optimal siting, involving market potential and logistics, is another major requirement for commercial development. For example, utilization of the ocean thermal resource in one location could reduce its potential downstream, depending on how the thermal effluents are discharged. (Fortunately, there is an economic incentive for operating OTEC power plants so as to cause minimal perturbation of their thermal environments: recirculation of its own thermal effluents could have an adverse effect on the performance of an OTEC power plant, since its power output will be roughly proportional to the square of the available temperature difference.) Other considerations involved in siting include possible impacts of the plant on the environment, possible impacts of the environment on the plant, and—when submarine cables are to be used—sea-floor conditions between the plant and the shore.

Environmental effects of plant oper-

Figure 2a

Figure 2b

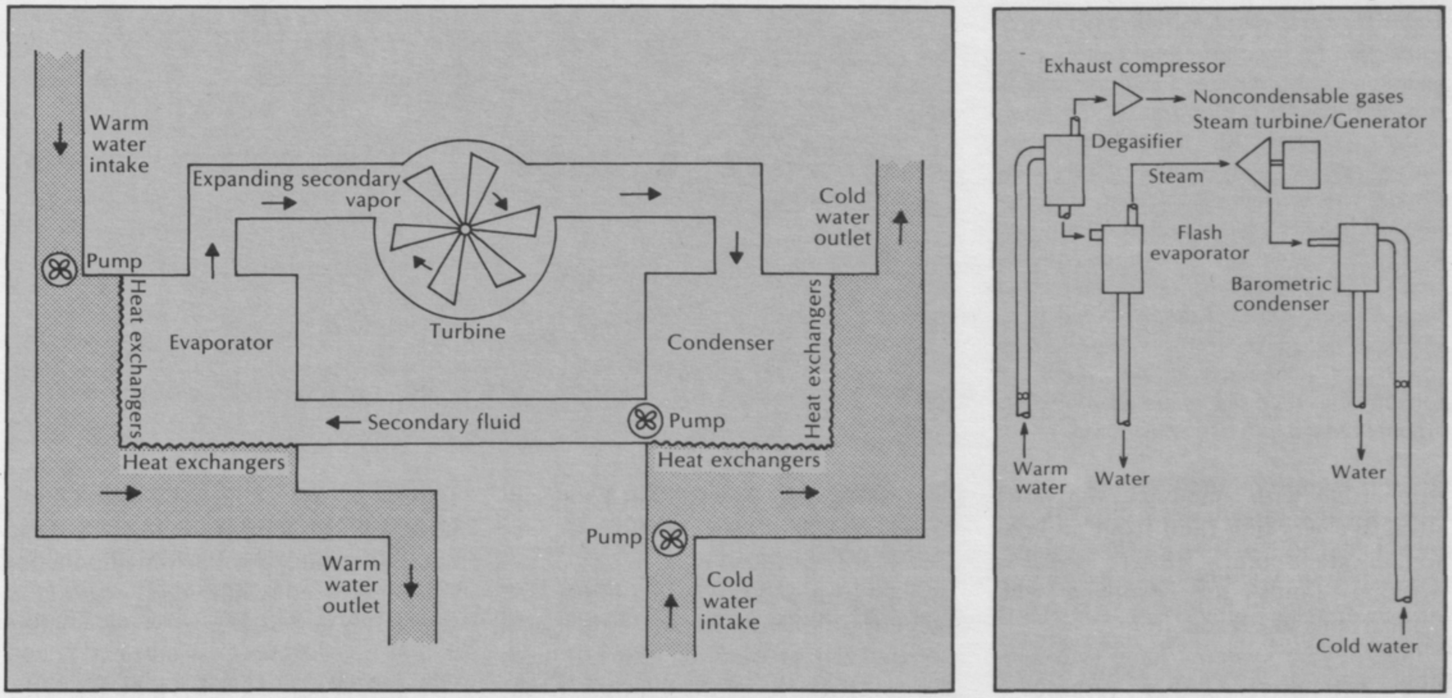


Figure 2. The two basic types of OTEC systems: closed-cycle (a) *and open-cycle* (b). *In closed-cycle systems, currently favored by industry, the evaporation of a working fluid such as ammonia drives the turbine and the vapor is condensed by cold water pumped from a depth of about 1,000 meters. Open-cycle systems use sea water under a partial vacuum as the working fluid.*

ation have been, in fact, an important consideration in the United States OTEC development program (see the article in this issue by Gerhard Jirka). Among the concerns under study are the impingement and entrainment of biota; possible discharges of biocides, corrosion products, and working fluids; impacts on birds and fish; and worker safety.

TWO MODES OF ELECTRICITY GENERATION BY OTEC

Both of the two basic kinds of OTEC systems (see Figure 2) hold promise for commercial applications.

In a closed-cycle system, warmth from surface waters is used to evaporate the working fluid (such as ammonia), thereby forcing the rotation of a turbine attached to an electrical generator. The vapor is then reliquefied by cold water pumped up from depths of 1,000 meters or so, and the process is repeated continuously. In an open-cycle system, warm surface water is flash-evaporated under vacuum, and the escaping steam causes a turbine to rotate. The spent vapor is cooled in a condenser by cold water pumped from depth. (The cycle is termed *open* because the condensate is not returned to the evaporator.)

Because the available temperature difference is limited, closed-cycle OTEC systems require that large quantities of water be circulated past the heat exchangers (the evaporators and condensers) in order to produce significant yields of electrical energy. Another requirement is a viable way of protecting the exchangers against corrosion and biofouling, both of which inhibit heat transfer. The use of titanium or stainless steel as heat-exchanger materials would minimize the corrosion problem, although alloys of aluminum are less expensive and might be adequate. Copper-nickel alloys resist biofouling, but may not be

Right: The first demonstration of net power production by ocean thermal energy conversion was accomplished with the experimental Mini-OTEC platform off the Kona Coast of Hawaii. This plant, not an optimized system, was sponsored by an industrial consortium (Lockheed, Dillingham, Alfa-Laval, Worthington Pump, and Roto Flow) and the State of Hawaii. Mini-OTEC, operating on a converted Navy barge, produced the predicted 10 to 15 kW of net power from its 50-kW gross power. Its cold-water intake, made of polyethylene pipe 0.6 meter in diameter, extended to a depth of 650 meters.

compatible with ammonia, the most attractive working fluid from an economic standpoint. Other possible working fluids are propane and halocarbons like freon.

Open-cycle systems have two specific difficulties. Large turbines—comparable in size to wind turbines—are needed because of the low steam pressure that can be obtained, and degasifiers must be used to remove dissolved gases from the seawater. Continuing research may provide cost-effective solutions, of course; for example, studies by the Westinghouse Corporation suggest that methods based on aerospace technology could be applied to the turbine problem. An advantage of open-cycle systems is that they can readily produce fresh water as a byproduct.

The closed-cycle mode, considered farther along in development by several years, is currently favored by United States researchers. Such a system was employed in Mini-OTEC, the experimental 50-kW (gross) power plant mounted on a barge off Hawaii, and in a land-based experimental 100-kW (gross) power plant being operated by the Tokyo Electric Power Company on Nauru.

A feature of OTEC that should be taken into account in assessing it as a commercial process is that although the net efficiency of the plants is intrinsically low (because of the limited temperature difference that is available), they are fuel-free. The low net efficiency leads (or, more precisely, misleads) some technical people who are accustomed to the higher net efficiencies of fueled power plants to become OTEC detractors. Of course, such a low net efficiency would be intolerable if fuel were consumed, but it may well be acceptable if the cost of OTEC-derived energy turns out to be competitive with that of alternative energy sources. This is especially likely for near-term competition with oil-fired power plants. The net efficiency of OTEC plants should be as high as possible, of course, but it must be compatible with system optimization, which must take into account capital cost as well as the costs of operation and maintenance. The important point is that the "bottom line" in OTEC economics is the cost of the energy in mills per kilowatt hour, *not* the net efficiency of the power plant in which it is generated.

ON-BOARD MANUFACTURE OF ENERGY-INTENSIVE PRODUCTS

Although transmitting electricity to adjacent shores via cable appears to be the most commercially competitive option for OTEC initially, the manufacture of energy-intensive products aboard OTEC plantships has tremendous long-term market potential for dispersed locations throughout the world. Aluminum, ammonia, hydrogen, chlorine, magnesium, and other sea chemicals are likely products, to be used either in the manufactured form for fertilizers, fuels, or feedstocks, or to be shipped ashore for restoration of electricity. This avenue of transmission can be regarded as an "electrical bridge." For example, hydrogen or ammonia could be converted to electricity in fuel cells, a process that would have the advantage of being able to supply peaking power to electric

Figure 3

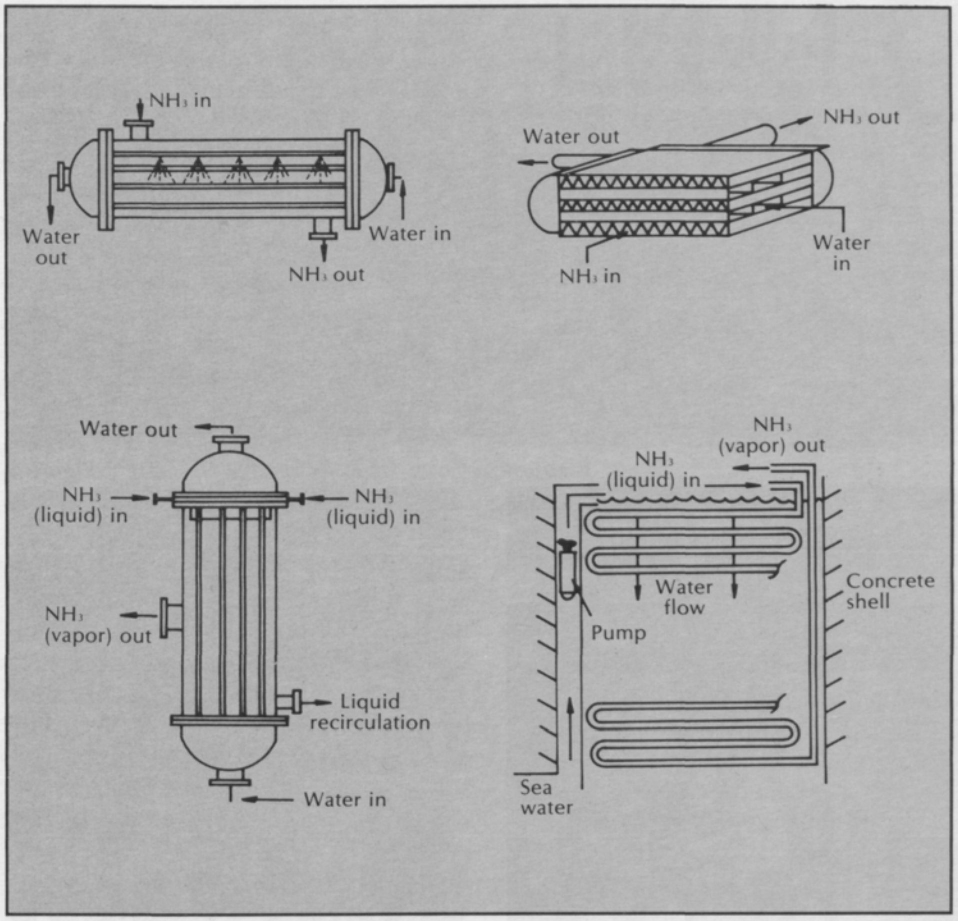


Figure 3. Examples of heat exchangers under consideration in the United States OTEC development program. They fall into two main geometric categories: shell-and-tube and plate.

Candidate exchangers have been tested for performance both in the laboratory and at sea. Evaluations have also been made of the susceptibility of the different models to biofouling, and techniques for its control: Heat-exchanger tubes can be cleaned by passing brushes and spongy spheres through them, and exchangers with plate configurations can be kept clean by chemical and mechanical methods.

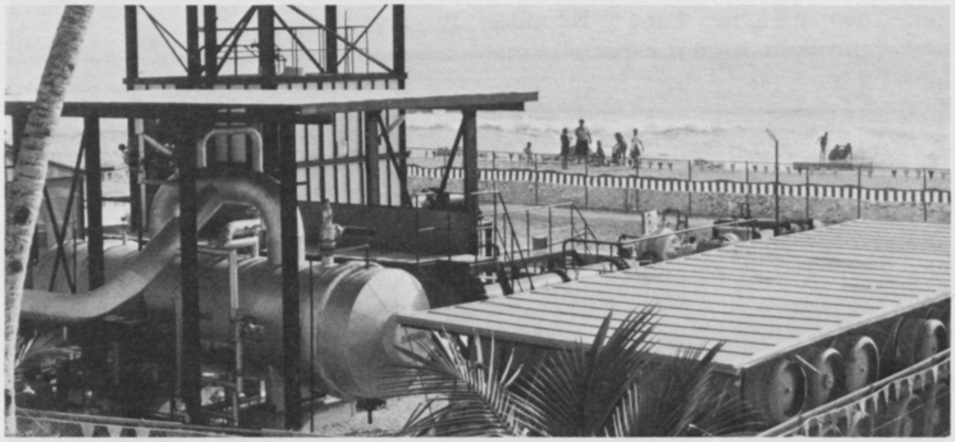
utilities. Another emerging market is lithium/air and aluminum/air batteries for electrical automobiles; OTEC plants could ship bulk aluminum or lithium for this application, and recycle the hydroxides or carbonates.

Two attractive OTEC byproducts that may be marketable are fresh water and crops such as shellfish or kelp that could be grown utilizing the nutrients upwelled in the cold water. The economics of OTEC energy production could benefit where such byproduct manufacture is viable.

CONTINUING DEVELOPMENT OF OTEC TECHNOLOGY

The Department of Energy's OTEC development program has included the testing of closed-cycle component hardware and subsystems, both in the laboratory and at sea, along with analytical studies. The programmatic strategy was to test components and subsystems of progressively increasing size, permitting the projection of performance and cost data relevant to commercial OTEC systems. Although component and subsystem testing has been encouraging, revealing no demonstrable show-stoppers so far, what is still needed is a prototype OTEC system of sufficient size to instill confidence in potential investors. A prototype plant about 40 MW in capacity would not only provide technical performance data for a complete system, but would allow a more accurate projection of costs for commercial plants in the 100- to 400-MW range.

