solving problems in this manner.

Naftalin adds that he thinks some of the rivalries between the basic science community, the engineers, and other groups will ultimately be broken down through exposure, as they were, he claims, in the summer panel workshops. "If you put a Berkeley political scientist in the same room with a retired G.E. vice president for 3 days, something's got to give," he says. Both Naftalin and Wenk point out that the individuals involved in the study, who might have been expected to take diehard positions that RANN threatened the health of NSF and of basic university research, did not do so. And RANN chief Joel Snow points out that the National Science Board, which had expressed sharp concerns over RANN and a year ago was supervising every award of $5000 on up by RANN, has now relaxed, and reviews RANN only on a program-by-program basis. Evidently, then, the originators and authors of the study feel that the schisms which RANN has in the past revealed, can be mended. In the meantime, as far as COPEP's endorsement of the RANN program goes, the sky is the limit.

—DEBORAH SHAPLEY

RECENT DEATHS

Willy E. Baensch, 79; professor emeritus of radiology, Georgetown University Medical Center; 1 November.

Lewis N. Brown, 81; former professor of pharmacy, Columbia University; 20 October.

Lawrence N. Canjar, 49; dean, College of Engineering, University of Detroit; 6 November.

Hans T. Clarke, 84; former professor of biochemistry, Columbia University; 21 October.

Ross M. Coxe, 50; professor of education, University of South Carolina; 17 October.

W. Gayle Crutchfield, 72; professor emeritus of neurological surgery, University of Virginia; 31 October.

Con Fenning, 67; former professor of physiology, University of Utah; 14 October.

Joe M. Hopping, 41; dean, Graduate School, Central Missouri State University; 15 September.

Richard L. Huntington, 76; research professor emeritus of chemical engineering, University of Oklahoma; 9 October.

Walter R. Kirner, 77; former director of chemistry, National Science Foundation; 7 October.

G. David Koch, 69; former professor of geography, Indiana State University; 18 September.

Solomon Lefschetz, 88; professor emeritus of mathematics, Princeton University; 5 October.

Robert H. MacArthur, 42; professor of biology, Princeton University; 1 November.

Harlow Shapley, 86; professor emeritus of astronomy, Harvard University and former president, American Association for the Advancement of Science; 20 October.

John E. Walsh, 53; professor of statistics, Southern Methodist University; 24 August.

Robert C. Williamson, 84; professor emeritus of physics, University of Florida; 4 September.

Richard J. Winzler, 57; professor of chemistry, Florida State University; 28 September.

John D. Withers, 50; zoologist and assistant director, American Institute of Biological Sciences; 30 September.

RESEARCH NEWS

Fuel Cells: Dispersed Generation of Electricity

ENERGY

The fuel cell was discovered by Sir William Grove in 1839, but it remained little more than a scientific curiosity until the first practical fuel cell was demonstrated 120 years later by Francis T. Bacon and J. C. Frost of Cambridge University. Since that demonstration, fuel cells have been widely used in the space program, but their high cost has effectively precluded their use as earthbound power sources. Only recently has it begun to seem likely that the cost problems could be overcome and that fuel cells could be commercially viable within this decade.

The road to viability has been a strange one. The euphoria of the space program attracted a number of companies into fuel cell development, but disillusionment set in rapidly. It is comparatively easy to produce electricity efficiently and for long periods of time when money is no object; it is far harder, they found, to do it when that electricity must compete economically with the relatively cheap product of large commercial generators.

The federal government, furthermore, provided fuel cell research funds almost exclusively for space and military applications, and even those funds dropped from nearly $16 million in 1963 to about $3 million in 1970. Unwilling or unable to assume the substantial investment required for commercialization, companies that had so eagerly rushed into fuel cell development quietly abandoned their research programs or reduced them to token operations. At present, only one company is actively pursuing a full-scale commercial fuel cell program—the Pratt & Whitney Aircraft division of United Aircraft Corporation, East Hartford, Connecticut.

Pratt & Whitney did have some help though. The natural gas industry has supported its effort because fuel cells seem to present an attractive, environmentally sound way to obtain a premium rate of return on natural gas sales by upgrading the gas to electricity. The electrical industry has also provided support because fuel cells promise to be small, clean power sources that can be quickly installed throughout its distribution systems to supplement central power stations without objections from residents or ecologists.

