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# Starpower: the quest for fusion energy today

*How close are we to 'breakeven' in this unlimited source of energy? Concluding a 3-part series abridged from the Office of Technology Assessment's recent report.*

## Scientific progress and reactor design

### Energy gain

An important measure of scientific progress toward attaining reactor-relevant conditions is *energy gain,* denoted as "Q." Energy gain is the ratio of the fusion power output that a device generates to the input power injected into the plasma. Input and output power are measured at some instant after the plasma has reached its operating density and temperature. In experimental plasmas that do not contain tritium and therefore do not produce significant amounts of fusion power, an "equivalent Q" is measured. It is defined as the Q that would be produced by the plasma if it were fueled equally by both deuterium and tritium (D-T) and if it had attained the same plasma parameters. . . .

**Figure 9** shows the plasma temperatures and confinement parameters needed to obtain Qs of at least 1, a condition known as "breakeven." The plasma temperatures and confinement parameters that have been attained experimentally by various confinement configurations are also shown. No device has yet reached breakeven, although tokamak experiments have clearly come the closest.

### Ignition

The most significant region in Figure 9 is *ignition* in the top right corner. An ignited D-T plasma not only generates net fusion power but also retains enough heat to continue producing fusion reactions without external heat. The Q of an ignited plasma is infinite, since the plasma generates output power without auxiliary input power from external sources. (Power to drive the currents in the plasma and to cool the magnets to their operating temperature will be required even for ignited plasmas, but, as stated above, this power is not included in Q.)

*Successfully reaching ignition—or at least successfully generating a plasma that produces many times more power than is input into it—will be a major milestone in determining fusion's technological feasibility.* The energy and the reaction products generated in a plasma producing appreciable amounts of fusion power will significantly affect the plasma's behavior. Understanding these effects may be crucial to utilizing self-sustaining fusion reactions in reactors, and these effects cannot be studied under breakeven conditions alone.

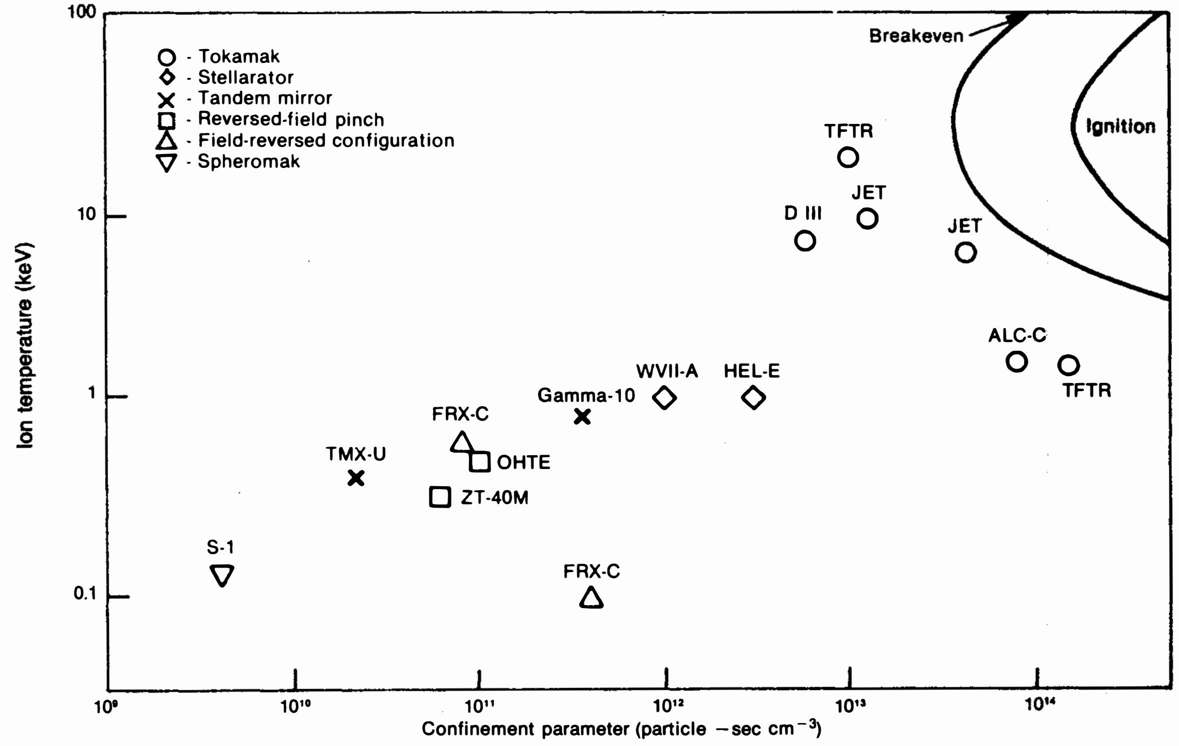
### Breakeven

The breakeven curve in Figure 9 shows the conditions under which a plasma generates as much power through fusion reactions as is injected into it to maintain the reactions. Although reaching breakeven will be a major accomplishment, it will not have the technical significance of reaching ignition. . . .

The Tokamak Fusion Test Reactor (TFTR) at Princeton Plasma Physics Laboratory was designed to take advantage of beam heating. It is expected that breakeven-equivalent (breakeven conditions in a plasma not containing tritium) will be obtained sometime between fall 1987 and spring 1988. Experiments to realize true breakeven using tritium are scheduled for the end of 1990. These achievements will be important because, for the first time, a significant amount of heat from fusion power will be produced in a magnetic fusion device. Moreover, successful D-T operation of TFTR will provide important tritium-handling experience necessary for future reactor operation. . . .

