Nuclear Fusion: The Next Big Step Will Be a Tokamak

Of the many approaches that have been suggested for controlling fusion, the most promising continues to be the tokamak, which is a toroidal device that holds and heats reactive isotopes of hydrogen with a magnetic field. Most of the countries heavily engaged in fusion research are concentrating on this particular design, including the United States, which allocates 60 percent of its research support for magnetic containment to the tokamak. That support has increased rapidly from $30 million per year in the 1960's to $105 million in the current fiscal year, and will grow considerably more if the ambitious plans of the controlled thermonuclear research (CTR) division, which was part of the old Atomic Energy Commission and is now part of the Energy Research and Development Administration, are approved by Congress. Accelerating the rate of construction of fusion test experiments and increasing the reactor engineering component of its program, the CTR division plans to spend at least $1.2 billion over the next 5 years. The centerpiece of this expanded program will be a very large tokamak with significant power production capabilities, which is expected to be completed by 1981 at a cost of $215 million. However, it is expected that still larger tokamaks will be needed to prove the feasibility of fusion.

The plans for the biggest tokamak have apparently been blessed by the Office of Management and Budget, and will be presented to the 94th Congress in the coming months. If authorized, the project will be built on the Forrestal campus of Princeton University. Hardly a small facility, the new tokamak will be enclosed in a radiation-tight test cell 40 meters square and 20 meters high, in the middle of a multistructure enclave. Much of the cost arises from the decision that it should be able to use fusion fuel, which is a mixture of deuterium and tritium, in addition to hydrogen, which is routinely used in magnetic containment experiments. The plasma effects of the heavier reacting isotopes are generally believed to be the same as those of hydrogen, but the cost of a facility that can burn fusion fuel is considerably greater because of the safeguards that must be used in handling tritium, which is radioactive, and the expense of shielding people and equipment from the high energy neutrons that are produced in fusion.

In the initial stages, many physicists in the CTR community objected to the plan, preferring more emphasis on the purely scientific studies and less on reactor engineering. By most accounts, the pressure to build a machine that could produce thermonuclear power came from the CTR division in Washington, whose director is Robert Hirsch, rather than from the scientists in various plasma laboratories around the country. The difference in emphasis is still reflected in names for the project. Princeton scientists refer to the proposed device as the Two-Component Tokamak (TCT), which describes the nature of the plasma to be studied, while the CTR office calls it the Tokamak Fusion Test Reactor (TFTR). Early skeptics among the physicists in the CTR community report that they have been assured that basic science will have first priority. The TCT-TFTR plan was extensively reviewed at an open meeting in Washington last July, and was approved by the Fusion Power Coordinating Committee of the old AEC. Most scientists with interests in CTR research now seem to support the project.

The way a tokamak works is that, for a period of time, the tokamak magnetic fields compress and mold the plasma into a toroidal shape slightly smaller than the inner wall of the device, so the plasma is effectively contained without touching any surface. With the present tokamaks, this containment lasts about 20 milliseconds, but it should increase with larger experiments, and so should the plasma density. To extract power from a fusion reactor, very general considerations indicate that the product of the density and containment time should exceed 10^{14} sec/cm^3 and the ion temperature should exceed 10^8 °C (the Lawson criterion). The best density and containment time product as yet achieved is about 10^{12} sec/cm^3.

The tokamak magnetic fields also cause a very large current to circulate through the plasma, heating it. But as the temperature of the plasma rises, the effective resistance of the plasma decreases. Supplemental heating techniques are needed, in large as well as small tokamaks, to boost the temperature to the fusion ignition point.

In the past 2 years, experiments at Princeton and at Oak Ridge National Laboratory have demonstrated that tokamak plasmas can be heated effectively with energetic beams of neutral atoms. When injected through ports in the tokamak, the beams easily cross the magnetic field, because they are neutral, and heat the plasma as they collide with it and slow down. More than any other single development in recent years, the technological improvements in neutral beam "guns" have improved the chances for successful tokamak fusion (see box). Neutral beam injection will be used in the Princeton Large Tokamak (PLT), which will precede the TCT-TFTR into operation in late 1975, and then in the TCT-TFTR 5 years later.

