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ABSTRACT

This publication is one of a series of information booklets for the general public published by The United States Atomic Energy Commission. Among the topics discussed are: Importance of Fusion Energy; Conditions for Nuclear Fusion; Thermonuclear Reactions in Plasmas; Plasma Confinement by Magnetic Fields; Experiments With Plasmas; High-Temperature Plasma Studies; Nuclear Fusion Reactors With Magnetic Confinement; Inertial Confinement; and Nuclear Fusion Research Programs. A reading list and free-loan film list are included. Schools and public libraries may obtain the booklets without charge. (BT)

CONTROLLED NUCLEAR FUSION

by Samuel Glasstone

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Nuclear energy is playing a vital role in the life of every man, woman, and child in the United States today. In the years ahead it will affect increasingly all the peoples of the earth. It is essential that all Americans gain an understanding of this vital force if they are to discharge thoughtfully their responsibilities as citizens and if they are to realize fully the myriad benefits that nuclear energy offers them.

The United States Atomic Energy Commission provides this booklet to help you achieve such understanding.

THE AUTHOR

Samuel Glasstone — Ph.D. (1922), D.Sc. (1926) University of London, in Physical Chemistry — holds a preeminent position as a lucid expositor of scientific subject matter. He has written 34 books, sometimes with the cooperation of other scientists. In 1959 the American Society of Mechanical Engineers awarded him the Worcester Reed Warner Medal in recognition of his "outstanding contribution to permanent engineering literature in . . . writings on atomic energy". In 1968 he received the Arthur Holly Compton Award from the American Nuclear Society for "his distinguished contributions to nuclear science and engineering education".

Dr. Glasstone's best known book in the nuclear field is *Sourcebook on Atomic Energy*, first published in 1950 and revised in 1958 and 1967, it is still a best seller. He has also written for scientists and engineers about reactor theory, nuclear engineering, nuclear weapons, and controlled thermonuclear research, as well as various aspects of physical chemistry.

Contents

Nuclear fusion, the process by which the sun and other stars generate their energy, is being developed to produce electrical power on earth. It will be safe, environmentally attractive, and its fuel, deuterium, exists in abundance in ordinary water. The deuterium in the oceans could provide enough energy to satisfy the world's electricity requirement at the present rate of consumption for millions of years.

Scientists hope to build a fusion reactor by about the year 1995.

IMPORTANCE OF FUSION ENERGY

Need for Energy Sources

The availability of energy (or power) for the operation of machinery has been a decisive factor in the improvement of man's standard of living. With the steady rise in population and in the use of mechanical devices to increase the productivity of labor, the world's power requirements are growing rapidly. In the past, the chief sources of energy were the fossil fuels--coal, oil, and natural gas--and, to a smaller extent, water power. The increasing demand for energy has spurred worldwide exploration for fuels, especially for oil, and so far the newly discovered reserves have kept pace with consumption.

Although this appears to be a satisfactory situation, there are limitations. First, the time must come, possibly by the end of the present century, when the reserves begin to dwindle and a shortage of fossil fuels becomes a definite prospect. And, second, the distribution of oil and coal reserves is such that many industrialized countries must import their fuel supplies at considerable cost. Furthermore, the combustion of fossil fuels, especially coal, causes problems of atmospheric pollution by producing oxides of sulfur and nitrogen and fine particles of ash. A new and clean source of energy with a basic fuel that is cheap, abundant, and available to all, would thus be a great boon to mankind. Scientists hope that nuclear fusion will provide such an energy source. In order to understand this process it is necessary to know something about the background of nuclear energy.

Photo 1. *Large loop prominences on the sun, caused by a locally intense magnetic field. The U. S. program in controlled fusion is devoted to research on fusion reactions similar to those from which the sun derives its energy.*

Nuclear Energy

Soon after radioactivity was discovered at the end of the 19th century, physicists began to conjecture about the energy, which they called "atomic energy," that was apparently stored within the atom. Later, when the nuclear theory of the atom was developed in 1911, scientists realized that it was the nucleus, the central part of the atom, that was the source of this energy.* Hence, it should be called "nuclear energy" rather than atomic energy. Until 1939, however, no one knew how this energy could be released in a useful manner.

In the course of his studies in 1905 on the theory of relativity, Albert Einstein showed that mass and energy were, in a sense, equivalent. Consequently, energy should be liberated in any process associated with a net decrease in mass. By considering the measured masses of atomic nuclei, it became apparent that there were two general ways whereby nuclear energy could be made available by using reactions accompanied by a decrease in mass. One is by the splitting (fission) of the heaviest nuclei into nuclei of intermediate mass, and the other is by the combination (fusion) of some of the lightest nuclei. Actually, there are many other nuclear processes that are accompanied by a liberation of energy. But only with nuclear fission and fusion is there the possibility of producing more energy than is consumed during the reaction. In other words, only for these reactions is there a prospect that the process, once started, can be self-sustaining like a fire.

The discovery of nuclear fission in 1939 revealed a new and highly concentrated source of energy. Some 6 years later, this energy was first used in the atomic bomb, and since that time nuclear reactors have been developed in which fission energy is liberated as heat and converted into electric power.† The

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*For a description of atomic theory, see *Inner Space, The Structure of the Atom*, another booklet in this series.

†See *Nuclear Reactors* and *Nuclear Power Plants*, other booklets in this series.

impact of nuclear fission energy is already being felt in many countries. In 1973, about 4% of the electricity used in the United States was generated in nuclear reactor power plants and this proportion is expected to increase to more than 20% by 1980. But fission is not the complete solution to the energy problem. It is true that the world resources of the basic materials, namely uranium and thorium minerals, are fairly abundant. There are, however, many countries that either do not possess these minerals or do not have the means for producing nuclear fuels from them. Furthermore, special precautions must be taken in the operation of fission power plants to prevent undesirable environmental effects.

Nuclear Fusion Energy

It is such considerations that make nuclear fusion of exceptional interest as a possible source of power. The fuel is a form (isotope) of hydrogen, called "heavy hydrogen" or *deuterium*, that is present in all water; for every 6500 or so atoms of ordinary (light) hydrogen in water, there is one atom of deuterium. In other words, there is 1 pound of deuterium in some 30,000 pounds of water. But the enormous volumes of ocean and other surface waters on earth contain more than 10 million million (10^{13}) *tons* of deuterium!

Calculations show that the energy that could, in theory, be produced by the fusion of the deuterium nuclei present in a gallon (8 pounds) of water is equal to that obtainable from the combustion of 300 gallons of gasoline. The large amounts of deuterium available on earth thus represent a virtually inexhaustible potential source of energy.

The cost of obtaining the deuterium fuel from water is not large. At the present, it costs only a few cents to extract a quantity of deuterium equal to that in a gallon of water. The first fusion systems are expected to require lithium in addition to deuterium, but lithium is not an expensive material and ample supplies are available, as will be seen shortly. In fact, it is anticipated that the fuel costs for fusion power will be negligible. Furthermore, the safety and environmental aspects of fusion power are expected to be favorable (see page 68). Here then is apparently the ideal source of energy. Unfortunately, this is not the whole story. For one thing, as in a nuclear fission system, the price of the fuel would represent only a small proportion of the cost of the electric power produced. For another, there are difficult problems to be solved before fusion power can be a reality. The purpose of this booklet is to indicate the nature of these problems and to show how solutions are being sought.

CONDITIONS FOR NUCLEAR FUSION

Realization of Fusion

Before describing the conditions that must be met if fusion energy is to be released in a practical manner (i.e., in a fusion "reactor"), we will review the evidence which shows that nuclear fusion is indeed possible. In the first place, fusion is the energy source of the sun and other stars. The sun's fuel is not deuterium but ordinary hydrogen; in a series of nuclear reactions, four hydrogen nuclei are fused together to form a helium nucleus. There are good reasons, however, for stating that the sun's processes take place much too slowly to be useful on earth. In the sun, for example, the ability to generate energy at a high rate depends on the enormous quantity of hydrogen present.

Laboratory experiments have shown that nuclear fusion can be achieved with deuterium. Deuterons (i.e., deuterium nuclei) can be accelerated to high velocity (and kinetic energy) in a charged-particle accelerator, such as a cyclotron or similar machine.* If these deuterons strike a solid target containing deuterium, fusion reactions occur. But, of the collisions between the accelerated deuterons and those in the

*See *Accelerators*, another booklet in this series.

target, only a very small proportion lead to fusion. In the great majority of collisions, the impinging deuteron is merely deflected (scattered) and at the same time loses some of its energy; it then becomes essentially incapable of fusing with another deuteron. In effect, most of the energy of the accelerated deuterons is lost as heat in the target. Much more energy is consequently spent in accelerating the deuterons than is produced by the small number of fusion reactions that occur. Although the acceleration procedure is not a basis for the practical liberation of energy, it does show that fusion between two deuterium nuclei is possible.

Finally, nuclear fusion is the source of the large amount of energy released in the so-called hydrogen (or H-) bomb. Weapons of this type contain deuterium as one of their components together with a nuclear fission bomb that serves as a trigger. The latter supplies the energy required to make fusion reactions occur.