FIGURE 9

**Plasma parameters achieved by various confinement concepts**



**Key**

**S-1:** Spheromak-1; Princeton Plasma Physics Laboratory, Princeton, N.J.
**TMX-U:** Tandem Mirror Experiment Upgrade; Lawrence Livermore National Laboratory, Livermore, Calif.
**ZT-40M:** Toroidal Z-pinch, -40, Modified; Los Alamos National Laboratory, Los Alamos, N.M.
**FRX-C:** Field-Reversed Experiment C; Los Alamos National Laboratory, Los Alamos, N.M.
**OHTE:** Ohmically Heated Toroidal Experiment; GA Technologies, Inc., San Diego, Calif.
**Gamma-10:** University of Tsukuba, Ibaraki, Japan.
**WVII-A:** Wendelstein VII-A; Institute for Plasma Physics, Garching, Federal Republic of Germany.
**HEL-E:** Heliotron-E; Kyoto University, Kyoto, Japan.
**D III:** Doublet III; GA Technologies, Inc., San Diego, Calif.
**JET:** Joint European Torus; JET Joint Undertaking, Abingdon, United Kingdom.
**TFTR:** Tokamak Fusion Test Reactor; Princeton Plasma Physics Laboratory, Princeton, N.J.
**ALC-C:** Alcator C; Massachusetts Institute of Technology, Cambridge, Mass.

Source: Office of Technology Assessment, 1987.

## State of the art

**Temperature and confinement.** Figure 9 shows results that have been attained by each of the confinement concepts to date. Tokamak experiments have clearly made the most progress in terms of coming closest to the ignition region.

TFTR, in particular, has reached the highest temperature and confinement parameters of any magnetic fusion experiment. In 1986, TFTR attained ion temperatures of 20 kiloelectron volts (keV) or more than 200 million degrees C, well over the temperature needed for breakeven or ignition. However, these high-temperature results were obtained in a relatively low-density plasma having a confinement parameter of $10^{13}$ second-particles per cubic centimeter, which is about half the confinement parameter needed to reach breakeven at that temperature. The equivalent Q actually attained by the plasma was 0.23. Use of neutral beam heating under these conditions reduces the breakeven threshold by almost a factor of four; a plasma heated to 20 keV without use of neutral beams would need a confinement parameter 7.5 times higher than was attained to reach equivalent breakeven.

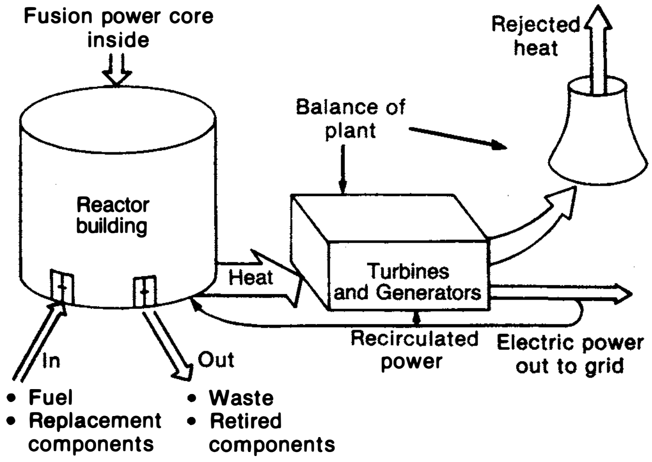
In a separate experiment at a lower temperature of 1.5 keV, TFTR reached a confinement parameter of $1.5 \times 10^{14}$ second-particles per cubic centimeter. Had this confinement been attained at a temperature of 20 keV, TFTR would have been well above equivalent breakeven, coming close to meeting the equivalent ignition condition. However, in practice, TFTR will not be able to attain temperature and confinement values this high simultaneously. Temperature can be raised at the expense of confinement, and vice versa, but the product of the two—which determines the equivalent Q—is difficult to increase. With additional neutral beam power and other improvements, TFTR may well be able to raise its equivalent Q from 0.23 to 1 and reach equivalent breakeven. However, it is extremely unlikely that equivalent Qs much greater than 1 are attainable in TFTR.

**Beta.** The beta parameter, also called the "magnetic field utilization factor," measures the efficiency with which the energy of the magnetic field is used to confine the energy of the plasma. Beta is defined as the ratio of the plasma pressure to the magnetic field pressure. Record tokamak values for beta of 5%, in the PBX experiment at Princeton Plasma Physics Laboratory, and 6%, in the D III-D experiment at GA Technologies, have been attained. These results are especially important in that they generally validate theoretical models that predict how further improvements in beta can be obtained.

In a fusion reactor, the fusion power output per unit volume of the plasma would be proportional to beta squared times the magnetic field strength to the fourth power. Since tokamaks have relatively low betas compared to many of the other confinement concepts currently studied, improving the beta of tokamaks can be useful. . . .

**Scaling.** Understanding how tokamak performance can be expected to improve is crucial to evaluating the tokamak's potential for future reactors as well as to designing next-generation tokamak experiments. As mentioned earlier, the complete theoretical mechanism determining tokamak scaling has yet to be understood. Observationally, plasma confinement has been found to improve with increased plasma size. Empirical data also show that tokamak confinement improves when plasma density is increased, but that this behavior holds only for ohmically heated plasmas. Non-ohmically heated plasmas follow what has come to be known as "L(Low)-mode" scaling, in which confinement degrades as increasing amounts of external power are injected.

FIGURE 10
**Systems in a fusion generating station**



Source: Office of Technology Assessment, 1987.