Neither the PLT nor the TCT-TFTR is planned to reach the Lawson criterion, but according to Harold Furth at Princeton, the TCT-TFTR will be conservatively designed to ensure that it reaches a density–confinement time within a factor of 10 of the Lawson criterion and a temperature within a factor of 2 of the Lawson criterion. To reach this temperature, 20 neutral beam guns will inject up to 40 megawatts of power into the tokamak.

Substantial Fusion Power Expected

For pure plasma experiments, the guns and the tokamak ring would probably be filled with hydrogen or helium. But to produce fusion neutrons, the ring would be filled with tritium, to be heated to 5×10^7 °C, and the guns would inject beams of deuterium at much higher energy, equivalent to about 2×10^9 °C. Hence the name TCT, because the two components of the plasma would have different masses and, initially, different energies. As the deuterium beams slowed down to the tritium temperature, they could produce approximately as much energy in fusion neutrons as they had to start with. That means that approximately 10^{18} neutrons could be produced in each pulse of the tokamak, or that the transient neutron power could be as great as 10 Mw.

The ratio of the neutron power to the plasma heating power from neutral beam injection is defined as the gain of the TCT-TFTR in a conceptual design study by the Princeton Plasma Physics Laboratory and the Westinghouse Electric Corporation, and the attainment of a gain of 1 has been made one of the criteria of the performance of the TCT-TFTR. The principal goal of the project is to produce a hot plasma with the

Rapid Development of Neutral Beams Boosts Fusion Research

The biggest advance in the magnetic fusion program recently has come not from basic science, but from rapid improvements in the technology and hardware for neutral beams, that is, beams of ions that have recombined with electrons to become electrically neutral. Inexpensive, high-powered neutral beam modules have been developed at Oak Ridge National Laboratory for heating tokamak plasmas and at the Lawrence laboratories in Berkeley and Livermore for filling magnetic mirror machines with plasma. The advances in neutral beam modules are the outcome of a successful program in applied physics that was motivated by the requirements of basic research. Neutral beam modules were developed because they were desperately needed in the fusion program, and the level of performance that has been achieved is considered spectacular. Still more stringent specifications must be met for future fusion experiments, and most reactor designers are confident they will be met.

A neutral beam cannot be made more intense than the beam of ions that produces it, and until about 4 years ago no one knew how to produce pure ion beams of hydrogen or deuterium with more than a few tenths of an ampere of current. The triumph of the improved technology is that now neutral beam modules can produce as much as 50 amperes of current.

The neutral beam modules are small, typically 10 by 20 centimeters in area, and have very few parts. Basically, a plasma is produced, positive ions are extracted from it, accelerated, and focused by a series of three grids, and then the energetic ion beam is neutralized by picking up an electron as it passes through a cell filled with hydrogen gas. The Oak Ridge module uses an ion source called the duoplasmatron, which has been specially adapted with an additional electrode to make an enlarged plasma region (called a PIG discharge region) from which intense ion beams can be extracted. The first grid, located at the plasma surface, has several hundred holes in it, through which the next two grids extract the beam and accelerate it to an energy of 25 to 40 kiloelectron volts. The beam then passes through the hydrogen gas that feeds the plasmatron and is neutralized. The many converging beamlets, as they are called, are focused well enough to pass through a 20-cm aperture at a distance of 3 to 4 meters. According to Bill Morgan at Oak Ridge, the grids of the Oak Ridge module, called a DuoPIGatron neutral injection module, are cooled in order to produce long pulses. It can produce beams of 10 to 12 amperes in pulses as long as 300 milliseconds, which is the length needed for heating the Princeton Large Tokamak.