Requirements for Fusion Reactions

In order to see how controlled nuclear fusion might be realized, let us examine the essential requirements. First, the two light nuclei must come close enough to permit interaction. Since each nucleus carries a positive electrical charge, the two nuclei repel each other more and more as they come closer together. Consequently, for the nuclei to interact they must have enough initial energy to overcome the force of electrostatic repulsion that tends to keep them apart. The magnitude of the repelling force increases with the electrical charges on the two nuclei. To keep this force small, therefore, the interacting nuclei should have the lowest possible charge (or atomic number*).

The element with the smallest atomic number is hydrogen, since its nuclei (and those of its isotopes) carry but a single charge. The obvious choice for fusion reactions on earth is

*The atomic number of an isotope is the number of protons in the nucleus.

thus some form of hydrogen. The fact that it happens also to be cheap and abundant is, of course, an advantage. Three isotopes of hydrogen are known. The lightest, with a mass number* of one, is ordinary hydrogen, H; the nucleus of an atom of this isotope is called a proton. Ordinary hydrogen is the isotope that undergoes fusion in the sun.

The next isotope is deuterium, mass number two, represented by ^2H or, more commonly, by the symbol D; its nucleus, the deuteron, is also indicated by D, although D^+ is used when it is necessary to distinguish between the neutral atom and the positively charged nucleus. It occurs in all natural water, as mentioned earlier, and can be extracted without too much difficulty. Finally, there is tritium, mass number three, represented by ^3H or T; the nucleus is called a triton. This isotope is radioactive and is very rare in nature, but it can be made by the interaction of neutrons with lithium nuclei.

Deuterium and Tritium Fusion

Fusion processes with deuterons and tritons take place fast enough to make them reasonably possible sources for the release of energy at a useful rate. These isotopes are, therefore, the most practical fusion fuels. Because of the low cost and availability of deuterium, it would be preferable to use this isotope alone; the fusion process would then involve only deuterons. Two such reactions, occurring with roughly equal probabilities, are known; they are

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

and

$$D + D \rightarrow T + H + 4.0\ MeV,$$

*The mass number of an isotope is the total number of protons and neutrons in the nucleus.

where n represents a neutron. The energy release is expressed in units of million electron volts (MeV)*. In the first of these two reactions, the products are a helium-3 nucleus and a neutron, and in the second they are a triton and a hydrogen nucleus (proton). The triton formed in this manner can then react fairly rapidly with another deuteron, that is,

$$D + T \rightarrow {}^4He + n + 17.6\ MeV,$$

leading to the formation of a helium-4 (ordinary helium) nucleus and a neutron, plus the large energy release of 17.6 MeV.

The fusion of deuterium alone would be the preferable reaction for the release of energy, but we shall see that the conditions required to make the process practical are very severe. It is possible that these conditions could be alleviated by adding a small proportion of tritium in a so-called "catalyzed" D–D reaction. The general feeling at present, however, is that controlled fusion will first be realized through the reaction between deuterium and tritium nuclei, in accordance with the D–T reaction given above. Since the tritium would not be available from natural sources, it would be made artificially by the interaction of neutrons with lithium nuclei. The neutrons released in the D–T reaction would be used for this purpose. The process is consequently referred to as tritium "breeding".

The raw materials for the production of energy by the D–T reaction would thus be deuterium and lithium. Ample reserves of the latter are available on land at a moderate cost. In fact, the known and reasonably inferred reserves in the United States will last for hundreds of years and probable reserves would last for a few thousand years. Even larger amounts are present in the oceans, but, before the lithium

*An electron volt (eV) is the energy acquired by a unit (electronic) charge in accelerating through a potential of 1 volt. The MeV (million electron volt) unit is equivalent to 1.60×10^{-6} erg or 3.8×10^{-14} calorie.

supplies on land are exhausted, the conditions for fusion of deuterium alone should be realized.

A pictorial representation of the three fusion processes of immediate interest is given in Figure 1, which shows the rearrangements among the constituent neutrons (n) and protons (p). A deuteron consists of one proton and one neutron, and a triton of one proton and two neutrons. The energy released appears as kinetic energy and is divided between the two products in inverse proportion to their masses. The amount of energy carried by each of the products is indicated. In the reaction between deuterium and tritium nuclei most—about 80%—of the fusion energy is associated with the neutron, which is not electrically charged.

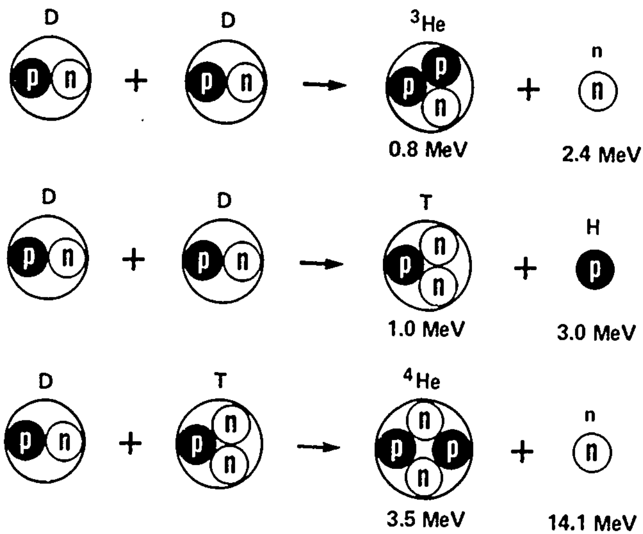


Figure 1. *Fusion reactions with deuterium (D) and tritium (T) nuclei. The numbers indicate how the fusion energy is divided between the products in each case. The neutrons (n) are not electrically charged, but the other products carry electrical charges.*

In addition to the three fusion reactions just described, which involve only isotopes of hydrogen, there is also some interest in the nuclear fusion reaction between deuterium and helium-3, namely,

$$D + {}^3He \rightarrow {}^4He + H + 18.3\ MeV.$$

The helium-3 required for this process would be generated by the first of the D–D reactions. The D–^{3}He reaction will not be discussed but it will be mentioned later in a special context (page 69). Both products, ^{4}He and H, carry electrical charges.

High-Energy Requirement

So far, we have established that the nuclear reactions of primary interest for the controlled release of fusion energy involve either deuterium alone, deuterium and tritium, or deuterium and helium-3. The forces of repulsion between these light nuclei are the minimum possible, and the resulting reactions could be expected to take place at a reasonable rate. The next point to consider is how to give sufficient energy to the nuclei to permit them to overcome the repelling forces. One obvious way is to make use of an accelerator and a solid target, as described earlier. But we saw that this procedure wastes too much energy to be of practical value. It has been used extensively, however, in the laboratory to study the probabilities (*nuclear cross sections*) of the D–D and D–T reactions. Much of what is now known about the conditions under which these reactions will occur was determined in this manner.

Another way of supplying energy to the nuclei is to raise the temperature of a gas consisting of the isotope (deuterium) or isotopes (deuterium and tritium) that are to undergo fusion. The kinetic energy of an atom (or nucleus) is proportional to its absolute temperature*; hence, it is only a matter of attaining a sufficiently high temperature to permit fusion reactions to occur. This is precisely what happens in the sun. At first sight, it might appear that the situation is somewhat similar to that in which particles are accelerated. However, if the nuclei are confined in some manner, so that they cannot escape, the consequences are very different. Although many of the nuclear collisions in a high-temperature system result in scattering instead of fusion, the effect is a redistribution of energy rather than a loss of energy. Temperature and average energy are unchanged. In a confined space, the nuclei moving in random directions would collide repeatedly until fusion reactions take place.

THERMONUCLEAR REACTIONS IN PLASMAS

Thermonuclear Reactions

Fusion reactions brought about by means of high temperatures are referred to as *thermonuclear reactions.* Strictly speaking, however, the adjective thermonuclear implies temperature equilibrium, in which the energies (and velocities) of the nuclei or other particles have a range (or distribution) of values determined by their random motion. The equilibrium energy distribution can be calculated theoretically, and it is found that, although most of the nuclei have energies in the vicinity of the most probable value, there are always some with lower and others with higher energies. It is the relatively small proportion of nuclei with these high energies—much higher than the average—that is responsible for the great majority of thermonuclear fusion reactions.

The thermonuclear approach, through the use of very high temperatures, appears to be the most promising for con-

*Temperatures on the absolute (or Kelvin) scale are obtained by adding 273 to the temperature on the Celsius (centigrade) scale (e.g., 25°C = 25 + 273 = 298°K).

trolled fusion. The actual temperature required depends on the particular fusion reaction that is being employed. From calculations based on measured cross sections, and other considerations to be described shortly, it has been determined that a system for the release of energy by nuclear fusion of deuterium and tritium would have to operate at a temperature of about 100,000,000°K. The fusion of deuterium alone would require even higher temperatures.

It is evident, therefore, that exceptionally high temperatures, much higher than the 15,000,000°K of the sun's interior, must be reached before useful thermonuclear fusion reactions can occur on earth. Such temperatures have been achieved in a number of experiments; however, to release practical amounts of energy using thermonuclear fusion reactions, it is necessary to confine the high temperature gases for a longer period of time than has been attained to date.