A few years ago, experiments on the German Axisymmetric Divertor Experiment (ASDEX) discovered a mode of tokamak behavior described by a more favorable scaling, labeled "H(High)-mode." In this mode, performance even with auxiliary heating behaved more like the original, ohmically heated plasmas. However, H-mode scaling could be achieved only with a particular combination of device hardware and operating conditions. Subsequently, additional work at other tokamaks has broadened the range of conditions under which this more favorable behavior can be found. The challenge to tokamak researchers is to obtain H-mode scaling in configurations and operating regimes that are also conducive to attaining reactor-like temperatures and densities.

## Reactor design

Just as an automobile is much more than spark plugs and cylinders, a fusion reactor will contain many systems besides those that heat and confine the plasma. Fusion's overall engineering feasibility will depend on supporting the fusion reaction, converting the power released into a more usable form of energy, and ensuring operation in a safe and environmentally acceptable manner. *Developing and building these associated systems and integrating them into a functional whole will require a technological development effort at least as impressive as the scientific challenge of creating and understanding fusion plasmas.* . . .

The overall fusion generating station (**Figure 10**) consists of a *fusion power core,* containing the systems that support and recover energy from the fusion reaction, and the *balance of plant* that converts this energy to electricity using equipment similar to that found in present electricity generating stations. Features that might convert fusion power to electricity more directly in advanced fusion reactors are described in a subsequent section.

## Fusion power core

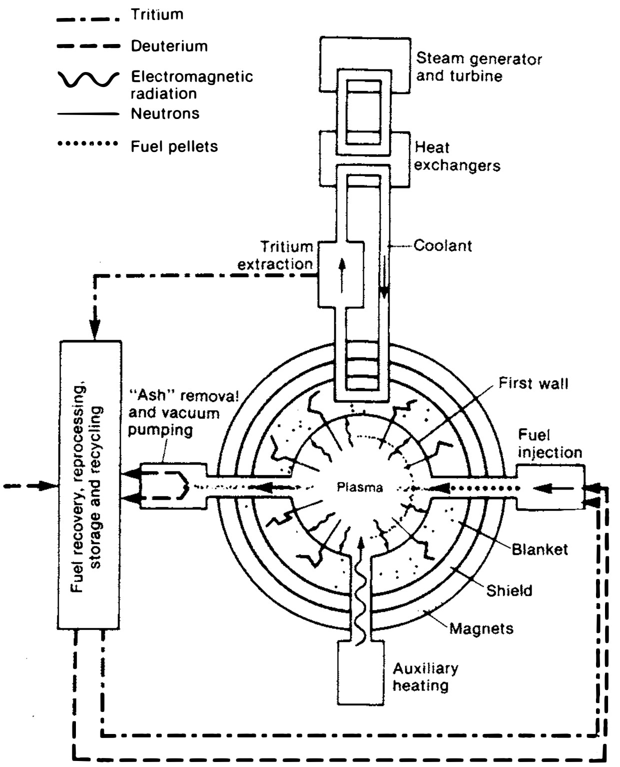
The fusion power core, shown schematically in **Figure 11,** is the heart of a fusion generating station. It consists of the plasma chamber, the surrounding blanket and first wall systems that recover the fusion energy and breed tritium fuel, the magnet coils generating the necessary magnetic fields, shields for the magnets, and the fueling, heating, and impurity control systems. Before an acceptable design for a fusion power core can be developed, the behavior of fusion plasmas must be understood under all conditions that might be encountered. Furthermore, significant advances must be made in *plasma technologies* which confine and maintain the plasma, and *nuclear technologies,* which recover heat from the plasma, breed fuel, and ensure safe operation.

## Balance of plant

Balance of plant generally describes the systems of a fusion generating station outside of the fusion power core. In the example shown in Figure 11, the balance of plant resembles systems found in other types of electric generating sta-

FIGURE 11

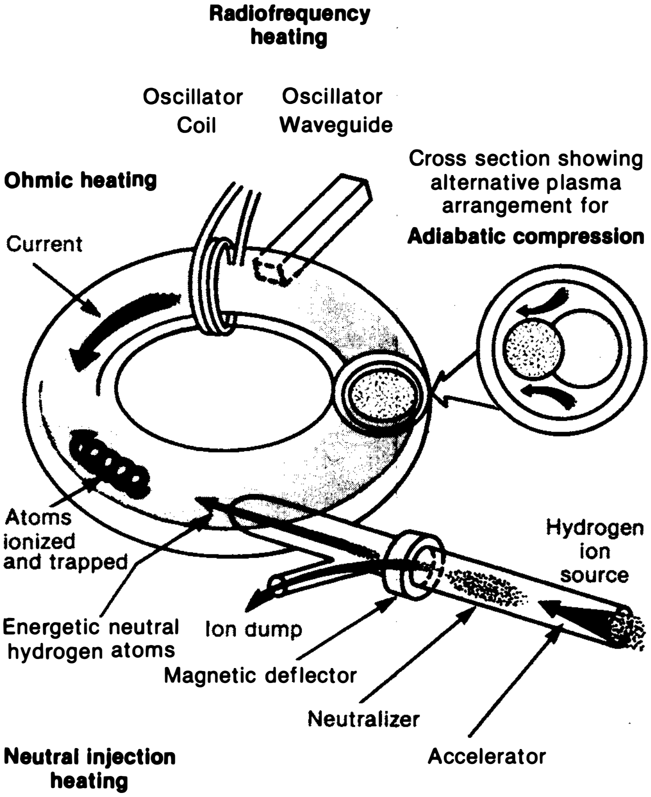
## Systems in the fusion power core



Source: Modified from "The Engineering of Magnetic Fusion Reactors," by Robert W. Conn. Copyright © 1983 by Scientific American, Inc. All rights reserved.

FIGURE 12

## Plasma heating mechanisms



Source: Oak Ridge National Laboratory.

tions. These systems use heat provided by the fusion core to produce steam that drives turbines and generates electricity. The steam is cooled by passing through the turbines, and the remaining heat in the steam is exhausted through cooling towers or similar mechanisms.