The neutral beam module of the Lawrence Berkeley Laboratory cannot operate for such long periods, but it can produce up to 50 amperes of current. Shorter pulses of neutral beams are needed for magnetic mirror machines, such as the Livermore 2X experiment. According to Wulf Kunkel at Berkeley, higher currents were achieved by using a plasma source without a magnetic field, and by carefully designing the shape of the grid apertures, to get uniform focusing. Trapezoidal slits are used instead of holes for the beamlets to pass through. The plasma initially is produced with a simple filament discharge from a cathode to an anode. The Berkeley module typically produces a pulse of neutral atoms lasting 0.01 second, with an energy of 10 to 20 kev.

Perhaps the most crucial factor in both neutral beam module designs is that throughout its path the ion beam is kept in a space charge neutralized state, which means that the ions are surrounded by equal numbers of electrons as soon as possible. If this were not done, the cumulative effect of the repulsion of the ions in a beam with such a high current density would literally blow it apart.

Neutral beam sources with energies of 25 kev have been sufficient for experiments in the present generation of rather small tokamaks, but for larger tokamaks with more dense plasmas, more energetic neutral beams will be needed to penetrate into the center of the plasma. Beams at 150 kev will be needed for the TCT-TFTR tokamak (see accompanying story) and even more energetic beams, probably with energies in excess of 400 kev, will be needed for a reactor-sized tokamak.

To extend the beam energizes to 150 kev will require a modest extrapolation of the present technology that can probably be achieved before the new tokamak is turned on. But at higher energies, the modules producing neutral beams from positive ions become much less efficient at converting electrical power into neutral beam power. The overall electrical efficiency of the injection system will drop from 60 percent in the present modules to 20 percent or less when the present design is extrapolated to 150 kev or more.

A different sort of neutral beam source, based on negative rather than positive ions, will be needed to produce high energy neutral beams efficiently. So far there are no reliable negative ion sources suitable for the production of neutral beams, but G. I. Dimov at the Institute for Nuclear Physics in Novosibirsk has reported producing as much as 1 amp/cm^2 of negative deuterium ions over a small area for a short time. Theodore Sluyters at Brookhaven National Laboratory at Upton, Long Island, is studying negative ion sources and will attempt to repeat the experiment. A major program to develop more efficient neutral beam sources is also being undertaken at the Lawrence laboratories.

The technology of neutral beam production does not involve the most conceptually innovative physics in the fusion program, but practitioners of the art of sorcery are achieving some of the most impressive results.—W.D.M.

power density expected in a thermonuclear reactor.

Some scientists have worried that there may not be enough time to digest the results from the PLT tokamak, which is the direct precursor of the TCT-TFTR. The accelerated plan of the Washington CTR office calls for the beginning of fabrication for the TCT-TFTR in July 1976, so probably only 9 months will be available to incorporate what is learned from the PLT into the basic design of its successor.

The scientists in the CTR office and at Princeton are optimistic about the future of the large tokamaks, and at times their attitude seems to belie the fact that these devices are still experiments. At the yearly plasma physics meeting held in Albuquerque, New Mexico, last fall, one prominent researcher said, "What bothers me is not that [the CTR office] is going into power production too quickly, but that they are selling what is an experiment, that may or may not work, as a certainty." Plasma physics has a history of unexpected thresholds, and some new effects could scuttle the tokamaks. When one physicist asked, from the floor of an open session at the Albuquerque meeting, what if the upcoming PLT experiment developed some rather bad instabilities, the session moderator quipped, "Bob Hirsch won't allow it."

Other scientists are worried that the emphasis on power production from the TCT-TFTR is a gamble that gains support from the Administration and the Congress now, but may sour them on the fusion program if the project is less than successful. The criterion of energy gain seems particularly difficult to understand and could be misinterpreted. One prominent scientist thinks it is a no-win situation, saying "If you do get some power, everyone will be surprised to find you don't really have a reactor, and if you don't, they'll crucify you." Others have privately recommended to the CTR office that the word reactor should be taken out of the name for the upcoming experiment. Speaking after dinner at the Albuquerque meeting, Louis Rosen, who is director of the Clinton P. Anderson Meson Physics Facility at Los Alamos Scientific Laboratory, seemed to be alluding to such potential problems when he told the assembled physicists that credibility was the most important requisite in dealing with the Congress these days.