One focus of the testing program is heat exchangers, which are key components, representing up to half the total plant investment. For example, at-sea measurements have been underway for several years to establish biofouling rates for various candidate exchangers (see Figure 3) and to experiment with countermeasures for the control of biofouling. Laboratory measurements of heat-exchanger performance have been conducted at increasing scales since 1974, with encouraging results: through the use of special surface shapes and coatings, heat-transfer rates more than twice those for standard industrial units were achieved. And in 1981, studies under ocean con-



Right: The Tokyo Electric Power Company operates a shore-based closed-cycle OTEC plant on the island-nation of Nauru. The plant, which uses the halocarbon R-22 as its working fluid, has a gross power of 100 kW and a net power production of 34 kW. The horizontal shell-and-tube evaporator is in the foreground; the shelter houses the vertical condenser column. Aqueducts 0.7 meter in diameter carry the cold and warm water to shore and the mixed effluents back out to sea. The cold-water pipe, made of polyethylene, extends about 900 meters along the ocean floor to a depth of about 520 meters.

ditions were made aboard OTEC-1, a tanker converted to a 1-MW engineering test facility and deployed in waters off Hawaii. The performance of standard heat-exchanger configurations tested on OTEC-1 was close to that predicted, and apparently unaffected by ship motion.

OTEC ocean systems present a number of additional technical problems. In particular, adequate cold-water pipes and submarine cables must be designed and ways of deploying them worked out. Possible pipe materials include fiberglass-reinforced plastic and elastomers. The pipes will need to be about a thousand meters long and have diameters of about 10 meters for a 40-MW power plant, and about 20 meters for a 400-MW net power output. Submarine power cables rated at 100 MW or greater will need to be designed to withstand unprecedented electrical and mechanical stresses.

Various platform configurations have been considered for commercial OTEC power plants. Some of these look like ships and some are submersible, resembling spar buoys; examples

Figure 4

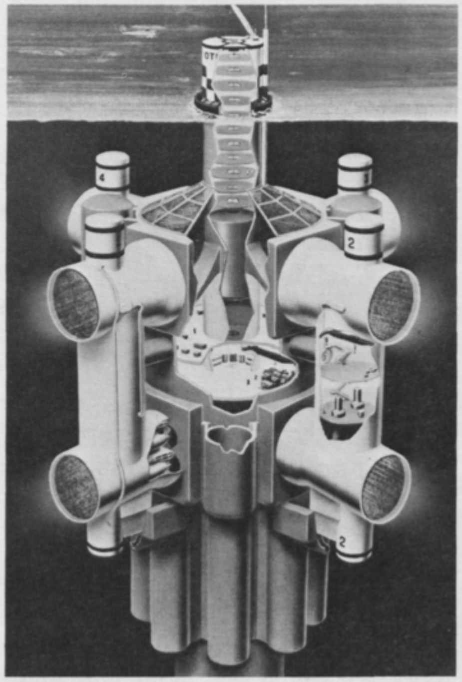


Figure 4. The Lockheed Corporation concept of a 260-MW closed-cycle OTEC power plant, showing details of one of the four external 65-MW power modules. The cold-water pipe is 38 meters in diameter and consists of reinforced concrete sections.

Figure 5

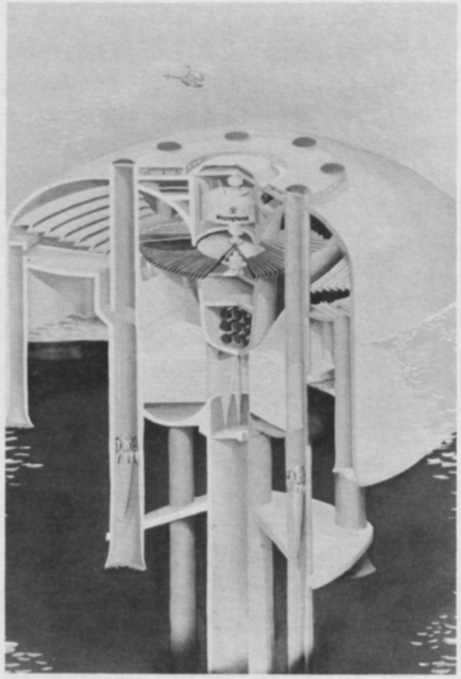


Figure 5. A Westinghouse Electric Corporation concept of a 100-MW open-cycle OTEC plant that also produces 30 million gallons of fresh water per day. The cutaway reveals evacuated flash chambers on the sides and a large central single-stage axial turbine above condenser tubing.

are shown in Figures 4 and 5. Keeping the platform in place is especially important if the electricity is to be transmitted to shore; this station-keeping can be done by dynamic positioning or by mooring. Severe weather conditions might require the use of a submersible platform. Actually, much of the technology developed by the offshore petroleum industry, and many of its construction facilities, are applicable to OTEC. The success of that industry has improved the credibility of commercial OTEC.

THE SIGNIFICANCE OF OTEC AS A SOURCE OF ENERGY

The potential of OTEC for producing electricity for United States markets is considerable. Plants in the Gulf of Mexico could provide power equivalent to a significant portion of the present installed electrical capacity of the United States. A consideration even more important is the potential of OTEC to provide, in this century, a substantial increment to the world's energy supply. OTEC plants will require an initial investment of large amounts of energy in materials and construction, but the payback time—the interval before net energy becomes positive—is favorable, about a year. OTEC could supply tens of thousands of megawatts of electricity via submarine cable to numerous developing nations in tropical and subtropical regions (see Figure 1). In many of these locations, oil-derived electricity is the only other recourse. In addition, OTEC plantships could supply worldwide markets with energy-intensive products that could also be converted to electricity.

In principle, much of the electricity now produced by the combustion of oil could be replaced by OTEC power. The amount of oil displaced would be about forty barrels per day for each megawatt of baseload OTEC power. Supplying 50,000 MW to the near-term OTEC electricity market would thus represent a savings of two million barrels of oil per day.

Technical and economic viability is essential for OTEC to achieve market penetration, and therefore is the first concern in development efforts. But the significance of the technology goes beyond these considerations. OTEC could help significantly in alleviating the problem of declining global reserves of depletable energy resources. It could help meet the growing worldwide demand for additional energy. And in the process, it would work to reduce tensions and polarizations among the energy-hungry nations of the world.

Robert Cohen, a Cornell Ph.D. in electrical engineering, organized the original United States development program for ocean thermal energy conversion (OTEC) during a nine-year period with the solar energy program of the Department of Energy and its predecessor agencies. His work with OTEC has focused on legal, institutional, and international aspects. He also played a key role in preparing federal solar-energy planning documents, including the Project Independence Blueprint. He recently retired from government service and is now an energy consultant specializing in renewable energy technologies.

After receiving his Cornell doctorate in 1956, Cohen conducted ionospheric research for the National Bureau of Standards (NBS) in Boulder, Colorado. This activity included six years of research in South America, where he participated in studies for the International Geophysical Year (1957-58) and at the Jicamarca Radar Observatory in Lima, Peru (1961-65). His aeronomy laboratory at NBS later became part of the National Oceanic and Atmospheric Administration.

Cohen founded and chaired the Committee on Geophysical Energy Resources of the American Geophysical Union, and is a member of the Energy Committee of the Institute of Electrical & Electronics Engineers. He received the Boulder Scientist Award in 1964 and the Compass Distinguished Achievement Award of the Marine Technology Society in 1980, in recognition of his contributions to the development of ocean thermal technology. He has published more than forty papers on ionospheric and ocean thermal research.

Cohen has returned to Cornell twice in recent years to give talks on solar-energy development as part of the electrical engineering seminar series.

OCEAN THERMAL ENERGY AND THE ENVIRONMENT

by Gerhard H. Jirka

The vast amount of solar heat stored in the surface layers of the oceans offers tremendous potential for extracting useful mechanical and electrical energy. But there is a basic problem that is intrinsic to the whole family of "alternative" energy schemes: while the total energy that could be derived from solar radiation is immense, it is diffuse.

Ocean thermal energy conversion (OTEC) is one of the promising technologies that must compensate for low efficiency by providing very large collectors. A complication is that the movement of huge quantities of warm surface water and cold water from the depths will cause disruptions of the ocean layers that must be taken into account in engineering design.

Picture a 100-megawatt (MW) OTEC plant situated in warm ocean waters such as those off Hawaii. It would have internal heat-exchanger surfaces totalling perhaps a square kilometer in area, and it would circulate a thousand cubic meters of water every second. A 1,000-MW unit—comparable in capacity to a typical modern fossil-fuel or nuclear plant—would require a flow rate equal to half the mean discharge of the Mississippi River.

The consequences are significant from the standpoints of both engineering efficiency and environmental impact. An OTEC plant might act like a giant eggbeater, stirring up the ocean water. Disruption of the thermal layers could deplete the very resource OTEC depends on: the temperature difference between surface and subsurface waters. Furthermore, an OTEC plant would change the marine environment in its vicinity, and a large number of units might have significant regional, or even global, effects.

ENVIRONMENTAL EFFECTS OVER A RANGE OF SCALES

The potential environmental consequences are related to both the constant movement of large water masses and the associated chemical releases. As indicated in the table, the effects would occur over vastly different scales.

An extensive OTEC installation comprising a large number of plants would affect *global* climate patterns by changing meridional heat fluxes in the ocean waters and fluxes of heat and humidity in the atmosphere, and by causing artificial upwelling of carbon dioxide dissolved in bottom waters. To assess large-scale effects such as these, it would be necessary, of course, to compare them with the global environmental effects of other extensive energy-production, industrial, and agricultural activities.

Regional effects might arise in locations with large OTEC concentrations: around archipelagoes such as Hawaii, for example, or in ocean basins such as the Gulf of Mexico. OTEC could cause changes in the ocean circulation pattern, including basin inflows or outflows, and in the temperature structure as a result of the depression of surface temperature.

On the *mesoscale,* OTEC could affect ocean anomalies, such as cold-core eddies, current separation and meandering, and local upwelling or downwelling, that are frequently superimposed on the mean structure and may have significant effects on

INTERACTION BETWEEN OTEC AND ITS ENVIRONMENT

Scale	Distance (km)	Effects: Climatic	Biochemical	Thermal
Global	10^4	↕ Changes in Ocean-Atmosphere Climate System		
Regional (Basin-wide)	10^3			
Mesoscale (Anomalies)	10^2	↕ Changes in Ocean "Climate"	↕ Ecosystem Changes	
Intermediate (near Cluster)	10			↕ Plant Interaction
Near-field	1		↕ Plant Biofouling	↕ Local Recirculation

ocean "climate" and biochemical properties. Significant details of the mesoscale structure of the oceans have become available with recent improvements in synoptic measurement techniques, notably the use of satellites for gathering data, but little is understood about the formation of anomalies, and there is a possibility that OTEC plants, with their source-sink action, could be an additional trigger mechanism. As artificial upwelling devices, OTEC plants will pump up large amounts of nutrient-rich water, and since the upper layers of tropical seas are usually nutrient-deprived, a further disturbance of the ocean environment might result: Under favorable light and temperature conditions, significant biostimulation could occur, and this could lead to an ecosystem build-up.

The *intermediate* field, in the region around an OTEC cluster, would be affected by currents created by the intake and discharge operations of all the individual plants. The distribution of the intake and discharge motions in the intermediate field is governed mainly by buoyancy-driven currents which transport temperature perturbations, altering the thermal resource of other plants. These currents also transport nutrients from the bottom ocean layers or pollutants caused by corrosion or biofouling-control measures.

The *near-field* environment, in the region around an individual plant, is dominated by the dynamics of the source-sink flow.

CHARACTERIZING THE THERMAL RESOURCE

The thermal stratification of tropical oceans—the energy resource utilized by OTEC—is represented by temperature profiles such as those shown in Figure 1 for various locations of interest in the current United States program. Profiles of this kind are quite dynamic in nature, forming part of the general ocean circulation pattern as warm surface water drifts to the polar regions and cold bottom water returns. There can be substantial diurnal, seasonal, or even longer-term variability.

Apparent in Figure 1 is the presence of a warm reservoir in a surface layer 50 to 100 meters thick, and a deep cold reservoir that is usually 500 to 1,000 meters beneath the surface. Theoretically, this thermal resource could be tapped by installing a standard Rankine-cycle heat engine between the two reservoirs; the warm water would be moved past the evaporator of the heat engine and the cold water would be moved past its condenser. The result would be a net flux of energy, a small portion of which could be extracted as useful energy. The small portion can be estimated by computing the ideal Carnot efficiency of the system:

$$\eta = (T_{\text{warm}} - T_{\text{cold}}) / T_{\text{warm}}$$

with temperatures expressed in degrees Kelvin. If T_{warm} is 25°C and T_{cold} is 5°C, η is calculated as 6.7 percent. Practically, efficiencies are even lower, about 2 percent, because of parasitic energy losses. While this order of efficiency might appear to be wastefully low, it should not be forgotten that the energy itself is free.