More advanced systems that convert plasma energy directly into electricity also may be possible. Fusion reactors incorporating such systems could be made more efficient than those using steam generators and turbines.

## Fusion power core systems

### The fusion plasma

At the center of a fusion reactor, literally and figuratively, is the fusion plasma. A number of supporting technology systems create and maintain the plasma conditions required for fusion reactions to occur. These technologies confine the plasma, heat and fuel it, remove wastes and impurities, and, in some cases, drive electric currents within the plasma. They also recover heat, breed fuel, and provide shielding.

Further development of many of these plasma technologies is inevitable . . . but, with good confinement, the losses can be made up by external heating and/or by fusion self-heating. Different mechanisms for heating the plasma, illustrated in **Figure 12,** are listed below.

**Ohmic heating.** Like an electric heater, a plasma will heat up when an electrical current is passed through it. However, the hotter a plasma gets, the better it conducts electricity and therefore the harder it is to heat further. As a result, ohmic heating is not sufficient to reach ignition in many configurations.

**Neutral beam heating.** Energetic charged or neutral particles can be used to heat fusion plasmas. However, the same magnetic fields that prevent the plasma from escaping also prevent charged particles on the outside from easily getting in. Therefore, beams of energetic neutral (uncharged) particles that can cross the field lines are usually preferred for heating the plasma.

**Radiofrequency heating.** Electromagnetic radiation at specific frequencies can heat a plasma like a microwave oven heats food. Radiofrequency or microwave power beamed into a plasma at the proper frequency is absorbed by particles in the plasma. These particles transfer energy to the rest of the plasma through collisions.

**Compression heating.** Increasing the confining magnetic fields can heat a plasma by compressing it. This technique has been used in tokamak devices and is one reason for studying the field-reversed configuration confinement approach. As stated earlier, there is hope that compression may be sufficient to heat an FRC plasma to ignition.

**Fusion self-heating.** The products of a D-T fusion reaction are a helium nucleus—an alpha particle—and a neutron. The neutron, carrying most of the reaction energy, is electrically uncharged and escapes from the plasma without reacting further. The alpha particle, carrying the rest of the energy from the fusion reaction, is charged and remains trapped with the confining magnetic fields. Hundreds of times hotter than the surrounding plasma, the alpha particle heats other plasma particles through collisions.

**Status.** Recent system studies show that radiofrequency (RF) heating offers significant advantages over neutral beam heating. Consequently, the U.S. neutral beam research program has been reduced while the RF heating program has grown. Various types of RF heating, using different frequencies of radiation from tens of megahertz (millions of cycles per second) to over a hundred gigahertz (billions of cycles per second), are under study. Each frequency range involves different technologies for generation and transmission.

**Issues.** Additional research and development (R&D) in heating technologies is essential to meet the needs of future experiments and reactors. Key technical issues in RF heating are the development of sufficiently powerful sources of radiofrequency power (tens of megawatts), particularly at higher frequencies, and the development of launchers or antennas to transmit this power into the plasma, particularly at lower frequencies. Resolution of these issues will require technological developments as well as improved understanding of the interaction between radio waves and plasmas.

Since no ignited plasma has yet been produced, the effects of fusion self-heating on plasma confinement and other plasma properties are not experimentally known. Confinement could degrade, just as it does with other forms of auxiliary heating. Although self-heating can be simulated in some ways in non-ignited plasmas, its effects can be fully studied only upon reaching high energy gain or ignition. The ignition milestone, therefore, is crucial to the fusion program, and understanding the behavior of ignited plasmas is one of the program's highest scientific priorities.

## Fueling

**Description.** Any fusion reactor that operates in pulses exceeding a few seconds in length must be fueled to replace particles that escape the plasma and, to a lesser extent, those that are consumed by fusion reactions. Firing pellets of frozen deuterium and tritium into the plasma currently appears to be the best approach for fueling. Both pneumatic (compressed gas) and centrifugal (sling) injectors have been used. Neutral beam fueling has been used in experiments, but fueling reactors in this way would take excessive amounts of power.

**Status.** Pellets up to 4 millimeters in diameter have been fired into experimental plasmas at speeds of up to 2 kilometers per second and at repetition rates of 5 to 40 pellets per second. U.S. development of pellet fueling technology, centered at Oak Ridge National Laboratory, is well ahead of fueling technology development elsewhere in the world. By building state-of-the-art pellet injectors for use on foreign experiments, the United States is able in return to gain access to foreign experimental facilities.

**Issues.** Reactor-scale plasmas will be denser, hotter, and perhaps bigger than the plasmas made to date in fusion experiments; moreover, reactor plasmas will contain energetic alpha particles. All these factors will make it much more difficult for pellets to penetrate reactor plasmas than plasmas made in present-day facilities. . . .

## Current drive

**Description.** Several confinement concepts, including the tokamak, require generation of an electric current inside the plasma. In most present experiments, this current is generated by a transformer. In a transformer, varying the electric current in one coil of wire generates a magnetic field that changes with time. This field passes through a nearby second coil of wire—or in this case the conducting plasma—and generates an electric current in that coil or plasma. Varying the magnetic field is essential; a constant magnetic field cannot generate current.

In tokamak experiments, a coil located in the "doughnut hole" in the center of the plasma chamber serves as one coil of the transformer. Passing a steadily increasing current through this coil creates an increasing magnetic field, which generates current in the plasma. When the current in the first coil levels off at its maximum value, its magnetic field becomes constant, and the current in the plasma peaks and then starts to decay. If the fusion plasma requires a plasma current, its pulse length is limited by the maximum magnetic field of the first coil and the length of time taken for the plasma current to decay.

