FUSION ENERGY

As far as is known, *nuclear fusion*, which drives the stars, including the Sun, is the primary source of energy in the universe. The process of nuclear fusion releases enormous amounts of energy. It occurs when the nuclei of lighter elements, such as hydrogen, are fused together at extremely high temperatures and pressure to form heavier elements, such as helium. Whereas practical methods for harnessing fusion reactions and realizing the potential of this energy source have been sought since the 1950s, achieving the benefits of power from fusion has proved to be a difficult, long-term challenge.

Fusion is widely held to be the ultimate resource for the world's long-term energy needs. The fuel reserves for fusion are virtually limitless and available to all countries. Fusion fuels can be extracted from water. Additionally, fusion promises to be an energy source which is potentially safe and environmentally benign. Radiological and proliferation hazards are much smaller than for fission power plants. The atmospheric impact is negligible compared to fossil fuels, and adverse impacts on the Earth's ecological and geophysical processes are smaller than for large-scale renewable energy sources (see also Coal; Fuel resources; Fuels, synthetic; Gas, natural; Petroleum; Renewable energy resources). The economics and costs of fusion power plants are still being studied, but appear comparable to those for other medium- and long-term energy sources (see Power generation). The tantalizing promise of affordable essentially unlimited supplies of clean, safe energy, free of political boundaries, has motivated a worldwide research effort to develop this energy resource.

The nuclear burning mechanism of the Sun was elucidated in the 1930s (1). In a complex sequence of reactions starting with hydrogen, atomic nuclei are fused to form heavier species. Because of a mass deficit, Δm, exhibited by the reaction products, large amounts of energy, E, are released, as dictated by the well-known Einstein equivalence $E = \Delta mc^2$ where c is the speed of light. Large-scale fusion energy production was demonstrated dramatically on earth in the early 1950s with the explosion of thermonuclear fusion, ie, hydrogen, bombs. These weapons used the heat of nuclear fission (atomic bombs) to cause the fusion of deuterium [16873-17-9], D, and tritium [15086-10-9], ^{3}H or T. Subsequently, an international research effort was undertaken to harness this awesome power on a controllable scale for peaceful purposes. Several impressive advances in the 1980s and early 1990s have led to a well-founded feeling of optimism that fusion energy should become a practical energy source during the early twenty-first century.

In order to effect a fusion reaction between two atomic nuclei, it is necessary that these nuclei be brought together closely enough to experience an attractive nuclear force. All nuclei are positively charged and repel one another via Coulomb's law, the electrostatic law of the repulsion of like charges. This electrostatic barrier can be overcome by imparting sufficient kinetic energy to the reacting species so that the nuclei can approach closely enough together that quantum mechanical tunneling can occur. The repulsive forces increase rapidly with the magnitude of the nuclear charge; therefore, nuclear fusion research has concentrated on the lightest elements and the isotopes having the lowest atomic numbers.

The reactions of deuterium, tritium, and helium-3 [14762-55-1], ^{3}He, having nuclear charge of 1, 1, and 2, respectively, are the easiest to initiate. These have the highest fusion reaction probabilities and the lowest reactant energies.

1. Deuterium–Tritium Fusion

The D–T reaction involving the two heavy isotopes of hydrogen

$$D + T \longrightarrow {}^4He + n$$

is especially attractive to fusion scientists because of its relative ease of ignition. The products of this reaction are an alpha particle, ie, the helium nucleus, ^4He, and a free neutron, n, carrying kinetic energies of 3.5 and 14.1 MeV, respectively. In an electric power-generating facility the neutrons would be absorbed in a blanket surrounding the fusion region, and the kinetic energy converted into heat. Conventional power conversion systems could then be used to transform this heat into electrical energy. Fusion reactions are extremely energetic, and yields are measured in units of millions of electron volts, MeV ($1\ \text{MeV} = 1.6 \times 10^{-13}\ \text{J}$) (see DEuterium and tritium; Helium group, gases).

Another set of reactions of practical interest involves only deuterons. The D–D reaction can proceed along either of two pathways with roughly equal probabilities:

$$D + D \longrightarrow T + p + 4.0\ \text{MeV}$$

or

$$D + D \longrightarrow {}^3He + n + 3.2\text{MeV}$$

Finally, the D–^{3}He reaction

$$D + {}^3He \longrightarrow {}^4He + p$$

is noteworthy not only because of its high (18.3 MeV) energy release, but also because the reaction products are both charged particles, offering the possibility of high efficiency, direct energy conversion. Direct energy conversion would involve the extraction of the positively charged ions and negatively charged electrons from the reaction region directly onto collection electrodes having a potential difference of the same order of magnitude as the mean kinetic energy of the charged particles. A variation of the above reaction schemes is the catalyzed D–D reaction wherein the external feedstock is deuterium but the ^3He and T produced in the D–D reactions are recycled and burned *in situ* to enhance the net energy yield.

Because of its relatively high reactivity (2), the D–T fusion-fuel cycle is very likely to be employed in the first generation of fusion reactors. This implies the use of a neutron absorbing blanket and thermal (Carnot) conversion efficiencies. Deuterium, also known as heavy hydrogen, occurs naturally in the ratio of 1:6700 relative to ordinary hydrogen; 30,000 kg water contains one kilogram of deuterium. The separation of deuterium from water is a relatively simple and inexpensive process. Tritium, on the other hand, is a radioactive isotope of hydrogen found in nature only in trace amounts and has a half-life of only 12.36 yr. The initial inventory of tritium for a power-producing D–T fusion reactor is a few kilograms and could be supplied, for example, from heavy-water fission reactors where it is produced as a by-product. Further tritium needs can be met by breeding additional tritium in the fusion reactor itself, by absorbing the fusion-produced neutrons in a blanket of lithium and exploiting the reaction

$$n + {}^6Li \longrightarrow T + {}^4He + 4.8\ \text{MeV}$$

^6Li accounts for about 7.5% of natural lithium and is abundantly available in the earth's crust and oceans. Detailed fusion-blanket designs incorporate additional isotopes, such as ^7Li and ^9Be, which provide neutron-multiplying reactions, to compensate for the leakage and absorption losses of neutrons. A D–T fusion reactor, then, is in reality a consumer of deuterium and lithium. The estimated reserves of lithium should prove sufficient for at least several hundred years of D–T fusion reactor operation, even allowing for a significant increase in the world demand for energy (3). A common fusion evolution scenario relies on D–T fusion to fulfill the energy needs until the more difficult fuel cycle involving pure deuterium can be implemented. Then deuterium alone would be the fuel for the fusion energy economy. Because each liter of seawater contains enough deuterium to supply the energy equivalent of 300 L of gasoline, long-term energy needs would be assured.

