Fusion Research (II): Detailed Reactor Studies Identify More Problems

Fusion is in the unique position of being the only technology to be identified as an energy option before it has shown the ability to produce energy. Because the basic research problem is so crucial to the credibility of fusion, relatively little attention has been given to the sort of technical and engineering development that composes the bulk of the work on other new energy sources. Not long ago it was difficult to put together more than a fuzzy picture of what a fusion reactor might look like.

The manyfold expansion of the fusion program in the last 5 years has included a modest increase in support for systems studies, which are funded at $3.6 million for magnetic fusion, and the situation is changing. A number of very detailed conceptual designs for large fusion reactors have recently been completed, and for the first time these studies provide comprehensive pictures of a reactor—its size, power, materials, hardware, fuel requirements, maintenance requirements, and cost. Fusion engineers and fusion program managers caution that these studies do not represent reactors that would ever be built, but rather they are reference designs made to identify problems and provide a basis for more realistic designs. Nevertheless, they are tantalizing documents.

Among the various inventions for magnetic confinement of a plasma, the tokamak concept is the one that is proving most successful in plasma experiments. Apparently for this reason, it has been the subject of more systems studies than any other magnetic confinement concept, although a number of observers think that the technological problems of the tokamak may be greater than those of some alternatives. The tokamak system is the bulwark of the government research in magnetic fusion, and will be the focus of this article.

The tokamak concept is a Russian invention and the name is a transliteration of three syllables: *to*, toroidal; *ka*, chamber; and *mak*, magnetic. The device is a hollow toroidal chamber enclosed by a set of toroidal magnets, which are at room temperature in present experiments but will necessarily be superconducting to be economical at reactor sizes. Besides these magnets, the tokamak has a very large transformer, needed to maintain a plasma current of millions of amperes circulating around the torus in racetrack fashion. The superconducting magnets together with the magnetic field produced by the toroidal current combine to give stable magnetic confinement of the plasma. To heat the plasma so that the particles reach the 10 kiloelectron volt (kev) energies needed for fusion (corresponding to a temperature of 10^8 °C), most reactor designs will use injectors that shoot very intense beams of neutral atoms (deuterium or tritium) into the plasma chamber.

The most obvious feature of the conceptual tokamak reactor studies is the large size of the power plants (Fig. 1). The first reactor designed in a series of studies performed at the University of Wisconsin under the direction of Gerald Kulcinski and Robert Conn is housed in a circular building 102 m tall and 120 m in diameter, with an adjoining structure for steam turbine generators. Together the primary buildings for the reactor design, called UWMAK-I for University of Wisconsin Tokamak, would be as large as the Houston Astrodome, and there would be many other secondary buildings, for energy storage for the transformer coils, helium storage for the superconductor system, rectifiers to produce direct current for the magnets, and cooling towers to disperse the waste heat. The entire plant, including a high-voltage switchyard, would cover approximately 0.5 km^2.

The reactor would generate a net electrical power of 1473 Mw. Tokamaks cannot produce power continuously, but during the burn cycle, which lasts 90 minutes in the UWMAK-I design, the thermal power produced would be 5000 Mw.

Larger Than Fission Reactors

Tokamak fusion reactors seem inevitably to be large because they are limited to very low power densities by the basic physics of the magnet geometry. Inside the plasma chamber, the power density of a tokamak is only about 1 Mw/m^3 (0.7 for the UWMAK-I), compared to 100 Mw/m^3 or more in the core of a light water reactor or fast breeder reactor. This factor governs the cost of a fusion plant, because it drives up the size of the plasma chamber; the size of the magnets, which are the most expensive single item; and the size of the rest of the plant. The cost of a tokamak reactor is generally estimated to be higher than the cost of the fast breeder reactor, perhaps three or more times higher.

