Fusion Power: Optimism and a Tokamak Gap at Dubna

During the 20-year effort to control the release of thermonuclear energy, hopes have been raised and dashed with sufficient frequency to preclude the possibility of any research result triggering wild optimism, but reports at a recent conference in the Soviet Union have raised the spirits of plasma physicists to the highest level in years. Progress made by several research groups was reported, including very long confinement time in a new device at Gulf General Atomic, but the most significant reports were on the continuing success of the Soviet's Tokamak device. Last year's results from this device were impressive enough to inspire two American laboratories to start their own Tokamak programs. New work this year, especially measurements of plasma density and temperature made by a British team using laser technology, should give an added push to Tokamak research.

Tokamaks and Lasers

The most successful of the four Soviet Tokamak devices is a doughnut-shaped plasma chamber with an overall diameter of 2 meters and a chamber diameter of 36 centimeters. The magnetic field used to confine the plasma is a composite of two separate fields. One field is formed by a current flowing through coils wrapped around the outside of the plasma chamber. The other is formed at right angles to the first by a current induced to flow within the plasma. The resultant field is helically shaped, but all of the reasons for its successful confinement are not yet understood.

At the Third International Atomic Energy Conference held in the Soviet Union during August 1968, results were reported that indicated that the Tokamak was operating more successfully than any other device. The Soviet claims were greeted with some skepticism, however, because of difficulty in interpreting the results of their measurements.

Just about any method used to measure the temperature and density of ions within a plasma disturbs the confinement, so indirect measuring methods are generally used. The indirect measurements on the Tokamak plasma were subject to several interpretations, and although most physicists believed that the Soviet interpretation was correct, the posibility that the plasma was colder and less dense than reported could not be ruled out. Even Lev Artsimovich, the guiding light of the Tokamak program from the beginning, said during a visit to the United States that this country should wait 2 years to see the results confirmed before turning to Tokamak research.

Artsimovich underestimated the value of international cooperation when he gave 2 years as the time necessary to confirm his results. British scientists at Culham Laboratory had developed a laser technique for measuring the plasmas in their zeta pinch devices. They found that the photons in the laser beam could be passed through small windows in the chamber without disturbing the plasma. By analyzing the scattering of a beam from a pulsed ruby laser, they could determine plasma temperature and density.

The physics of zeta pinch devices is similar to that of Tokamaks; therefore last year R. S. Pease, head of the Culham Laboratory, and Artsimovich began discussing the possibility of using the British technique on the Tokamak. In March of this year R. Peacock and D. C. Robinson of Culham and N. Sammikov of the Kurchatov Institute near Moscow began measurements on the Tokamak, and they were ready to report their results by the time of the International Symposium on Closed Confinement Systems held in Dubna from 29 September to 3 October.

Word from Dubna

The key values used in evaluating plasma devices are temperature, confinement time, and plasma density. A plasma device will be considered potentially operational when the ions have a temperature equivalent to 10,000 electron volts, confinement times are in the order of tenths of seconds, and densities are in the order of 10^{15} ions per cubic centimeter. Greater densities require shorter confinement times, and a convenient way to consider this relationship is to use the expression $n\tau$—the product of the density (in particles per cubic centimeter) and the confinement time (in seconds). When $n\tau$ is 10^{14} or greater, the fusion system becomes economically attractive.

During the collaborative experiment the Tokamak was not run at full magnetic field strength, but confinement times of around 25 milliseconds were obtained. It was reported at Dubna that the laser measurements gave electron temperatures around 900 electron volts. This is somewhat higher than earlier measurements, but slightly over a factor of 10 below reaction temperature. The new measurement of particle density was 2×10^{13}, giving an $n\tau$ value of 5×10^{11}—a factor of 200 below reactor value, but still the best results obtained in any plasma program.

In addition to confirming the earlier Soviet results, the laser measurements confirmed the value of cooperative efforts. Pease told *Science* that he believes it would have taken about a year longer for either the Soviet Union or Britain to have done the work alone.

An Eye on the Bandwagon

The Soviet Tokamak program is the most successful of perhaps six programs that might result in an operational controlled fusion device. It is being watched closely because the nature of fusion research is such that, after a certain level of knowledge is reached, much of the research in a program that does not eventually produce a workable device is wasted.

In the late 1940's it was realized that the series of reactions that fuse deuterium into helium could be initiated if deuterium ions (the plasma) were held together long enough at sufficiently high temperature and density. It has been believed from the beginning of the controlled fusion effort that the best way to confine the deuterium fuel is with a "bottle" formed by strong magnetic fields. Several magnetic configurations are possible, and it was assumed in the early days of the program that, if several approaches were tried, continued research would reveal the best one. This procedure was successful in both the atomic and hydrogen bomb projects, but has not yet succeeded in the controlled thermonuclear reaction effort.

In the first theoretical models, the plasma was treated as two interpenetrating fluids—one composed of positively charged and the other of negatively charged particles. Devices built on the basis of these models lost their plasmas much more rapidly than the theory predicted, and subsequent research showed that a number of loss mechanisms (instabilities) were involved. Since the plasma behavior was much more complex than the first theoretical models indicated, it soon became apparent that the program would have to broaden its research base and begin building devices that might not be suitable for the ultimate fusion system but that would enable researchers to study plasma behavior.