Although the D–T reaction is the easiest route to fusion power production, it is no easy task to meet the conditions required to produce net fusion energy. Relative kinetic energies between the deuterons and tritons of 10 keV or more are necessary for practical energy generation, corresponding to relative particle velocities on the order of 10^6 m/s. Fusion-produced neutrons have, in fact, been created by impinging a beam of accelerated deuterons onto a solid target containing tritium. Unfortunately, a fusion reactor cannot be built around this concept because most of the incident beam energy is dissipated nonproductively through scattering and collision events in the target, and only a relatively small number of energy-producing fusion reactions occur. Other approaches, involving colliding beams of particles, have been proposed, but such schemes are inherently of very low power density and are not likely to yield practical energy sources.

2. Plasma Conditions Required for Net Energy Release

The most promising approach to attaining significant reaction rates is to heat the reacting species to a high temperature, thereby imparting large kinetic energies to the nuclei in the form of thermal motions. By doing so, the particles, eg, deuterons and tritons, may scatter among themselves many times before undergoing fusion reactions, without losing significant energy from the system. At any given temperature, a system of particles in thermal equilibrium is characterized by a Maxwellian distribution of kinetic energies. The particles at the high energy end of this distribution account for most of the fusion reactions in fusion experiments.

The fusion fuel, when undergoing thermonuclear reactions, exists as an ionized gas called a plasma. In physics, the plasma state usually means a high temperature gas of net electrical neutrality consisting of free electrons and ions exhibiting collective behavior. The collection of charged particles exhibits characteristics of an electrically conducting fluid that can interact with electromagnetic fields. As such, its physical behavior is much more complex than that of an ordinary gas, and plasma confinement can be disrupted or reduced by many different kinds of plasma instabilities and other loss mechanisms. There exists a large literature and a number of outstanding books on plasma physics, such as Reference 4 (see also Plasma technology).

In a plasma undergoing fusion reactions, the reactivity, and thus the fusion-power output rate, increases with increasing temperature. However, over a wide range of temperatures, as the temperature of the plasma is raised, the radiation losses are also increased, primarily because of bremsstrahlung, or continuum, ie, braking radiation from the electrons. For any fusion-fuel system there exists a unique temperature at which the fusion power production is precisely balanced by the radiation losses. This temperature is called the ideal ignition temperature, and equals about 50 million K (5 keV) for a D–T plasma ($1\ \text{keV} = 11.6 \times 10^6\ \text{K}$). For a D–D plasma, this temperature is considerably higher, about $400 \times 10^6\ \text{K}$ (40 keV), a fact which considerably increases the difficulty of using pure deuterium fuel. Furthermore, a fusion system must be operated above the ideal ignition temperature for net power production, typically by a factor of 2–5.

Besides having to satisfy a minimum temperature requirement, the plasma must be sufficiently dense and contained for a long enough time to yield net power. If the plasma burns above the ideal ignition temperature for some time period, τ, the fusion energy released must at least equal the energy required to heat the plasma to that temperature plus the energy radiated during that period. It can be shown that this condition is met by requiring that the product of the plasma density, n, and confinement time, τ, exceed a characteristic value which depends only on the temperature. The minimum value of the product $n\tau$ represents the least stringent condition for the plasma to be a net producer of fusion energy. For D–T plasmas, this minimum occurs at a temperature of about 100×10^6 K, for which $n\tau \sim 10^{20}$ s/m^3. This mininum $n\tau$ product is called the Lawson cirterion product is called the Lawson criterion (5). For D–D, the minimum $n\tau$ product is about 10^{22} s/m^3 at a higher temperature, again indicating that a pure deuterium system requires a higher quality of confinement. A commonly used measure of the quality of plasma confinement is given by the triple product of the plasma density, n, ion temperature, $T_{\rm i}$, and energy confinement time, τ, usually expressed in units of keV·s/m^3. A primary goal of fusion research is to achieve $n\tau T_{\rm i}$ values of $\sim 10^{22}$ keV·s/m^3, as required for a D–T reactor. Experiments as of this writing (1993) have reached a value of 1.1×10^{21} keV·s/m^3 in the JT-60 tokamak in Japan (6).

Plasmas at fusion temperatures cannot be kept in ordinary containers because the energetic ions and electrons would rapidly collide with the walls and dissipate their energy. A significant loss mechanism results from enhanced radiation by the electrons in the presence of impurity ions sputtered off the container walls by the plasma. Therefore, some method must be found to contain the plasma at elevated temperature without using material containers.

Once a fusion reaction has begun in a confined plasma, it is planned to sustain it by using the hot, charged-particle reaction products, eg, alpha particles in the case of D–T fusion, to heat other, colder fuel particles to the reaction temperature. If no additional external heat input is required to sustain the reaction, the plasma is said to have reached the ignition condition. Achieving ignition is another primary goal of fusion research.

3. Paths to Fusion Power

Two diverse technical approaches to fusion power, magnetic confinement fusion, also known as *magnetic fusion energy (MFE)* and inertial confinement fusion, also known as *inertial fusion energy (IFE)* are being pursued worldwide. These form the basis of a large number of fusion research programs. Magnetic confinement techniques, studied since the 1950s, are based on the principle that charged particles such as electrons and ions, ie, deuterons and tritons, tend to be bound to magnetic lines of force. Thus the essence of the magnetic confinement approach is to trap a hot plasma in a suitably chosen magnetic field configuration for a long enough time to achieve a net energy release, which typically requires an energy confinement time of about one second. In the alternative IFE approach, fusion conditions are achieved by heating and compressing small amounts of fuel ions, contained in capsules, to the ignition condition by means of tightly focused energetic beams of charged particles or photons. In this case the confinement time can be much shorter, typically less than a millionth of a second.