We can also estimate the flowrate

Figure 1

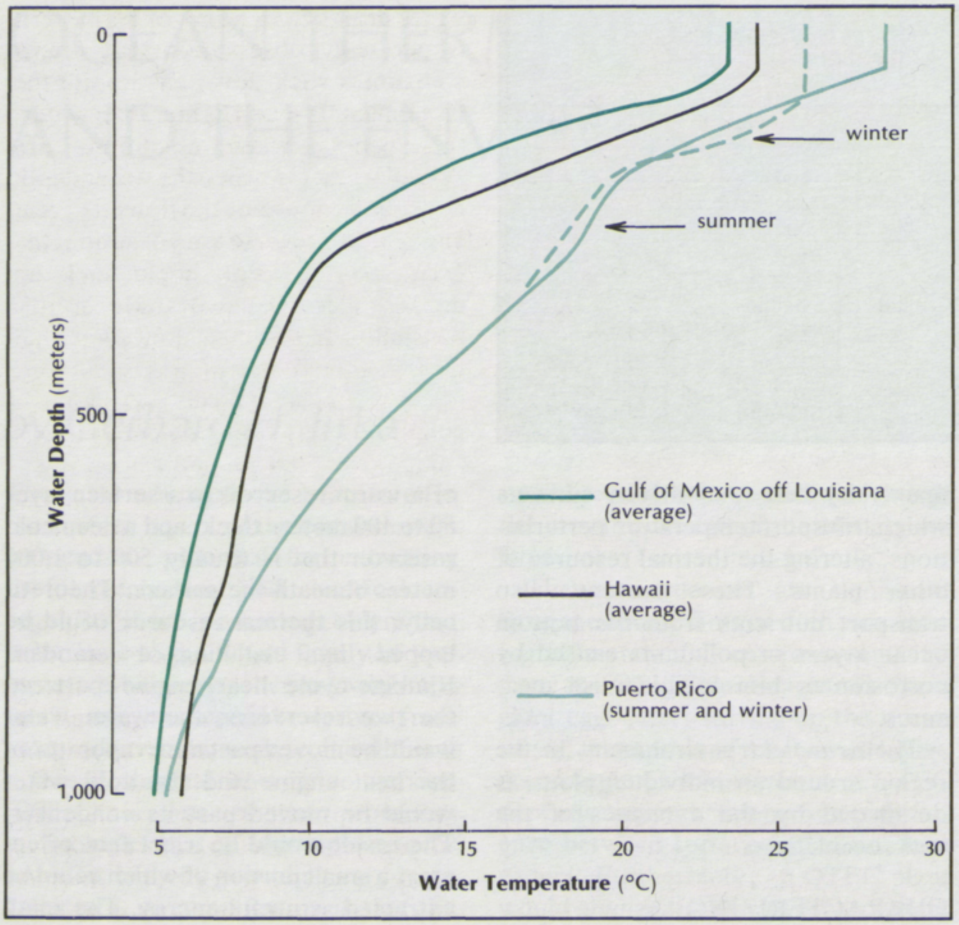


Figure 1. The thermal resource for OTEC. Temperature profiles for tropical ocean locations show a gradient of the order of 20°C between surface and bottom layers separated by a distance of about 500 to 1,000 meters. These profiles may vary considerably because of short-term and seasonal weather fluctuations.

Figure 2. A schematization of OTEC operation. The temperature profile is represented as two temperatures in two zones—surface and bottom—divided by a thermocline. The density profile corresponds, since density is inversely related to temperature.

An OTEC plant can be considered as an array of sinks and sources located along a vertical axis in the density-stratified ocean. The intake and discharge temperatures shown in the diagram are typical for tropical waters. The evaporator and condenser discharges may be separate or may be combined, in which case the average temperature is intermediate—in this example, 15°C.

required to achieve a reasonable output of power in a system with such a low efficiency. The required flowrate is expressed as

$$Q = P / (\eta \rho c \, \delta T)$$

in which P is net output, η is efficiency, ρ is water density, c is specific heat, and δT is the temperature change experienced by the water flowing past either the evaporator or the condenser. In a typical optimized system, δT is about 2.5°C. If our target output is 100 MW, Q would be calculated as 500 cubic meters per second for both evaporator and condenser flows, for a total of 1,000 cubic meters per second—large by any standard of engineering design.

It is important to understand that power production is very sensitive to changes in the temperature difference,

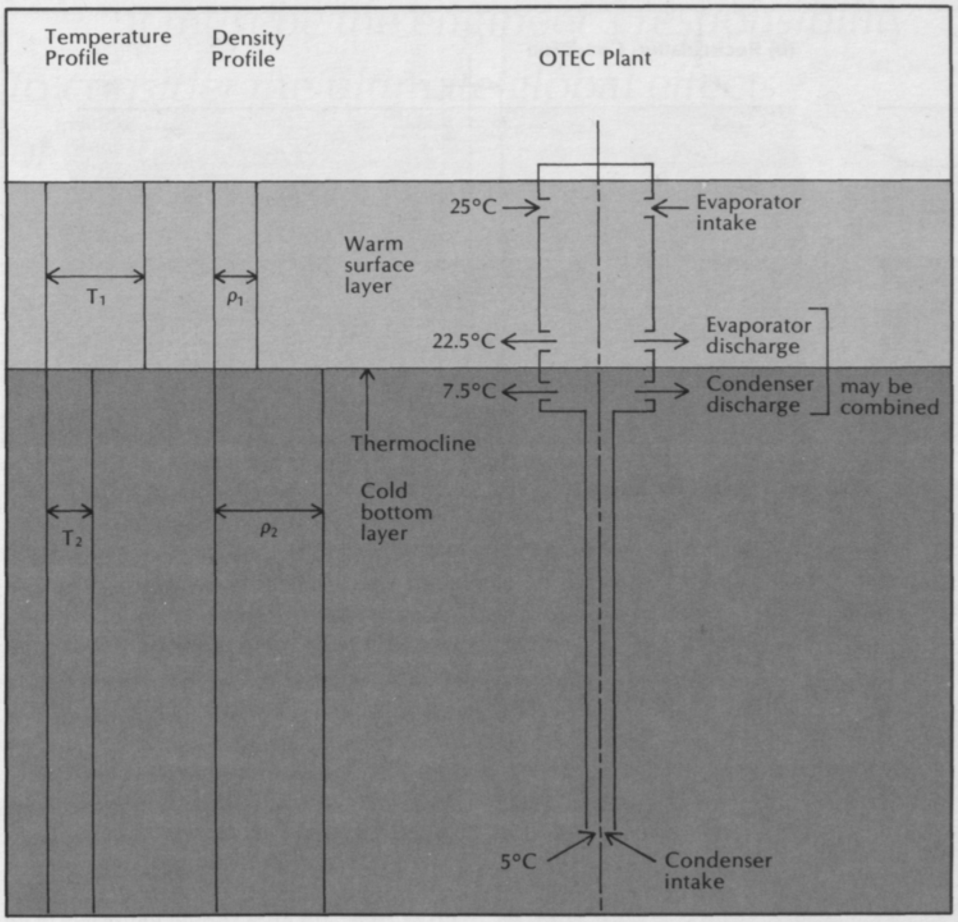
$$\Delta T = T_{\text{warm}} - T_{\text{cold}}.$$

Such changes may be the result of natural fluctuations or of local recirculation effects caused by improper plant design. Detailed optimization studies have shown that the percentage change in power output is about 2.5 times the change in ΔT. For our hypothetical plant with ΔT = 20°C, for example, a loss of only 1°C in ΔT would mean a power loss of 2.5 X 5 percent, or 12.5 percent! Economically, it is of the utmost importance to ensure that the maximum available temperature difference is utilized at all times.

TAPPING THE RESOURCE: SOURCE-SINK FLOW

The convenient schematization of Figure 2, although simplified, adequately represents the essential fluid mechanics of OTEC operation. The stratified ocean is simply divided into two

Figure 2



homogeneous layers separated by a thermocline with a temperature jump. Because of the temperature-density relationship of water, such a stratification is stable: a lighter layer floats on a heavier one. As indicated in the figure, an OTEC plant is essentially a vertical array of sources and sinks in the stratified ocean, taking in and expelling water masses. (The two discharge flows may be mechanically independent, in the so-called *separate scheme*, or they may be combined in a *mixed scheme*.)

Using the schematization of Figure 2, several fundamental questions have been studied at Cornell. In all cases, attention is focused on the action within the surface layer, which is shallow and constraining.

The most worrisome question concerns the possibility of uplift of the dense (and cold) bottom water into the surface intake (see Figure 3*a*.) Clearly, this would be catastrophic if it were to occur in actual practice. Such a catastrophic uplift may be considered as analogous to what happens when water drains from a sink or bathtub. It is our daily observation that drains sometimes suck down air despite the fact that air is much lighter than water; this occurs when conditions are "right"—that is, when the water depth is shallow enough or the flowrate great enough. In a reverse kind of action, the OTEC surface sink might suck up dense water. Detailed study of this possibility has shown, however, that OTEC should be quite safe in this respect: under typical surface-layer conditions, flowrates as great as 10,000 cubic meters per second can be tolerated, and this corresponds to a plant in the 1,000-MW range, well above the current target of 100 MW.

Other flow conditions could lead to local recirculation that would degrade the resource. This would occur, for example, if the discharge flow, which is always in the form of entraining turbulent jets, were superimposed on the intake flow. In general, the discharge flow will be denser than the surface layer and therefore will fall toward, and stay close to, the thermocline; if the flowrates are small enough and the stabilizing density effect sufficiently large, the jet flow will simply spread along the thermocline while an ambient water supply flows toward the intake from the upper portion of the surface layer. However, if some critical condition were exceeded, there might be vigorous interaction between source and sink, and some short-circuiting might occur. Since the discharge flow is colder, this would lead to the very undesirable effect of temperature reduction at the evaporator intake.

This recirculation problem has been

Figure 3

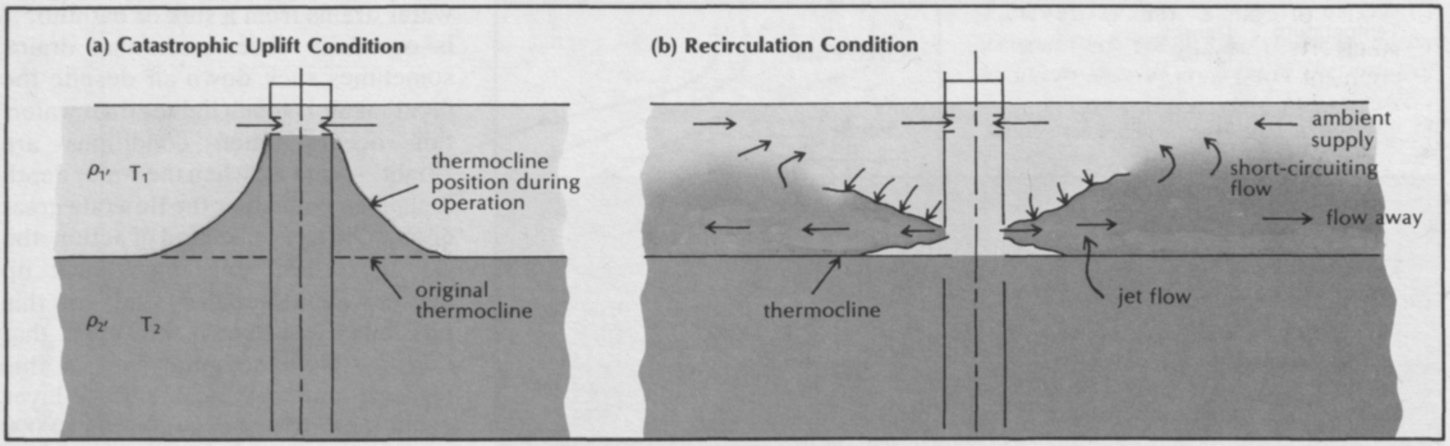


Figure 4

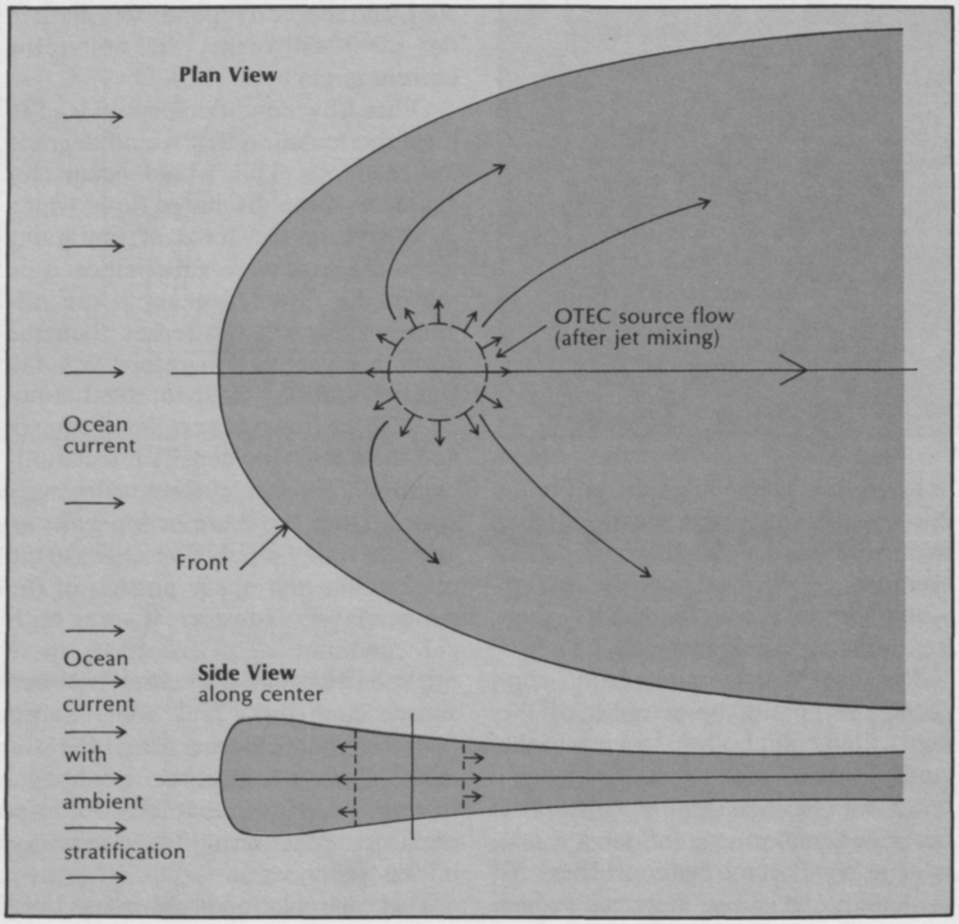


Figure 3. Two conditions that lead to an undesirable reduction of the available thermal resource: (a) *catastrophic uplift of the interface and* (b) *recirculation of discharged water back into the evaporator intake. The shallow surface layer is a region of intense fluid dynamic activity.*

Figure 4. Effects of the stratified flow motions of the OTEC effluent. The sketches illustrate current work in the Hydraulics Laboratory at Cornell's School of Civil and Environmental Engineering.