The project might have been dropped when the full extent of the difficulties was realized, but the advantages of controlled fusion over other methods of generating power were too great. The amount of deuterium in seawater is great enough for many plasma physicists to refer to the fuel as "unlimited." There would be few toxic or radioactive waste products, and there would never be enough deuterium present in the devices for a runaway reaction to occur. Looking well into the future, physicists even saw the possibility of converting directly from nuclear to electrical energy without the intermediate production of heat.

So the research teams built devices to study the complexities they had discovered. According to the scheme of classification used by Amasa Bishop, assistant director (for Controlled Thermonuclear Research) at the AEC, there are now 115 major plasma devices in the world, and they utilize 16 different types of magnetic configurations. Most plasma physicists would say that no more than six of these have any chance of being developed into an operational device.

In the United States program there are four major fusion laboratories: Oak Ridge National Laboratory (Tennessee), Princeton Plasma Physics Laboratory (New Jersey), Los Alamos Scientific Laboratory (New Mexico), and Lawrence Radiation Laboratory (California). In addition, about 40 universities, several private laboratories, and several government laboratories have small programs. Each of the major laboratories tends to concentrate on only a few types of devices, and each has a special competence with at least one type that might eventually be developed into an operational model.

Although American physicists have known about Tokamak devices since controlled thermonuclear research was declassified in 1958, no Tokamak program was started in the United States until recently because these devices looked no more promising than any of several efforts in which the United States had special competence.

The Tokamaks, like many of the devices being operated today, were thought of before fusion work became declassified and have been operating for about a decade. For years, experiments only turned up new difficulties and gave little sign of progress, and some devices in the United States, especially the multipoles, the 2X machine at Lawrence Radiation Laboratory, and theta pinch machines, were showing promising results.

The best fusion conditions achieved in the United States have been with a theta pinch, the Scylla IV device at Los Alamos. Temperatures are about twice as high as those of Tokamak, and the $n\tau$ values are about half as high. The main weakness of this device is the short confinement time of about 0.005 millisecond. Better confinement times should be obtained in the next generation device—the Scyllac, which is scheduled for completion early in 1971.

At the Dubna conference, there were reports of plasmas in a multipole device at Gulf General Atomic with decay times of 60 to 70 milliseconds. These results were obtained with cold, dilute plasmas, but the long confinement times will make the device useful for plasma instability studies. However, few physicists believe that multipoles will ever be developed into operational devices, so Gulf is planning no second-generation machines.

The closest thing America has to a Tokamak is a small device built at Gulf General Atomic. Called Doublet, the device uses a carefully tailored cross section to concentrate the internal current into two areas instead of one like the Tokamak. The device has successfully confirmed a portion of plasma theory that it was designed to test. A larger machine has been designed, and Tihiro Ohkawa, designer and head of the project, says he has "hopes" that AEC funds are forthcoming. It could be completed in about 1½ years after construction begins.

Funds have already been provided for two United States Tokamaks that should be completed by next summer. After the initial Tokamak results were reported in August 1968, several physicists in the United States started making plans for a program. Interest was increased with Artsimovich's visit in March, and by June the AEC okayed plans for Tokamaks at both Oak Ridge and Princeton.

The Oak Ridge program is moving at a rapid pace. The design of their ORMAC is complete, components are being ordered, and the $1,000,000 construction is expected to be finished by next summer. The first set of experiments will be refinements and extensions of those done in the Soviet Union, and the second set will utilize the device's potential for stronger magnetic fields.

The Princeton project is a conversion of their Model C stellerator into a Model T Tokamak. Although the design of the Princeton device is different from the Soviet Tokamak, its temperature, density, and confinement characteristics will be about the same. It will be completed next spring.

The Soviet Tokamak program is the most successful one in the present world fusion effort, but it is by no means certain that it will lead to the successful controlled fusion device. The Tokamak effort plodded along for a decade before obtaining significant confinement, and it is possible that one of the other programs may develop in the same way. There is even an extremely remote chance that some confinement method not involving the magnetic "bottle" will be developed.

If the Tokamak program is the right road to controlled fusion, then the Soviets have a large lead. They have almost completed their fifth device, the T6. This is not a second-generation Tokamak, but is designed to test the part of their scaling law that predicts that confinement time increases as the square of the radius of the chamber. Their second-generation device, the T10, is designed but not constructed.

The Soviet lead in the fusion program is not the result of simply having stumbled onto a good magnetic configuration. They spend about twice as much money and employ about three times as many people in controlled fusion research as the United States. Although they direct a large fraction of their effort toward Tokamaks, they have a high-caliber program in most other areas. They have left the lion's share of research in multipole and theta pinch devices to other countries, and have nothing equivalent to the Astron at Lawrence Radiation Laboratory, but they are experimenting with all other major types of magnetic configurations.—ROBERT W. HOLCOMB