3.1. Magnetic Confinement

In magnetic confinement, strong magnetic fields are used to confine the plasma. Electrons and ions in magnetic fields spiral in circles around the field lines but translate freely along the direction of the magnetic field. Thus the magnetic field of a long solenoid, for example, confines the plasma in two directions but does not prevent the particles from streaming from either end of the system. Furthermore, collisions between particles displace them from one field line to another, producing a net diffusion of plasma across the field toward the walls of the container. By employing more complex magnetic field configurations, fusion researchers have made significant progress toward solving the problem of magnetic confinement of plasmas by substantially reducing plasma losses.

One of the earliest configurations studied was the simple magnetic mirror. A simple mirror system is depicted in Figure 1. Particles gyrating about the field lines move freely along these lines until they enter regions of increased field strength at either end of the device. Conservation of angular momentum considerations dictate that, as the particles approach the end regions, they gyrate more energetically about the field lines and slow

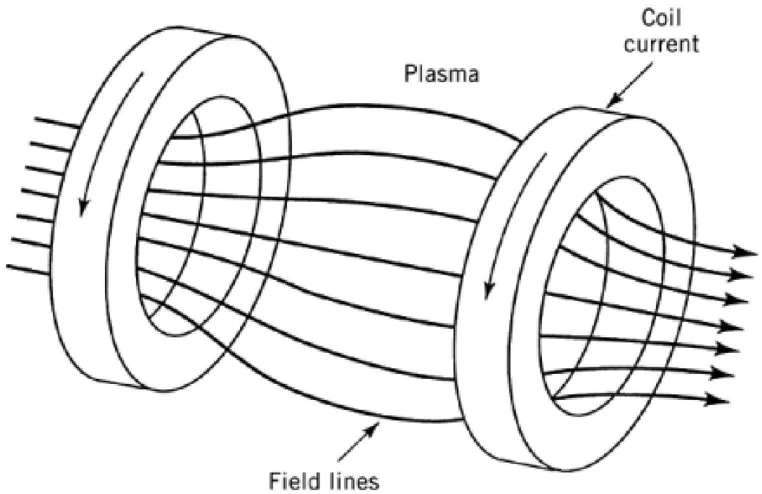

Fig. 1. Simple magnetic mirror open configuration.

down in the direction of motion along the lines. Ultimately, their kinetic energy is completely converted into gyration energy, at which point the particles are reflected from these mirror points and return to the central, weaker field region. Particles having motion exactly along the axis of the device are not reflected and are lost through the ends. Although ingenious attempts have been made to reduce end losses from mirror machines and to make them stable against magnetohydrodynamic (MHD) and other instabilities, all single-cell mirror reactor designs have suffered from a high recirculating power fraction, ie, a lot of the output power has to be used to operate the reactor itself. In single-cell mirror machines these losses are fundamentally too high. The machines are referred to as too lossy, and the amount of injected power required to maintain the plasma, usually in the form of high energy neutral beams, has been too large to be practical.

A more advanced mirror approach involving multicells, called the tandem mirror, has been studied as a means to overcome the leakage problem. One way to view the tandem mirror is as a long uniform magnetic solenoid with two single-cell mirrors installed at the ends to electrostatically plug the device. Plasma end losses are impeded by electrostatic potentials developed by the plasma as the electrons and ions attempt to leave the device at different rates.

Another mirror variation is the field-reversed mirror configuration, in which the diamagnetic nature of the plasma is exploited to cause the interior magnetic field lines within the central region of a single-cell mirror to reverse and close on themselves. The plasma current responsible for this field modification is at right angles to the original field lines.

The problem with all the mirror approaches is that none has achieved the degree of confinement quality that the closed systems have. Closed systems are characterized by magnetic field lines that close on themselves so that charged particles following the field lines remain confined within the system.

The simplest way of producing a closed configuration is to employ a torus or doughnut-shaped container having current-carrying coils wrapped around the minor diameter as shown in Figure 2. In this geometry, the magnetic lines of force are circles that traverse the torus and provide endless paths for the plasma ions and electrons to spiral about. Unfortunately, such a simple toroidal configuration is well known to have very poor confinement properties, because the magnetic field strength is not constant across the plasma. Instead, it is stronger at the inner wall and weaker at the outer wall of the toroidal chamber. As a result, the positive ions and electrons drift in opposite directions across the field lines and establish an electric field within the plasma.

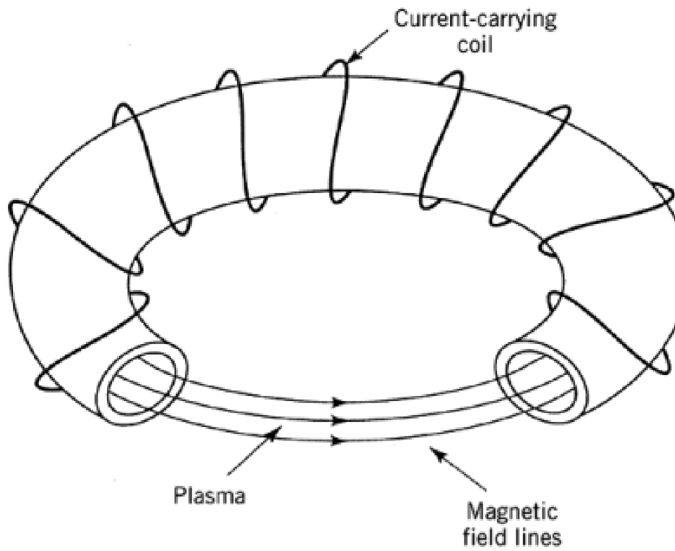

Fig. 2. Cutaway view of a simple toroidal field configuration.