Since the layered ambient ocean waters always have some current velocity, the OTEC flow does not spread uniformly in all directions, but is deflected in the direction of the ocean current. The predominant flow occurs laterally, in a thin layer within the ocean. For a 100-MW plant, typical lateral dimensions (plan view) *are of the order of 10 kilometers, while the vertical dimension* (side view) *is only 10 meters. All OTEC effluents, such as chlorine releases for the control of biofouling in the heat exchangers, ammonia leaks, and nutrients pumped up from the bottom layer of the ocean, will be transported within the thin layers of OTEC flow and will then undergo various chemical or biological transformations. Layers of this kind can also interact with adjacent plants.*

" . . . it must be the engineer's responsibility to consider the ultimate global effects of the technology."

explored in a series of laboratory and analytical investigations, which indicate that the potential for recirculation is critically dependent on the density of the discharge water relative to the density of the surface layer. With the separate discharge scheme (see Figure 2) there is little temperature (or density) difference and therefore a very high likelihood for recirculation. The mixed discharge scheme is preferable: it operates with a much higher stabilizing temperature difference, the discharge jet tends to hug the thermocline, and the potential for recirculation is much smaller. Even so, the studies indicate that for safe operation, maximum plant capacity should be of the order of 500 MW.

LOCAL ENGINEERING PLANS VS. GLOBAL CONSEQUENCES

In addition to the OTEC design proposals I have mentioned, there are, of course, many other possibilities. Some of them completely eliminate the recirculation danger. One proposal might be to pump the mixed discharge water to the bottom of the ocean or to a depth of, say, 200 meters, where—given the stratification indicated in Figure 1—it should find some equilibrium level without interfering with the surface or bottom intake. Another strategy might be to point the discharge jets vertically downward so as to push the flow well below the surface layer; this would be quite similar to the way an industrial smokestack pushes gas up into the atmosphere. Such solutions tend to be costly or impractical, however. For instance, an OTEC plant—except for the cold-water pipe—needs to be built near the surface because of construction difficulties.

A particularly important concern, and one that may be easily overlooked in the quest for an optimized design, is the effect a particular plant would have on the thermal resource and, ultimately, on the global ocean system. This may be illustrated by considering two extreme modes of operating a 100-MW OTEC plant. With a separate discharge scheme, energy is constantly being transferred from the warm layer to the cold layer, thereby reducing the capability of doing useful work. The rate at which this occurs is equal to $Q\rho c\delta T$—that is, P/η, the net power output divided by the efficiency. Because efficiency is low, about 2 percent, the calculated rate is a large number, about 5,000 MW. In the other assumed operating mode, the entire evaporator flow is released deep in the lower layer. In this case, much more energy—namely, $Q\rho c\Delta T$ or about 40,000 MW—is being lost from the ocean surface layer. And all of this is to generate 100 MW of useful power!

Large as they are, these energy-loss rates appear miniscule (by a factor of 1/10,000 or less) in the context of the energy fluxes that occur over the entire tropical ocean, or even an ocean basin such as the Gulf of Mexico. Indeed, it may seem immaterial what mode of discharge is used by a 100-MW OTEC plant; one might argue that full prevention of local recirculation, by means of an evaporator discharge well below the thermocline, should be the preferred solution to the recirculation problem, since it is the most efficient one. If many plants were to be deployed, however, the outlook might be quite

Figure 5

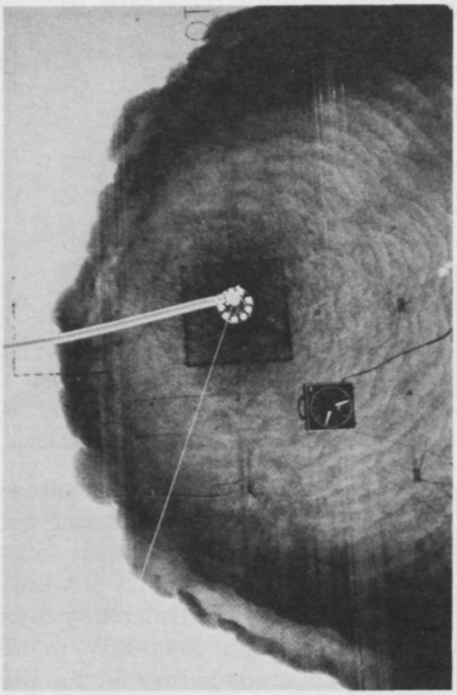


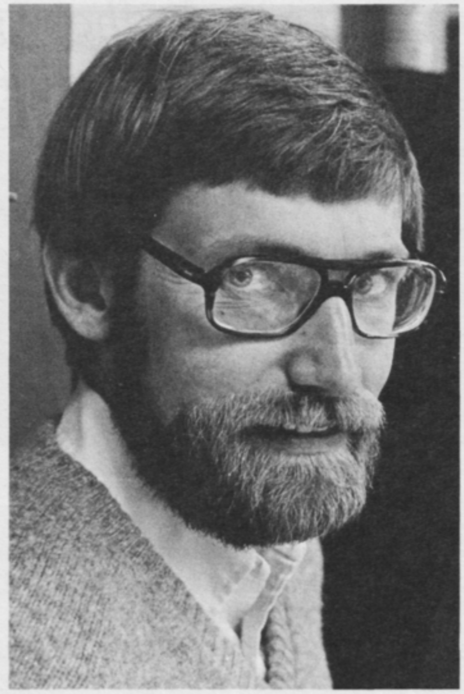
Figure 5. A laboratory simulation of layered motions of flows emanating from an OTEC plant. The photograph is an overhead view of a stratified flow-modeling basin in the Hydraulics Laboratory at Cornell. In this simulation the ambient flow is from left to right. The model OTEC plant is about 20 centimeters in diameter; the basin is about 5 X 8 meters in surface area and about a half meter in depth.

Analytical predictions that were developed in conjunction with such laboratory work have compared well with actual field measurements taken during the 1980 pilot study of a 1-MW OTEC plant off Hawaii.

different. Even at the present early stage of development, it must be the engineer's responsibility to consider the ultimate global effects of the technology. The introduction of fossil-fueled power plants provides an analogy: While the effect of a single midwestern plant on the distribution of sulfur in the atmosphere is not even measurable, the cumulative discharge from many plants has caused an acute problem of acid precipitation over the entire northeast region of the American continent!

Many factors are involved in the interaction of OTEC and the environment, and much research, in the laboratory and with pilot plants, remains to be done. The effects of ocean currents, for example, is an area of ongoing research at Cornell (see Figures 4 and 5). The effects of variable ocean conditions must be studied, and the influence of the Earth's rotation should be investigated.

The ultimate goal is to devise engineering designs and operating modes that will provide reasonable compromises. For example, intermediate discharge strategies, such as the scheme for mixed discharge at the thermocline, may provide reasonable tradeoffs between local efficiency and overall environmental protection—specifically, between minimal local recirculation and minimal disruption of the existing thermal energy distribution in the ocean. Intelligent choices depend on a thorough understanding of the interaction between the vast thermal energy resource of the oceans and the technology for using it.



Gerhard H. Jirka, associate professor of environmental engineering, is a hydrodynamicist with a special interest in pollutant transport in the water environment. He has conducted research on waste-water discharge, stratified flow, thermal mixing, and waste-heat disposal, and is active as a consultant in this country and abroad.

After studying in his native Austria, he received a Fulbright Travel Grant that enabled him to begin graduate study at the Massachusetts Institute of Technology, where he received his doctorate in 1973. He stayed on as a lecturer and manager of the Environmental Management Program at the M.I.T. Energy Laboratory, and moved to Cornell four years later.

Jirka is active in a number of professional organizations, including the American Society of Civil Engineers (ASCE), which awarded him the Freeman Hydraulics Prize in 1981. He is now serving as chairman of the Committee on Hydrological Transport and Dispersion of the Hydraulics Division of the ASCE, and as a member of that group's Committee on Alternative Energy Sources.

ENERGY FROM CORNSTALKS

Local Crop Residues As a Substitute for Imported Oil

by William J. Jewell

While the United States continues its dangerous dependence on foreign oil, a substantial renewable source of energy in our own neighborhoods is being ignored.

Take the community around my hometown of Ithaca, New York, as an example. From our own resources we could be producing all the synthetic natural gas we need for home heating—the equivalent of half the total amount of fuel we use. We could reduce our consumption of foreign oil by three-quarters, decrease unemployment, improve the economic well-being of our farmers, and promote a closer sense of community. We could accomplish these things with a modest capital investment and without detriment to our environment. And what we could do, so could communities throughout the agricultural regions of the nation and the world.

The resource that could make all this possible is not an abundant gas well or a nuclear power plant or a solar-energy installation fifty years in the future. It is simply cornstalks, straw, and other agricultural residues gathered from the farms within a ten-mile radius of our city and converted to methane by hard-working bacteria. It is a resource we already have, usable by a technology that has already been demonstrated, and with few discernible drawbacks. Using crop residues for methane production doesn't reduce the food supply, deprive the soil of natural nutrients and mulch, pollute the atmosphere, create a hazard, make a noise, or impair the landscape. All it requires is a processing plant, some transportation and storage facilities, and a hookup to the municipal natural-gas supply system. The raw material could be trucked in by the farmers, who could then haul out nutrient-containing residue to spread on their fields and liquid fuel (alcohol produced in a separate fermentor) for their farm equipment. An additional alternative, now under study, is to use the biogas to fuel a cogenerator. This would provide not only electricity, but heat that would be wasted in the operation of a conventional generator.

The idea of using crop residues for producing biogas has been under development at Cornell since 1976. It grew out of a study of the anaerobic fermentation of animal manures that has resulted in the design of a successful on-farm reactor: about twenty units are now operating on farms and more than one hundred are probably under construction. Subsequently, the research effort was directed to crop residues, which have the potential for yielding much greater quantities of energy. Laboratory experiments progressed rapidly to pilot-scale operations, and by the fall of 1981, to initial testing in a full-sized reactor, suitable for use on a farm.

The research team in the Department of Agricultural Engineering estimates that two more years of intensive effort would have brought the process to a stage at which it would have been suitable for commercialization. Unfortunately, federal budget reductions have nearly eliminated solar energy R&D support, and the crop-residue-conversion effort has been discontinued, leaving the future of the technology uncertain.

This article, therefore, is not only a

Figure 1

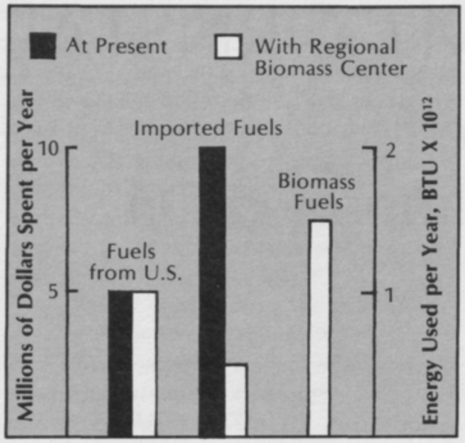


Figure 1. Energy sources and expenditures for a hypothetical United States community of ten thousand people living in a small city and on farms within a ten-mile radius. The total energy consumption is taken as $3X10^{12}$ BTU/year, valued at $15 million.

At present a third of the region's total fuel supply is produced in the United States and $5 million a year is returned to the nation's economy. Twice this amount of energy is imported in the form of oil and gas, mostly from the Middle East and Africa; this results in a flow of about $10 million a year to foreign countries.

With the establishment of a community facility for the production of $1.5X10^{12}$ BTU/year in the form of biogas, the need for imports would be substantially reduced, to $0.5X10^{12}$ BTU/year. The amount spent for United States-produced energy (including electricity) would be the same, but the annual flow of money to foreign countries would be reduced from $10 million to $2.5 million.

brief description of a promising energy technology, but a testimonial to the need for a national energy policy with balance and direction.

BIOMASS AS A RENEWABLE SOURCE OF ENERGY

One of the alternatives for tapping the energy of the sun is to extract the energy stored in biomass. In fact, biomass is considered one of the most promising of the solar energy sources, at least for the next few decades (see Figure 3). The realization of potential

Figure 2

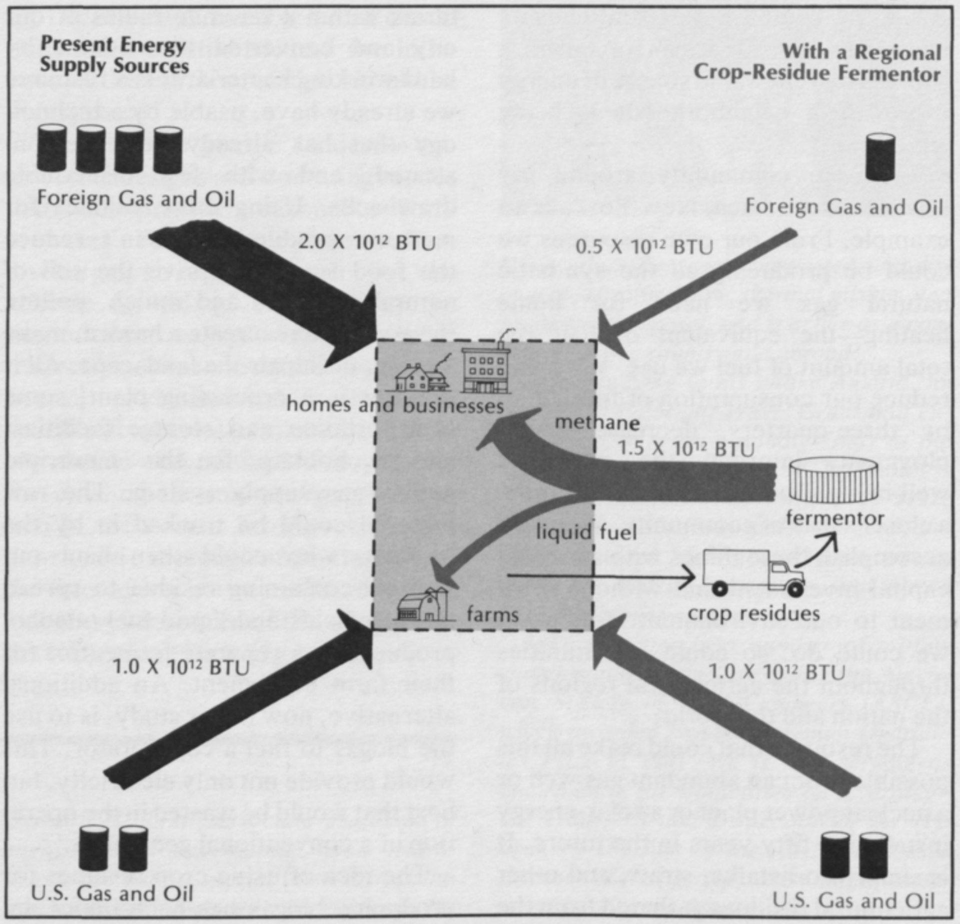


Figure 2. How the regional system of Figure 1 would work. The region's farms would provide biomass in the form of crop residues, yielding $1.5X10^{12}$ BTU/year. Some of this could be returned to the farmers in the form of liquid fuel produced by using a small fraction of the farmer's crop to make alcohol; this plan would provide additional incentive for participation in the program. Most of the output of the regional energy center would be used by the community in the form of biogas for heating, electricity generation, or other purposes.

depends, of course, on the development efforts. Funding for the biomass segment of solar-energy research has been low; in 1978 it amounted to 5.6 percent of the total for federally-supported solar energy research, and the prospects for the near future are even less auspicious.