**Status.** Techniques are now being studied for generating continuous plasma currents, rather than pulsed ones, because steady-state reactors are preferable to ones that operate in pulses. Injecting radiofrequency power or neutral beams into the plasma might be able to generate such steady-state currents in tokamaks. The injected power or beams generate currents either by "pushing" directly on electrons in the plasma or by selectively heating particles traveling in one direction. Experiments have confirmed the theory of radiofrequency current drive and have succeeded in sustaining tokamak pulses for several seconds.

Some other confinement concepts, such as the reversed-field pinch or the spheromak, can generate plasma currents with small, periodic variations in the external magnetic fields. Such current-drive technologies do not involve complex external systems. . . .

## Reaction product and impurity control

**Description.** Alpha particles, which build up as reaction products in steady-state or very long-pulse fusion reactors, will have to be removed so that they do not lessen the output power by diluting the fuel and increasing energy loss by radiation. Devices that collect ions at the plasma edge can be used to remove alpha particles from the plasma. Alpha particles, when combined with electrons that are also collected at the plasma edge, form helium gas that can be harmlessly released. Unburned fuel ions also will be collected; these will be converted to deuterium and tritium gas, which will have to be separated from the helium and reinjected into the plasma.

The same devices that collect ions at the plasma edge help prevent impurities from entering the plasma. Even small amounts of impurities can cool the plasma by greatly accelerating the rate at which energy is radiated away.

**Status.** Two types of devices are being considered for these tasks: *pumped limiters* and *divertors*. A limiter is a block of heat-resistant material that, when placed inside the reaction chamber, defines the plasma boundary by intercepting particles at the plasma edge. A variant, the pumped limiter, combines a limiter with a vacuum pump to remove the material collected by the limiter. A divertor generates a particular magnetic field configuration in which ions diffusing out of the fusion plasma, as well as those knocked out of the vessel walls and drifting toward the plasma, are diverted away and collected by external plates. . . .

## The fusion blanket and first wall

The region immediately surrounding the fusion plasma in a reactor is called the *blanket*; the part of the blanket immediately facing the plasma is called the *first wall*. . . . The blanket serves several functions. Cooling systems in the blanket remove the heat generated by fusion reactions and transfer it to other parts of the facility to generate electricity. . . . In addition, the tritium fuel required by the reactor is produced, or "bred," in the blanket. Furthermore, the blanket must support itself and any other structures that are mounted on it. . . .

A wide variety of designs have been proposed for the blanket and first wall. However, since the fusion research program has concentrated to date primarily on plasma science issues, relatively little experimental work has been done on blanket design or fusion nuclear technologies in general. . . .

## The magnets

**Description.** The external confining magnetic fields in a fusion reactor are generated by large electric currents flowing through magnet coils surrounding the plasma. These magnets must withstand tremendous mechanical forces. . . .

Superconducting coils lose all resistance to electricity when cooled sufficiently; below a temperature called the

TABLE 7

### Fusion fuel cycles[a]

| Cycle | Primary reaction | Percent of energy carried by charged particles |
|---|---|---|
| D-T cycle | $D + T \rightarrow {}^{4}He + n + 17.59$ MeV | 20% |
| | [D = deuterium; T = tritium; $^{4}He$ = alpha particle, or helium nucleus] | |
| D-D cycle | $D + D \rightarrow p + T + 4.03$ MeV | 62%[b] |
| | $D + D \rightarrow {}^{3}He + n + 3.27$ MeV | |
| | [p = proton; $^{3}He$ = helium isotope with one less neutron than $^{4}He$] | |
| D-$^{3}$He cycle | $D + {}^{3}He \rightarrow {}^{4}He + p + 18.34$ MeV | up to 98%[c] |
| D-$^{6}$Li cycle | $D + {}^{6}Li \rightarrow 5$ different reactions | over 65% |
| | [$^{6}Li$ = isotope of lithium] | |
| p-$^{11}$B cycle | $p + {}^{11}B \rightarrow {}^{4}He + {}^{4}He + {}^{4}He + 8.66$ MeV | almost 100%[d] |
| | [$^{11}B$ = isotope of boron] | |

[a] Presented in order of increasing difficulty; the last reaction is from 100 to 10,000 times harder to ignite than the first one, depending on temperature.

[b] 62% is the fraction of the energy carried off by charged particles, assuming that the intermediate reaction products (T and $^{3}He$) react further via D-T and D-$^{3}$He reactions. With these additional reactions, the full reaction is

$$6D \rightarrow p + p + n + n + {}^{4}He + {}^{4}He + 43.23 \text{ MeV}.$$

[c] 98% can be attained for mixtures lean in D and rich in $^{3}He$. . . .

[d] A low-energy (0.15 MeV) neutron is produced in the secondary reaction $^{4}He + {}^{11}B \rightarrow n + {}^{14}N + 0.158$ MeV [$^{14}N$ = isotope of nitrogen].

Source: U.S. Department of Energy, *Background Information and Technical Basis for Assessment of Environmental Implications of Magnetic Fusion Energy*, DOE/ER-0179, August 1983, p. 2-3 (table 2.1) and pp. 2-24, including table 2.2.

*critical temperature,* their magnetic fields can be sustained without any additional power. However, power is required to establish the fields initially, and a small amount of refrigeration power is required to keep superconducting magnets at their operating temperature. . . .

**Status.** The first fusion device built with superconducting magnets was the Soviet T-7 tokamak, completed seven years before any Western fusion device using superconducting magnets. . . . The Soviets are now building T-15, a much larger superconducting tokamak. . . . The Tore Supra tokamak being built in France will also use superconducting magnets. . . . In the United States, MFTF-B was completed in 1986; its superconducting magnets have been successfully tested at their operating conditions. . . .