The basic guideline for the UWMAK-I study was that it be designed as much as possible with available technology. The second Wisconsin study, UWMAK-II, used technologies slightly beyond present-day capabilities, but the size, cost, and operating conditions turned out to be similar to those in the first study. The third study used advanced materials, and was specifically designed to be smaller (500-Mw electrical generation) and achieve an improved thermal efficiency (40 percent). Its cost was estimated to be more than twice the cost of the earlier studies (*Science*, 25 June 1976).

Inside the reactor building all the parts of the UWMAK-I reactor would be enclosed by a 2.4-m-thick primary containment shield 40 m high and 56 m in diameter, made of steel and concrete to protect against leakage of neutrons and tritium. Inside it would sit the reactor itself, a torus 44 m in diameter made up of 12 identical pie-shaped segments mounted on motorized caterpillar tracks and each weighing 3500 tons.

If each module were peeled back as if it were an onion, the investigation would reveal many layers with different functions—and the layers would become increasingly radioactive toward the center, where the neutron flux during plasma burning would be 10^{14} per square centimeter per second. The outermost layer would be the toroidal magnet coil, one to each module, enclosed in its vacuum cryostat and cooled to 4°K. Since too many neutrons would degrade the superconducting alloys, destroy the thermal insulation, and overload the helium refrigerators, the next layer is a 0.8-m-thick shield of boron carbide and lead. Inside the shield is a complicated blanket that is made of many stainless steel honeycomb cells about 1.5 m thick (87 sections in each module). The many cells are filled with liquid lithium flowing in U-shaped channels, plus smaller amounts of other materials. The blanket has the threefold purpose of slowing down the fast neutrons, which at 14 Mev from a fusion reactor are many times more energetic than those produced in a fast breeder reactor; of serving as the medium to extract heat from the reactor; and of breeding new fuel. In the UWMAK-I design lithium is used for all these functions, although other designs use different media for breeding and cooling.

The surface of the blanket that faces

the plasma is called the first wall. It is not smooth but convoluted in the Wisconsin designs, and its various parts must be welded together in such a way that they can sustain a good vacuum (10^{-5} torr) in the plasma chamber.

There is no doubt that the amount of radiation damage the first wall of a fusion reactor would be subjected to is unprecedented in reactor design. Over a lifetime of 30 years, each atom in the first wall would be subjected to 500 displacements by neutron collisions, approximately ten times more damage than fast reactor fuels are now required to withstand. The high neutron flux enhances all of the many possible modes of radiation damage failure in metals, and in particular the high energies of fusion neutrons increase the rates for nuclear reactions that produce helium embrittlement.

While the Wisconsin studies found loss of ductility to be the most severe problem, other radiation-induced phenomena of swelling and creep were nearly as limiting. Considering these effects together, the Wisconsin group identified radiation damage as the "second most serious obstacle to commercialization" of fusion power, after the plasma physics problems. A conceptual study for a 2100-MW tokamak reactor prepared at Princeton University under the direction of R. G. Mills concluded that the first-wall life would be only 5 years. The UWMAK-I Wisconsin study concluded that the first-wall life would be exceedingly short—only 2 years—and succeeding studies arrived at estimates of 2 and 3.5 years.