For the physicists who are seeking to learn as much as possible about the plasma behavior in the TCT-TFTR, power production seems to be last on the list of priorities. Harold Furth estimates that the tokamak will be operated for at least 18 months with nonradioactive plasmas to learn as much new physics as possible before tritium is introduced to the machine. Once tritium is introduced, parts of the machine will become radioactive, and alterations will be difficult. "It depends entirely on how good things are," Furth says. "If there are complications, no one is going to put in tritium until they are resolved."

The first thing the new experiment will check is the overall stability of the plasma—that is, whether it will hold its doughnut shape. Then physicists will want to know how certain types of microscopic instabilities, called trapped particle instabilities, will effect the containment of the plasma. These instabilities are predicted by theoretical calculations, but are not expected to occur until tokamaks as big as the TCT-TFTR are built.

Plasma Impurities May Limit Heating

More than any other single problem, impurities introduced into plasmas from tokamak walls seem to threaten the success of tokamak fusion now, because the impurities, which have higher atomic numbers than the hydrogen ions, can radiate away the heat of the plasma and hold down its temperature. Physicists will want to learn how well the TCT-TFTR handles the problem of impurities, since it was intentionally designed as an oversized machine for its temperature and containment to keep the plasma away from the walls. Last of the important plasma questions to be checked before tritium is introduced into the new tokamak is whether the more energetic neutral beams to be used with the TCT-TFTR cause any undesirable heating effects. Other effects, now unexpected, could also crop up. When the French TFR tokamak was turned on, a peculiar series of minor effects added up to produce "runaway electrons" which drilled holes in the liner of the plasma ring. The problem was not insoluble, but not negligible either.

Clearly, in the opinion of the scientists at Princeton, the TCT-TFTR is essentially a pure plasma physics experiment, with a sort of fusion physics overdrive that can be engaged to check some effects that are peculiar to reacting plasmas after the more basic questions have been affirmatively answered. Foremost in the reacting plasma category is the effect of alpha particles, which are products of deuterium-tritium fusion, on the plasma. Since the TCT-TFTR is expected to have the same power density (1 watt/cm^3) as a reactor, it should have the same alpha particle production rate, and thus the effects of the alpha particle heating should be ascertained.

The European Economic Community under the aegis of EURATOM is also planning to build a tokamak as large as the TCT-TFTR. The European device, called JET for Joint European Tokamak, should be operational by 1979 or 1980, and will have limited capability for producing fusion neutrons. The European estimate of the cost of JET is about half the projected cost of the TCT-TFTR. A similar sized Japanese device is scheduled for the same time period, but definitely will not be a deuterium-tritium burner. Russian researchers are planning to skip over the TCT-TFTR size device and go directly to a tokamak large enough to demonstrate feasibility. The Russian T-10 tokamak, which is very similar to the U.S. PLT machine, is due to be completed this summer, and next the Russians will build the T-20. It will be far larger than the tokamaks other countries are attempting, and could function as an experimental reactor.

Besides tokamak research, the United States devotes substantial portions of its magnetic containment research support to studying two other concepts: magnetic mirror and theta pinch devices. These two devices have magnetic fields shaped differently from those of a tokamak and would have considerable advantages as fusion reactors because they could compress the plasma more efficiently. But the two, which together receive about 40 percent of the CTR office support, have not come as close to the Lawson criterion as tokamaks. Pinch and mirror machines can heat a plasma better than a tokamak, but so far they have been much less effective at producing the required containment.

In spite of the fact that tokamak fusion research has gone smoothly in recent years and that neutral beam sources function well in conjunction with tokamaks, the research tasks ahead for controlled fusion are considerable, and the earliest date when its feasibility might be demonstrated in this country is 1985. Few people expect to see any fusion power produced for commercial consumption this century. Although fusion could have enormous social benefits, it is the longest of the long-range energy options.—WILLIAM D. METZ