operational in the course of 1984, and utilizes the tokamak system, which consists of using, as the vessel taking in the plasma and the mix confining it before fusion, a torus in the middle of which circulates a strong electrical current. From the fact that the plasma (ionized gas) is what conducts the current, it undergoes not only a phenomenon of heating, but, equally, a phenomenon of confinement.

Because it is necessary to keep this plasma some distance from the inner walls of the vessel in order to prevent a drop in temperature, the European specialists found a solution that had been used earlier and brought into play for this: a toroidal field produced by coils placed around the torus. For adjusting the form and position of this plasma, supplementary coils have been placed around the exterior wall of the enclosure, in order to obtain a complementary magnetic field called a poloidal field. According to a communication given before the Academy of Sciences in May 1990, Paul-Henry Rebut, director of the JET, had already presented the encouraging results of more than six years of the functioning European tokamak. During the same period, Edouard Fabre, a researcher at the Ecole Polytechnique, although a partisan of inertial confinement, had underlined how impressed he had been by the results attained by the JET.

The most recent information shows the considerable progress achieved by the Europeans in magnetic confinement. Certain basic problems have been resolved, including: Both the level of temperature attained as the confinement time (1.8 seconds!) and the density in the center of the plasma, parameters defined by the famous Lawson criterion, have been obtained. Unfortunately, so far, the JET experiments have not yet achieved all these criteria simultaneously and homogeneously in the different parts, corresponding to the energy discharges of the reactor.

In any case, the achievement remains fundamental, and it appears that the European physicists understood precisely what they must do and not do in developing further experiments that would be even more probing: The attempts conducted at JET between 1984 and 1991 have allowed us to specify that the deuterium-tritium mix used would often lead to the formation, in the middle of this plasma, of residual poles of helium curbing the chain reaction. They came up with the solution of adding magnetic fields designed to hold back this helium, to keep it distant from the plasma. Other modifications under way, consisting of utilizing beryllium tiles for the inside walls of the JET, ought to allow it to advance a further supplemental step toward efficiency. Thanks to the improved JET, to the French project Tore Supra, which uses superconducting coils to achieve the magnetic field, the Europeans are well on the way to achieving their goal in the realm of fusion research.

Now, with the projects for the Next European Torus (NET) and Intor on the table of decision-makers before they appropriate their budgets, the outline for an industrially usable fusion reactor is becoming clearer every day.

The next step is a pilot power plant

by Charles B. Stevens

Academician Boris Kadomtsev, scientific leader of the Soviet magnetic fusion program, has proposed to leapfrog the world thermonuclear fusion effort, by presenting a design of a pilot tokamak power plant as the next step. Where does the rest of the world stand, in the face of this Soviet challenge?

Two key parameters in measuring the capabilities of tokamaks are: 1) the size of the electrical current which the plasma carries, measured in millions of Amperes (MA); 2) the power level of various systems used to heat the hydrogen plasma to fusion temperatures, usually measured in megawatts (MW) of applied heating power.

The following comparison of international tokamak research efforts is taken from the September 1990 "Report of the Technical Panel on Magnetic Fusion of the Energy Research Advisory Board" of the U.S. Department of Energy.

"The Joint European Torus (JET), the largest tokamak in the world, operates with plasma currents up to 7 MA, ion cyclotron radio-frequency (ICRF) heating up to 16 MW and neutral beam heating up to 18 MW. JET has produced reactor level plasma parameters. . . . The Tore Supra, a superconducting toroidal field coil tokamak, has begun operation in France, along with a superconducting toroidal field coil tokamak, T-15, in the Soviet Union. The ASDEX tokamak in Germany continued to provide advances in enhanced confinement and current drive, and will soon be replaced by ASDEX Upgrade, a 2 MA tokamak dedicated to studying plasma-wall interactions. In Japan lower-hybrid heating was used to drive plasma currents of 1.5 MA in the large tokamak (JT-60) and, in the smaller Triam superconducting tokamak, lower hybrid sustained the discharge in steady state for more than 1 hour. JT-60 is current being upgraded to have an overall capability comparable to JET. . . .

"Both the European Community (EC) and Japan have operating tokamaks which are substantially larger and more expensive than the largest U.S. device (TFTR). Furthermore, both have funded major upgrades of their principal experiments—unlike the U.S. All three foreign parties to the International Thermonuclear Experimental Reactor (ITER) discussions have operating superconducting tokamaks, with the U.S. only now beginning to plan for such a device in the late 1990s. Thus, while the U.S. has contributed significantly to world progress on tokamaks in the 1980s, it will fall behind in the 1990s unless new investments are made."