To date, 43 U.S. and three foreign utilities and Pratt & Whitney have invested more than $50 million to prove the technical feasibility of commercial fuel cells. Roughly twice that amount is expected to be invested by the same groups during the next 3 years in an attempt to demonstrate the economic viability of fuel cells.

The object of this effort is actually a relatively simple concept. The fuel cell's main components are a fuel electrode (anode), an oxidant or air electrode (cathode), and an electrolyte. In a typical application, hydrogen is fed to the anode, where it is catalytically converted to hydrogen ions, releasing electrons to an external circuit. At the cathode, these electrons reduce oxygen to ions which then migrate through the electrolyte and combine with hydrogen ions to form water. This process—effectively the reverse of electrolysis—continues as long as fuel and air are supplied to the cell, and its structural integrity is maintained. Fuel cells can be adapted to a variety of fuels by changing the catalyst, but hydrogen fuel cells are the most efficient and have received the most development.

A single hydrogen fuel cell creates an electric potential of about 1 volt and generates from 100 to 200 milliamperes of direct current per square centimeter of electrode area. By connecting a number of cells, it is possible to create useful potentials of 100 to 1000 volts and power levels of 1 kilowatt (kw) to nearly 100 megawatts (Mw).

A fuel cell power plant generally also contains a reformer and an inverter. The reformer uses chemical processes to convert the fuel to a form that can be utilized by the cell. In some Pratt & Whitney systems, steam and a catalyst are used to convert hydrocarbons into hydrogen and carbon dioxide. The inverter changes the direct current output into alternating current at the frequency and voltage levels required.

Some of the advantages of fuel cells over conventional power sources are obvious. Emission of air pollutants, for example, is negligible because fuel cell operation is not based on combustion. Thermal pollution is not a problem because excess heat is released directly to the atmosphere. Noise pollution is also minimal because moving parts are restricted to the fuel and cooling systems.

Another major advantage is efficiency of electrical production. The best steam and gas turbine generators now operate at a thermal efficiency of about 39 percent at power levels greater than 100 Mw. The best fuel cell power plants may be only slightly more efficient, but that efficiency can be achieved at power levels as low as 25 kw, where other generating systems are much less efficient (Fig. 1). If the power plant is operated on hydrogen and doesn't require a reformer, the efficiency may be close to 55 percent. Conventional generators, moreover, are much less efficient when operated at less than their maximum capacity, whereas fuel cells maintain high efficiency even when operated under a partial load.

The primary problems of fuel cell development are initial cost and service life. Pratt & Whitney has estimated that current technology would permit the production of fuel cell power plants, independent of size, at a cost of about $350 to $450 per kilowatt and with a service life of about 16,000 hours. To be competitive commercially, the company says, the cost should be halved and the service life doubled. These objectives must be met by increasing the power output and by developing less expensive, more stable materials of construction.

Most Improvements Are Proprietary

Much progress has apparently been made in these areas, but Pratt & Whitney's statements on the subject must be taken largely on faith because all the new technology and materials developed in its program are proprietary. More than 85 percent of the materials and technology on which the power plants are based, the company claims, have been developed within the past 5 years. These improvements have already reduced the cost per kilowatt by a factor of nearly 20 and have increased the economic operating life by a factor of 5, and there is a reasonable probability that the break-even point could be reached within the next 3 years. Full-scale commercialization of fuel cell power plants could then be achieved within this decade.

Pratt & Whitney's efforts are directed primarily toward three interrelated applications:

► Transformers for on-site conversion of natural gas to electricity.

► High output power plants (25 to 100 Mw) to supplement central station facilities.

► Low output power plants (10 to 200 kw) for reliable production of power in remote locations and in unattended operation.

A fourth application of fuel cells would be for central station generation of electricity, but only Westinghouse Electric Corporation, Pittsburgh, Pennsylvania, is investigating this approach.

Although Pratt & Whitney is devoting effort to each of the alternatives, on-site generation of electricity for residences and small businesses has thus far received the most field testing. The 35 natural gas companies that comprise the nonprofit Team to Advance Research for Gas Energy Transformation (TARGET) have installed and tested nearly sixty 12.5-kw fuel cell power plants at 37 locations throughout the United States and Canada. These tests were designed, among other things, to gain installation and operating experience in a variety of climates, to assess problems related to the ratio of peak to average electrical requirements, and to obtain experience in estimating the maximum electrical demand in different types of buildings. Developing the capability to determine the customer's precise electrical requirements, Pratt & Whitney says, is as important for commercial success of fuel cell energy service as is development of the power plant itself.