The forms of biomass that are potentially feasible for energy production include aquatic and land plants grown for that purpose, and residues from forestry and agricultural operations (see Figure 4). Organic wastes, including garbage and sewage, can also be used. Biochemical and thermochemical processes can convert these materials to liquid fuels (alcohols and fuel oil), gaseous fuels (synthetic natural gas and hydrogen), electricity, or direct heat. Sometimes valuable by-products such as petrochemical substitutes can be obtained along the way.

Some of the biomass materials hold greater potential than others, and there are drawbacks and limitations to all the possible technologies. Wood, for example, is a good source of heat, but supplies are limited, especially if forests are to be preserved, and extensive use would be accompanied by problems of atmospheric degradation. Growing trees as a fuel crop would require land that might be used for food production. Using crops like sugar cane to produce alcohol, as is being done in some countries, depletes the food supply. Thermochemical conversion processes destroy plant nutrients and materials useful for soil conditioning. In addition, all the schemes are subject to economic constraints (which, however, may change over time). Among all the possibilities for

Figure 3

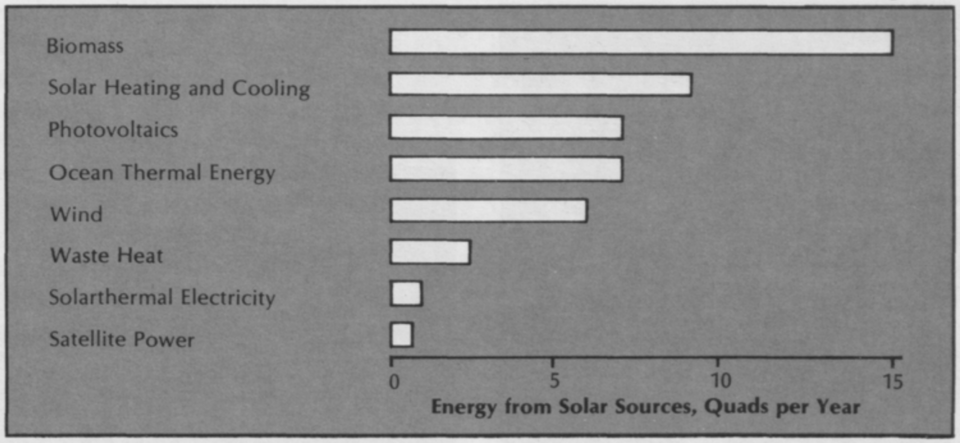


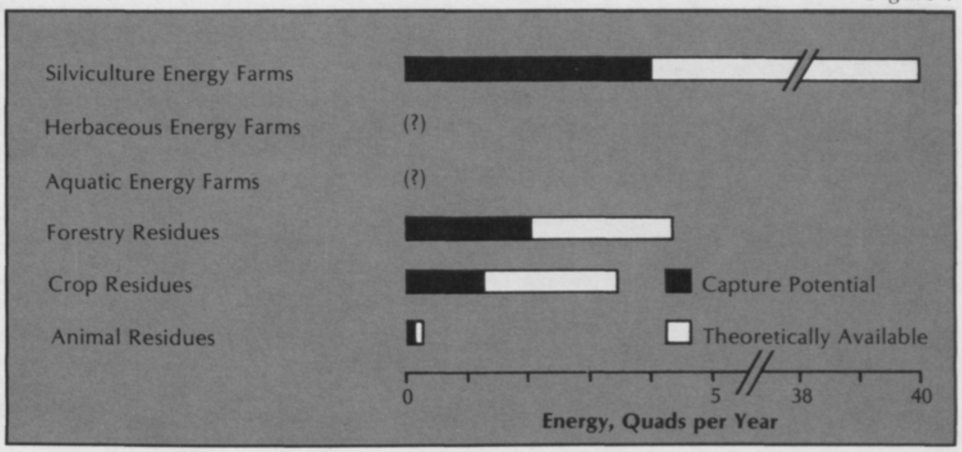
Figure 3. Estimates of energy that is potentially available from various solar sources by the year 2000. Waste heat *is from agricultural and industrial operations. A quad equals* 10^{15} *BTU.*

The figures are based on estimates from a dozen sources, largely government agencies. A more complete assessment would include considerations of additional quantitative and qualitative factors. These factors include the prospects for market penetration, the capability for rapid deployment, the potential for development that is not so rapid or so immediately competitive, environmental impact, the potential for conserving petroleum and natural gas, advantages afforded by on-site or decentralized operations, and effects on international relations.

Figure 4. Biomass residues potentially available for energy production. Capture potential *refers to the estimated amount that could be utilized feasibly. The larger potential of crop residues, as compared with animal manures, is apparent.*

Energy farms offer the largest potential, but are subject to contraints such as the allocation of land.

Figure 4



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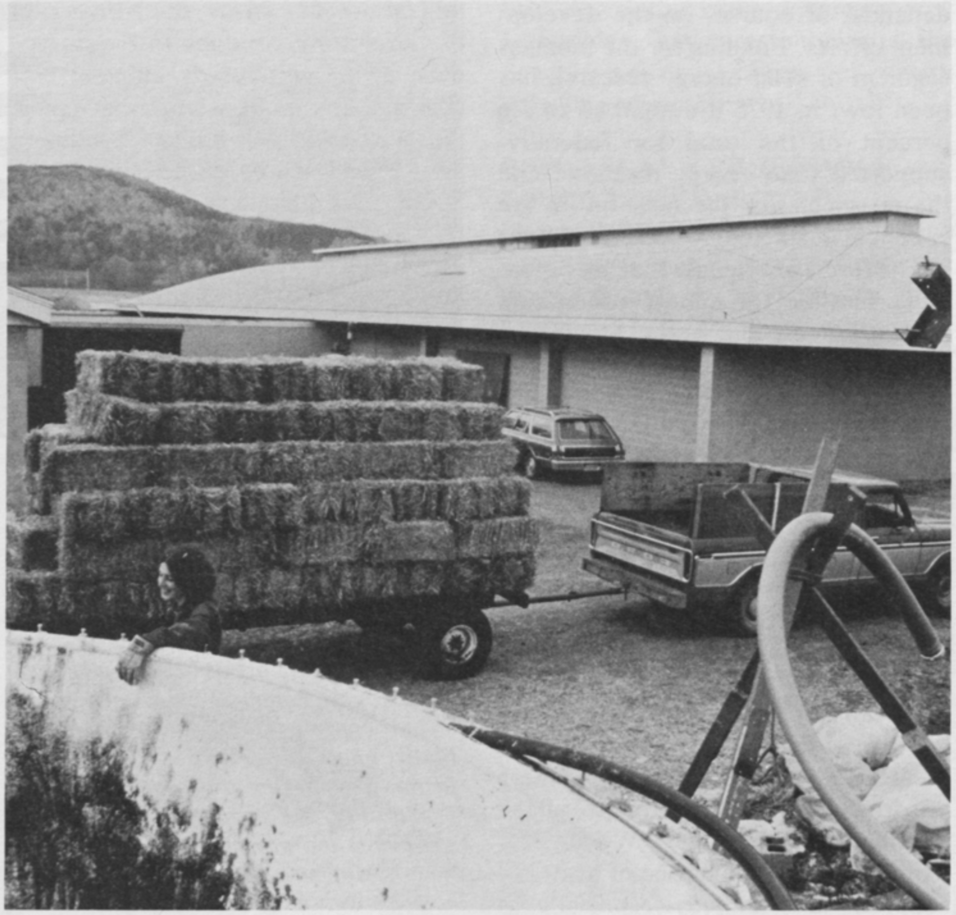

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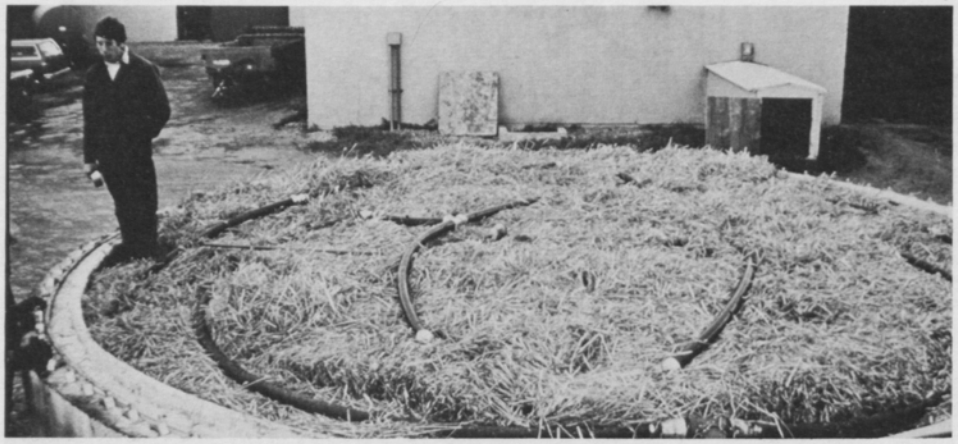

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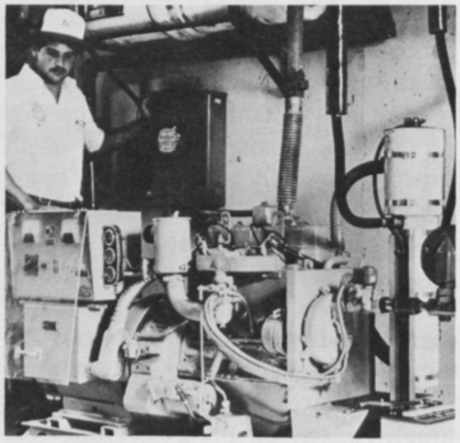


Left: Cornell's program to develop a dry fermentor for producing biogas from crop residues has proceeded through laboratory, pilot, and full-scale experiments.

1. The first pilot scale-up was attempted in 1978 with straw as the material. The reactor had a volume of about 5 cubic meters.

2. Here a prototype fermentor 110 cubic meters in volume is being loaded with wheat straw.

3. Fully loaded with straw, the prototype fermentor is ready for reaction. The pipes provide a backup system for moisture distribution and heating.

4. An efficient use of biogas is to fuel a cogenerator, which not only produces electricity, but conserves the "waste" heat. This 25-kW commercial cogenerator is being used at Cornell in studies that are now the chief line of research by Professor Jewell's group. The researcher is graduate student Roeby W. Ledford.

The efficiency of a cogenerator is about 70 percent. This may be compared with the 20 percent efficiency of a conventional generator run by an internal combustion engine. The 50 percent efficiency of the heat exchanger of the cogenerator—which is, of course, in addition to the efficiency of the electricity generation—approximates that of most hot-water boilers.

The electricity generated as part of a biogas-production system could be used by an industrial plant, for instance, or to operate a farm, or it could be sold to the local utility company. For example, if a farmer were paid 6 cents per kW (as required by current New York State law), he could finance the cost of the cogenerator in about two years. In addition, of course, he could make use of the extracted heat.

utilization of biomass, the conversion of agricultural residues to biogas appears to be particularly efficient, accessible, and inoffensive, especially if the nutrients and humus remaining after digestion are returned to the soil.

The production of fuels from biomass involves a wide range of technologies. Most of them have been known for a long time and many—such as methane generation from sewage sludge—have been commercially used in some form for decades. The primary task is to identify and develop those methods that are most suitable and economically competitive under particular circumstances of location and energy demand.

THE CORNELL PROGRAM FOR UTILIZING FARM WASTES

The biomass conversion method we have been working on at Cornell is fermentation by anaerobic bacteria, a process that yields a high-quality, clean gaseous fuel, a mixture of carbon dioxide and methane. The technology is commercially feasible; a large-scale facility in Oklahoma, for example, uses the residue from a 50,000-head beef feedlot. And the feasibility of small-scale operations is demonstrated by the successful operation of the Cornell-developed farmstead manure digesters. The total energy that could be derived from animal manures is relatively small, however; it has a potential value of perhaps \$5 billion a year, as compared with annual imports at \$60 billion. Much larger quantitites of biomass are available as crop residues (see Figure 4).

An immediately perceived advantage of crop residues is that they are available in a dry form and therefore can be transported easily. Not only farm-based facilities would be feasible, but units for residences or city buildings, and even large, centralized community plants. Unfortunately, however, fermentation processes work best with wet materials. Furthermore, crop residues are available only at harvest time, not continuously as manure is. Our first objective, therefore, was to develop an essentially dry, batchwise fermentation process that would work as well as the continuous-feed,

Right: Manure digesters, developed in the first phase of the Cornell program, are in operation or are being built on more than one hundred farms in the area.

"It is a resource we already have, usable by a technology that has already been demonstrated."

wet process that had proven so successful with animal manures.

ENCOURAGING THE BACTERIA IN DRY FERMENTORS

When we began the work with crop residues, little information about the requirements for dry anaerobic fermentation was available, even though the process has been used on a practical basis for many years by farmers, principally in Europe. We began with laboratory-scale experiments to determine the effects of moisture, additives, and temperature.

Moisture content was identified as the most limiting variable. It was found that for good fermentor performance (defined as one in which 90 percent of the solids that are biodegradable to volatile compounds can be converted in less than a year) the initial solids content must not be greater than 30 percent.