This electric field, coupled with the applied magnetic field, then causes the plasma as a whole to move to the container wall and dissipate its energy (2).

This deleterious effect can be obviated by introducing additional components of magnetic field, causing the field lines to circumscribe the torus without ever closing on themselves. The net magnetic field is then composed of a major, or toroidal, field component produced by the current coils, plus a smaller poloidal component which gives the desired twist to the lines. Particle drifts weaken or nullify the harmful electrical field and the plasma no longer tends to move to the walls.

Several geometries for producing the required poloidal magnetic field component have been studied. The class of plasma devices called tokamaks generates the poloidal, ie, around the minor circumference, field component from a toroidal, ie, around the major circumference, current in the plasma itself, either induced by a pulse from an external transformer or driven by external current-drive systems. The basic components of a tokamak are shown in Figure 3. External current-drive systems, such as high energy neutral beam injection or radio-frequency (r-f) current drive, impart a net toroidal momentum to one of the charged species, ions or electrons. A toroidal system related to the tokamak, which has a higher plasma energy density, is called the reversed field pinch (RFP). The RFP is an inherently pulsed, or batch-burn device.

The poloidal field component can also be created externally by using current-carrying coils that wind helically around the outside surface of the torus. Such devices, called stellerators or torsatrons, have the advantage of not requiring a net toroidal current. The helical field windings, however, make these machines mechanically and magnetically more complex than the tokamak.

3.1.1. Tokamak

The design concept that has come the closest by far to achieving energy breakeven conditions is the tokamak. Invented in the 1950s by the Russian physicists Andrei Sakharov and Igor E. Tamm (7), the tokamak derives its name from the Russian acronym for toroidal magnetic chamber. Technical progress in tokamaks was dramatic in the late 1980s and early 1990s (8, 9). Central ion temperatures of 400×10^6 K have been reached, and energy confinement times have increased from 0.02 to about 1.4 seconds for strongly heated plasmas. The result has

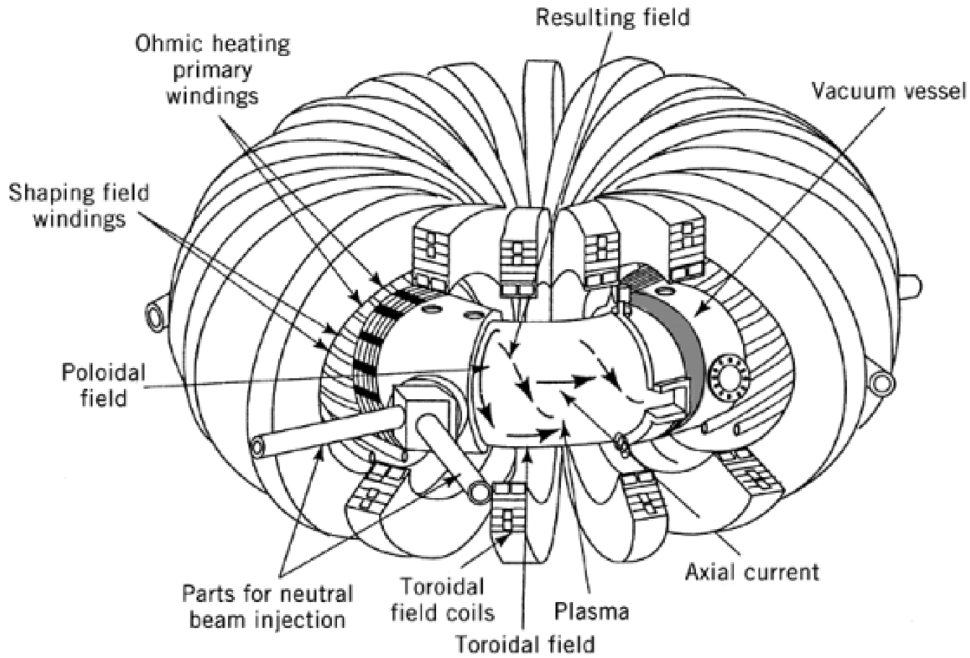

Fig. 3. The tokamak fusion approach.

been $n\tau T_i$, triple products, of about 10^{21} KeV·s/m^3, compared to the value of $\sim 10^{22}$ keV·s/m^3 required for a steady state D–T reactor.

Other important parameters have also shown dramatic gains. The normalized plasma pressure which is usually called beta, the plasma pressure divided by the confining magnetic field pressure, has been increased fourfold, to about 10%. This value is actually higher than that needed in a reactor. Bootstrap currents have been measured for the first time in several experiments. Bootstrap current is the name given to a toroidal current, theoretically predicted to arise spontaneously in tokamaks under near-reactor conditions. These in principle can eliminate much of the need for external current drive. *Bootstrap currents* open the possibility of a self-sustained steady-state tokamak reactor. Results from the large Japanese tokamak JT-60 are particularly interesting in this regard, where up to 80% of the 500,000 A of total plasma current is attributed to the bootstrap effect (8). Table 1 summarizes some of the progress made in the parameters of interest for magnetic fusion since 1971.

Some of the tokamaks in operation around the world, on which the data in Table 1 were obtained are Additionally, two other reactors, the international thermonuclear experimental reactor (ITER) for which the location is under negotiation, and the Tokamak Physics Experiment at PPPL, Princeton, New Jersey, are proposed. The most impressive advances have been obtained on the three biggest tokamaks, TFTR, JET, and JT-60, which are located in the United States, Europe, and Japan, respectively. As of this writing fusion energy development in the United States is dependent on federal funding (10–12).

