with osteopathic hospitals in surrounding cities for clinical education. (There are still many unresolved questions about the interactions between the two medical schools at MSU; these will be discussed in a final article.)

It should be noted that medical education at MSU will not necessarily prove less expensive than the more common big-university-medical-center model. Certainly the expense of a major teaching hospital will be saved at MSU, but the operating costs in a community-based system of administration, deployment of faculty, and student travel may well counterbalance the saving.

The ultimate question, of course, is what kind of doctors MSU will produce. So far, graduates have fared well in moving on to other medical schools (when MSU had a 2-year school) and in gaining acceptance in good internship and residency programs. But the question of whether or not MSU medical graduates will stay in Michigan and improve the condition of health care must await some years for an answer. At MSU, however, there seems to be a genuine feeling that the prognosis is good for both the partnership between the medical schools and the communities and, in the longer term, for MSU's alternative style of medical education.

—JOHN WALSH

APPOINTMENTS

Charles A. Payne, professor of chemistry, Morehead State University, to dean, School of Sciences and Mathematics at the university. . . . **Charles D. Michener**, professor of systematics, ecology, and entomology, University of Kansas, to chairman, entomology department at the university. . . . **Donald R. Progulske**, head, fisheries and wildlife department, South Dakota State University, to head, forestry and wildlife management department, University of Massachusetts. . . . **Cyrus Mayshark**, associate dean, College of Education, University of Tennessee, Knoxville, to dean, School of Education, University of Texas, El Paso. . . . **Louis S. Harris**, professor of pharmacology, University of North Carolina, to chairman, pharmacology department, Virginia Commonwealth University. . . . **Martin W. Donner**, acting director, radiology department, Johns Hopkins University School of Medicine, appointed director of the department. . . . **Kenneth J. Ryan**, chairman, obstetrics and gynecology department, University of California, San Diego, School of Medicine, to head, obstetrics and gynecology department, Harvard University. . . . **Raymond R. Walsh**, professor of physiology, Southern Illinois University at Edwardsville, School of Dental Medicine, to chairman, biology department, St. Louis University. . . . **Stephen E. Fienberg**, assistant professor of statistics and theoretical biology, University of Chicago, to chairman, applied statistics department, University of Minnesota. . . . **Lewis J. Sherman**, professor of psychology, University of Missouri, St. Louis, to chairman, psychology department at the university. . . . **Gordon E. Stone**, associate professor of anatomy, University of Colorado, to chairman of biological sciences, University of Denver. . . . **Orlando F. Gabriele**, professor of medicine, University of North Carolina, to chairman, radiology department, West Virginia University. . . . **Earl W. Collard**, associate professor of dentistry, University of California, Los Angeles, to chairman, operative dentistry department, University of Oklahoma. . . . **Maurice Bender**, former chief, research and training, grants branch, division of air pollution, Public Health Service, to director, Arctic Health Research Center, Alaska. . . . **Warren F. Jones**, dean of administration, University of Louisville, to dean, School of Arts and Sciences, Georgia Southern College.

RESEARCH NEWS

Magnetic Containment Fusion: What Are the Prospects?

ENERGY

Very early in the atomic age it was realized that the reaction that produces the hydrogen bomb could be a great source of energy if it could only be controlled. At one time it was thought that the research on a fusion reactor might proceed so quickly that it would possibly be an alternative to the first generation of fission reactors of the breeder type, but the early projections were too optimstic. No one knew in the early 1950's how slow progress toward a fusion reactor would be because few scientists realized that it would be necessary to unravel and master the details of a whole new field of science—plasma physics—first. Scores of different shapes for magnetic systems have been tested to see how well they would contain a fusion reaction. But so far none has shown that net production of energy is feasible.