Plasmas: Fourth State of Matter

At these very high temperatures, essentially all the hydrogen atoms will be stripped of their electrons. Such a gas, consisting entirely (or almost entirely) of positively charged nuclei (*ions*) and free negative electrons, is said to be highly *ionized*. A highly ionized gas is commonly called a *plasma*. It should be remembered that, although a plasma contains free positive ions and free negative electrons, the numbers of positive and negative electrical charges balance exactly, and the plasma as a whole is neutral. Because of the presence of the electrically charged particles, plasmas have a number of interesting properties, some of these can be used to advantage in controlled fusion research, but others create unique problems. The unusual characteristics of plasmas have led to the revival in recent years of the expression, the "fourth state of matter", first used by William Crookes in 1879, to describe them.

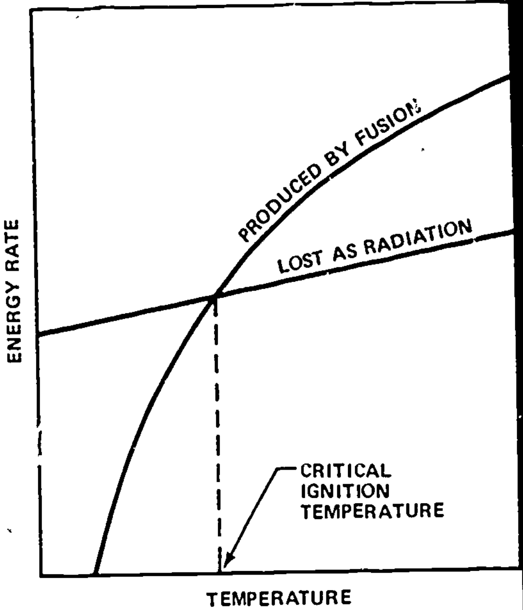
Critical Ignition Temperature

In a reactor that would produce useful energy by fusion, energy would have to be supplied initially in order to establish the proper conditions (temperature and ion density) for the thermonuclear reactions to take place at a significant rate. Once these conditions are reached in the plasma, they must be maintained long enough to generate recoverable energy by fusion at least equal to the amount supplied initially to bring the reactor to its operating condition. If this requirement is met, the system would be described as "self sustaining". Any excess energy beyond that needed for a self-sustaining process would be available for use as a power source for external purposes. Thus, a fusion system must be at least self-sustaining for it to have any practical value. One of the conditions for a self-sustaining fusion reactor is the temperature, as will now be shown; another is related to the ion density and the confinement time (see page 21).

At the very high temperatures necessary for nuclear fusion reactions, a plasma loses a considerable amount of its energy in the form of radiation. This loss takes place so rapidly that the energy would not be available for heating the reacting nuclei. The radiation energy is not lost entirely, because it can be absorbed and used to some extent. But it escapes from the region where it is needed to maintain the fusion reaction temperature. Clearly, a system cannot be self-sustaining unless the rate at which energy is produced by fusion exceeds the rate at which it is lost from the plasma as radiation. This requirement determines the minimum operating temperature for a nuclear fusion reactor.

Calculations have been made of the rate of energy production in a plasma by fusion, on the one hand, and of the energy loss by radiation, on the other hand, over a range of temperatures. At lower temperatures, the radiation loss rate is larger than the rate of energy generation and a self-sustaining reaction would not be possible. As the temperature is increased, both rates increase, but the energy

Figure 2. *Evaluation of the critical ignition temperature that is the minimum for a thermonuclear fusion reaction to be self-sustaining. Below this temperature the rate of energy loss as radiation exceeds the rate at which energy is produced by the fusion reactions.*



production increases faster than does the radiation loss (Figure 2). Therefore, above a certain temperature, called the *critical ignition temperature,* more energy is produced by fusion than is lost. At this temperature, a self sustaining fusion reactor is theoretically possible, although a higher operating temperature would be needed in a system for producing significant amounts of fusion energy. For practical purposes, the minimum operating temperature for the deuterium–tritium reaction is believed to be about 100,000,000°K and that for the fusion of deuterium alone is about 500,000,000°.*

The energy loss calculations used in deriving critical ignition temperatures are based on the supposition that the

*In nuclear fusion studies, temperatures are expressed in terms of the kilo-electron volt or keV (1 keV = 1000 electron volts). Thus, 1 keV is equivalent to a temperature of 1.16×10^7 degrees K or very roughly 10,000,000°. Hence, the minimum useful thermonuclear temperatures are thought to be about 10 keV for the D–T reaction and 50 keV for the D–D reactions.

energy consists solely of *bremsstrahlung*, which is radiation resulting from decelerating interactions between rapidly moving charged particles in the plasma, chiefly electrons interacting with ions. Moreover, it is assumed that the only nuclei in the system are those of hydrogen isotopes. The presence of nuclei of higher charge, that is, higher atomic number, will increase the rate of energy loss as bremsstrahlung. Hence, impurities, and even the helium nuclei formed in the fusion reactions, will tend to raise the ignition temperature.

In addition, there is a possibility that, at very high temperatures, another kind of radiation loss may become important. This is the *synchrotron radiation* that is emitted by high-energy charged particles (electrons in particular) moving in a magnetic field; as will be seen shortly, such fields play an important role in plans for achieving controlled fusion. However, whereas the fraction of the fusion energy lost as bremsstrahlung is the same for all plasma densities, the loss as synchrotron radiation decreases at higher densities. Consequently, the synchrotron radiation loss can probably be minimized by operating at the highest possible plasma density.

PLASMA CONFINEMENT BY MAGNETIC FIELDS

Need for Confinement

Suppose, for the moment, that we know how to produce a deuterium–tritium plasma at a temperature of some 100,000,000° or more. How is such a plasma confined? The difficulty does not lie in the very high temperature because, at the low gas densities in a fusion reactor, the total energy content of the plasma would be insufficient to cause any significant damage to a containing vessel if the plasma were to come in contact with it.

The problem arises from the loss of energy by the nuclei when they strike the walls of the container. At a temperature of 100,000,000°, the nuclei (and electrons) in a plasma are moving randomly in all directions at average speeds of several thousand miles per second. Consequently, within a small fraction of a second, all the particles will have hit the walls of the containing vessel, as a result, they lose essentially all their kinetic energy. In other words, the plasma would be rapidly cooled. Even if the high-temperature plasma could be generated instantaneously, it would not last long enough to allow a significant number of fusion reactions to take place.

A method must therefore be found to prevent the plasma particles from striking the walls of the containing vessel. In this connection the electrical charges carried by the nuclei and electrons can be used to advantage. It is difficult for charged particles to cross the lines of force of a magnetic field. A plasma can therefore be confined by a magnetic field of suitable form. (See Photo 2.) The concept of *magnetic confinement* is often described as the use of a "magnetic bottle". Many different magnetic field arrangements have been proposed for the confinement of the high-temperature plasmas required for fusion reactions. Some of the more promising will be discussed later.

Another possible type of confinement, called *inertial confinement,* which does not involve magnetic fields, has been proposed (see page 71). For the moment, however, we will restrict ourselves to magnetic confinement.

Magnetic Confinement and Plasma Density

A plasma, like a normal gas, exerts a pressure that comes from the motion of the particles present; this pressure is proportional to the absolute temperature and to the particle density (i.e., the number of particles per cubic centimeter). The maximum plasma pressure that can be confined by a magnetic field depends on the strength of the latter. Because there is a practical limit to the magnetic field strength, there

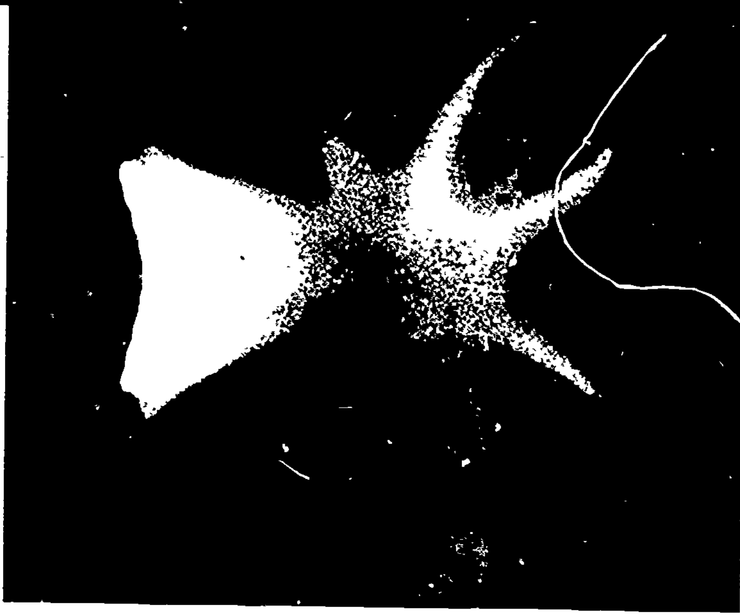


Photo 2. *Light emitted by plasma confined in a "magnetic bottle".*

is a corresponding limit to the particle pressure of the plasma that can be confined. Since the temperatures are extremely high, the other factor that determines the particle pressure, namely, the plasma particle density, must inevitably be low so that it does not exceed the limit on the plasma pressure.