Until 1992, tokamak experiments were performed using deuterium or hydrogen only. The use of radioactive tritium greatly complicates the operation of experimental facilities, impeding the pace of research. Certain experiments, however, such as those directly involving D–T fusion, cannot be done without the use of tritium. A European research team in 1992 produced nearly 2 million watts of fusion power for about one second in the JET device, and opened the modern frontier of D–T fusion experiments (13). Only about half of the JET fusion energy release came from fusion in the thermal plasma, at temperatures of 15–20 keV. The other half

Table 1. Tokamak Plasma Parameters

Parameter	Achieved 1971	1981	1991	Required for steady-state D–T reactor
central ion temperature, T_i, keV	0.5	7	35	30
central electron temperature, T_e, keV	1.5	3.5	15	30
energy confinement time, τ, s	0.007	0.02	1.4	3
triple product, $n\tau T_i$, keV·s/m^3	1.5×10^{17}	5.5×10^{18}	9×10^{20}	7×10^{21}
normalized plasma pressure, β, %	0.1	3	11	5
fusion reactivity, reactions per second				
D–D		3×10^{14}	1×10^{17}	
D–T			6×10^{17}	10^{21}

Designation	Tokamak	Location
ALC-A	Alcator-A	Plasma Fusion Center, Massachusetts Institute of Technology (MIT), Cambridge, Mass.
ALC-C	Alcator-C	Plasma Fusion Center, MIT
ASDEX	Axially Symmetric Divertor Experiment	Max Planck Institute for Plasma Physics, Garching, Germany
ATC	Adiabatic Toroidal Compressor	Princeton Plasma Physics Laboratory (PPPL), Princeton, N.J.
C-MOD	ALC-C Modified	MIT
DIII	Doublet III	General Atomics, San Diego, Calif.
DIII-D	Doublet III-D	General Atomics, San Diego, Calif.
ISX-B	Impurity Studies Experiment B	Oak Ridge National Laboratory (ORNL), Oak Ridge, Tenn.
JET	Joint European Torus	Abingdon, England
JFT-2M		Japan Atomic Energy Research Institute, Tokai, Japan
JT-60		Japan Atomic Energy Research Institute, Naka, Japan
ORMAK	Oak Ridge Tokamak	ORNL
PDX	Princeton Divertor Experiment	PPPL
PLT	Princeton Large Torus	PPPL
T-3	Tokamak-3	Kurchatov Institute, Moscow
T-10	Tokamak-10	Kurchatov Institute, Moscow
T-15	Tokamak-15	Kurchatov Institute, Moscow
TFR	Tokamak Fontenay-aux-Roses	Centre d'Etudes Nucleaire, Fontenay-aux-Roses, France
TFTR	Tokamak Fusion Test Reactor	PPPL

came from fusion of the injected tritium beams striking the deuterium in the plasma. The ratio of tritium to deuterium was about 2% in JET. If a 50:50 mixture of tritium and deuterium had been used instead, an amount of fusion energy would have been released roughly equal to the energy required to heat and sustain the plasma, giving an energy gain, Q, of about unity. In December 1993, scientists at the Princeton Plasma Physics Laboratory initiated a series of experiments on the Tokamak Fusion Test Reactor (TFTR), introducing D–T fuel into the machine and producing over 6 MW of fusion power. For the first time in a tokamak experiment an approximately 50:50 mixture of deuterium and tritium was used as the fusion fuel. Preliminary analysis of the first 100 experimental runs indicated that the confinement in a D–T fuel mixture was better than in a pure deuterium plasma, the ion and electron temperatures were higher, and the plasma stored energy longer. No enhanced loss of alpha particles (the product of D–T fusion reactions) was observed as the fusion power was increased. These results are encouraging for tokamak-based power generation.

3.1.2. International Thermonuclear Experimental Reactor

One of the largest obstacles to the development of fusion power has been that high powered, and correspondingly expensive, research facilities are needed at each step of the reactor development path. ITER (pronounced "eater") is a project supported by the United States, Japan, the European community, and Russia, wherein each party contributes equally to the effort and shares equally in the results (9). The main reason for making the ITER an international effort is cost sharing. The project is managed under the auspices of the International Atomic Energy Agency (IAEA), and the design is based on the tokamak concept. The central purpose of the ITER is to demonstrate the scientific and technological feasibility of fusion power by achieving, for the first time, controlled ignition and extended burn in a D–T plasma. ITER is expected to accomplish this by demonstrating technologies essential to a reactor in an integrated system, and by integrated steady-state testing of the high heat-flux and nuclear components (9).

A preliminary design of ITER, done in 1988–1990 by an international team (14), utilizes superconducting magnets. The heating and current drive are provided by a combination of 1.3 MeV negative-ion neutral beams, lower-hybrid frequency rf, and electron-cyclotron frequency rf. The negatively charged beams of deuterons or tritons are to be accelerated to 1.3 MeV, neutralized, and then injected, unperturbed by the confining magnetic field, into the plasma. The design is based on a conservative assessment of physics knowledge and allows for operational and experimental flexibility. The design calls for plasma major radius of 6 m, plasma minor radius of 2.1 m, plasma current of 2 MA, magnetic field of 4.85 T, average neutron wall loading of about 1 MW/m^2, and fusion power of about 1 GW thermal.

The second phase of ITER, the engineering design activity (EDA), was begun in 1992 and is scheduled to be completed in 1998. The ITER engineering design is being conducted at three cocenters: San Diego, California; Graching, Germany; and Naka, Japan. At these cocenters, multinational teams focus on developing a mature design in sufficient detail to allow the construction of the machine, with industrial vendors able to bid on the fabrication and installation of ITER systems. The first ITER plasma could be made as early as 2005. D–T operation could begin a few years later.

3.2. Inertial Confinement

Because the maximum plasma density that can be confined is determined by the field strength of available magnets, MFE plasmas at reactor conditions are very diffuse. Typical plasma densities are on the order of one hundred-thousandth that of air at STP. The Lawson criterion is met by confining the plasma energy for periods of about one second. A totally different approach to controlled fusion attempts to create a much denser reacting plasma which, therefore, needs to be confined for a correspondingly shorter time. This is the basis of inertial fusion energy (IFE). In the IFE approach, small capsules or pellets containing fusion fuel are compressed to extremely high densities by intense, focused beams of photons or energetic charged particles as shown in Figure 4. Because of the substantially higher densities involved, the confinement times for IFE can be much shorter. In fact, no external means are required to effect the confinement; the inertia of the fuel mass is sufficient for net energy release to occur before the fuel flies apart. Typical burn times and fuel densities are 10^{-10} s and 10^{31}–10^{32} ions/m^3, respectively. These densities correspond to a few hundred to a few thousand times that of ordinary condensed solids. IFE fusion produces the equivalent of small thermonuclear explosions in the target chamber. An IFE power plant design, therefore, must deal with very different physics and technology issues than an MFE power plant, although some requirements, such as tritium breeding, are common to both. Some of the challenges facing IFE power plants include the highly pulsed nature of the burn, the high rate at which the targets must be made and transported to the beam focus, and the interface between the driver beams and the reactor chamber (15).