As a result of rather encouraging experiments in the last 4 years, many scientists now think that controlled fusion is probably attainable with magnetic containment systems, possibly about 1980. Some scientists have estimated that an alternate approach to fusion—with a laser to heat the fuel—might be feasible sooner (*Science*, 29 September 1972). If the scientific feasibility of either magnetic or laser fusion were demonstrated, commercial sales of fusion reactors would still not begin until after experimental reactors were extensively tested and a demonstration reactor proved successful. The specific studies necessary to begin to assess the size, cost, operating characteristics, radioactive hazards, and environmental effects of a fusion reactor are in a very early stage for laser fusion and are just becoming available for magnetic fusion. However, it is clear that fusion reactors would have two great advantages: virtually unlimited fuel resources and no conceivable danger of an explosive accident.

Two heavy isotopes of hydrogen are commonly considered as the likely fuels for fusion: deuterium and tritium. Deuterium is so plentiful in seawater that it would be an extremely cheap fuel (costing only 0.003 mill per kilowatt hour); but tritium would have to be bred in a fusion reactor, much like plutonium can be bred in a fission reactor. The temperature for burning a mixture of deuterium and tritium is so high that no material could contain the fuel without melting. But magnetic fields shaped like bottles can keep the hot fuel from touching any walls.

Three types of magnetic field designs seem to be quite promising: toroidal shapes (of which the Soviet design, the tokamak, is the best-known example), pinch devices, and magnetic mirror machines.

Although no assurances are possible, there are reasons to think that increasing the size of each of the three designs would be sufficient to demonstrate scientific feasibility. But it won't be cheap. The total cost of the U.S. fusion research program necessary to build all three machines by 1980 would be about $1 billion, and some Atomic Energy Commission (AEC) officials have estimated that about $5 billion will be necessary to build an experimental reactor based on any one design. The budget for the Controlled Thermonuclear Reactor division of the AEC for fiscal year 1973 is $40 million.

Reactor Design Problems

Since the concepts and the status of various plans for magnetically confined fusion have been discussed previously (*Science*, 21 May 1971 and 27 August 1971), this article will be focused on the problems of building a practical reactor and the environmental effects that might be expected if fusion were to become a major energy source.

The most recent designs for a fusion reactor have been based on a tokamak design for the magnetic containment system. The fuel for a tokamak would be injected every 3 minutes into a toroidal chamber where it would be heated and compressed into a dense plasma to produce fusion. In order to absorb the energy of the fusion reaction and to breed new tritium, it would be necessary to surround the inner chamber with a blanket of lithium or lithium salts about 1 meter thick. A comparably thick shield of water or other neutron-absorbing material outside the lithium blanket would be necessary to protect the coils of the superconducting magnets, which would be on the outside of the multilayer assembly. The toroidal reactor would be a massive device, with a minor radius of about 5 meters and a major radius greater than 15 meters.

Many design parameters for a fusion reactor are changing. Early design studies postulated an electrical power capacity of 5000 megawatts for a reactor based on a tokamak design, but the flux of neutrons passing through the inner wall proved to be so great that no material considered would last long enough to be practical. A recent design by Art Fraas, of the Oak Ridge National Laboratory, Oak Ridge, Tennessee, has a much lower total power, about 500 megawatts, and a correspondingly lower neutron flux. Though the lower-powered reactors appear to have less troublesome materials problems, the capital costs and the operating costs will almost certainly be higher because the very expensive magnets will be used less efficiently. However, according to Robert Hirsch, acting director of the Controlled Thermonuclear Research divsion of the AEC, improvements in the technology of large superconducting magnets and efficiencies of mass production could offset the increased magnet costs. All costs are quite uncertain now; estimates of the cost of the superconducting magnets alone range from $20 to $60 per kilowatt of electrical capacity.

The design of a fusion reactor will present many difficult engineering problems because enormous differentials of temperature and neutron flux must be sustained over very small distances. Typically, the temperature at the center will be 100×10^6 °C, and the neutron flux will be greater than 10^{13} neutrons per square centimeter per second; but only 2 meters away, where the superconducting magnets will be situated, the neutron flux and the absolute temperature must be almost zero.