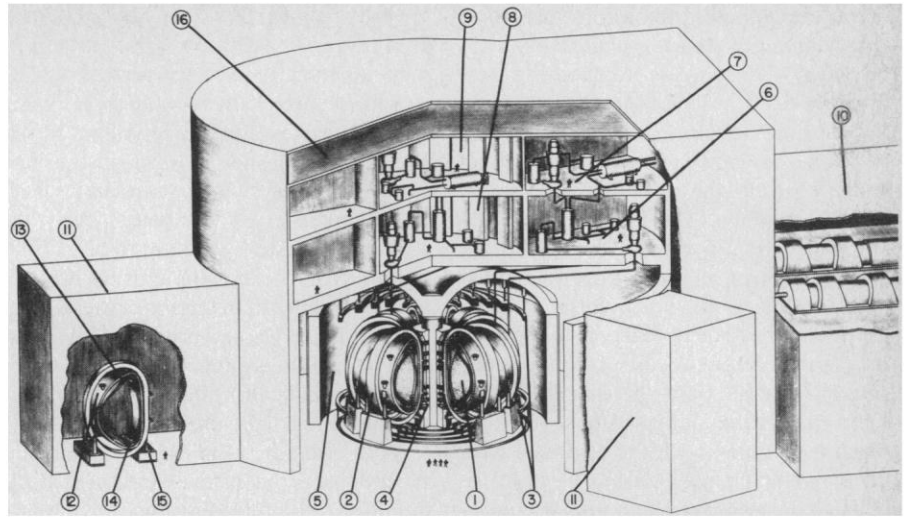

Fig. 1. Conceptual design of a 1483-Mw tokamak fusion reactor (UWMAK-I) prepared at the University of Wisconsin. The toroidal reactor is made of 12 massive components, one seen in the repair area at left. The various components of the reactor are the plasma (1), the toroidal field coils (2), the divertor coils (3), and the tranformer coil (4). Other plant components are the primary containment building (5), the liquid lithium and liquid sodium secondary systems (6 and 7), the turbogenerator building (10), and repair hot cells (11). The reactor torus is 27 m tall, and four human figures are reduced to dots in front of it.

Short Wall Life

Frequent changing of the first wall of a tokamak would be an unprecedented maintenance problem and would also produce large amounts of high-level radioactive wastes. Not only the wall but also the first 10 cm of the blanket would have to be replaced—500,000 kg of stainless steel for UWMAK-I. Most important, changing the wall frequently would undermine the already shaky economics of fusion. Kulcinski estimates that a reactor with a 2-year wall life would produce electricity at a 17 to 28 percent economic premium compared to a reactor with at least a 10-year wall life, and the penalty for a 1-year life could be a 65 percent cost increase.

There is an alternate school of thought that says that the first wall can be made to last about 10 years. Almost all radiation damage effects are quite sensitive to temperature, and there is no doubt that lowering the temperature below 500°C generally assumed in the studies cited above will extend the wall life. The debate is about how much improvement to expect.

At the Oak Ridge National Laboratory, Don Steiner and his associates think that with cold-worked stainless steels and a temperature near 400°C the wall life will approach 10 years, even with a higher flux of neutron energy through the wall than the canonical number used in the past (1 Mw/m^2). The penalty for lowering the temperature is normally a reduction of the thermal efficiency, which was already a modest 32 percent at the 550°C temperature of UWMAK-I. Steiner and his associates propose a way to circumvent the efficiency limitation by making the first wall cooler than the rest of the blanket—a temperature gradient counter to the one that would be naturally established in a uniform blanket. The Wisconsin researchers think that lowering the temperature is helpful, but "even at nominal wall loadings, ten years is still unlikely," according to Kulcinski.

Much more testing, particularly with actual fusion neutrons, is needed to assess the radiation damage problems mentioned above, and even if they are solved another materials problem—metal fatigue—could limit the life of a tokamak structure. Tokamaks are necessarily pulsed machines because the practical limitations on the transformer restrict the length of time for which the reaction can burn. UWMAK-I would be pulsed on and off 6000 times a year, and the effect of such thermal stress combined with radiation is unknown. It is something that fission reactors, which are steady-state power producers, give no data about.

Lastly, failures unconnected with radiation can be expected. Any structure as complicated as a fusion blanket is unlikely to last more than 10 years, simply because the statistical chances of failure due to corrosion, hot spots, and defects in fabrication are too great. Pinhole leaks are recurring problems in light water reactor operation and breeder development, and such leaks would seem even more serious for fusion. A leak from the blanket into the plasma chamber would contaminate the plasma and quickly stop the fusion reaction.

For many reasons, therefore, maintenance will have to be done on tokamak reactors. But it will be difficult. There is no way to take the top off a tokamak, no way to shield the intensely radioactive blanket well enough that workmen can repair it by hand. All work will have to be done by remote control, and the sort of machinery that could perform complicated tasks in the restrictive spaces of a torus has not even been imagined, much less designed.