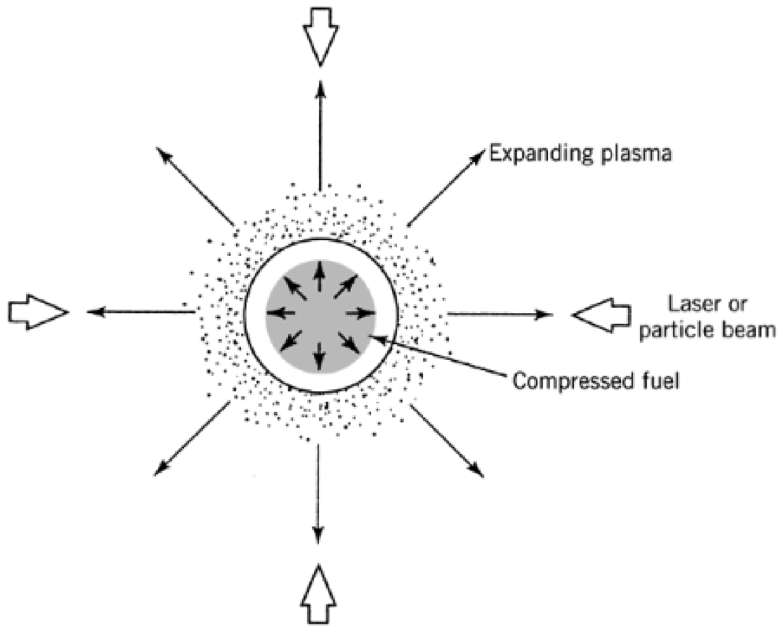

Fig. 4. ICF capsule compression.

3.2.1. Drivers

In inertial fusion the fuel is compressed and heated using driver beams. Achieving ignition requires a large amount of energy to be precisely controlled and delivered to the fuel target in a very short time, and the target must be capable of absorbing this energy efficiently. To produce net energy, the IFE system must have gain, ie, more energy output than was used to make, compress, and heat the fuel. Driver efficiency and capsule design and fabrication are therefore important issues for an IFE reactor (16).

The necessary energy can be delivered to the fuel by a variety of possible drivers. The four types of drivers receiving the most research attention are solid state lasers, KrF lasers, light-ion accelerators, and heavy ion accelerators. The leading driver for target physics experiments worldwide is the solid-state laser, and in particular the Nd:glass laser. The reason is that the irradiances required for IFE are in the 10^{18}–10^{19} W/m^2 range (17). The Nd:glass laser was the first driver which could produce these large power densities on target and it has remained in the forefront because of its high performance, reliable technology, and relative ease of maintenance. Low efficiencies and pulse rates have traditionally eliminated Nd:glass lasers from serious consideration in IFE reactor designs. However, new Nd:glass technology, replacing flash lamp pumping with higher efficiency diode pumping and utilizing crystalline disks and gas cooling, could change this view. Higher driver efficiencies are achievable in KrF lasers and particle beam accelerators. Particle beams have thus far had difficulty in achieving the low divergences and small focal spots required for IFE experiments, a technical area where lasers have a natural advantage. In IFE reactors, however, focal spots as large as 1 cm are permitted, and it appears that both light and heavy ion drivers could meet this requirement.

3.2.2. Targets

Two types of IFE targets have been investigated known as direct and indirect drive targets. Direct-drive targets absorb the energy of the driver directly into the fuel capsule, whereas indirect-drive targets use a cavity, called a hohlraum, to convert the driver energy to x-rays which are then absorbed by the fuel capsule.

This latter method can tolerate greater inhomogeneities in driver illumination, albeit at the expense of the efficient delivery of energy to the capsule.

The extremely high peak power densities available in particle beams and lasers can heat the small amounts of matter in the fuel capsules to the temperatures required for fusion. In order to attain such temperatures, however, the mass of the fuel capsules must be kept quite low. As a result, the capsules are quite small. Typical dimensions are less than 1 mm. Fuel capsules in reactors could be larger (up to 1 cm) because of the increased driver energies available.

3.2.3. Laser Fusion

The largest and most powerful operating laser in the world is the NOVA 10-beam Nd:glass laser facility at the Lawrence Livermore National Laboratory in California. NOVA can deliver up to 40 kJ of 351-nm light in a 1-ns pulse onto the target. NOVA is primarily used for indirect-drive experiments. Other large Nd:glass laser facilities include the GEKKO XII laser at Osaka University in Japan, and the OMEGA laser at the Laboratory for Laser Energetics at the University of Rochester (Rochester, New York). The latter is used primarily for direct-drive experiments (see Lasers).

The krypton–fluoride (KrF) laser, which uses a gaseous lasing medium, can in principle operate at much higher pulse repetition rates and efficiencies than solid-state Nd:glass lasers. Moreover, the shorter (250 nm) wavelength and broad bandwidth, both of which improve coupling to the target, provide additional advantages. However, the use of KrF lasers is complicated by the long pulse length, which, for the 1 ns time scales of IFE, has to be shortened by a factor of about 100. At least two schemes have been proposed and demonstrated (15). In one method, angular multiplexing, many short, low power pulses are sent sequentially through the laser power amplifier stage for the entire duration of the pumping pulse, each at a different angle. After traversing paths of different optical length, these pulses are recombined at the target into a single high amplitude short pulse. In the second method, a long pulse is extracted and subsequently shortened in a Raman scattering cell filled with, for example, SF_6 gas (see Infrared technology and Raman spectroscopy). Through Raman backscattering, the pulse can be shortened by the desired factor of 100. Both techniques have been demonstrated (15). KrF laser technology is not as well developed as the technology for Nd:glass lasers, however, and no KrF lasers have been constructed which are as powerful as NOVA. The efficiency of KrF lasers may also fall a little short of that needed for a power producing reactor.