Another important factor is the kind and amount of bacteria-containing inoculum that is added to the reactor. Raw manure was found to be a poor source of inoculum, presumably because of the presence of large numbers of acid-forming bacteria that can overpower or reduce the action of the methane-forming strains. Dairy manure that had been digested was found to be effective, however, and was used successfully to start the reaction in subsequent experiments. Although the rate of gas generation increased with the quantity of inoculum added, our aim was to use the smallest possible amount in order to avoid the necessity of maintaining a liquid-slurry fermentor as part of the dry-fermentation facility. One way of minimizing the inoculum requirement was found to be a recycling, or "reseeding," of digested effluent. The penalty is a reduced overall rate of gas production, but this is not necessarily a drawback: gas produced over a year's time might be quite suitable for a digester that is loaded once or twice a year with crop residues.

Prevention of depressed pH caused by the formation of volatile acids, especially during start-up of the fermentor, was a problem in the early experiments. Sodium bicarbonate is effective as a buffer, but its use is undesirable because of the expense—which would amount to a significant fraction of the total operating cost—and because the presence of excess sodium would limit the usefulness of the digested residue. We found that the need for buffer can be reduced or eliminated by increasing either the water content or the amount of inoculum. After hundreds of fermentor tests, we have eliminated the need for expensive buffers and specialized bacterial inoculums. Moisture control combined with the addition of animal manure appears to be capable of successfully initiating the reaction.

Temperature was found to have the expected large influence on reaction rates. At 55°C extremely high reaction rates were observed, even with concentrations of inoculum lower than those used in the measurements at 35°C. The rates of gas production increased to peak values greater than seven volumes of biogas per volume of reactor per day (v/v-d). These results suggested that temperature regulation could be an effective way of speeding up or controlling the reaction rates.

Figure 5

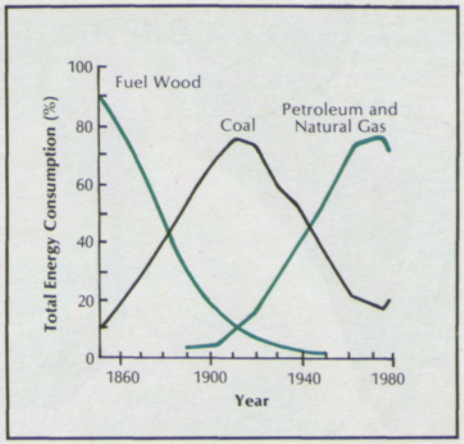


Figure 5. Fuel sources and major energy transitions in the United States. Wood was the first dominant fuel, then coal, and now petroleum and natural gas. The first two transitions were stimulated by technological advances that led to abundant, low-cost, clean, and more easily handled fuels. The present transition differs in that it is caused primarily by a decreasing supply. Another difference is that the time period for transition must be shorter: the first two transitions took place over periods longer than fifty years, but the present pattern of energy use must be changed in about half that time if serious shortages are to be avoided.

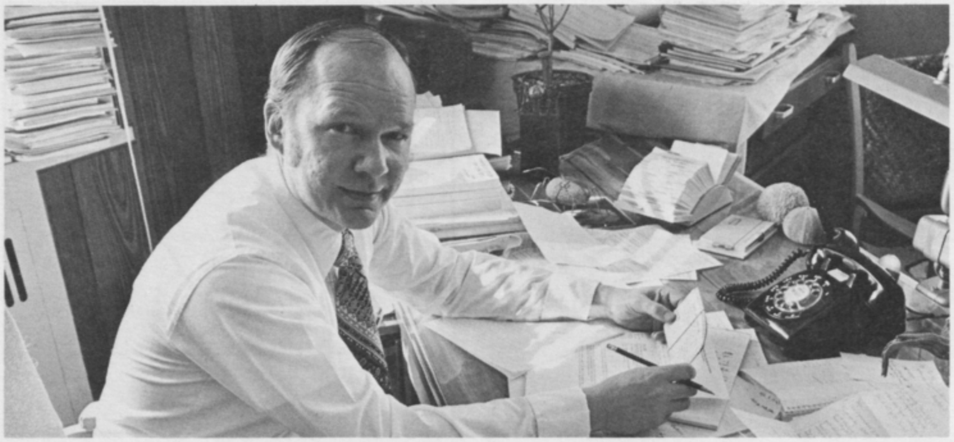
Partly because of the promising laboratory results, the experiments were enlarged rapidly to pilot scale—with reactors up to five cubic meters in capacity—and last year to a full-sized, 110-cubic-meter reactor. Three readily available and representative materials have been tested: corn stover (the stalks and leaves), grass, and wheat straw. In the large reactor, wheat straw was used in the form in which it is available from the farm: bales of straw were simply packed in layers. The only additive was digested cow manure, in an amount sufficient to achieve a moisture level of about 75 percent of the total weight. Results have been very encouraging, with gas-production rates peaking at 0.75 v/v-d and still continuing at a significant rate after six months. During cold winter months, only about 5 percent of the output energy was required to maintain the process. Since the reactor does not require daily attention, the operation has focused on gas use.

It is difficult to compare the performance of a long-term batch dry fermentor with a continuously operated slurry system; still, our results suggest that a dry-fermentation reactor two or three times the size of a slurry reactor could produce the same total amount of gas over a year's time. Such a schedule would fit well with harvesting times for many crop residues, but if higher reaction rates were desired, they could be achieved at higher, controlled temperatures. The amount of labor and attention required would be considerably less for the dry reactor.

THE POSSIBILITIES AND THE PROSPECTS

Much work remains to be done. We know the dry-fermentation techniques work, but we don't know in detail what occurs at the molecular level; further research is needed before the process becomes theoretically understood. The important reaction parameters must be defined, examined, and used to establish reactor requirements, and many system variables must be identified and studied. Economic studies must be made, and if large-scale systems are to be considered, the accompanying impacts on the community or region must be assessed.

The potential of biogas production from crop residues could be exploited in several modes. Farmstead reactors similar to the successful manure digesters are certainly possible. Small-scale operations at other locations appear feasible; a study I made of the potential for home heating, for example, indicated that my ten-room house near Ithaca could be heated for a year with biogas generated from a 4,000-cubic-foot reactor stocked with three



hundred dollars' worth of straw. But the most exciting possibility we have explored so far is the implementation of a community system with the capability of supplying a major part of the region's overall energy requirements.

An additional important possibility would be to apply the technology to the treatment of municipal garbage. Although there is considerable interest in recovering biogas from sanitary landfill, existing methods operate under the natural conditions—that is, slow gas production over a period of fifty years or more. Ways of enhancing the conditions have not been considered. Dry fermentation shows promise of being capable of stabilizing garbage in less than a year while producing as much as a third of the natural gas needed by a community. An additional benefit would be a reduction in the amount of land required for the sanitary landfill to about 5 percent of the area used with a conventional system. Also, dry fermentation would permit a recycling of humus matter and would eliminate leachate pollution.

In its relatively brief history, the United States has experienced two major energy transitions (see Figure 5) and is headed for another one as petroleum and natural gas supplies decline. The need for practical new sources of energy, available soon enough to help avert crisis, is obvious. Biomass is such a source. It has the potential of supplying more than $150 billion worth of energy before the year 2000, yet it is not receiving the support needed to expedite the necessary research and development. In 1979 the federal budget for work on biomass fuels was about $35 million. If an average of 3 quads (3×10^{15} BTU) of energy a year were generated from biomass between 1985 and 2000, the total value of this energy would be $135 billion. It would seem that a small fraction of this amount should be spent now and in the near future on research and development.

The strongest limiting factor in the development of technologies for converting biomass to fuel—and of other potential means of producing energy from renewable sources—is the lack of a national energy policy supported by the public. The economic impact of continued purchase by our nation of more than half the petroleum we use needs to be recognized and quickly dealt with. And as part of that effort, the potential contribution of small agricultural operations should be recognized and encouraged.

William J. Jewell, professor of agricultural engineering at Cornell, has concentrated his research efforts in recent years on the subject of this article—the use of agricultural wastes for energy production.

Jewell holds the B.S. degree in civil engineering from the University of Maine, the M.E. in sanitary engineering from Manhattan College, and the Ph.D. in environmental engineering from Stanford University. He came to Cornell in 1973 after serving as a postdoctoral research fellow in England and then teaching at the Universities of Texas and Vermont.

He is on the editorial boards of several professional journals in the fields of environmental engineering and water-pollution control, and he is active in a number of professional organizations.

REGISTER

■ Two members of the electrical engineering faculty were named professors, emeritus, this summer. Both *Paul D. Ankrum* and *William H. Erickson* have been at Cornell for forty years.

Ankrum is recognized as a pioneering teacher in his specialty area of electronics. He is the author of two textbooks, one of which—*Semiconductor Electronics,* published by Prentice-Hall—became a standard in the field. He has also been active as an industrial consultant; his experience working with several companies during sabbatic leaves helped keep the electronics curriculum relevant to industrial needs.

Ankrum received the B.S. degree in electrical engineering from the Indiana Institute of Technology in 1935, the A.B. in mathematics from Ashland College in 1939, and the M.S. in engineering from Cornell in 1944. He is a senior member of the Institute of Electrical & Electronics Engineers and for the last five years has served as faculty adviser to the student branch of that organization. He is also a member of

Ankrum

the American Society for Engineering Education and chairman of the Ithaca section of the Institute of Electrical & Electronics Engineers. He has had a continuing interest in student activities, and is often visited by alumni who come back to the campus as company recruiters.

Erickson has been active as both an educator and administrator. A specialist in electrical circuits, systems, and machinery, he co-authored the widely used introductory text, *Electrical Engineering: Theory and Practice*,

Erickson

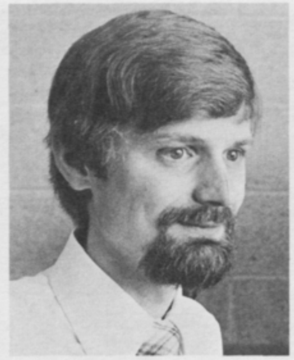
published by John Wiley and Sons. He served as acting director of the School of Electrical Engineering from 1956 to 1958, assistant director from 1959 to 1965, and associate dean of the College from 1965 to 1971.

Erickson received the B.S. degree in electrical engineering from the University of Pittsburgh in 1938 and the M.S. in the same field from the Carnegie Institute of Technology in 1946. He worked as a transmission and distribution engineer for the Duquesne Light Company, in Pittsburgh, from

1938 to 1942, when he came to Cornell as an instructor in the Naval Training School. In 1945 he joined the regular electrical engineering faculty. He is a licensed professional engineer in New York state, and a fellow of the Institute of Electrical & Electronics Engineers.

Ankrum plans to continue teaching and carrying out administrative functions on a reduced schedule. Erickson expects to remain active in community affairs in Ithaca and to devote more time to his long-standing interest in horse racing by developing "the ultimate computer-based handicapping system."

Berger
ASEE prizewinner



Kohlstedt
Guggenheim fellow

Mayer
Von Hippel award winner

■ A number of College faculty members received national recognition during the 1981–82 academic year. Awards, prizes, and other honors that have come to the attention of the *Quarterly* are noted here.

Toby Berger, professor of electrical engineering and a specialist in information theory, received the 1982 Frederick E. Terman Award of the American Society for Engineering Education. The award recognizes contributions to the profession by a young electrical engineering educator and is accompanied by a $2,000 prize. The recipient must be the principal author of an outstanding text; Berger's book, *Rate Distortion Theory*, has been a leading publication in that field for the past ten years.

Thomas E. Everhart, dean of the College and professor of electrical engineering, was one of three educators honored at the tenth biennial International Conference on Electron and Ion Beams in Science and Technology, which was held in Montreal in May under the sponsorship of the Electrochemical Society. Also recognized for their contributions to education in the field of electron and ion beams were scientists from Cambridge University in England and the University of Osaka in Japan.

Douglas Haith, associate professor in both the civil and environmental engineering and the agricultural engineering faculties, was awarded the Walter L. Huber Prize of the American Society of Civil Engineers (ASCE) for research on mathematical modeling of nonpoint-source water pollution and land application of wastes.

Juris Hartmanis, the Walter R. Read Professor of Engineering and a member of the computer science faculty, was elected a fellow of the American Association for the Advancement of Science.

Gerhard H. Jirka received the $2,500 Freeman Hydraulics Prize of the ASCE for 1981. The prize was in recognition of his research on multihost diffusers for waste-heat disposal from power plants.

David L. Kohlstedt, associate professor of materials science and engineering, was awarded a Guggenheim fellowship for work on the development, structure, and sliding of grain boundaries in geologic materials. He was one of eight Cornell professors to receive Guggenheims this year.

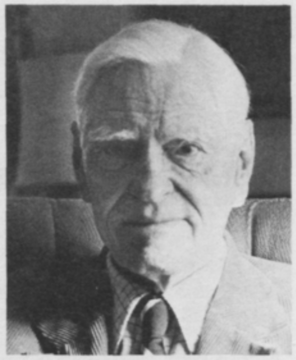
Fred H. Kulhawy, professor of civil and environmental engineering, won the Walter L. Huber Prize of the ASCE for his work in formulating basic stress deformation relationships for soil and rock.

John L. Lumley, the Willis H. Carrier Professor of Engineering at the Sibley School of Mechanical and Aerospace Engineering, received the 1982 Fluid and Plasmadynamics Award of the American Institute of Aeronautics and Astronautics for his work in turbulence, particle motion in fluids, and related areas of research. The citation noted the immediate applicability of this research in the fields of aerospace engineering, meteorology, and oceanography.

James W. Mayer, the Francis N. Bard Professor of Materials Science and Engineering, received the Mate-

Taylor
TRW fellow

Cocchetto
Teaching award winner



Ward
College award recipient

rials Research Society's Von Hippel Award, which is generally regarded as the highest honor in the United States in the field of materials science. A specialist in near-surface properties of solids, Mayer received the award in recognition of his contributions to interdisciplinary research. At Cornell he directs a new facility for backscattering analysis and conducts research at the National Research and Resource Facility for Submicron Structures, an interdisciplinary laboratory operated by Cornell.

Dean L. Taylor, associate professor in the Sibley School of Mechanical and Aerospace Engineering, was awarded the 1982-83 TRW Fellowship for research in manufacturing engineering. He will conduct the research at the University of Birmingham, England, during his sabbatical leave. (The first recipient of the fellowship, in 1977-78, was Cornell Professor K. K. Wang.)