The goal of the TARGET program is to produce electricity at a cost competitive with that of central station generation—with no credits for environmental benefits or waste heat utilization. One major factor that may allow attainment of this goal is the relatively high price of transmitting and distributing electricity. Transmission and distribution costs for natural gas are only about 20 to 30 percent of those for electricity, on the basis of energy content. Capital investment should also be significantly lower for fuel cell energy service, the company predicts.

A further factor is lowered fuel costs. While a central generating station may have a thermal efficiency of 39 percent, transmission losses reduce the overall system efficiency to about 34 percent. Utilities, moreover, must supplement their main generators with less efficient standby and peak power sources that further decrease efficiency. The net effect, TARGET assumes, is that on-site fuel cell power plants produce about 20 to 25 percent more useful energy per unit of fuel.

A final benefit of on-site fuel cells, and one that has not yet been fully explored, is the use of by-product heat from the power plant. Pratt & Whitney suggests that this energy could not only help provide heating, hot water, and air conditioning, but could also be used to purify, deodorize, humidify, or dehumidify air, to dispose of waste, and to purify water. Such uses would make the overall thermal efficiency even higher.

The principal argument against such an application would seem to be the shortage of natural gas. If gas supplies are already tight, new uses would presumably only aggravate the problem. But fuel cells, argues TARGET president Robert Suttle, are the most efficient method of converting fossil fuels to electricity. If natural gas can be used more efficiently in this fashion, he points out, there will be greater quantities of oil and coal available for other applications, the implication being that natural gas may eventually be diverted from industry and utilities to residential use.

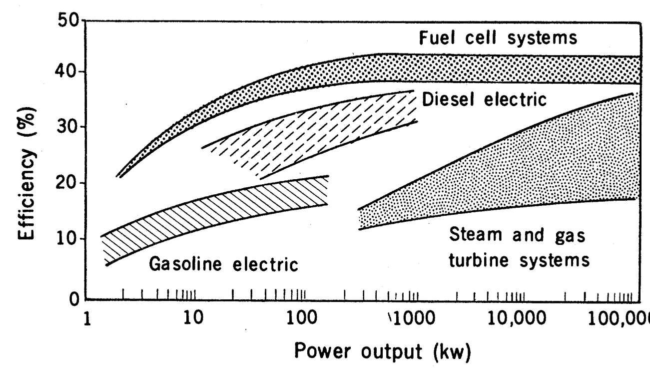

Fig. 1. Thermal efficiency of electrical production of fuel cells and other types of generators as a function of output. [Source: Pratt & Whitney Aircraft]

Most of the arguments favoring onsite fuel cells can also be applied to the use of fuel cells by electric utilities. The attributes that particularly suit fuel cells for this use, however, are their ability to be placed virtually anywhere without disruption of the environment and the relatively short time required for their construction. Electric utilities could thus use such plants to supplement their systems in rapidly growing areas and in areas where siting or transmission problems prevent the construction of conventional plants.

Fuel cells could also be useful as part of an electrical storage system to supplement nuclear or thermonuclear power systems. During periods of minimum electrical demand, the output of central stations could be used for electrolysis of water; the hydrogen thus produced could then be used at times of peak demand to produce electricity at high efficiency, thereby lowering the total capacity requirement of the system.

The larger fuel cell power plants would, in essence, be composed of several smaller units linked together. This type of modular construction would speed installation by allowing units to be assembled at a central plant and trucked to the site. It also provides an inherent redundancy that would allow generation of electricity even when some sections of the facility are disabled or shut down for maintenance.

The chief difference from residential units is that the larger facilities will most likely consume a distillate fuel such as No. 2 fuel oil or jet fuel. This choice is dictated by the expected shortage of natural gas and the absence of practical technology for reformation of heavier hydrocarbons. Such fuels are relatively expensive, but they are already widely used for supplemental generators; the higher efficiency of fuel cells, moreover, could offset the increased fuel cost. The first field test of such a unit began last month when a 37.5-kw experimental unit was installed at the Public Service Electric and Gas Company in Newark, New Jersey.