3.2.4. Particle Beam Fusion

Advances in pulsed power technology have enabled large quantities of electrical energy to be generated in short pulses using relatively high efficiency and low cost. In a light-ion particle accelerator, an initial electrical pulse of the required energy is progressively shortened through a series of pulse forming steps to be delivered with an amplitude of several tens of megavolts to a diode which emits and accelerates the selected ions, eg, lithium, across a short gap to converge on the fuel capsule. The light-ion particle beam fusion accelerator II (PBFA II) at Sandia National Laboratory in New Mexico is the most energetic IFE driver, delivering up to 1 MJ on target. However, obtaining good beam divergence has been a challenge.

To survive the effects of the target explosion, the diode must be located at least several meters away from the target. The diode on PBFA II is only about 15 cm from the target. Long-lived, reliable diodes having 10 Hz repetition rates and beam-transport systems several orders of magnitude longer than those in use as of this writing are required to make a light-ion beam reactor feasible (15).

The Fusion Policy Advisory Committee of the Department of Energy has identified the heavy-ion accelerator as the leading candidate for an IFE reactor driver (16). The reasons include ruggedness, reliability, high pulse-rate capabilities, and potential for high efficiency. There are two different technologies being developed for heavy-ion accelerators: induction acceleration and radio frequency (rf) acceleration. The induction accelerator approach is pursued mainly in the United States, at the Lawrence Berkeley Laboratory. The rf accelerator approach is pursued primarily in Europe and Japan (15). The same types of heavy ions can be utilized in both approaches; typically cesium, bismuth, or xenon are chosen. To obtain the required 10^{18}–10^{19} W/m^2 on target in a reactor, using targets of 1 cm^2 size and accelerator energies limited to 5 GeV to provide the requisite stopping distance inside the target fuel, particle beam currents of around 100,000 A are required. These currents are quite large compared to traditional high energy physics accelerators, and in experiments where high currents have been achieved, the beam divergence has been unsatisfactorily large.

4. Environmental and Safety Aspects

Fusion reactors are expected to be relatively benign environmentally when compared to other sources of power. A 1989 National Research Council report cites the environmental issue as a persuasive reason for pursuing the fusion energy option (10). A general environmental advantage of nuclear power plants whether fission or fusion, compared to fossil fuel plants, is the minimization of mining requirements and no emission of noxious effluents. A further advantage of fusion, relative to fission, is the absence of meltdown dangers and avoidance of long-lived radioactive wastes (see Nuclear reactors, waste management). An accidental runaway reaction cannot occur in a fusion reactor for two reasons. First, the amount of deuterium and tritium in the reactor at any given time is small, and any uncontrolled burning quickly consumes all the available fuel and extinguishes itself. Second, a neutron chain reaction of the fission-reactor type is impossible in fusion, because fusion reaction rates are not sustained by neutrons.

The fusion of deuterium and tritium produces only energetic neutrons and alpha particles (helium nuclei), which are not themselves radioactive. The 14-MeV neutrons are absorbed in a blanket surrounding the reacting plasma, and the only unavoidable ash of the D–T reaction is ordinary helium gas. The main concern about radiation comes from a secondary process, namely activation of the reactor components by the fusion neutrons. The secondary nuclear reactions which result from the energetic neutrons depend on the materials selected for the reactor blanket and support structure (18). The materials aspects of fusion reactors have been reviewed (19), and the calculated decay of radioactivity following shutdown of D–T fusion reactors constructed of various materials is shown in Figure 5, together with that of a fission reactor (8, 18). If advanced structural materials such as silicon carbide, SiC, can be used, fusion reactors are expected to reduce the amount of radioactive waste by six orders of magnitude or more.

A D–T fusion reactor is expected to have a tritium inventory of a few kilograms. Tritium is a relatively short-lived (12.36 year half-life) and benign (beta emitter) radioactive material, and represents a radiological hazard many orders of magnitude less than does the fuel inventory in a fission reactor. Clearly, however, fusion reactors must be designed to preclude the accidental release of tritium or any other volatile radioactive material. There is no need to have fissile materials present in a fusion reactor, and relatively simple inspection techniques should suffice to prevent any clandestine breeding of fissile materials, eg, for potential weapons diversion.

5. Future Developments and Applications

The goal of fusion development is central station electrical power generation. Using the D–T fuel cycle, power would be extracted from the thermalization of the neutron kinetic energy deposited in the blanket. Pulsed systems such as inertial fusion require storage techniques to provide a continuous output of electrical power. In some cases, this storage medium may be simply the thermal blanket surrounding the reaction chamber. In MFE, significant technological challenges include the development of large superconducting magnets, efficient current drive systems, and adequate diverter plates and plasma facing components to handle the high particle and radiation heat loads. Provisions must also be made for the replacement and maintenance of components by remote handling techniques.

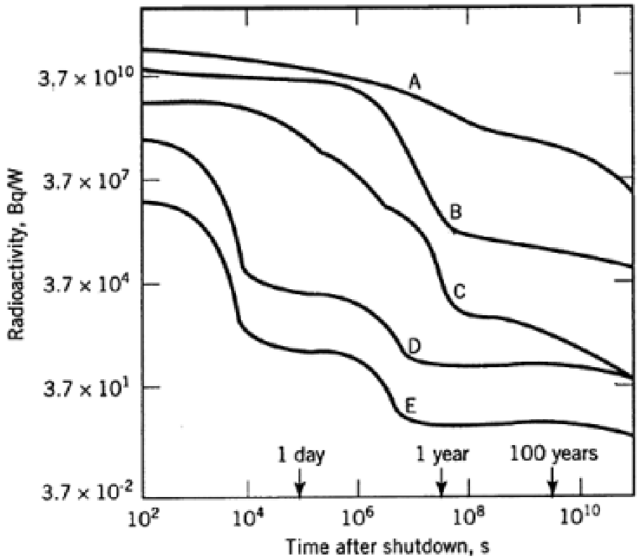

Fig. 5. Radioactivity after shutdown per watt of thermal power for A, a liquid-metal fast breeder reactor, and for a D–T fusion reactor made of various structural materials; B, HT-9 ferritic steel; C, V-15Cr-5Ti vanadium–chromium–titanium alloy; and D, silicon carbide, SiC, showing the million-fold advantage of SiC over steel a day after shutdown. The radioactivity level after shutdown is also given for E, a SiC fusion reactor using the neutron reduced D–^{3}He fuel cycle. To convert Bq to curie, multiply by 2.70×10^{-11}.