In the first Wisconsin design, the first wall would be changed by remotely disconnecting all the couplings of one module from the rest of the torus. Then the 3500-ton module—including the very heavy magnet segment—would crawl on its caterpillar wheels out of the primary containment enclosure into one of three very large hot cells at the periphery of the reactor building. In the United Kingdom, a study of a 2500-Mw tokamak reactor at Culham Laboratory proposed that a large number of modules, 32 in all, be used, with smaller replaceable sections in each module. An Italian study for a small reactor called Fintor proposed a system for changing the blanket while keeping the very heavy toroidal magnet in place. The blanket would be composed of 216 rings of two different cross sections, put together somewhat like a Chinese puzzle to form a torus. In the more recent Wisconsin designs the toroidal magnet coils were made considerably larger than the inner parts of the torus—at an increased cost—so that blanket modules could be removed with the magnets in place.

Even the improved solutions will probably require remote maneuvering and welding of massive components in very tight quarters. Compared to the simple cylindrical geometry of the fission reactor, the three-dimensional toroidal geometry is an engineering nightmare. Devising an effective system of maintenance is an unsolved problem.

The immediate environmental advantage of fusion is that there could be no uncontrolled runaway reaction of the sort possible with fission. Basically, this is true because only about 0.25 g of deuterium-tritium mixture would be contained in the reacting zone of a fusion power plant, compared with 3 or 4 tons of plutonium in a fast breeder reactor.

But there would be a considerable potential hazard from radioactive materials. At 13 kg, the inventory of tritium in UWMAK-I would represent 10^8 curies of radioactive gas. Recent estimates give a larger inventory, perhaps 50 kg, because tritium has to be recycled through the reactor 20 or more times before it is burned up. Escape of part of this inventory from the plant, would constitute the major radioactive hazard, and routine emissions of tritium could also be a problem, but the UMWAK and other designs have concluded that an emission as low as 10 curies per day can be achieved by measures, such as evacuating the entire containment building and devising techniques to remove tritium at concentrations of parts per million from secondary and tertiary coolant circuits.

The buildup of solid radioactive isotopes in the reactor structure would be the second major environmental problem, and it would depend critically on the choice of the stuctural material. If stainless steel or niobium alloys were used, the total biological hazard potential of the reactor structure would be comparable to that of plutonium in the fast breeder reactor, according to R. Hancox a Culham Laboratory. But since it is hard to conceive of an accident that would vaporize the structural material of a fusion reactor, the associated danger would be less. The structure is essentially a waste disposal problem. In the UWMAK-I design, assuming the first wall is changed every 2 years and the entire blanket every 10 years, the total amount of waste was found to be 736,000 kg per year. At a volume of 94 m^3, this would be more than ten times the volume of high-level wastes produced by a fission plant. The radioactivity of the waste could be reduced if materials other than stainless steel were used.

With vanadium alloy the biological hazard potential of the structure would decrease 1000-fold, but there are no engineering data for the alloy and no industry to produce large amounts in the high quality that would be needed. With aluminum the long-term activity of the structure would be reduced, but aluminum requires a low temperature, is not compatible with liquid lithium, and suffers severe radiation damage.

In actual operation, a tokamak reactor would progress through about ten steps (detailed for UWMAK-I) during each cycle. First, the large transformer is used to break down the gas to make a plasma and build up the toroidal current in the central chamber until it reaches 21 million amperes. This first step takes 100 seconds and requires 500 Mw drawn from the local electrical system plus a comparable amount of power from the energy storage system on the reactor site. In the next step, 20 large neutral-beam guns are turned on. Half of them produce 500-kev deuterium beams and half produce 500-kev tritium beams—the high energy determined by the requirement that the beams penetrate to the center of the plasma. These beams deliver 15 Mw of power to the plasma, and within 11 seconds they raise its temperature to the point where the fusion reaction is self-sustaining—called ignition. Shortly afterward, the plasma reaches full power (5000 Mw) and continues to burn for 90 minutes.