In deciding upon the plasma density, another factor must be considered in addition to the magnetic field strength. The rate at which energy would be generated per unit volume of a fusion reactor increases with the particle density. For energy to be released at a useful rate, therefore, the density must not be too low. On the other hand, it must not be so high that the nuclear fusion energy cannot be removed (and used) as fast as it is released. Both consideration of magnetic field strength and heat removal suggest that the plasma in a controlled fusion system will probably have a density of 10^{14} to 10^{16} particles per cubic centimeter. This may be compared with 3×10^{19} particles (molecules) in a gas at normal room temperature and pressure. At the temperatures that must be attained in a deuterium -tritium fusion reactor, a density of 10^{15} particles per cubic centimeter would represent a pressure of about 200 pounds per square inch. It is this pressure that must be contained by the magnetic bottle.

The Lawson Criterion

In addition to the specifications of temperature and plasma particle density, a fusion reactor must satisty another condition. This is known as the *Lawson criterion* because it was first pointed out by J. D. Lawson in England in 1957. It is based on the requirement that, in a self-sustaining system, the reacting nuclei must be confined long enough to produce sufficient recoverable energy by fusion to compensate for the amount supplied initially to heat the plasma. The criterion is expressed as the product $n\tau$, where n is the plasma density (in particles per cubic centimeter) and τ is time (in seconds) for which the plasma of that density can be confined by the magnetic field. For a practical fusion reactor, $n\tau$ must exceed about 10^{14} for the D–T reaction and about 10^{16} for the D–D reactions.

Since the Lawson criterion is a product of particle density and confinement time, there is a range of conditions over which it can be satisfied. For example, if the density is at the lower practical limit of 10^{14} particles per cubic centimeter, the confinement time for the charged particles in a deuterium–tritium system must exceed 1 second. On the other hand, in the vicinity of the upper limit of about 10^{16} particles per cubic centimeter, the confinement time would have only to be longer than 0.01 (i.e., one hundredth part) of a second.

The three essential requirements for the production of useful energy by nuclear fusion are summarized on the next page. For deuterium alone, the temperature required is higher and the confinement time is longer than for a mixture of deuterium and tritium. It is clear, therefore, that a deuterium fusion reactor would be more difficult to devise than one based on deuterium and tritium. This is the reason for the

ESSENTIAL REQUIREMENTS FOR FUSION REACTORS

Reaction	Minimum temperature (°K)	Particle density (per cm³)	Minimum confinement time (seconds)
D–T	100,000,000	10^{14}–10^{16}	1–0.01
D–D	500,000,000	10^{14}–10^{16}	100–1

statement made earlier that practical controlled fusion may be reached first by way of the D–T reaction. On the other hand, the engineering problems of a D–D reactor could prove easier since it would not require the breeding of tritium.

The Significance of Beta

A magnetic field that confines a plasma effectively exerts a pressure on the plasma. The ratio of the plasma particle pressure to the pressure due to the magnetic field is called *beta* (Greek, β); thus,

$$\text{beta} = \frac{\text{plasma particle pressure}}{\text{magnetic field pressure}}.$$

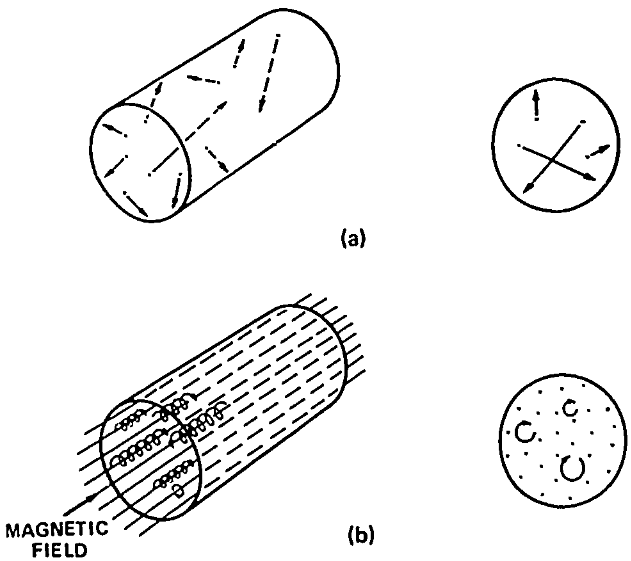
The value of beta for a confined plasma can range from 1, when the plasma pressure is equal to the magnetic pressure, down to almost zero, when the plasma · ressure is very low. For magnetic confinement to be possible, beta must not exceed unity, for otherwise the plasma would immediately escape from the magnetic field. The plasmas being studied in connection with controlled fusion fall into two broad categories: *High beta*, in which beta is generally 0.5 or more, and *low beta* with beta equal to about 0.2 or less.

If beta were exactly unity, that is to say, if the plasma and magnetic pressures were equal, the magnetic field lines would enclose the plasma without penetrating it; in other words, there would be no magnetic field lines inside the plasma. In practice, however, beta is invariably less than unity and the lines of force of the magnetic field penetrate the plasma to some extent. The smaller the value of beta, the greater is the penetration of the plasma by the field lines. Nevertheless, the magnetic field can still confine the plasma as will be seen in the next section.

Motion of Plasma Particles in a Magnetic Field

The presence of a magnetic field in a plasma causes the electrically charged particles to move in a particular manner. For example, in the absence of a magnetic field, an assembly (or plasma) of charged particles in a cylindrical vessel will move in straight lines in random directions and will quickly strike the walls (Figure 3a). Suppose, next, that a uniform (homogeneous) magnetic field is applied. The particles will now be compelled to follow helical (i.e., corkscrew or spiral) paths, as depicted in Figure 3b, encircling the lines of magnetic force. Positively charged particles spiral in one direction and negatively charged particles in the opposite

Figure 3. *Effect of uniform magnetic field on charged particles. In (a), no field is present. In (b), a homogeneous magnetic field is applied.*



direction. As a result, the particles are not free to move across the magnetic field lines; access to the walls of the vessel is thus restricted. In a sense, each particle is "tied" to a line of force along which it travels in a helical path of constant radius.

The radius of curvature of the path of a charged particle along a field line depends on three factors: (1) the strength of the magnetic field, (2) the mass of the particle, and (3) the component of the particle velocity in the direction at right angles to the lines of force. The first two factors can be explained quite easily, but the third will require a little more consideration.

Other things being the same, the radius of the spiral's curvature is inversely proportional to the field strength and directly proportional to the mass of the particle. Hence, for two particles with the same mass (and electric charge), the greater the magnetic field strength the smaller the spiral's radius. Furthermore, in a plasma confined (and penetrated) by a given magnetic field, the electrons will move in much tighter spirals than do the much heavier ions (atomic nuclei).

We will now consider the effect of the right-angle component of the particle velocity. Suppose v in Figure 4 represents

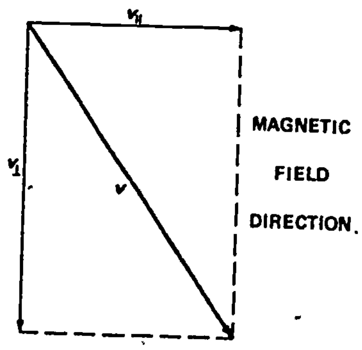


Figure 4. *The velocity of a particle moving in a given direction, indicated by* v, *can be treated mathematically as consisting of two components: One,* $v_{\parallel}$, *parallel to the magnetic field lines, and the other,* $v_{\perp}$, *perpendicular to the field lines.*

the magnitude and direction of the velocity of a particle; this can be divided (mathematically) into two components, one, $v_\parallel$, parallel to the magnetic field lines, and the other, $v_\perp$, at right angles. The radius of the spiral path is then proportional to the component $v_\perp$. The other component, $v_\parallel$, determines how fast the particle travels in the direction of the field during the course of its spiraling around the field lines.

Two extreme cases of particle motion in a magnetic field are of interest. First, suppose the particle is moving at right angles to the line of force; v is then the same as $v_\perp$, and $v_\parallel$ is zero. The path of the particle would be a circle and not a spiral (or helix), since there is no motion along the field lines. The other extreme occurs when the velocity v is directed along the lines of force; then v is equal to $v_\parallel$, and $v_\perp$ is zero. The radius of the spiral is now zero, and the particle travels in a direct manner along the line of force. Between these two extremes, there is an infinite number of possibilities. Thus, even in a uniform plasma contained in a uniform magnetic field, there is a wide variation in the radius of curvature of the spiral paths and in the rate of progression of the particles in the direction of the magnetic field lines because of the many different velocities and their components.