Power plants for use in remote locations represent a much smaller market than those previously discussed, but the technical requirements are similar. The chief attributes of fuel cells for this application are unattended operation, freedom from maintenance, and quiet operation. Engelhard Minerals and Chemicals Corporation, Murray Hill, New Jersey, is also developing fuel cells —based on the use of ammonia or methanol—for this market, but it too does not yet have a commercial product.

Central-station generation of electricity with conventional fuel cells is impractical. Because such cells are no more efficient than the best large turbines, no advantage is gained in their use. Westinghouse has been investigating high temperature fuel cells to be used in conjunction with coal gasification plants, and these could have thermal efficiencies greater than 60 percent.

At temperatures near 1000°C, oxidation at the anode is spontaneous and requires no catalyst (conventional catalytic fuel cells operate at about 250°C). These cells, which operate on carbon monoxide, can generate as much as 600 milliamperes of direct current per square centimeter of electrode area. The main problem in constructing them is providing inexpensive materials that resist interaction at high temperatures.

Arnold O. Isenberg of the Westinghouse Research and Development Center is investigating a series of metal oxides for use in such cells. The solid electrolyte is zirconium oxide doped with yttrium oxide. The yttrium stabilizes zirconium oxide in a cubic fluorite crystal structure and creates oxygen ion vacancies; these vacancies permit oxygen ion conduction at elevated temperatures. The fuel electrode is finely divided nickel in a zirconium oxide matrix. The air electrode is antimony-doped stannic oxide or tin-doped indium oxide.

The cells are mounted on a porous, calcium oxide–stabilized zirconium oxide tube that serves both as a cell carrier and as a conduit for the fuel. A typical tube would have an inside diameter of about 1 centimeter and a wall thickness of about 1.5 millimeters. The fuel electrode is sintered to the carrier, and the electrolyte and air electrode are then applied by chemical vapor deposition in the manner shown in Fig. 2. Each layer is about 30 micrometers thick. The cells are electrically connected in series with a gas-tight layer of chromium oxide, also applied by chemical vapor deposition.

In operation, a mixture of carbon monoxide and a small percentage of hydrogen is fed through the core of

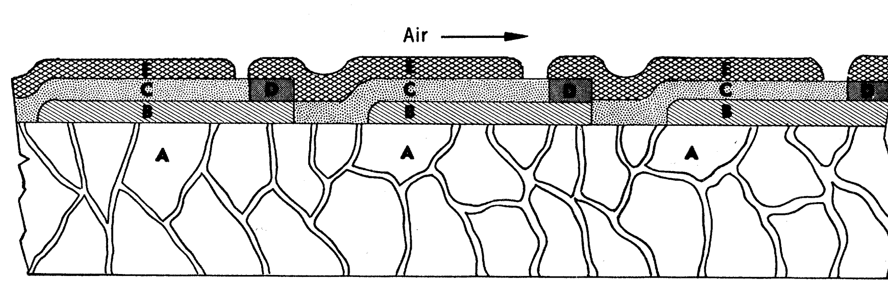

Fig. 2. Cross-section of high temperature fuel cell assembly. Key: (*A*) porous carrier tube; (*B*) fuel electrode; (*C*) electrolyte; (*D*) interconnections; (*E*) air electrode. [Source: Westinghouse Electric Corporation]

the tube. Electrochemical oxidation at the fuel electrode converts them to carbon dioxide and water vapor, thereby releasing a flow of electrons to an external circuit. Air is forced past the outside of the tube to provide oxygen and to remove excess heat (which can, in principle, be used to maintain the operating temperature in a coal gasifier). A 120-centimeter tube of this design, containing about 120 cells, would generate more than 80 watts, but the best that Isenberg has obtained so far is a 15-cell unit that generates 8 watts.

The foremost difficulty in constructing such assemblies is applying the components in a thin film that is pinhole and crack free; if fuel leaks through the cell assembly, it will burn in air and destroy the electrodes. The chromium oxide interconnections have also not worked well yet, and may be replaced with other metal oxides.

A commercial fuel cell of this design is obviously some distance in the future, but a Westinghouse contract with the Department of the Interior's Office of Coal Research calls for delivery of two 100-watt units within 2 years to show progress in process and materials development. A 1-kw fuel cell could be produced within 4 years, Isenberg suggests, and a 100-kw prototype power plant within 10 years. Full-scale commercialization of high temperature fuel cells, however, seems certain to be many years beyond introduction of the Pratt & Whitney units.