Refueling and Impurities

The initial load of fuel is not nearly enough to last 90 minutes, however, and even if it were it would quickly be lost because the magnetic field can only confine a particle for 14 seconds, on the average, before it drifts into the walls in the UWMAK-I design. (This number is based on an average of plasma scaling predictions.) So the reactor must be continuously refueled during the 90-minute burn time. This will presumably be done by injecting small pellets of deuterium-tritium ice. The length of the burn time is limited by the maximum current that can be achieved in the transformer, which must continuously operate during burning to sustain the toroidal plasma current. At the end of the burn time more impurities—defined as elements with a considerably larger atomic number than helium—are injected into the plasma to cool it. Thirty more seconds are required to reverse the transformer and shut down the plasma current, then the chamber is pumped empty of all gases and refilled with fresh deuterium-tritium fuel.

The UWMAK reactor thus produces power for 90 minutes and is idle for 6.5 minutes—a duty cycle of 93 percent. Since few utility systems would want a 1500-Mw power source disconnected from the grid every 90 minutes, the UWMAK system uses a thermal reservoir of 15,000 tons of liquid sodium to store heat during the burn period and feed it into the turbogenerator system during the off period to level out the electrical production.

The electrical power balance is relatively favorable: 208 Mw is required to run the reactor and 1473 is available for "export." But the power balance can be upset by two serious problems: refueling and impurities.

If high-energy neutral beams used for heating were needed for refueling, the energy requirement of the beam guns would be so great that they would use up most of the output power. The proposed scheme of refueling with pellets would require only a small amount of energy, but the proposal is very shaky on both scientific and technical grounds. Research is only beginning, and it is not yet known how far a pellet of a certain size would penetrate into the plasma before it vaporized. If large pellets about 2 mm in diameter are needed, there is a grave question whether they could be accelerated to the velocities required to reach the center. Present proposals have an air of unreality—gun barrels more than 15 m long or electrostatic accelerators producing millions of volts. On the other hand, with small (40 μm) pellets, 20 million pellets per second would be needed for UWMAK. Unburned and newly bred tritium would have to be mixed together to make new pellets at an extremely rapid rate, and it is not known what effect the injection of pellets would have on the stability of the plasma.

The buildup of impurities when particles are knocked off the first wall could also make tokamaks unfeasible for fusion reactors. When highly charged impurities are present among the helium,

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tritium, and deuterium ions of a reactor plasma, they produce bremsstrahlung radiation and leak energy much faster than the fusion ions can produce it. They could quickly radiate away enough energy to cool the plasma below the ignition temperature. A complicated scheme for modifying the magnetic field near the first wall was incorporated in UWMAK and is used in most reactor design studies. This is an extra system, called a divertor, added to the tokamak to trap 90 percent of the plasma ions before they hit the wall and 90 percent of the impurities knocked off the wall before they can get into the plasma. Tokamak experiments are just beginning to test various divertor types. In the second and third UWMAK studies a woven carbon curtain is placed in front of the first wall, to make a false first wall with an atomic number as low as possible ($Z = 6$). Divertors add considerably to the complexity of fusion reactors (the divertor also collects 250 Mw of power in the UWMAK design), and if their effectiveness is less than hoped for the buildup of impurities in the plasma could put a basic limitation on the length of time for which ignition can be maintained.

The conceptual reactor studies have uncovered a number of crucial problems for which it is uncertain whether a solution exists—such as impurity control, refueling, extending the life of the first wall, and effective maintenance. They have also identified a long list of requirements that will necessitate major extrapolations of the present technology.