As a consequence of these variations in its spiral motion, a charged particle will occasionally collide with others, both positive and negative. As a result, the center of curvature of the path can shift from one field line to another. In this way, it is possible for a charged particle to move across the lines of force and there is a possibility that it will eventually escape the confining action of the magnetic field. The process of gradual escape of particles by motion across the field lines is referred to as plasma *diffusion;* more will be said about this phenomenon later.

Particle Drift in Magnetic Fields

There are other situations in which charged particles can move across the lines of force of a magnetic field; an

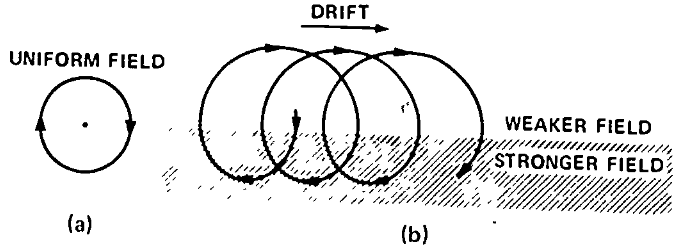


Figure 5. *Motion of a positively charged particle in (a) a homogeneous (uniform) magnetic field and (b) an inhomogeneous (nonuniform) magnetic field directed upward perpendicular to the plane of the paper. In (b), the field is stronger in the shaded region than above it. In this case, the positively charged particles drift to the right. Negatively charged particles would spiral around the line of force (and drift) in the opposite direction.*

important one arises when the magnetic field is not uniform (i.e., inhomogeneous) in strength. The particles no longer follow a spiral path of constant radius because, as seen earlier, the radius varies inversely with the field strength. The general behavior can be illustrated by considering a simple example.

Let the magnetic field lines run perpendicular to the plane of the page so that a line of force appears as a point. If the field is uniform, the spiral path of a charged particle is then represented by a circle, as in Figure 5a. Suppose now that the magnetic field is nonuniform and varies in such a manner that it is stronger below a horizontal line and weaker above the line (Figure 5b). The radius of curvature of the particle's path is then smaller below the line than it is above, as shown. The net result is that the charged particle drifts to the right, across the field lines, and may reach the walls of the containing vessel.

The particle drift in a nonuniform field is in a direction perpendicular both to the magnetic field (out of the page) and to the direction in which the field strength varies (top to bottom). Since particles with different electric charges spiral in opposite directions, the positively charged particles (nuclei) drift in one direction while the negative particles (electrons) drift in the opposite direction. Thus, in the case represented in Figure 5b, the nuclei move to the right and the electrons to the left. The separation of positive and negative charges generates a local electrical field, and now the particles are subjected to both electrical and magnetic forces. The combined action causes a motion of ions and electrons, that is, the plasma as a whole, in the direction of decreasing magnetic field. This drift can result in the plasma moving to the walls of the containing vessel. Specially shaped magnetic fields are commonly used to eliminate or reduce plasma drift in nonuniform fields.

As seen above, the tendency for positively and negatively charged particles to drift in opposite directions results in the development of an electric field that then causes motion of the plasma as a whole. The same situation is produced in either uniform or nonuniform magnetic fields if an electric field is deliberately applied in a direction perpendicular to the magnetic field lines. The charged particles travel in paths similar to those shown in Figure 5b, except that both positive and negative particles now move in the same direction. Consequently, the plasma as a whole tends to drift across the magnetic field with no tendency for charge separation to occur.

Open-ended and Closed Confinement

Magnetic confinement systems fall into two general categories, depending upon whether the vessel, chamber, or tube containing the plasma is open ended or closed. In an *open-ended arrangement*, like a cylinder, the magnetic lines of force run parallel to the length (axis) of the cylinder, as in Figure 3b. Escape of plasma to the walls is hindered as a result of the difficulty experienced by the charged particles in crossing the field lines. Escape through the open ends

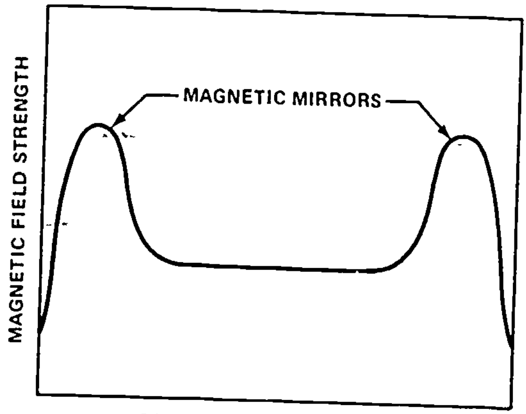


Figure 6. *In a magnetic mirror system, the magnetic field at the ends of a cylinder containing a plasma is stronger than in the central region. Electrically charged particles approaching the mirror regions (stronger magnetic field) in certain directions are turned back (i.e., reflected) and so are prevented from escaping at the ends of the cylinder.*

along the lines of force can be almost entirely prevented by having the magnetic field much stronger at the ends than at the center of the cylinder (Figure 6). Such an arrangement is called a *magnetic mirror* because, under suitable conditions, the charged particles moving toward the end, where the field strength is highest, will be reflected back toward the region of lower field strength. In fact, the particles may be reflected back and forth, from one mirror to the other, many times before they ultimately escape.* The magnetic mirrors thus serve as partial "stoppers" for the open-ended containing vessel.

Closed magnetic confinement systems are generally in the form of a torus, that is, a doughnut-shaped hollow chamber.

*The Van Allen radiation belt of charged particles surrounding the earth owes its existence to the mirror effect of earth's magnetic field; this is stronger near the poles, where reflection occurs, than near the equator.

The magnetic field lines are closed and charged particles cannot escape by traveling along the field lines, but the plasma can drift to the walls, especially if the magnetic field is nonuniform. Suitable steps must then be taken to decrease this effect.

The magnetic fields for confining plasmas are generated by electric currents. Two cases are of interest in connection with the confinement of plasmas. For purposes of illustration, we will consider a toroidal containment chamber, bearing in mind that the conclusions reached are equally applicable to a plasma in an open-ended vessel.

In Figure 7a, the electric current is passed through rings surrounding the torus; these may be separate or they may be connected in series to form a coil (or solenoid). The current flows in the same direction in all the rings, or the turns, of a coil. The magnetic field thus produced is described as a *toroidal field*, it is also referred to as a *longitudinal field* or, especially in a straight tube, as an *axial field*. In Figure 7b, the current flows through the plasma or in a metal ring suspended within the torus; the resulting magnetic field is called a *poloidal field* or sometimes an *azimuthal field*. These two types of fields—toroidal and poloidal—play important roles in the confinement of plasmas.

Plasma Diffusion

Suppose a plasma could be confined in a cylindrical tube by a uniform magnetic field in the direction parallel to the tube axis, as in Figure 3b. In the absence of collisions, the electrically charged particles would simply spiral along the field lines without crossing them. As noted earlier, however, because of the variations in the characteristics of the spiral motions, collisions inevitably occur. If two ions collide, fusion may result, but collisions of electrons with ions may cause the plasma to diffuse across the lines of force and escape from confinement.

The simplest type of plasma diffusion, resulting from particle collisions, is called *classical diffusion*. Loss of plasma from a confining magnetic field as a result of this diffusion cannot be avoided, but calculations show that the effect is not serious. Moreover, by increasing the magnetic field strength, the spiral paths of the charged particles around the field lines become tighter (i.e., they have a smaller radius of curvature) and collisions are less frequent. It is expected, therefore, that in an operating nuclear fusion reactor, in which a strong magnetic field is used to confine the plasma, losses due to classical diffusion will not be important.

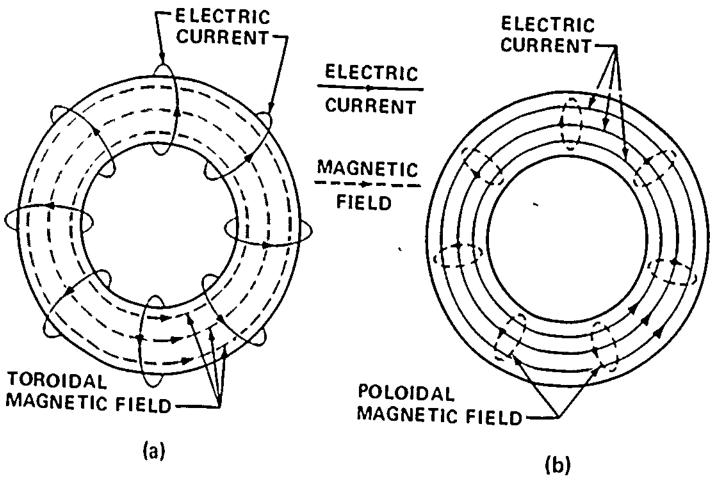


Figure 7. *An electric current is always associated with a magnetic field perpendicular to the direction of current flow. A toroidal magnetic field is shown in (a) and a poloidal magnetic field is shown in (b). Similar magnetic fields can be produced in a linear (cylindrical) tube in an analogous manner: the field corresponding to (a) is then called an axial magnetic field.*

Theoretical studies indicate, however, that classical diffusion is modified (and increased) in a system with closed magnetic field lines (e.g., in a torus). The curvature in the lines of force causes an increase in the diffusion rat. In addition, the schemes used to minimize plasma drift arising from nonuniformity in the confining magnetic field (page 25 *et seq.*) can also affect the diffusion rate. These schemes generally involve a combination of toroidal and poloidal magnetic fields that lead to local variations in the net field strength. In some circumstances, such variations can increase the plasma diffusion rate by permitting the charged particles to move across the field lines. By taking these arguments into consideration, calculations have been made of what is called *neoclassical diffusion*. Although the diffusion rates are substantially higher than for classical diffusion, they are still not considered to be high enough to prevent the operation of a useful fusion reactor.