**Issues.** Recent discovery of new superconducting materials with critical temperatures far above those of previously known materials, and possibly with the capability to reach very high magnetic field strengths, will have a profound impact on a great many fields, including fusion. . . .

## Advanced fuels

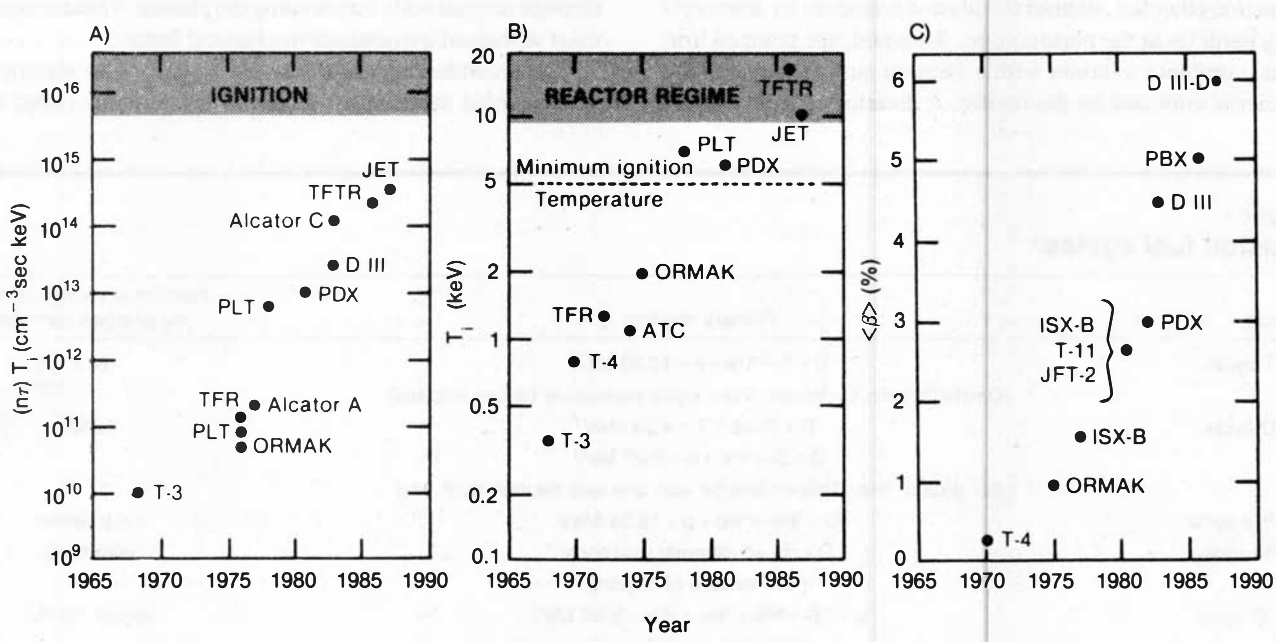
The fusion power core described in the previous section uses D-T fuel because it is by far the most reactive of all potential fusion fuels. This reactivity can be increased still further by aligning the internal spins of the deuterium and tritium nuclei, a technique known as *spin polarization*. If the spins can be aligned initially, the magnetic field of the fusion reactor will tend to keep them in alignment. Therefore, research is ongoing at Princeton Plasma Physics Laboratory to develop intense sources of spin-polarized fuel.

The principal disadvantage of D-T fuel is that the D-T reaction produces energetic neutrons that cause radiation damage and induce radioactivity in reactor structures. Moreover, reactors using D-T must breed their own tritium, substantially adding to reactor complexity and radioactivity levels. For these reasons, the possibility of using other fuels in fusion reactors is being investigated.

Fuels other than D-T require higher temperatures and

FIGURE 13

**Progress in tokamak parameters**



(A) n≅$T_i$, representing the simultaneous achievement of three parameters—density, ion temperature, and confinement time—needed to produce fusion power

(B) $T_i$ = ion temperature

(C) $<\beta>$ = beta = ratio of plasma pressure to magnetic field pressure; provides a measure of the efficiency with which the magnetic fields are used

Source: Updated from National Research Council, *Physicis Through the 1990s: Plasmas and Fluids* (Washington, D.C.: National Academy Press, 1966), figure 4.6, p. 180.

Lawson confinement parameters to reach ignition and higher beta values to perform economically. Achieving these parameters will require stronger magnetic fields, higher plasma currents, and substantial improvements in other plasma technologies beyond those needed to reach ignition with D-T fuel—a task that in itself has not yet been accomplished. However, reactions that use advanced fuels would have a number of advantages:

- They would require little to no tritium, reducing or eliminating the need for the blanket to breed tritium and permitting a much wider range of blanket designs. Tritium inventories would be smaller and the consequent radioactivity levels would be lower.
- They would generate fewer and lower energy neutrons, alleviating radiation damage and minimizing radioactive wastes.
- They might permit the use of more efficient methods to generate electricity from fusion energy. In advanced fuel fusion reactions, more energy is released in the form of energetic charged particles, such as protons or alpha particles, than is the case in the D-T reaction. Therefore, these advanced fuels may be amenable to various techniques that generate electricity directly from the fusion plasma or from plasma-generated radiation without having to first convert the energy into heat. (See the following section on "Advanced energy conversion.")

**Table 7** presents five fusion fuel cycles, including the "baseline" D-T cycle and four possibilities for advanced fuel cycles. Of the advanced cycles, the D-$^3$He cycle is currently drawing the most attention within the fusion community. The primary reaction produces no neutrons, and neutrons resulting from corollary D-D reactions can be minimized by using a mixture consisting mostly of $^3$He or by using spin-polarization.