—Thomas H. Maugh II

Fusion: Princeton Tokamak Proves a Principle

One of the smallest machines represents a big advance in the quest for controlled fusion. In order to achieve fusion with a tokamak, which is only one of the many designs being proposed for a "magnetic bottle" to control fusion, it will be necessary to reach higher temperatures and contain the fuel for longer times than ever before. Recent experiments at Princeton University (*1*), with a device called the Adiabatic Toroidal Compressor (ATC) tokamak, were not designed to beat the record for confinement times; hence a major question about the viability of fusion remains unanswered. But the experiments have quite successfully proved the viability of one method of heating the fuel in a tokamak.

With the ATC tokamak the fuel plasma was compressed after it had been made as hot as possible by normal techniques. First a doughnut-shaped plasma with a large radius was heated with the current induced by an external magnet; then the plasma was squeezed to a smaller radius with other magnets (Fig. 1). Compression tripled the temperatures of both deuterium ions and electrons in the plasma. The maximum ion temperature achieved in this way was 6×10^6 °C and the maximum electron temperature was 25×10^6 °C. (For fusion to become a practical source of energy for a power plant, the ion temperature must reach 100×10^6 °C.)

New methods for heating the plasma in a tokamak were necessary because the method by which the plasma discharge is started—ohmic heating—becomes progressively less efficient as the plasma temperature gets higher. The reason is that the effective resistance of the plasma decreases. Compression is not the only new method for heating that is being considered. Proposals to heat the plasma by exciting turbulence (Texas Turbulent Tokamak) and by injecting neutral beams of hydrogen at high velocities (Oak Ridge Tokamak) will be tested soon.

At the same time as the Princeton experiments proved a new method to beat the heating problem, they also debunked a widely believed rule for designing tokamaks. Previous machines had always had a copper shell enclosing the plasma. Many designers were concerned that without such a conductive shell the plasma would not know what shape to assume, but the plasma in the ATC was adequately controlled without any such shell.

The significance of the ATC experiments is that a plasma heated and compressed the same way in a larger device could reach the ignition of fusion. To extract power from a fusion reaction not only must the ion temperature exceed 100×10^6 °C, but also the particle density and the confinement time of the plasma must be large. Specifically, the product of the two must exceed 10^{14} sec/cm^3 (called the Lawson criterion). The ATC experiments did not come as close to meeting the Lawson criterion as other tokamak experiments. Although the electron density (which reached 10^{14} particles per cubic centimeter) slightly exceeded previous records, the confinement time (about 2 msec) was considerably less than that in the larger tokamaks. But confinement time increases rapidly with the size of the machine. According to Harold Furth, of the Plasma Physics Laboratory, Princeton, New Jersey, with a machine five to ten times the linear size of the ATC, operating at somewhat higher magnetic fields, the ion temperature should be high enough for ignition and the confinement time should be long enough to meet the Lawson criterion.

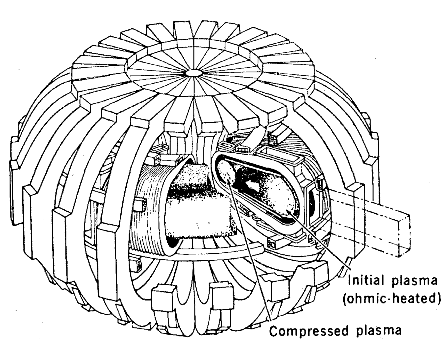

Fig. 1. Compression of a plasma in the ATC tokamak has proved a viable method of heating fusion fuel.

While the results from Princeton indicate that at least one solution is in hand for the problem of heating a tokamak, no one can yet be sure that machines bigger than the tokamaks available today would actually achieve fusion. Instabilities of the plasmas have been the bane of fusion research ever since it began, and theoretical calculations indicate that a new instability—called a trapped particle instability—may appear when scientists explore for the first time the behavior of plasmas under conditions still closer to the Lawson criterion. Results from the ATC don't tip the balance toward optimism for the eventual success of fusion, but they prove that in at least one important way mother nature could have been mischievous, she wasn't.

—William D. Metz

References

1. K. Bol *et al.*, "Adiabatic compression of the tokamak discharge," *Phys. Rev. Lett.* **29**, 1495 (1972).