Another type of plasma diffusion at one time presented a serious threat to magnetic confinement for controlled fusion. It is actually a form of plasma instability and it will be described shortly.

Plasma Instabilities

A plasma in a magnetic field has a tendency to be unstable; as a result, it can break up and escape from confinement by the field. Plasma instabilities are due basically to the presence of electrically charged particles; the electric and magnetic fields produced by their motion cause the particles to act in a *collective* (or cooperative) manner. An example of such collective action is the drift of a plasma in a nonuniform magnetic field, described above. Similar collective effects give rise to plasma instabilities. These instabilities fall into two broad categories called gross *hydromagnetic instabilities* and more localized *microinstabilities*.

Suppose a small displacement of a plasma occurs in a magnetic field, if the system reacts in such a way as to restore the original condition, then it is stable. In the case of a hydromagnetic (or gross) instability, however, the plasma does not recover, but the displacement increases rapidly in magnitude. The whole plasma may then break up and escape even from a strong magnetic field.

Microinstabilities, as the name implies, are on a small scale compared with the dimensions of the plasma. As a rule, these instabilities do not lead to complete loss of confinement, but rather to an increase in the rate at which the plasma diffuses out of the magnetic field. Microinstabilities apparently result from the interaction of electrically charged particles with electromagnetic waves, similar to radio waves, in the plasma. They are, therefore, sometimes called *wave-particle instabilities*. Under certain conditions, the energies of the charged particles can be repeatedly added to the waves so that they grow in amplitude. As a result, a high-frequency turbulence can develop in the plasma that makes its escape from the confining field easier.

One of the most serious consequences of turbulence, especially in toroidal (closed) systems, is called *Bohm diffusion*.* Little attention was paid to Bohm diffusion until the early 1960s when its importance in controlled fusion studies became very apparent. The rate of Bohm diffusion is so high that, unless it could be controlled, the realization of a practical fusion reactor with magnetic confinement was considered to be almost impossible.

The ability to understand and overcome plasma instabilities is vital to the success of the controlled fusion research program. Consequently, the highly complex problems involved have been the subject of extensive experimental and theoretical studies. As a result of the step-by-step interplay between theory and experiments over a period of years, considerable progress has been made.

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*So called because it was first mentioned in a report, published in 1949, by D. Bohm and others of observations made during World War II on a weakly ionized arc plasma in a magnetic field.

Magnetic field configurations have been devised in which hydromagnetic (gross) instabilities are no longer a serious problem. In systems using toroidal magnetic fields, microinstabilities have not been significant, except for Bohm diffusion in some cases. Fortunately, there are operating conditions for which this phenomenon is largely suppressed and the observed diffusion rates are in fair agreement with the classical or neoclassical requirements.

Several different kinds of microinstabilities have been identified in straight, open-ended (mirror) systems, but they have been controlled. Other types have been predicted theoretically but not yet detected; should they occur, means have been proposed for dealing with them. Methods are also known for suppressing hydromagnetic instabilities in magnetic mirror confinement and these will be described in due course. In mirror systems, loss of plasma as a result of instabilities is now a much less serious problem than escape out of the ends of the confining tube (page 63).

Studies of high-temperature plasmas during the past 20 years or so have been full of surprises, most of them unpleasant. However, there is now a general feeling of optimism among scientists that plasma instabilities are reasonably well understood. It appears that they can be controlled, at least to the extent that they will not interfere with the realization of a fusion reactor. Indeed, some instabilities are now being utilized to heat plasmas.

Factors Affecting Confinement Times

The time for which a plasma can be confined by a particular magnetic field arrangement is one of the factors in the Lawson criterion. It is desirable for the confinement time to be as long as possible and this means keeping the various types of plasma diffusion to a minimum. We are assuming, of course, that hydromagnetic instabilities have been controlled. Diffusion rates and hence confinement times can be changed by varying such quantities as magnetic field strength, plasma temperature, and the dimensions of the containing chamber.

When Bohm diffusion does occur, it increases with temperature, thus leading to shorter confinement times at higher temperatures. It now appears, however, that Bohm diffusion can be avoided if the charged-particle *mean free path* (i.e., the average distance a particle travels between successive collisions) is long in comparison with the dimensions of the containing vessel. High temperatures and low densities lead to an increase in mean free path and thus to a decrease in Bohm diffusion.

Under conditions that result in mean free paths that are long in comparison with the plasma dimensions, neoclassical diffusion predominates and, fortunately, the confinement time increases markedly as the temperature is raised

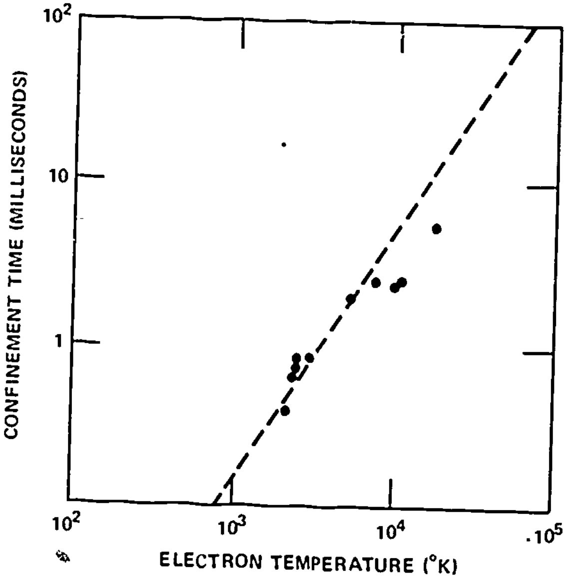


Figure 8. *Plasma confinement time as a function of electron temperature: the confinement time increases with plasma temperature. The broken line shows the variation expected for classical (or neoclassical) diffusion.*

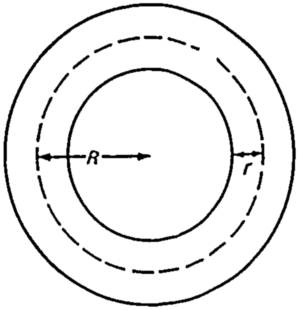


Figure 9. *The major radius of a torus is* R *and the minor radius is* r; *the aspect ratio is* R/r.

(Figure 8). Increase in magnetic field strength increases the plasma confinement time for all types of diffusion and the relative increase is greater for classical and neoclassical diffusion than for Bohm diffusion. These facts explain why losses by diffusion across the magnetic field lines are expected to be of minor significance in a fusion reactor in which a strong magnetic field would be used to confine a plasma at a very high temperature.

The geometry of a torus is determined by its *major radius*, *R*, and its *minor radius*, *r* (Figure 9); the ratio of the major radius to the minor radius (i.e., R/r) is called the *aspect ratio* of the torus. For a given aspect ratio, the confinement time with respect to diffusion increases as the square of the minor radius: that is ay, if the minor radius is increased by a factor of 2, the confinement time is increased $(2)^2 = 4$ fold. This is a useful method for increasing confinement times. For neoclassical diffusion, the confinement time can also be increased by decreasing the aspect ratio of the torus. In a fusion reactor, the toroidal containment chamber may thus resemble a large doughnut with a moderately small central hole. Experiments are under way to determine if some new type of plasma instability (or diffusion loss) occurs in a reaction chamber of this shape.

In a magnetic mirror system, high temperatures and strong magnetic fields are helpful in increasing the confinement time for diffusion across the field lines, but no advantage is to be gained by increasing the radius of the cylindrical containing vessel. Confinement times then depend on classical diffusion* and on the extent to which microinstabilities can be controlled, assuming that hydromagnetic instabilities are essentially absent. Experimental measurements have confirmed the theoretical prediction that microinstabilities can be decreased by reducing the " .ance between the magnetic mirrors that serve as partial stoppers of the open-ended tube.

EXPERIMENTS WITH PLASMAS

Plasma Formation

Once a thermonuclear fusion reactor begins operation, the temperature should be high enough to ionize the injected deuterium–tritium or deuterium gas and to convert it into a plasma. In starting up, however, and also in controlled fusion research, it is necessary to generate a plasma by special methods. The simplest way of forming a plasma is to pass a high-voltage electrical discharge through a gas; this is done, for example, in fluorescent and neon lamps. High-frequency alternating electric fields, such as are employed in radio communications, are particularly useful for producing partial ionization (or "breakdown") of the gas. The weak plasma so formed is an electrical conductor, and further ionization can be readily achieved by means of a direct current or a low-frequency alternating current. If a high voltage is to be applied to the gas in any event, as is sometimes the case, the breakdown stage may not be necessary.