However, the D-$^3$He reaction is much more difficult to start than the D-T reaction. The minimum temperature required to ignite D-$^3$He is several times higher than that needed for D-T; the minimum confinement parameter is about 10 times higher. Given that the requirements for igniting D-T have not yet been experimentally achieved, attaining conditions sufficient to ignite D-$^3$He is considerably further off. On top of its technological requirements, $^3$He is scarce. It is an isotope of helium with one less neutron than natural helium ($^4$He), and it occurs on Earth only as the end-product of tritium decay. The only way to collect $^3$He is to make tritium and wait for it to decay or to breed $^3$He as the product of another advanced fuel fusion reaction, the D-D reaction. Due to the scarcity of $^3$He, the D-$^3$He reaction has been considered primarily an academic curiosity until recently.

Today, a resurgence of excitement about $^3$He comes with the discovery that it is found in substantial amounts in the uppermost layers of soil on the Moon. Analysis of Moon rocks brought back by the Apollo missions shows that $^3$He, which is constantly emitted by the Sun and carried by the solar wind, is deposited and retained in the lunar surface. In principle, a rocket with the cargo volume of the space shuttle could carry back enough liquid $^3$He to generate all the electricity now used in the United States in one year. . . .

## Advanced energy conversion

Despite the very high-level technology in the fusion core, a baseline fusion reactor would generate electricity in much the same way that present-day fossil fuel and nuclear fission power plants do. Heat produced in the reactor would be used to boil water into steam, which would pass through turbines to drive generators. Through this process, about 35-40% of the energy produced in the fusion reaction would be converted into electricity, with the remainder discharged as waste heat. This efficiency, roughly the same as that of fossil fuel and nuclear fission generating stations, is determined primarily by the process of generating electricity from the energy in the steam. Efficiency could be raised if advanced, high-temperature materials in the blanket and first wall of a fusion reactor permitted higher coolant temperatures to be used.

If the intermediate step of heating steam could be bypassed, a higher percentage of the energy released in fusion reactions could be converted into electricity. Several techniques to integrate generation of electricity directly into the fusion power core have been conceived. One of these, applicable to D-T reactors as well as to advanced fuel reactors, would convert energy carried off by escaping charged particles directly to electricity by collecting the particles on plates. This technique is most applicable to open confinement concepts, in which charged particles can be allowed to escape along magnetic field lines.

Other techniques, which can work with closed confinement concepts, require plasma temperatures significantly higher than the 10- to 15-kiloelectron-volt D-T ignition temperatures. Very hot plasmas radiate more energy away in the form of microwave radiation than cooler plasmas do, and it appears that this radiation could be captured at the first wall or in the blanket and converted directly into electricity. These "direct conversion" techniques would be better suited to advanced fuels, which not only burn at higher temperatures than D-T but also produce most of their energy in the form of energetic charged particles. Unlike neutrons, which escape from the plasma without heating it, charged particles are retained within the plasma. The D-T reaction, in which only 20% of the energy is given to charged particles, is less suitable for techniques that recover energy directly from the plasma.

Several direct conversion techniques that may convert well over 35% of the fusion energy to electricity have been identified. Until they can be tested experimentally under conditions similar to those in an advanced fusion reactor, they must be considered speculative. Nevertheless, they provide a tantalizing goal.

## Research progress and future directions

In 35 years of fusion research, the technological requirements for designing a fusion reactor have become clearer, and considerable progress has been made toward meeting them. Improved understanding, based on both experiments and increased computational ability, is providing much of the predictive capability needed to design, and eventually to optimize, future plasma experiments and fusion reactors.

FIGURE 14
**Emphases of major programs on confinement concepts, 1986**

| Block \ Confinement concept | Tokamak | Tandem mirror | Stabilized Bumpy torus | Stellarator/Heliotron/Torsatron | Reversed field pinch | Other pinch | Compact toroids | Alternate fuels/materials |
|---|---|---|---|---|---|---|---|---|
| U.S. | ● | ▲ |  | ■ | ■ | ▲ | ■ | ▲ |
| Japan | ● | ■ | ■ | ● | ■ |  | ■ |  |
| U.S.S.R. | ● | ■ |  | ■ | ▲ | ▲ | ▲ |  |
| E.C. | ● |  |  | ■ | ■ |  |  |  |

● = Major effort ■ = Moderate effort ▲ = Minor effort

Source: Fusion Power Associates.

Major advances in plasma research have been made possible by progress in tokamak plasma technologies:

- By the 1960s, experiments demonstrated the crucial importance of attaining high vacuum and low impurity levels in the plasma to achieve high densities, temperatures, and confinement times.
- In the mid-1970s, neutral beam technology was first used to heat plasmas to temperatures several times higher than those previously attained. High-performance, high-field copper magnets were used to obtain high Lawson confinement parameters in compact tokamak plasmas.
- The development in the late 1970s of pellet injectors to fuel plasma discharges led to further advances in plasma density and confinement. Development of the poloidal divertor at about the same time led to the discovery of the "H-mode," a mode of tokamak behavior that was not subject to degraded confinement when auxiliary heating was used.
- In the early 1980s, advances in high-power radiofrequency technology gave experimenters new tools to modify the temperature, current, and density distributions within the plasma. Much of this new capability has yet to be exploited.

These accomplishments have contributed to the steady progress in plasma parameters plotted in **Figure 13.** Figure 13a shows the product of the temperature, density, and confinement time that has been achieved simultaneously in various experiments over the last 20 years. Since all three of these parameters must be high simultaneously for the product to be high, this product provides a rough measure of how well these three requirements have been simultaneously achieved.