Donald L. Turcotte, chairman of the Department of Geological Sciences, received the 1981 Arthur L. Day Medal of the Geological Society of America for "distinguished applicaton of chemistry and physics to geology."

George Winter, professor emeritus of structural engineering, received the Ernest E. Howard Award of the ASCE in recognition of his teaching and his research, especially on concrete and cold-formed steel.

■ *Joseph F. Cocchetto*, assistant professor of chemical engineering, was selected as the 1982 recipient of the $1,000 Award for Excellence in Engineering Teaching. Cocchetto, who has been on the faculty since 1979, is also a graduate of the College. The award is sponsored by the Cornell Society of Engineers, an alumni group, and the local chapter of the student honorary society Tau Beta Pi. It is given annually on the basis of nominations by engineering students.

Cocchetto received his Cornell degree in chemical engineering, with distinction, in 1973. He did his graduate work at the Massachusetts Institute of Technology, earning the S.M. degree in 1974 and the Ph.D. in 1979 after two years as a research engineer with E. I. duPont de Nemours and Company. A specialist in chemical reaction engineering and heterogeneous catalysis, his research interests include the development of fuel cells and the conversion of coal to liquid fuels.

■ The College honored an auspicious alumnus, Engineering College Council member, and benefactor with the presentation this spring of the Engineering Award to *J. Carlton Ward, Jr.* A silver medal inscribed "in recognition of his service to the college" was presented to Ward by Dean Thomas E. Everhart at the Cornell Club in Hartford, Connecticut on March 17. The occasion was a dinner for alumni, with University provost W. Keith Kennedy as principal speaker.

Ward, a 1914 mechanical engineering alumnus of Cornell, has served as president and chairman of the board of the Vitro Corporation of America; vice president of United Aircraft Corporation and general manager of its Pratt and Whitney Aircraft Division; and president and director of the Fairchild Engine and Airplane Corporation. During World War II he was an adviser on military aircraft to France and Great Britain, and in 1967 he received the Distinguished Public Service Medal of the United States Department of Defense. He retired in 1961.

For many years he served Cornell on the University's Board of Trustees and the Cornell University Council, as well as the Engineering College Council. He contributed to the design and establishment of the J. Carlton Ward Laboratory of Nuclear Engineering, which opened here in 1961, and several years ago he established a professorship in that field.

■ *Solomon Cady Hollister,* who served Cornell, the engineering profession, engineering education, and the nation throughout a long and productive career, died in Ithaca on July 6 at the age of ninety.

Hollister was dean of engineering here for twenty-two years, from 1937 until his retirement in 1959. Under his leadership, the College experienced an expansion of faculty and programs, and an entire new engineering campus was built. Hollister Hall, which houses the School of Civil and Environmental Engineering, was named in his honor.

A national figure in the profession as well as in education, he was the recipient of numerous awards and honors, including election to the National Academy of Engineering and the American Hall of Fame of the American Society of Civil Engineers. He served as president of the American Concrete Institute and of the American Society for Engineering Education, and he subsequently received honors from both: the first Wason Research Medal of the ACI (for the innovative design of a skew-arch concrete bridge) and the Lamme Award of the ASEE. He was elected an honorary member or fellow of six professional societies, and he received honorary doctoral degrees from four institutions. In the spring of 1980 his extensive work in concrete technology was the subject of a colloquium held in his honor at Princeton University.

Hollister made significant contributions in the design of thin-shell structures such as ships, boilers, penstocks, and pressure vessels. During World War I, at the age of twenty-six, he served as chief design engineer in an emergency program to build concrete ships; some of the world's first practical seagoing concrete vessels were constructed. Later he had a major role in the design and fabrication of the 30-foot-diameter welded steel penstocks at Hoover Dam.

Hollister was born in Crystal Falls, Michigan, on August 4, 1891. His undergraduate education was begun at Washington State University (which last year honored him with the Alumni Achievement Award). He received the B.S. degree from the University of Wisconsin in 1916, and later earned the Civil Engineer degree from that institution. Before coming to Cornell in 1934 as director of the School of Civil Engineering, he taught at the University of Illinois, worked as an independent consultant in Philadelphia, and was professor of structural engineering and assistant director of the materials testing laboratory at Purdue University.

During his years at Cornell, he participated in various engineering studies for government groups and for the National Academy of Sciences, and he served on the Second Hoover Commission on the reorganization of the federal government. Through his work in professional societies, especially in the Engineers' Joint Council for Professional Development and the ASEE, he was influential in the development of engineering education in the United States. He was active also as an industrial consultant, and he was a director of Raymond International, Inc.

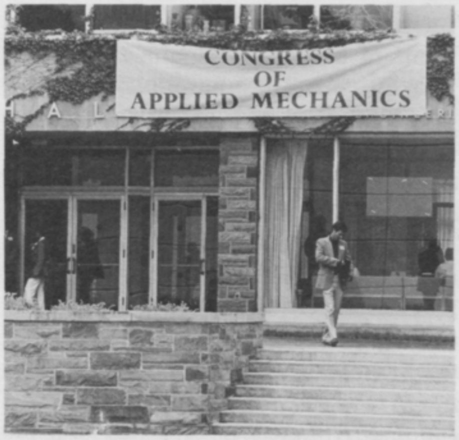
Hollister is survived by his wife of sixty-three years, Ada; and by three children, ten grandchildren, and six great-grandchildren. A memorial service will be held at Cornell in the fall.

The following are excerpts of comments by three men at Cornell who have served as dean of the College of Engineering.

Dean Hollister was a practicing engineer, an educator, and an administrator whose vision of what engineering and education ought to be was matched only by his dedication to Cornell. He was an exceptional man and his influence will be felt for many years.—Andrew Schultz, Jr., Professor, emeritus

Hollister was a force nationally in engineering education and he made a tremendous impact at Cornell: he built the Engineering Quad and he created innovative programs, including those in aeronautical engineering and engineering physics. I consider Holly one of the greatest administrators Cornell has ever had.—Dale R. Corson, Professor and President, emeritus

Hollister was Dean of Engineering at Cornell for twenty-two years—longer than any other man—and had a continuing strong presence. His breadth of interests, from civil engineering to paleontology, and his concern for his fellow men have impressed all who have been touched by him.—Thomas E. Everhart, Dean of Engineering



Sidelights of 1981–82

■ Cornell was host the week of June 21–25 to more than six hundred delegates to the Ninth U.S. National Congress of Applied Mechanics. *Yih-Hsing Pao*, Cornell professor of theoretical and applied mechanics, was general chairman and also scientific chairman. Other members of Cornell's T&AM faculty were active as organizers and participants.

The agenda included five general lectures, symposia in twelve subject areas (an innovation introduced by the Cornell planners), and about thirty sessions at which contributed papers were read. The week's activities also included entertainment, various alumni dinners, and a concluding banquet. The guest of honor at Cornell's alumni dinner was *H. D. Conway,* who has been a member of the T&AM department here for thirty-five years.

The congress, considered the major event in the United States in the field of applied mechanics, is held every four years at a leading university. Under the auspices of the National Academy of Sciences, the conference is sponsored by eleven professional societies. The fields represented include civil engineering, mechanical engineeering, theoretical and applied mechanics, physics, mathematics, aeronautics and astronautics, chemical engineering, and materials science.

Cornell members of the scientific committee, in addition to Pao, were *John L. Lumley*, the Willis H. Carrier Professor of Engineering, and *Francis C. Moon*, chairman of the T&AM department. Other members of the department who served on the organizing committee are *Richard H. Lance*, *James T. Jenkins*, and *Wolfgang H. Sachse*.

Of the five general lectures, one was presented by a Cornell faculty

Right: Honored at Cornell's alumni dinner during the applied mechanics congress was H. D. Conway (at right), who is being congratulated by Cornell colleague John F. Abel. A number of universities held reunion dinners the opening evening of the conference.

member—*John F. Abel* of the Department of Structural Engineering, who spoke on interactive computer graphics—and one was by a Cornell Ph.D. in astrophysics—*Peter Goldreich* of the California Institute of Technology. *Sidney Leibovich*, Cornell professor of mechanical and aerospace engineering, led the symposium on geophysical fluid dynamics. Cornell professors who participated in the symposia were Lumley, Moon, *S. Leigh Phoenix, Shan-Fu Shen*, and *Philip J. Holmes*.

■ Visitors from industry attended a series of five "Conversations at Cornell" sponsored by the College during the spring. The two-day programs each included a general talk at the opening dinner, brief summaries of Cornell research activities, and laboratory visits. The topics were "Intersections with Biology," "Manufacturing Engineering and Productivity," "Energy Sources and Systems," "Mathematics in Action: New Approaches to Engineering Problems," and "Programming for the Eighties."

Above: Ellenwood Prize winner Jonathan N. Myers (at right) explains his wind-turbine design to Professor A. R. George, director of the School of Mechanical and Aerospace Engineering.

Below: Professor Jack Muckstadt of Cornell's School of Operations Research and Industrial Engineering speaks to visitors attending a conference on manufacturing engineering and productivity. This was one of five "Conversations at Cornell" sponsored this spring by the College of Engineering.

■ The first recipient of the $1,000 Frank O. Ellenwood Prize at the Sibley School of Mechanical and Aerospace Engineering was *Jonathan N. Myers*. The prize was established last year by an anonymous donor in honor of Ellenwood, who held the John Edson Sweet Professorship in the Sibley School during the 1940s and is widely known as co-author of the classic text, *Heat-Power Engineering*. The award was presented this spring at a reception attended by faculty members and students in the School.

Myers won the prize by earning the highest grades (all A+) in three courses offered in the area of power production. He ranked second among the School's 127 graduating seniors. As a participant in the College's Engineering Cooperative Program, Myers worked with the Hughes Aircraft Company. On campus, he worked on a senior project, "Design and Testing of a Wind Turbine," with Professor Dennis G. Shepherd, another holder of the Sweet chair.

■ The newly refurbished Ellis L. Phillips Lounge at the School of Electrical Engineering was dedicated in a ceremony held in the lounge last October. The work on the room was accomplished with funds from the Phillips Foundation and represents a continuation of support for the School. The electrical engineering building, Phillips Hall, was a gift of the late Mr. Phillips, a Cornell graduate of 1895 who became a central figure in the development of the American electric utility system. He founded or organized several utility organizations and operated a consulting firm. He was a member of Cornell's Board of Trustees.

The lounge area has been divided by folding doors into a seminar room and a casual lounge area with a kitchenette, an arrangement that makes the room suitable for special occasions as well as for everyday use.

Right: A portrait of Ellis L. Phillips hangs in the newly dedicated lounge in Phillips Hall. Photographed with the portrait at the October 17 dedication were Ellis L. Phillips, Jr. (at left) and Ellis L. Phillips III.

■ The College's admissions office won one of ten cash prizes awarded by the University in this year's "Service Improvement/Cost Reduction Program." The engineering prize of $300 was part of a total of $2,340 awarded.

The idea, submitted by admissions director *Robert E. Gardner*, was to reorganize the management of on-campus visits by prospective undergraduates. The new program includes group lectures and discussions with department representatives and overnight stays with students.

According to *William G. Herbster*, Cornell senior vice president, the twenty-two ideas submitted for the contest may save the University as much as $750,000 a year, as well as improve services. The various ideas, he said, reflected the University's tradition, dating back to founder Ezra Cornell, of finding simple, more effective, and more economical ways of doing things. He cited Ezra's invention of glass insulators, which made cross-country telegraphy possible and economically feasible.

■ *Engineering: Cornell Quarterly* is a prize-winner again this year in a national recognition program for university publications. The *Quarterly* received three awards in the competition sponsored by the Council for Advancement and Support of Education.

The *Quarterly* was one of thirteen periodicals to receive the Exceptional Achievement Award, the highest rating in the judging, in the Magazine Publishing Program category. All four issues published during the year were considered. The *Quarterly* also received one of four Exceptional Achievement Awards for a special issue, which was "The Advance of Computer Graphics," the Winter 1981–82 edition. The magazine earned the Special Merit Award for research coverage in institutional periodicals; a total of four awards were given.

Members of the production staff are *Gladys McConkey*, editor, and *David Price*, associate editor. Price, who joined the College publications staff in January, has a degree in English, an advanced degree in anthropology, and experience in publications design.

Left: Members of the College admissions staff showed up in force to receive a $300 prize for their idea on how to improve service or reduce costs at the University. Robert E. Gardner, director of engineering admissions, accepts the check from Vice President William G. Herbster. Others in the front row, left to right, are Leilani Bilinski, Mariea Blackburn, Martha Topor, and Thomas E. Everhart, dean of the College. In the back row, left to right, are Stephen Nesterak, Judith Zubal, Robert Smith, and Karen Lankton. Nesterak and Lankton worked with the staff as "student ambassadors."

■ A gift car for President Rhodes "wrapped" around a tree, a tug of war in the snow, music on the Quad, a beer-chugging contest, and a Saturday night ball. Those are some of the features that enlivened the celebration of Engineers' Week in February.

There was another side, too: the large Memorial Room at the Willard Straight student union was filled with well-attended exhibits from the various engineering departments and local enterprises. And tours to places of interest on campus, like the Ward Laboratory of Nuclear Engineering and the computer-graphics center in Hollister Hall, were conducted with proprietary pride by engineering students. As Peter Poole '82, head of the student planning committee, remarked, "It's really fun. Engineers enjoy seeing other engineers' work."

1

1. The students had permission to weld the car around the tree in front of Day Hall as a gift to President Frank H. T. Rhodes, but how was the buildings and grounds director supposed to know that? James Kidney ordered the mysterious car removed and it had to be retrieved from the dump. Here Kidney discusses the mistake with (left to right) students Peter Poole, Tom Keane, and Bryan Clark. A note accompanying the gift explained that "it portrays the synthesis of technological genius and esthetic design," and "like the best of modern engineering . . . exists in harmony with nature," harming neither snow nor air nor tree.

2

2. Contests on the Quad were part of the Engineers' Week festivities. There was some uncertainty about which team wobbled the frozen keg to victory.

3


3. The Friday afternoon Quad party during Engineers' Week included a tug-of-war won by the civil engineers. Six teams from various schools and departments competed.

4. The sale of T-shirts was supervised by Tracy Cahill (left), and Renee Sweney, who was the treasurer for Engineers' Week.