The discharge method is used when the plasma can be formed directly in the containing chamber. In some experi-

*Neoclassical diffusion occurs only in a toroidal system (see page 31).

mental systems employed in controlled fusion research, plasma or high-energy particles are produced outside and various devices are used for injection into the chamber. Among such devices are ion sources and plasma guns. In general, a plasma is produced by an electrical discharge, and it is then accelerated by an electrical field or by a combination of electric and magnetic fields into the experimental vessel.

Plasma Heating

Several methods have been proposed for attaining the very high temperatures required for nuclear fusion reactions. For temperatures up to a few million degrees K, a deuterium–tritium or deuterium plasma can be heated by passing an electric current through it. The procedure is called *ohmic heating* (or *resistance heating*) because it depends on the resistance (in ohms) of the medium carrying the current. The principle is the same as in an ordinary electric light bulb or an electric heater. To heat a plasma in this manner, the current is generally induced from outside, to avoid the need for inserting electrodes into the gas. As the temperature increases, the resistance of the plasma decreases and eventually becomes too low for resistance heating to be useful.

A number of techniques have been developed for heating plasmas to higher temperatures: One method is based on compression of the plasma by a magnetic field. It is well known that a gas can be heated if it is compressed with a pump or in any other convenient manner. Similarly, a plasma is heated if it is compressed by suddenly increasing the strength of the confining magnetic field. As seen earlier, a magnetic field exerts a pressure on a plasma of charged particles. By increasing the strength of the field, the confined plasma can be compressed and heated. If two or more successive stages of magnetic compression are employed or if the plasma is preheated prior to compression, very high temperatures can be attained.

Another procedure is based on the injection of high-energy neutral atoms into a magnetic field. Neutral atoms cannot be accelerated to high velocities (or high energies) directly and so they are produced in an indirect manner. First, deuterium ions* with energies in the kilo-electron volt (1 kilo-electron volt = 1000 electron volts) range are generated in an ion source, and the resulting high-energy D^+ ions pass into a chamber containing neutral deuterium gas. Here a *charge exchange* occurs; the high-energy ions transfer their charge to low-energy neutral deuterium atoms (D^0), that is,

$$D^+ \text{ (high energy)} + D^0 \text{ (low energy)} \rightarrow D^0 \text{ (high energy)} + D^+ \text{ (low energy)}.$$

The result is the formation of a stream of high-energy neutral deuterium atoms that enter the magnetic field region. If this region already contains some charged particles, such as a weak plasma, they will collide with the neutral atoms and ionize them. Hence, a high-energy plasma will be formed and trapped within the magnetic field.

If a strong turbulence occurs in a plasma, the plasma will tend to become unstable and escape from the magnetic field. There are indications that turbulence not severe enough to cause significant instability can be induced in a plasma by applying an electric field for a very short time. After the field is removed, the turbulence dies out and the energy is transferred to the plasma, which may thus be heated to high temperatures.

A process called *magnetic pumping* has been proposed for heating plasmas. A toroidal chamber is surrounded at one or more regions by magnetic coils whereby the local magnetic

*Although the earliest fusion reactors will probably use both deuterium and tritium, researches on controlled nuclear fusion are performed with hydrogen, deuterium, or helium in order to avoid handling radioactive (and expensive) tritium.

field strength is continuously increased and decreased in rapid succession. When the field is increased, the plasma is compressed and heated, but, during the subsequent decrease in field strength, the plasma expands and is cooled. If the frequency of the alternations is chosen correctly, the heating during the compression phase exceeds the cooling in the expansion phase. The net result is that the plasma is heated.

An approach somewhat related to magnetic pumping is the *ion cyclotron* method of plasma heating. By adjusting the alternating frequency of the local magnetic field so that it is slightly lower than the frequency at which the ions spiral about the confining magnetic field lines, a wave motion develops in the plasma. The damping of these ion cyclotron waves results in the conversion of their energy into heat. In *electron cyclotron heating,* electron cyclotron waves are produced in a similar manner. The plasma is then heated by the damping of these waves. Plasma heating is also being studied with waves at other (lower) frequencies.

In addition, the generation and heating of plasmas by means of laser light beams, intense beams of high-energy electrons, microwave radiation, and shock waves are receiving increasing attention. A different application of laser heating in controlled fusion is described on page 71.

Plasma Diagnostic Techniques

In studying the behavior of magnetically confined and heated plasmas, it is necessary to determine such properties as temperature, pressure, electron and ion densities, electron and ion energies, magnetic field distribution, current strength, and extent of thermonuclear reaction. The experimental procedures used to obtain such information are referred to as "diagnostic techniques". The nature of plasmas is such that considerable skill and ingenuity are required to apply these techniques and to interpret the results of the measurements made. Some plasma properties that are being studied and the methods employed are summarized in the accompanying table. (See Photo 3.) Since neutrons are produced in fusion reactions, the number and energy of these particles liberated provide some indication of the extent of such reactions. Detailed explanation of these procedures is beyond the scope of this booklet, but the listing indicates the complexity of plasma research and the variety of equipment and techniques in use.

PLASMA DIAGNOSTIC TECHNIQUES

Quantity measured	Diagnostic method
Plasma current	Current shunts; current transformers (Rogovsky coils)
Plasma pressure distribution	Magnetic probes; piezoelectric crystals
Electron density	Microwave interferometer; Thomson scattering
Ion density	Optical spectroscopy (Stark effect); Langmuir probes
Plasma density	Laser interferometer
Electron energy and temperature	Microwave emission; X-ray emission; Langmuir probes; Thomson scattering; optical spectroscopy
Ion energy and temperature	Optical spectroscopy (Doppler effect); mass spectroscopy
Electric and magnetic fields	Magnetic probes; Hall-current probes; optical spectroscopy (Zeeman effect); thallium ion beams
Neutron emission	Boron counters; scintillation detectors; silver or indium foil activation

HIGH-TEMPERATURE PLASMA STUDIES

Understanding Plasma Behavior

With the facts already presented as a background, it is possible to outline some of the more important experimental researches on plasmas, as related to controlled fusion, now being conducted. Because the behavior of magnetically confined plasmas at high temperatures is so complex, several different lines of investigation are being followed. Basically, the approaches differ in the arrangement (or geometry) of

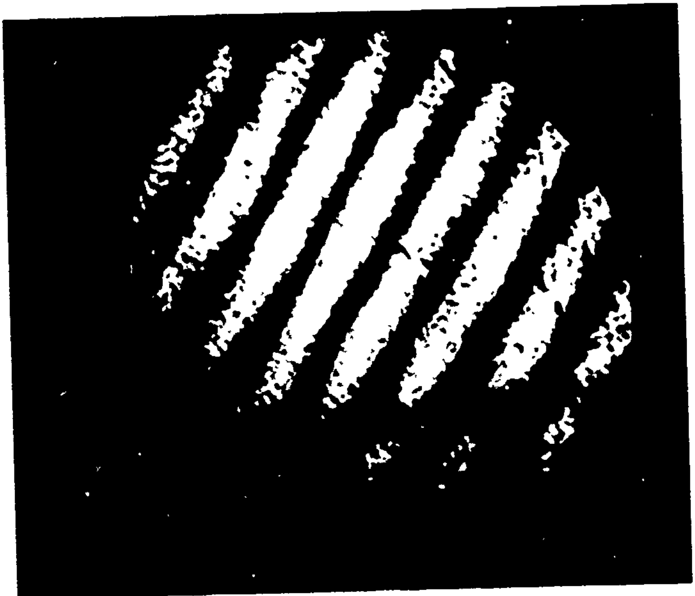
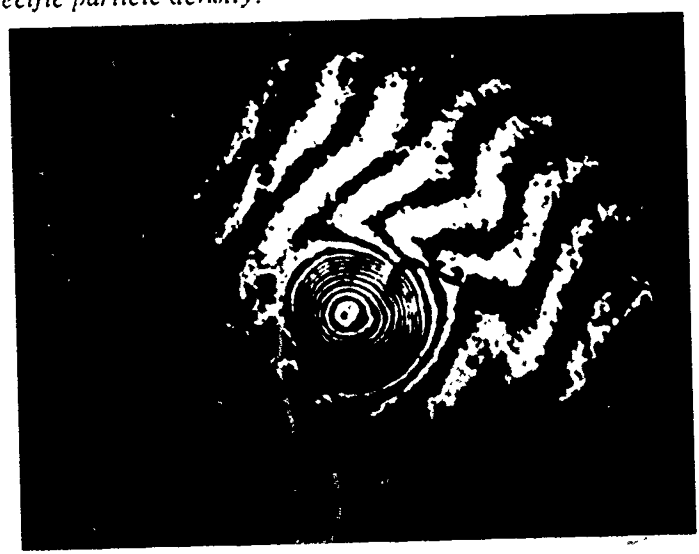


Photo 3. *Ruby laser interference patterns (interferograms) are used to determine particle densities in a plasma. The upper photograph shows the pattern obtained in the absence of a plasma, the lower one is the interferogram obtained with a plasma. Each circle in the central region corresponds to a specific particle density.*



the magnetic field for confining the hot plasma. The purpose of this many-pronged attack is to study the properties of plasmas under a wide variety of confinement conditions. Only by understanding these properties will it be possible to develop a reactor for producing useful power from controlled nuclear fusion.