One of the most troublesome engineering problems is the choice of material for the inner wall. It should not react with very hot liquid lithium (1000°C), and it should last at least 10 to 20 years in a very large flux of neutrons. (The neutron flux in reference designs for a fast breeder fission reactor cooled by liquid metal is several orders of magnitude greater, but the higher energy neutrons from a deuterium-tritium fusion reaction are much more damaging to the structure.)

Pure lithium would be desirable for a blanket because it breeds tritium more efficiently than lithium salts do, but it could be very troublesome to pump liquid lithium through the system. Since liquid lithium is a conductor, it can only be pumped in certain directions without resistance from the magnetic field. Other ways to extract heat from the reactor, for instance, with helium pumped through the lithium blanket, are being investigated.

Outside the blanket a shield will be needed to protect the superconducting magnet from heat, fast neutrons, and x-rays. An efficient shield against neutrons would be 1 meter of water, but if lithium came into contact with water in the shield, a violent reaction would occur. Some engineers think that another material for the shield, such as graphite, would be a better choice.

Though any reactor would be carefully designed in order to minimize the probability of malfunctions of any system, the hazard of an accident to the magnet system would be considerable, because the total energy stored in the magnetic field would be 2×10^{11} joules, about the energy of an average lightning bolt. An even greater hazard would be a liquid lithium fire.

The thermal pollution produced in a fusion reactor could possibly be less than in a fossil fuel plant because the high operating temperature would make possible a large thermal conversion efficiency. The design proposed by Fraas would convert 55 to 60 percent of the thermal power to electrical power—compared to 40 percent for a modern fossil fuel plant—by use of a binary vapor generating cycle. However, the amount of energy needed to power a plasma gun for injection of the fuel is not known and could reduce the efficiency significantly.

Possible Tritium Hazard

Many proponents of fusion have argued that very high conversion efficiencies might be achieved by directly converting fusion energy into electrical energy, bypassing the thermal cycle. If the charged particles in the plasma passed through an electric or magnetic field, electricity could be produced. However, the most likely fuel for fusion—a deuterium-tritium (D-T) mixture—would be the least practical one for direct conversion because only 20 percent of the energy is released in charged particles. The feasibility of direct conversion for other fuels, such as deuterium plus deuterium (D-D) or deuterium plus helium-3 has not yet been shown, according to David J. Rose of the Massachusetts Institute of Technology, Cambridge, Massachusetts. The direct conversion chamber for a mirror or pinch type of fusion reactor would be a huge disk, about 100 meters in diameter, from which it would by very difficult to recover the spent plasma.

The greatest hazard of a fusion reactors—whether the magnetic containment type or the laser type—would undoubtedly be the release of tritium, the volatile and radioactive fuel, into the environment. Tritium has a relatively short half-life, about 12 years, but its spreads rapidly, both because it is a light gas and because it can replace hydrogen in molecules such as water. The radioactivity of tritium (low-energy beta emission) is relatively benign compared to many fission products, however, and the biological hazard from the inventory of tritium in a fusion plant would be much less dangerous than the hazard of the inventory of the volatile product, iodine-131, from a fission plant (*1*).

The problem with tritium is that it is very difficult to contain, and the most optimistic estimates agree that at least 0.03 percent of the total inventory would probably escape from the reactor each year. A great deal more tritium would penetrate the structural components, according to David Rose, but would normally not escape. Most metals that seem suitable for reactor structures tend to become very permeable to tritium at the working temperatures of a fusion reactor. In a preliminary appraisal of the tritium hazards (*1*), Fraas estimated that 60 curies of tritium would be released per day, with one-fourth released in the form of water through the steam cycle. Tritium in water is much more dangerous than tritium as gas because it is much more rapidly assimiliated by the human body. But if the entire cell in which the reactor is contained were evacuated, Fraas thinks that the total tritium release could be held to 1 curie. However, he emphasizes that any estimate of the tritium release is necessarily uncertain at this time because many of the data necessary for such a calculation are not known.