Fusion reactors built with present-day materials would seem to have many of the problems that fission reactors have, made much less manageable in some cases by the complexity of the reactor. The most optimistic fusion researchers argue that such a comparison is unfair, because a fusion reactor will be built with much improved future materials. But solutions suggested lightly, such as choosing a new material for the first wall, often roll a 30-year development program into a single sentence. A different approach to the technical problems appears to be needed. Finally, fusion is still a basic research enterprise. No device, tokamak or other type, has yet produced the plasma conditions (temperature and confinement time) needed for a practical reactor. It sometimes seems necessary to suspend one's normal critical faculties not to find the problems of fusion overwhelming.

—WILLIAM D. METZ

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of life" was the conference theme. The presidential address by Professor Kosonike Thomas, professor of engineering at the University of Sierra Leone, pointed out that the theme reflects three important convictions held by WASA: (i) that the improvement of the general well-being of the people depends on the planned conservation, systematic development, and rational utilization of natural resources; (ii) that much too little has been done with natural resources for the countries' own good; and (iii) that it is long overdue for persons in the field of science in the various West African countries to start improving the situation.

Although the conference plenary sessions addressed a variety of themes, they stressed the application of scientific research to pressing national development problems. They included talks on the scourge of natural disasters, the place of indigenous technologies in the development process, aims and objectives of the teaching of science, health problems in the development process in West Africa, and increasing livestock production.

Many of the papers of the "ordinary sessions," which included 15 to 20 talks lasting 10 to 15 minutes each, could reasonably be interpreted as being potentially related to development problems. They covered such topics as land use, plant resources, chemical and mineral resources, and physical environment, life sciences, and human resources. Among the papers were those on solar energy radiation, computer-controlled telephone exchanges for developing countries, utilization of natural energy resources, the ecology of schistosomiasis transmission in the Volta Lake complex, ecological effects of slash and burn agriculture in the Freetown peninsula and its consequences for development, scope and requirements of a modest nuclear medicine unit, variability of the tropical environment and its significance to land resource development, education for appropriate technology development, the interaction of science and education for environmental quality, and manpower training for the application of relevant technology to development.

As can be seen from these sessions, there appeared to be a general recognition at all levels that African science must be applied to national needs even though the countries have yet to develop any systematic mechanisms for channeling efforts in this direction and bringing a variety of organizational resources to bear upon the activity.

Notes from Other Offices

Chautauqua-Type Short Courses for College Teachers: Forty-five courses with places for over 3000 college teachers of the natural and social sciences will be held at 13 short course centers during the 1976–77 academic year. The 13 centers are grouped into three circuits—Western, Central, and Eastern. The program, which is administered by AAAS, is a cooperative enterprise with the National Science Foundation. The primary objective of the program is to make available to college teachers as quickly as possible new knowledge about topics and fields of current interest that will be directly useful in current or planned educational programs. The format of the program consists of 2-day sessions in late fall and early spring with a course-related project during the interim.

The courses range widely in content and thrust. Cosmology and Five Topics in Physics are included among the disciplinary courses; Genetics and Society, Perspectives in Bioethics, and Social Impact Assessment are among the interdisciplinary topics; while Mathematical Modeling in the Biological Sciences, Microcomputers Applied to Science Education, and Patterns of Problem Solving provide treatment of science applications.

A bulletin board poster listing the courses and course directors is now available. A brochure with course descriptions, schedules, and application form will be available this month. For further information write to the Office of Science Education, Dept. A, AAAS, 1776 Massachusetts Avenue, NW, Washington, D.C. 20036.

New Publications

Energy, Water, and the West, papers and discussion summaries from a workshop focusing on the impact of energy development on western water resources, has just been published. Cosponsored by AAAS and the National Conference of State Legislatures, the workshop was held 2–5 November 1975 in Albuquerque. Participants whose talks appear in the report include Governors Jerry Apodaca of New Mexico and Thomas Salmon of Vermont. Copies of the report are available at $5 each from the National Conference of State Legislatures, Office of Science and Technology, Executive Tower Inn, 1405 Curtis Street, Denver, Colorado 80202.