Despite continuing budget cutbacks and shortfalls, the U.S. magnetic fusion energy program has made exceptional progress over the past decade. The Princeton Tokamak Fusion Test Reactor (TFTR) has increased the peak ion temperature from 20 keV to 32 keV, and the product of plasma density, confinement time and temperature has increased from 200 trillion to 430 trillion particles per cm × seconds×keV). This was achieved by utilizing 32 MW of neutral beam heating. These all deuterium plasmas produced 50 kilowatts of fusion output. If tritium were introduced into these same plasma conditions, 10 to 30 MW of fusion energy output would have been achieved.

Kadomtsev details power plant design

The detailed Soviet design proposal is being published in the journal *Comments on Plasma Physics,* in two separate articles in 1991.

Dr. Kadomtsev points out that, in the case of the tokamak approach to harnessing thermonuclear fusion reactions, the "data base is sufficient for the design of an experimental fusion tokamak reactor." He notes that the current design for an International Thermonuclear Engineering Reactor is "uniformly loaded from the viewpoint of physics and technology," having as its main goal "to provide the scientific and engineering data for a demonstration power plant reactor design," a device that would follow ITER.

"However," he states, "some other strategies are possible in our rapidly changing world, e.g. we can imagine smaller machines aimed at faster progress along some specific directions. Respectively, for each of such facilities only one of the goals could be chosen as a first priority, others should be shifted to the second and the third priority background." Dr. Kadomtsev continues, "Let us discuss now, as an example, the machine, the first priority of which is the net electricity production. In other words, such a fusion device can be considered as a fusion power plant prototype. The very goal by itself—electricity production—is rather complicated. Therefore, all other engineering characteristics of such a fusion machine should be maximally simplified. In other words, the second priority aspects shouldn't pretend to be directly used in demonstration reactor."

Dr. Kadomtsev notes in his paper: "In order that the tokamak reactor would be able to produce power, it is necessary to reduce to a minimum its own power consumption." He then outlines the parameters of a pilot plant that would produce about 250 MW of thermal power and 40-50 MW of electricity, with the reactor itself consuming about half of the electric power. Among the technical characteristics of the plant are the following:

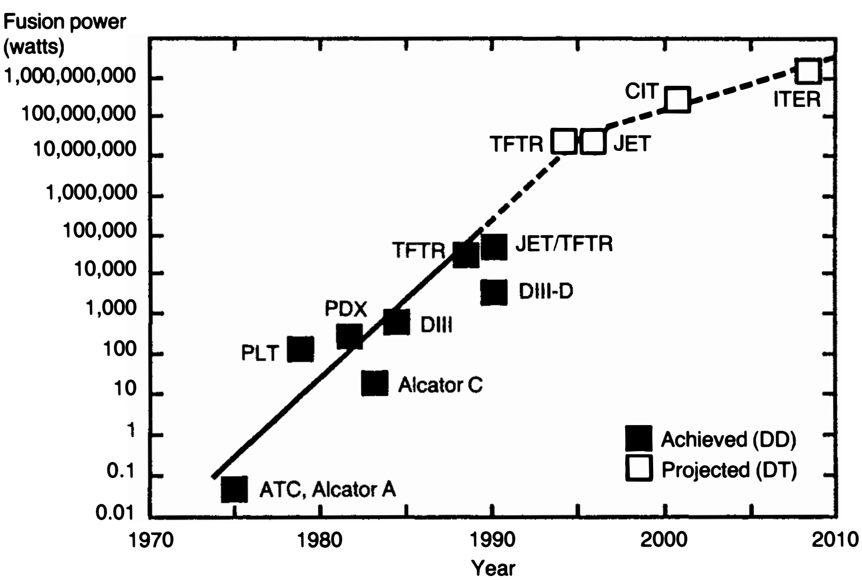
1) "It is desirable not to use non-inductive current drive, since it is an extra power consumption";

2) "It is desirable to have large aspect ratio (a value of 9 is selected) . . . in order to realize a long burn pulse with minimal power";

3) "With a low fusion power it seems not reasonable to breed tritium";

4) "It is desirable to use the simplest method of plasma heating to ignition, e.g., gyrotrons or CARM's masers based on cyclotron auto-resonance."

Progress in magnetic fusion power



CIT: Compact Ignition Tokamak
PLT: Princeton Large Tokamak
PDX: Princeton Divertor Experiment
JET: Joint European Torus
ITER: International Thermonuclear Experimental Reactor
DIII & DIII-D: General Atomics Tokamak Experiments
ATC & TFTR: Princeton Plasma Physic Laboratory
Alcator A, C: Massachusetts Institute of Technology

Source: Dept. of Energy Report of the Technical Panel on Magnetic Fusion of the Energy Research Advisory Board, September 1990.

Artist's conception of a functioning fusion power plant, using a magnetic confinement reactor. In 1974 when this picture appeared, the Atomic Energy Commission was predicting the first commercial reactors would be in operation by the year 2000.