Figure 13b plots the temperature alone and compares it to the minimum temperature below which neither breakeven nor ignition can occur no matter how high the density and confinement time. The TFTR point shows temperatures well

FIGURE 15
**Emphases of major programs on technology development, 1986**

| Program \ Technology area | Superconducting magnets/cryogenics | Neutral beams | RF heating | Pellet fueling | Tritium handling | Remote maintenance | First wall and attachments | Blanket | Shield | Materials studies | Particle handling | Impurity control | Diagnostics | Computing, data, processing and control | Energy storage, transfer and switching | Advanced reactor studies | Alternate applications | Environment and safety | Atomic physics |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| U.S. | ■ | ▲ | ● | ● | ■ | ▲ | ■ | ▲ | ▲ | ■ | ■ | ■ | ● | ■ | ▲ | ▲ | ▲ | ■ | ▲ |
| Japan | ■ | ● | ● | ▲ | ■ | ● | ● | ▲ | ▲ | ■ | ■ | ■ | ■ | ■ | ■ | ▲ | ▲ | ■ | ■ |
| U.S.S.R. | ▲ | ■ | ■ | ▲ | ▲ | ▲ | ■ | ▲ | ▲ | ■ | ■ | ■ | ■ | ■ | ■ | ▲ | ▲ | ▲ | ■ |
| E.C. | ■ | ■ | ● | ● | ● | ● | ● | ■ | ■ | ■ | ■ | ■ | ● | ● | ■ | ▲ | ▲ | ■ | ■ |

● = Major effort ■ = Moderate effort ▲ = Minor effort

Source: Fusion Power Associates.

into the reactor regime and far above that needed for ignition. However, the fact that the corresponding TFTR point in Figure 13a is below the ignition threshold indicates that high temperature is not sufficient; the product of density and confinement time must also be high for ignition.

Figure 13c shows progress in the parameter beta, the ratio of plasma pressure to magnetic field pressure. Note that devices that have achieved high values on one of the three plots often have not been the ones that have gotten the highest values in others. Future devices will have to achieve high values in all areas simultaneously. . . .

**Probability of success.** It seems likely that at the conclusion of the research program, fusion's technological feasibility—the ability to use fusion power to generate electricity—can be shown. The fusion program has made steady progress over the last 35 years on the key technical issues. It is still possible that fusion's scientific feasibility will be impossible to demonstrate, due to surprises in the behavior of a plasma that generates substantial amounts of fusion power. However, sucessfully attaining ignition in CIT [Compact Ignition Tokamak] will resolve most of the scientific uncertainties.

Most of the subsequent scientific and engineering challenges in designing and building a reactor have been identified. *Once scientific feasibility is established, a concerted and well-funded research effort should be able to develop a reactor that produces fusion power*. . . .

## Comparison of international fusion programs

Comparing levels of effort among the international fusion programs is complex. Qualitative measures show that the programs are similar in direction and achievement, but these measures are subjective. Quantitative measures are more objective, but they may be distorted. Moreover, different techniques give different results. . . .

Qualitative comparisons show that the four major fusion programs are comparable in levels of effort and accomplishment and in their near-term research objectives, although the stated long-term goals and rationales for the programs differ (see **Table 8**). Three of the programs operate tokamak experiments of similar capability and complexity, and the fourth (the Soviet Union) is in the process of building a large tokamak of somewhat similar capability; each program also studies alternative confinement concepts. All of the programs recognize the need for a next-generation experiment during the mid-1990s to advance fusion technology and science. . . .

**Figure 14** compares the programs' research and development emphases on confinement concepts, and **Figure 15** compares their technology development efforts. Variations among programs are influenced by differing program concentration, funding levels, technological capabilities, and program history. . . .

TABLE 8

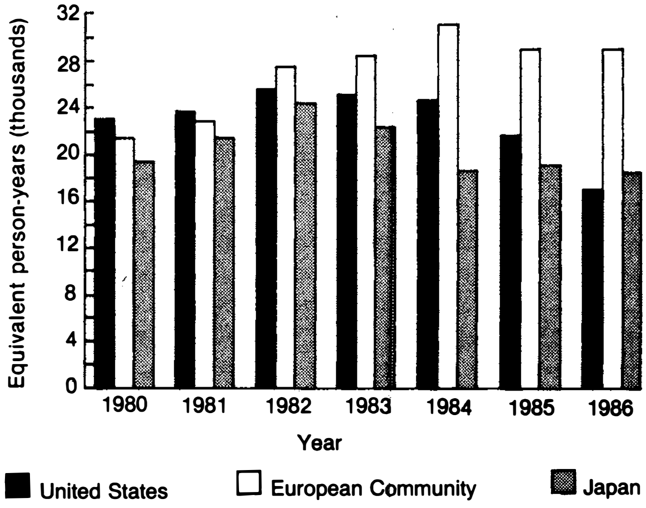
**Program goals of the major fusion programs**

| Program Goal | Rationale |
|---|---|
| **U.S.** | |
| Demonstrate science and technology base for fusion power | Determine potential as an energy option |
| **EC** | |
| Prototype construction | Develop energy option<br>Promote industrial capability<br>Strengthen political unity |
| **Japan** | |
| Demonstration plant | Develop energy option<br>Fulfill national project |
| **U.S.S.R.** | |
| Fusion hybrid system | Support fission program |

To correct for distortions from fluctuating exchange rates, DOE has used another method to compare fusion programs. In this method, the fusion budget of each program is divided by the average annual manufacturing wages prevailing in the country or region, with both values measured in local currency. The resulting value is a measure of the level of effort of each program in units of "equivalent person-years." Comparisons are shown in **Figure 16.**

FIGURE 16

**Comparison of international equivalent person-years**



Source: U.S. Department of Energy, Office of Fusion Energy, 1986.