Fusion Power: Progress and Problems

After almost two decades of trying to overcome plasma instabilities, of trying to bring particle losses down to a satisfactory level, and of wrestling with a host of persistent problems, plasma physicists now believe that they have a good chance to demonstrate that power can be produced from controlled fusion reactions. A number of difficult problems remain to be solved, however, and a new generation of machines will apparently be required before scientific feasibility can be determined.

As recently as 2 years ago, fusion researchers were not at all confident that fusion power would be possible. However, because of the results the Soviets obtained with their Tokamak-3 in 1969 (*Science*, 17 October 1969) and subsequent good results here in the United States, the tone is one of optimism at the nation's four major fusion laboratories: the Princeton Plasma Laboratory (PPL) in New Jersey, the Oak Ridge National Laboratory (ORNL) in Tennessee, the Lawrence Radiation Laboratory (LRL) in Livermore, California, and the Los Alamos Scientific Laboratory (LASL) in New Mexico.

A major obstacle to obtaining controlled fusion is the high temperature required for fusion to take place, about 75 million to 100 million degrees. The temperature requirement is such that the plasma fuel in which the fusion reaction takes place must not come in contact with the walls of its container, because if it did it would be instantly cooled. Hence, the primary research effort has been devoted to creating, in one way or another, a magnetic bottle to hold the hot, ionized gases of the plasma.

There are two basic magnetic bottle configurations: the open-ended mirror machines; and the torus, or doughnut-shaped, machines. Mirror machines are straight tubes with magnetic fields that are stronger at the ends than in the center. The stronger fields act as mirrors or stoppers in the magnetic bottle, thereby causing many of the charged particles to be reflected back into the tube, although some particles fly out of the ends. In the torus design, there are no ends, so that particle losses from end-leakage do not occur.

A sufficiently hot plasma is just one of three major criteria that must be met for fusion to take place. In addition the plasma must also be sufficiently dense, and the confinement time within the magnetic bottle must be long enough. Until recently, the biggest problem plasma physicists had to face was caused by extremely leaky magnetic bottles; that is, cooperative plasma effects, or instabilities, forced particles across the magnetic field too quickly for significant amounts of fusion to take place. For 15 years, particle losses have been a thousand times greater than those predicted to occur as a result of Coulomb scattering. Now, however, losses have been reduced to close to the theoretical limit in a number of plasma devices.

For a controlled fusion reaction to be scientifically feasible requires, in addition to high temperatures, that the product of density and confinement time for the plasma be higher than a certain limit, which was determined by the British physicist J. D. Lawson. For a deuterium-tritium reaction, this limit is 10^{14} seconds per cubic centimeter. There have been a number of machines in which the kindling temperature of a deuterium-tritium reaction has been reached or closely approached. But none of these machines has achieved the combination of factors necessary to attain the break-even point—at which the fusion energy generated in the reactor equals the energy input required to run the machine.

According to the AEC's Roy Gould, assistant director for the controlled thermonuclear research program, it is quite likely that scientific feasibility could be demonstrated in the 1970's provided that resources were concentrated on the right approach. But having a number of approaches increases the chances that at least one will prove successful; and each of the major approaches would have distinctly different features as a reactor. Flexibility of choice is also desirable because it is not yet clear which approach will be most economically feasible.

Fusion has many potential advantages over other forms of energy production. It does not consume valuable fossil fuels, nor does it release combustion products into the atmosphere. Nor would there be a possibility of a nuclear explosion, because of the small amounts of fuel required. But a fusion reactor's relative cleanliness and safety does not mean that the reactor is without problems. Even if scientific feasibility can be demonstrated, there are still extremely tough engineering and environmental problems that remain before fusion power becomes a reality.

Many of the problems are a consequence of the fuel—a mixture of deuterium and tritium—envisioned for the first generation of fusion reactors. In order for atomic nuclei to fuse, their Coulomb repulsion must be overcome by sufficient kinetic energy. The deuterium and tritium reaction has a high fusion cross-section, or reaction probability, and is, therefore, attractive for use in a fusion reactor. Much of the energy released by the fusion reaction is carried off by the 14-Mev neutrons that are emitted. But by using a fuel that can fuse at a relatively low temperature, physicists have to deal with radioactive tritium and with very energetic neutrons. The latter would have important effects on the structural material of the reactor. Neutron radiation damage would severely weaken most metals that might otherwise serve as the vacuum wall of the reactor; the neutrons displace atoms and produce helium and hydrogen within the structural material. Niobium and vanadium are being considered as wall materials, and tests of their resistance to neutron radiation damage are under way.

In one of several preliminary designs for a reactor, graphite would be used to absorb and reflect the neutrons. A layer of copper that is cooled by liquid nitrogen would provide additional shielding to protect the superconducting magnets from excessive nuclear heating. Borated water and a layer of lead would provide, respectively, neutron and gamma ray attenuation. Lithium, circulating through the "blanket" around the reactor, is expected to serve both as a coolant and for breeding tritium to be used as fuel. This reactor-bred tritium must be recovered, for economic as well as environmental reasons. But because tritium can diffuse even through stainless steel, its recovery is not a trivial problem.