Other characteristics of the plant are: maximum magnetic field of 160,000 Gauss, plasma current of 3 MA, amperes, and a plasma beta of 0.5%.

Kadomtsev asks in his paper whether this line of thinking is worthwhile since "this goal" of the pilot plant "can be realized due to rejection of other fusion technologies which will be necessary for the demonstration reactor." He concludes that the physics data base required for the pilot plant "can be used as a basis for the subsequent proceeding to more promising tokamak reactor concepts."

More precisely, we can argue:

1) the use of advanced reactions, such as the non-neutron-generating deuterium-helium-3 reaction, as a fuel with the virtually no radioactive wastes being generated;

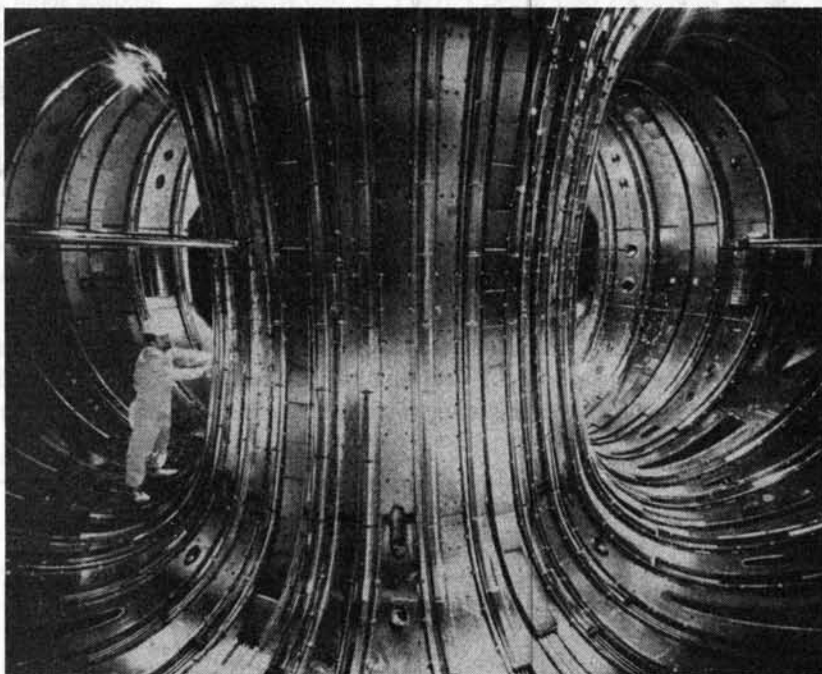
2) the development of schemes for direct synchrotron radiation conversion into electricity;

3) more acceptable solutions to the problem of plasma-wall interaction;

4) the possibilities of current drive by synchrotron radiation in combination with the bootstrap effect etc.

Thus the pilot plant "could show not only an opportunity to obtain electricity from fusion power but to initiate ways to some promising fusion technologies." Dr. Kadomtsev concludes, "The present data base for tokamaks with improved plasma confinement allows one to imagine the tokamak reactor concept for net electricity production."

How magnetic fusion works



Interior of the Joint European Torus Inconel vacuum vessel in which the hot gases are confined.

Nuclear fusion of hydrogen to form helium is the primary source of energy for stars like our Sun. In fact, other elements can be fused to form heavier elements, and in larger stars, helium is "burned" to form carbon. To achieve hydrogen nuclear fusion in the easiest case—fusing the two heavy isotopes of hydrogen, deuterium (D) and tritium (T)—the fuel must be raised to a temperature on the order of 100 million degrees Centigrade. At these temperatures, matter becomes ionized and this is called plasma. Plasma temperatures are measured in electron volts (eV); one electron volt is roughly equivalent to 11,000°C. For a fusion reactor, the temperature for D-T would have to be greater than 10,000 eV or 10 keV in scientific notation.

Because plasmas are good conductors, they can be confined and insulated by magnetic fields. Thus, magnetic "bottles" can be formed by magnetic fields which are either generated by external magnetic field coils or by electric currents carried by the plasma itself. The most stable and effective such magnetic bottle is the donut-shaped tokamak, which utilizes both external magnetic coils and a plasma current to generate its confining magnetic fields.

The electric current passing through the tokamak plasma does achieve some heating of the plasma to about 1 keV. But alternative heating systems, such as microwaves or radio waves or neutralized particle beams must be used to reach the required 10 keV temperatures.

For a power reactor, the product of the fuel density (in atoms per cubic centimeter) and the time the fuel is confined, measured in seconds, must be greater than 10^{14} second-atoms per cm^3. The tokamak operates in a density regime of about 10^{14} atoms per cm^3, so that the confinement time required is on the order of one second.