Potential fusion applications other than electricity production have received some study. For example, radiation and high temperature heat from a fusion reactor could be used to produce hydrogen by the electrolysis or radiolysis of water, which could be employed in the synthesis of portable chemical fuels for transportation or industrial use. The transmutation of radioactive actinide wastes from fission reactors may also be feasible. This idea would utilize the neutrons from a fusion reactor to convert hazardous isotopes into more benign and easier-to-handle species. The practicality of these concepts requires further analysis.

Fusion energy research is also the primary avenue for the development of plasma physics as a scientific discipline. The technologies and the science of plasmas developed en route to fusion power are already important in other applications and fields of science (see Plasma technology).

6. Cold Fusion

In the spring of 1989, it was announced that electrochemists at the University of Utah had produced a sustained nuclear fusion reaction at room temperature, using simple equipment available in any high school laboratory. The process, referred to as cold fusion, consists of loading deuterium into pieces of palladium metal by electrolysis of heavy water, D_2O, thereby developing a sufficiently large density of deuterium nuclei in the metal lattice to cause fusion between these nuclei to occur. These results have proven extremely difficult to confirm (20, 21). Neutrons usually have not been detected in cold fusion experiments, so that the D–D fusion reaction familiar to nuclear physicists does not seem to be the explanation for the experimental results, which typically involve the release of heat and sometimes gamma rays.

Room temperature fusion reactions, albeit low probability ones, are not a new concept, having been postulated in 1948 and verified experimentally in 1956 (22), in a form of fusion known as muon-catalized fusion. Since the 1989 announcement, however, international scientific skepticism has grown to the point that cold fusion is not considered a serious subject by most scientists. Follow-on experiments, conducted in many prestigious laboratories, have failed to confirm the claims, and although some unexplained and intellectually interesting phenomena have been recorded, the results have remained irreproducable and, thus far, not accepted by the scientific community.

BIBLIOGRAPHY

"Fusion Energy" in *ECT* 3rd ed., Vol. 11, pp. 590–603, by G. M. Halpern, Exxon Research and Engineering Co.

Cited Publications

1. H. A. Bethe, *Phys. Rev.* **55**, 103 (1939).
2. S. Glasstone and R. H. Lovberg, *Controlled Thermonuclear Reactions*, D. Van Nostrand, New York, 1960.
3. R. A. Gross, *Fusion Energy*, John Wiley & Sons, Inc., New York, 1984.
4. L. Spitzer, Jr., *Physics and Fully Ionized Gases*, 2nd rev. ed., John Wiley & Sons, Inc., New York, 1962.
5. J. D. Lawson, *Proc. Phys. Soc.* **B70**, 6 (1957).
6. O. Naito and co-workers, *Plasma Phys. Control. Fusion* **35**, B215–B222 (1993); T. Kondo and co-workers, "High Performance and Current Drive Experiments in JAERI Tokamak-60 Upgrade," *Phys. Plasmas* (in print) (1994); H. Ninomiya and co-workers, "Recent Progress and Future Prospect of the JT-60 Program," in the *Proceedings of the 15th Symposium on Fusion Engineering*, Hyannis, Mass., 1993.
7. I. E. Tamm and A. D. Sakharov, in M. A. Leontovich, ed., *Plasma Physics and the Problem of Controlled Thermonuclear Reactions*, Vol. **1**, Pergamon Press, New York, 1961.
8. H. P. Furth, *Science* **249**, 1522 (Sept. 1990); J. G. Gordey, R. J. Goldston, and R. R. Parker, *Phys. Today*, 22 (Jan. 1992).
9. R. W. Conn and co-workers, *Sci. Am.* **266**, 103 (Apr. 1992).
10. *Pacing the U.S. Magnetic Fusion Program*, National Academy Press, Washington, D.C., 1989.
11. *Fusion Policy Advisory Committee Final Report, DOE/S-0081*, Department of Energy, Washington, D.C., Sept. 1990.
12. *National Energy Strategy, First Edition 1991/1992*, Department of Energy, Washington, D.C., Feb. 1991.
13. The JET Team, *Nuc. Fusion* **32**, 187 (1992).
14. International Atomic Energy Agency, *ITER Conceptual Design Report*, IAEA, Vienna, 1991.
15. W. J. Hogan, R. Bangerter, and G. L. Kulcinski, *Phys. Today*, 42 (Sept. 1992).
16. *Review of the Department of Energy's Inertial Confinement Fusion Programs*, National Academy Press, Washington, D.C., Sept. 1990.
17. J. D. Lindl, R. L. McCrory, and E. M. Campbell, *Phys. Today*, 32 (Sept. 1992).
18. R. W. Conn and co-workers, *Nucl. Fusion* **30**, 1919 (1990).
19. J. P. Holdren and co-workers, *Report of the Senior Committee on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy*, report UCRL-53766, Lawrence Livermore National Laboratory, Livermore, Calif., Sept. 25, 1989.
20. *Cold Fusion Research, DOE Report S-0073*, U.S. Dept. of Energy, Washington, D.C., Nov. 1989.
21. F. Close, *Too Hot to Handle: The Role for Cold Fusion*, Princeton University Press, Princeton, N.J., 1991.
22. B. V. Lewenstein and co-workers, *Forum for Applied Research and Public Policy*, **7**(4), 67–107 (Winter 1992).

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