5. Exhibits in the Willard Straight Memorial Room included one of the high-speed bicycles with streamlined canopies that were designed by engineering students with the aid of wind-tunnel tests and computer calculations.

6. A speed-governing mechanism was demonstrated with a model train set.

7. One of the hits of the exhibit was a robot demonstrated by its inventor, Carl Fredericks of Wolfdata, Inc., in Ithaca. Omnivac I can talk, answering questions and volunteering remarks, and can move about and manipulate its "arms."

Other exhibits included displays sponsored by engineering departments. Among the subjects were mineralogy and seismology, computer chips and semiconductors, artificial limbs, computer simulation of tractor overturn, heat detection by infrared camera, and modeling for structural engineering.

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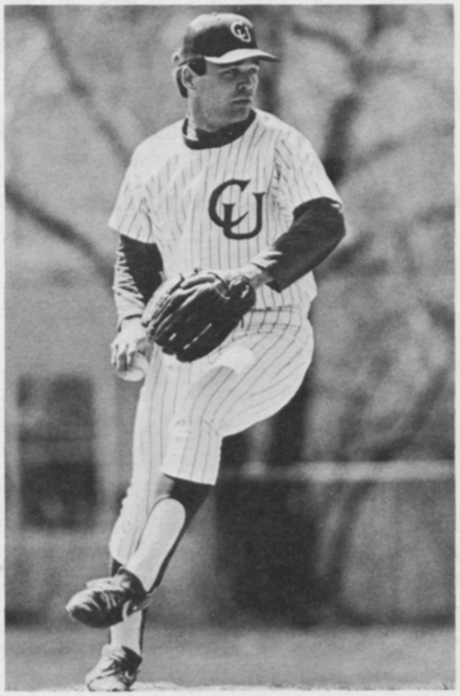
Winning Engineers

More than seventy engineering students took part this year in varsity sports—in football, soccer, basketball, gymnastics, swimming, baseball, fencing, crew, lacrosse, wrestling, track, field hockey, and skiing. Several were outstanding athletes.

▪ Eleven engineers were on the baseball team, which was especially strong this year, finishing in second place in the Eastern Intercollegiate Baseball League after a 26–13 season. Two of these players won special recognition. Co-captain and pitcher *Greg Myers,* a senior in mechanical engineering, was awarded the Eastern Collegiate Athletic Conference Merit Medal for combined excellence on the field of competition and in the classroom. In four years of baseball at Cornell, his win-loss ratio was 23–9 and his earned run average was 2.70. Also outstanding was *John DeMayo,* a senior in structural engineering, who was named most valuable player, with a batting average of .358, seven home runs, and forty-two runs batted in.

Eleven engineers were on the Big Red baseball team. Front row, left to right: Carl LaFraugh '84 (manager), Mike Kalfopoulos '85, David Rahr '85, Michael Held '84, and James Ritchey '85. Back row: John DiGiovanni '83, James DiGiorgio '85, John DeMayo '82, Stephen Huber '85, Daniel Hall '84, and Greg Myers '82.

▪ Outstanding in football was sophomore *Derrick Harmon,* who received this year's Charles Colucci Award for the non-senior who makes the greatest contribution to the team. Harmon had an impressive career at Bayside High School (in Queens, New York) and showed great promise as a tailback

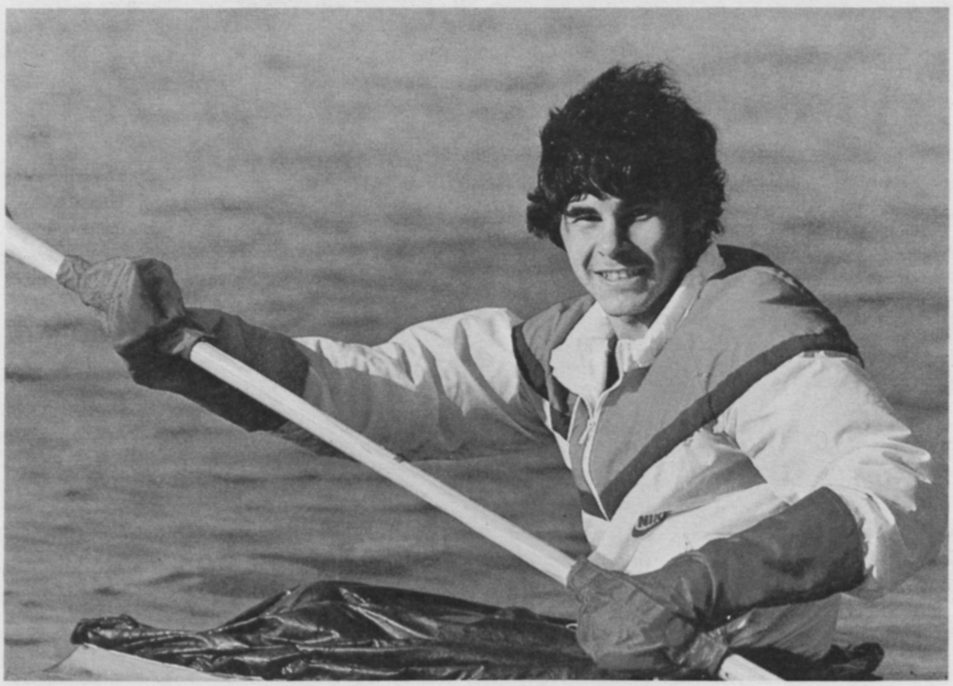


Left: Greg Myers '82, right-handed pitcher and co-captain, won the ECAC Merit Award for excellence in athletics and scholarship. "The key to effectiveness," he says, "is concentration."

Below: Derrick Harmon '84 received an award as the outstanding non-senior on the football team this year. He led the Big Red as rusher (carrying the ball 173 times for a total of 893 yards), as pass receiver (twenty-one times for 285 yards), and as scorer (seven touchdowns). He also achieved an impressive academic record.

during his freshman year at Cornell. When he failed to appear at training camp last fall, coaches feared he had been lured away by some other school. But Harmon was still here; he just could not decide whether he should take time from his studies to play football. He not only played, but became the team's leading rusher, pass receiver, and scorer, despite an injury that plagued him all season. And he made the dean's list both terms.

■ *Dave Clark,* a 6′4″, 200-pound senior in electrical engineering, rowed with the Cornell heavyweight eight that won the prized Intercollegiate Rowing Association varsity cup at the national regatta on Onondaga Lake last year and again this June. In 1981



Left: Dave Clark '82 rowed with the Cornell heavyweight eight last season and this. The crew won the Varsity Challenge Cup at the national IRA regatta both years. Last fall Clark stroked the U.S. National eight-man crew to a third place in international competition.

Left below: A freshman to watch is Terry Kent, an All-Ivy wrestler who is also outstanding in kayak racing.

the team went on to compete in the Netherlands, Switzerland, and England; at Lucerne, Clark and two teammates placed fifth in the pair-with-coxswain. Subsequently, Clark was selected for the U.S. National team and rowed at the stroke position (rather than his customary six seat) with the eight-man crew that placed third in the World Rowing Championships in Munich. It was the first time since 1974 that an American eight had won a medal in the competition.

■ Other noteworthy College athletes included *John Rudel,* a sophomore in chemical engineering, who set a new record (4:34.20) in the 500-yard event at the Eastern Seaboard Swimming and Diving Championships. Freshman *Terry Kent* wrestled his way to the All-Ivy first team at 190 pounds with eight victories in twelve matches; he is also a top kayak racer who hopes to compete in the 1984 Olympics. Freshman *Kathy McPherson* placed first in three cross-country races and was named most valuable member of the women's team.

FACULTY PUBLICATIONS

Current research activities at the Cornell University College of Engineering are represented by the following publications and conference papers that appeared or were presented during the three-month period from December, 1981 through February, 1982. (Earlier entries omitted from previous Quarterly listings are included here with the year of publication in parentheses.) The names of Cornell personnel are in italics.

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LETTERS

Thinking Big About Energy

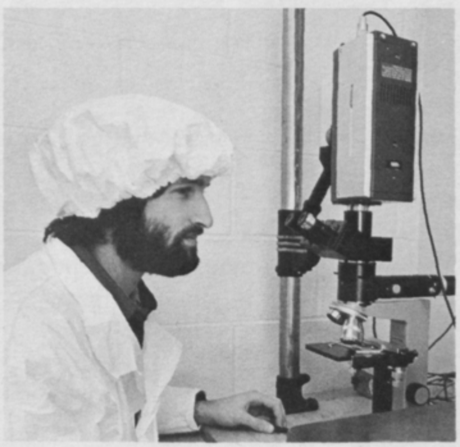
Professor Linke: I found your article on global hydro particularly thought-provoking, especially the figures on the magnitude of the resource. Another intriguing aspect of your proposed intercontinental transmission scheme is the possibility of peak-demand sharing between countries. For example, the peak demand in Moscow occurs some nine hours after it does in Los Angeles. Thus, it might be possible, if a transmission link existed between the two load centers, to use Soviet base plant to supply North American peak load and vice versa. This could be an additional economic benefit of your scheme, as well as another incentive for international cooperation. Perhaps we could make war an economic impossibility!
John Kaye
Berkeley, California

Editor: I write a weekly science news column for the *Los Angeles Herald Examiner;* a copy of my 14 June column is enclosed. I thought you would be interested, since it deals with your very fascinating articles [on microwave transmission of solar and hydro power].
Irving S. Bengelsdorf
Los Angeles, California

Macro Pictures with Micro Detail

Editor: I found the Autumn 1981 issue very interesting and well done. One thing, however, has often puzzled me when I see pictures of "clean rooms" (as on page 25). So many times there is a very bushy individual all covered up except for a luxuriant beard which could contaminate the environment. How is this justified or explained?
Kenneth F. Woehr
Sun City, Arizona

Mr. Woehr: The *Quarterly* forwarded to me your letter in which you comment on bearded individuals working in "clean" areas. In most industrial laboratories ("Class 10"), personnel wear hoods that cover the entire head. That precaution was judged unnecessary in Knight Laboratory—our goal is not high yield of thousands of devices, but research on a few devices, so we are able to relax our clean-room requirements somewhat. But we do have on hand beard "cots" in case the local contamination problem arises! I hope this clears up some of the confusion, and I thank you for your interest in the National Submicron Facility.
Edward D. Wolf, Director
NRRFSS, Cornell University
Ithaca, New York



Salaries for Engineers

Editor: In reference to the figure [on the average starting salary of $23,172 for a Cornell B.S.-degree graduate in engineering], I would like to comment that an employee, even with a diploma, is worth nothing to us for the first six months or a year. We believe that B.S. graduates should be willing to start for $19,000 or $20,000 or thereabouts because they are actually still students when they come to work for us. . . . It is true that a number of big companies offer students high wages. But, too, they dismiss these new employees as soon as they find they are incapable of the work to be performed. Or, when there is a bit of slackness in business, they put the man on the street. Contrarily, we intend to keep an employee through thick or thin, good business or bad—something that the student could rely on and should know.
F.M. Young, President
Young Radiator Company
Racine, Wisconsin

The Advance of Computer Graphics

Editor: All personnel reviewing the Winter *Quarterly* are impressed with Cornell University's capabilities in the field of computer graphics. . . .
E. M. Holub
Union Carbide Corporation
Tarrytown, New York

Editor: Your issue on computer graphics is great! Do you have extra copies to distribute at a CASE conference? The subject is "Capitalizing on the New Technology in Public Relations and Publications," and the program will be held in Boston this fall. The people who attend would be *fascinated* by this subject and your treatment of it.
Virginia Carter Smith, Vice President
Council for Advancement and Support of Education
Washington, D.C.

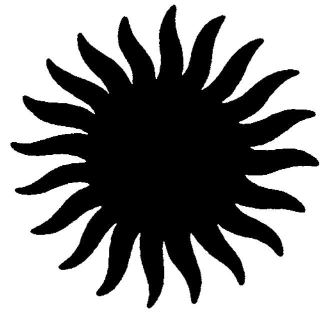
Solar Energy Projects in Jeopardy

Feasible ways of using solar energy on a large scale are attainable. Articles in this issue (and in the preceding one) show there is no lack of ideas. The obstacles are not primarily scientific or technical, but economic and political.

Innovation of the scope needed for significant large-scale applications requires an intelligent, sustained program. In many cases, R&D for a new technology requires government sponsorship to bring it to the stage of commercial feasibility. Proposals should be continually evaluated and reevaluated, and promising programs should be continued (or initiated), not abandoned in short-sighted budget-cutting. It should be a high national priority to encourage technologies that will reduce our dependence on imported energy and stimulate our economy by providing an expanded domestic energy base. And in a larger sense, the government has the responsibility of formulating a national policy that is wise as well as expedient, taking into account global as well as national needs, and posterity as well as contemporary society.

We must acknowledge that there is no panacea for the energy problem, that all solutions are partial. Conservation is a powerful route to greater energy self-sufficiency, and small-scale installations like rooftop solar collectors and farmstead gas generators could be significant. Yet these measures do not obviate the need for large-scale energy systems. The whole range of alternatives should be considered in terms of availability, cost, and suitability under local conditions of population density, geography, economy, and available resources. Ocean thermal energy conversion (OTEC), for example, would be impractical for Maine but might be excellent for Hawaii. Crop residues for biogas generation would be useless in Manhattan but might be feasible for upstate New York. An especially important consideration is the timing of development and implementation. Alternative energy schemes such as those described in this issue could help reduce our dependence on foreign oil in the next few decades. They are potentially valuable particularly in the near term, until technologies that require more lead time—such as nuclear fusion—become available.

Unhappily, the development of non-nuclear renewable sources of energy is now in jeopardy in the United States. Some relief may materialize. Perhaps private industry will pick up where government programs leave off. Perhaps government leaders will restore funding to endangered programs before the momentum of development falters. Perhaps a groundswell of public sentiment will influence the political climate. But the basic need is for adequate, continuous funding of the most promising proposals; worthwhile ideas should be rescued from the limbo of neglect before emergencies dictate responses. The life-giving sun (a fusion reactor in space) remains our best ultimate source of energy—abundant, safe, and accessible to those who discover ways of realizing its benefits.



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Opposite: An end-of-the-year party on the Joseph N. Pew, Jr. Engineering Quadrangle has become an annual event. Sponsored by the Society of Women Engineers, it features live music, refreshments, games, and relaxation.

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