Only about 5 percent of the injected fuel would react during the time it is confined within the plasma. As a result, the plasma recovery system would have to handle large amounts of unburned, unused tritium. Again, for both economic and environmental reasons, an extremely efficient tritium recovery system would be required.

The Machines

Within 5 months after the first tokamak results were announced by U.S.S.R. scientists, physicists at the Princeton laboratory had converted one of their machines into a tokamak. Although slightly smaller than the Russian machine, it has obtained comparable results. The plasma in the PPL tokamak is confined within the torus-shaped machine by a ring of magnets. In addition, two large coils are joined to the torus by iron yokes like the links of a giant chain. As a current passes through the coils, it induces a current in the plasma through a mechanism similar to induction in the secondary coil of a transformer. The induced current produces a poloidal magnetic field which stabilizes the plasma by causing the magnetic lines of force to twist on their path around the torus. The passage of the current through the plasma also heats the gas. Ion temperatures equivalent to 500 ev (1 ev = about 11,000°C) have been achieved in the Princeton machine, with a confinement time of about 10 milliseconds, and a density of about 5×10^{13} particles per cubic centimeter.

A tokamak machine has also recently been completed at Oak Ridge. Because of its low-aspect ratio, which is the ratio of the major radius to the minor radius, and its large minor radius (23 cm), the machine is theoretically capable of achieving high ion temperatures (over 1000 ev). It will make possible studies of heat conduction problems and plasma instabilities similar to those a real reactor might face.

In the Oak Ridge machine, the plasma will be in what is referred to as the collisionless state (where collisions occur infrequently); no tokamak has yet operated under these conditions. But any reactor of the toroidal configuration must, to be feasible, operate with collisionless plasma. Hence, according to ORNL scientists, the Oak Ridge machine will demonstrate whether or not the tokamak configuration is really suitable for a fusion reactor. If all goes well, they think it should be possible to go directly to a demonstration reactor.

Although it appears that merely making a tokamak larger should improve its containment time, this is not yet certain. Physicists point out that larger dimensions or a higher temperature might possibly bring in new factors that could make conditions better or worse than expected.

Resistive heating from an electric current in the plasma cannot produce temperatures high enough for fusion reactions, because the resistivity of a plasma decreases as its temperature rises. In order to raise temperatures and densities still higher, Princeton scientists are constructing a machine that will magnetically compress a toroidal plasma. In an alternate approach, researchers at ORNL plan to increase temperatures in their tokamak machine with a beam of highly energetic neutral particles that will be injected into the plasma.

At Oak Ridge, researchers working on plasmas confined within mirror machines plan to use electron cyclotron excitation to heat the plasma. In their new machine a neutral beam is injected at high energy into the confinement area where, through collisions, it gives up electrons to the cold plasma ions. As a result of the electron exchange, an energetic atom loses its electron and becomes a hot ion. The principle has been successfully demonstrated on a smaller scale, and the Oak Ridge device will allow ORNL researchers to see how it works with higher density and stronger magnetic fields.

Another mirror machine at Livermore has operated at containment times close to those predicted from theory. A new LRL mirror machine, which is designed to run at higher densities, is now being tested. Experiments with this machine may indicate whether certain microinstabilities that have been predicted by theory exist. Long-term prospects of the LRL machines apparently will depend upon how much the predicted instabilities affect the containment time.

Mirror machines also hold the possibility of directly converting fusion power to electricity. A plan advanced by Richard F. Post of LRL proposes fueling the mirror reactor with reactants, such as deuterium–helium-3, that would release their energy as kinetic energy carried entirely by charged particles. At one end of the magnetic bottle, positive and negative particles would be trapped on separate charged plates, and the kinetic energy of the particles would then be converted into direct current.

At Los Alamos the program in controlled fusion is concentrated on large pinch devices. These machines operate cyclically, heating and constricting the plasma only for short periods, in contrast to the more continuous operation of the machines discussed above. There are other differences as well. Both tokamak and mirror machines are normally what are known as low-beta machines, in which the magnetic field that contains the plasma is used somewhat inefficiently. In a high-beta machine, such as the pinch devices, the plasma pressure is comparable to the pressure of the magnetic field on the outside, and most of the magnetic field is excluded from the plasma.

The plasma is a pinch machine is heated by a shock wave that is generated within the plasma as it is constricted by the rapidly increasing magnetic field. There are two basic kinds of pinch devices, a theta pinch (in which the magnetic field runs parallel to the plasma column) and a z pinch (in which the magnetic field runs around the column). Most of the Los Alamos effort is devoted to the theta pinch; a new machine of this type, the largest and most expensive fusion device yet attempted, is now being developed. When it is finished, the machine will consist of a toroidal configuration some 15 meters in circumference. At present only the first third has been completed and is being used for preliminary experiments. Researchers expect that the device will allow them to study plasmas with densities of up to 3×10^{16} particles per cubic centimeter and with ion temperatures as high as 5000 ev. Pinch devices characteristically operate with much higher density plasma, but with much shorter containment times than do, for example, tokamaks. But the results of initial experiments reported by the LASL scientists indicate, they believe, that the toroidal theta pinch will improve the stability of the plasma and may allow its containment for times up to a millisecond.

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