One of the yet unanswered questions about fusion power is whether the tritium hazard would be small enough to permit siting of fusion reactors in the middle of cities, where much electric power is consumed and where the waste heat could be sold for industrial and home use, rather than be discharged to create thermal pollution. According to Robert Hirsch, if an exhaust stack were used for a fusion reactor, the maximum exposure anyone would receive at ground level would be one-fifth the current AEC tolerance. Such estimates are encouraging, but the leak rates assumed are near the best that have been achieved in any technology. Because the total tritium inventory of a fusion reactor will be about 10^8 curies, reactors will probably not be located in urban areas until after extensive operating experience has been accumulated.

A fusion reactor that burned deuterium (D-D) might become feasible at some time very far in the future, but it would not be free of tritium either because it would be produced in the D-D fusion reaction. It is possible that the tritium inventory of a D-D reactor would be almost as large as in a D-T reactor. Thus, the distinct advantage of the D-D fusion reactor would not be a reduced environmental hazard so much as a virtually limitless supply of cheap fuel, for the deuterium in seawater would supply the world's energy needs for more than a billion years.

Even though the D-T fusion reactor would not be free of radiation problems, many observers believe that the total release of tritium during the fuel cycle would be no greater than the release of tritium during the fission fuel cycle, most of which occurs during the reprocessing of fuel rods. Furthermore, because a fusion reactor would breed its own fuel—and immediately burn it—no massive shipments of radioactive fuel would be necessary. The only product of D-T fusion would be nonradioactive helium. The only significant radioactive remnant from a fusion reactor would be the inner structural assembly, which, if made of niobium, would cool fairly rapidly and would present fairly easy problems for waste disposal.

The radioactivity in structural members would generate a certain amount of heat even if the fusion reaction were stopped, but the amount would be so much less than the "afterheat" of fission reactors that it is not expected that any damage to the reactor would occur if the flow of coolant were interrupted.

Prospects for Proof of Fusion

What is the current status of U.S. research? Apparently large toroidal machines such as tokamaks are closest to feasibility; more money is spent on research for tokamaks than other designs. Problems for these are maintaining the purity of the plasma and heating it. At least three methods of heating are being intensively investigated, and preliminary results indicate that one of them, heating by compression, will very likely be successful. It is now being investigated with the adiabatic toroidal compression (ATC) tokamak at the Princeton Plasma Laboratory.

Magnetic mirror machines will only work if a quiescent plasma regime can be reached. Three approaches are being tried; a promising one (Baseball I at the Lawrence Livermore Laboratory) uses neutral beams for heating. If the quiescent regime can be reached, and if the losses of plasma through the ends of the mirror agree with theory, a machine large enough to demonstrate feasibility would be the next step. Substantial upgrading of the neutral beams would be required, however.

Large pinch machines, such as the Scyllac machine at Los Alamos Scientific Laboratory, will be thoroughly tested about 1975. However, such machines will be limited by their need for large amounts of power delivered very rapidly. The present power sources, banks of capacitors, will not be sufficient for a feasibility machine. If the Scyllac proves successful, different power sources—large inductors, for instance—and two-step compression and heating will be required.

No dramatic breakthroughs have occurred recently in the program of fusion by magnetic confinement, and controlled fusion is still far from a certainty. However, many scientists think that the answer to the question of scientific feasibility will be known within the decade. If fusion power works, some observers expect that the development of a commercial power plant will be rapid. Others, however, note that, in contrast to the history of fission power —less than 3 years elapsed between the idea of a fission chain reaction and the proof of scientific feasibility with a simple assembly of graphite braced in a wooden frame—almost 20 years has elapsed since the beginning of research to prove the feasibility of fusion. If the complexity of the feasibility experiments is any indication of the sophistication of a future fusion reactor, the development of a commercial reactor may be as halting and tedious as the progress toward proving the principle.—WILLIAM D. METZ

Reference

1. A. P. Frass and H. Postma, "Preliminary appraisal of the hazards, problems of a D-T fusion reactor power plant," *USAEC Report ORNL-TM-2822* (Oak Ridge National Laboratory, Oak Ridge, Tenn., 1970).