At present, four general classes of magnetic confinement of high-temperature plasmas are receiving major attention by scientists in many countries. They are (a) pinch systems, (b) the stellarator, (c) the tokamak, and (d) magnetic mirrors. If the required conditions of plasma temperature, density, and confinement time can be realized in any one of these systems, scaling up to a practical fusion reactor would seem to be possible. In addition, studies are being made with devices that do not directly form the basis of reactors but are intended for investigating plasma behavior, especially as related to stability.

Low-Beta Pinch

In the phenomenon known as the *pinch effect*, an electric current flowing through a plasma produces a poloidal magnetic field, as in Figure 7b, which confines the plasma. In a toroidal chamber, the current is induced in the plasma from outside in the general manner shown in Figure 10. The torus containing the plasma passes through an iron yoke that forms the core of a transformer. The primary circuit is wound around the yoke whereas the plasma acts as the secondary circuit. If a rapidly increasing (or varying) current is passed through the primary, a corresponding current is induced in the plasma, thus generating the magnetic field that both confines and compresses (i.e., pinches) the plasma. An early stage of pinch formation is represented in Figure 11.

When the pinch effect was first proposed for plasma confinement, there were hopes that the plasma would also be heated. Part of the heating would be resistance heating,

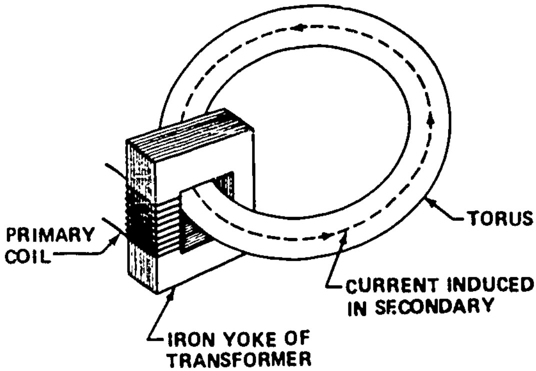
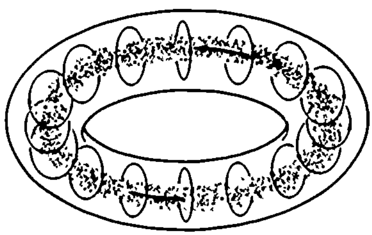


Figure 10. *A varying current passed through the primary coil induces a corresponding current in the plasma (contained in the torus) acting as the secondary of the transformer. In some cases, two identical yokes with primary coils may be used (see Figures 13 and 15).*

caused by the flow of electric current in the plasma, and part would result from compression by the strong poloidal field. Although such heating did occur, it soon became apparent that the pinched plasma was highly unstable and did not persist for more than a few millionths of a second (Photo 4). This time was too short for the production of a significant

Figure 11. *Representation of the pinch effect in a toroidal tube. The darker ring is the plasma in which an electric current is induced; the circles surrounding the plasma indicate the poloidal magnetic field produced by the current.*



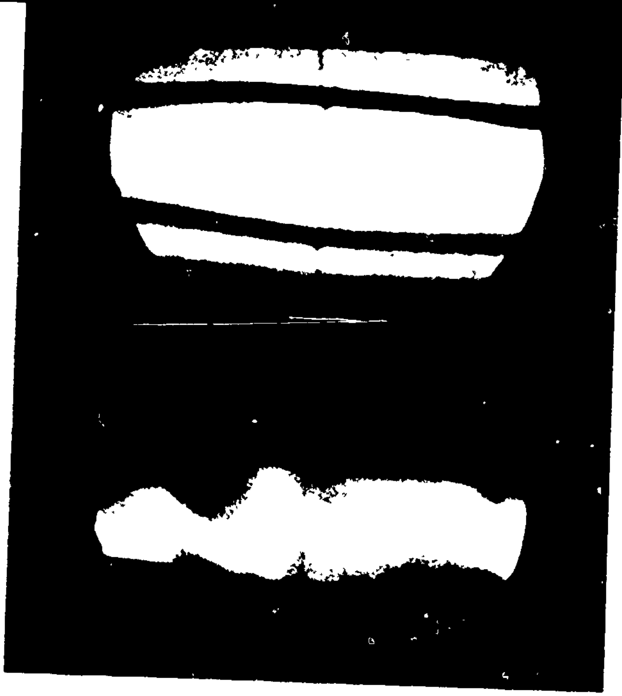


Photo 4. *The bright horizontal strip in the center of the upper picture is a portion of a pinched plasma while it is stable. A few millionths of a second later it breaks up, owing to the development of instabilities; as seen in the lower picture.*

amount of fusion energy, even if the temperature had been high enough.

Theoretical studies indicated that it might be possible to overcome hydromagnetic instabilities of the pinched plasma by trapping within it a toroidal magnetic field. The basic thought was that the field lines running around the torus (see Figure 7a) would act as a sort of stiffener, so that it would be more difficult for the plasma to break up. Another stabilizing device is the inclusion of a metal shell either within or outside the toroidal chamber. These procedures undoubtedly increased the plasma stability to some extent but did not eliminate instabilities entirely. Furthermore, it was found that the stabilizing magnetic field included in the plasma opposed the pinch action and thus limited the compression.

The pinch effect just described is called a *Z pinch*, where *Z* stands for the longitudinal direction around the torus. It is also referred to as a *low-beta pinch* because the plasma particle pressure is small in comparison with the magnetic field pressure, (i.e., beta is small). At one time, studies of low-beta *Z* pinches played an important role in controlled fusion research. But in recent years, the activity has diminished and is now largely concerned with the effort to understand and overcome instabilities in low-beta plasmas.

High-Beta Pinch

In the simplest form of the high-beta pinch, a wide single-turn coil surrounds a tube containing a plasma at ordinary temperature (Figure 12a). By using a bank of capacitors (see Photo 5), a powerful current is suddenly switched into the coil; this generates within the tube a sharply increasing magnetic field in the direction parallel to the axis. The situation is similar to that in Figure 7a, except that a single coil around a straight tube is used instead of a series of coils around a torus.

The surface of the plasma forms a cylindrical sheath that is driven rapidly inward by the fast-rising magnetic field as indicated in Figure 12a. The plasma is consequently heated by a shock originating from the moving sheath followed by compression (or pinching) when the magnetic field increases more slowly. As the field reaches its maximum strength, there is a relatively quiescent phase in which the plasma is held in a cigar-like shape as depicted in Figure 12b. However, in a short time, the plasma is lost by escape from the ends as shown by the arrow.

The current that generates the magnetic field runs around the containing tube in what is called the theta (Greek, θ) direction. The effect observed is thus referred to as a *theta pinch*. Since the plasma is strongly compressed, its pressure is high and so also is the beta value. This is why the fast magnetic-compression phenomenon just described is termed

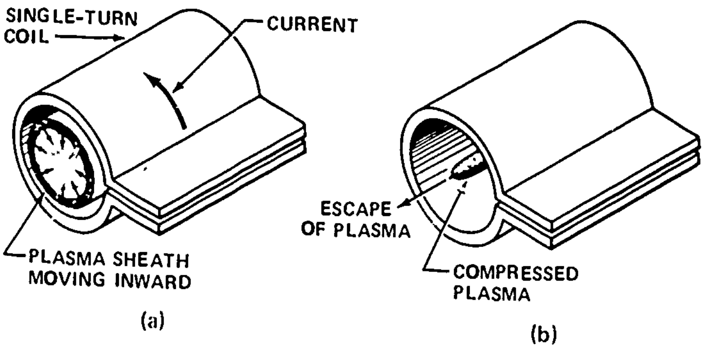


Figure 12. *Development of a theta pinch: (a) shock-heating phase, and (b) quiescent compression phase.*

the high-beta theta pinch. As will be seen shortly, high-beta Z pinches are also possible.

Experiments on linear (open-ended) theta pinches have led to the production of deuterium plasmas with temperatures in the vicinity of 50,000,000°K and densities up to about 5×10^{16} particles per cubic centimeter. Nuclear fusion reactions have been observed under these conditions. However, because of the rapid escape of the plasma, the confinement times have been very low, generally a few millionths of a second, so that the maximum Lawson $n\tau$ product has been roughly 2.5×10^{11}, compared with at least 10^{14} required for a deuterium–tritium system.

The confinement time of the plasma in a linear theta pinch is limited by the escape of plasma from the ends. One possible way whereby this escape can be prevented is to bend the tube into a circle, i.e., a torus, so that the two ends close

Photo 5. *Some thermonuclear research requires large amounts of electricity in short pulses. The photo shows the capacitor bank for Scyllac, a toroidal theta-pinch device, at the Los Alamos Scientific Laboratory. The full toroidal Scyllac experiment will have 3240 primary bank capacitors, 15,000,000 joules of stored energy, 60,000 volts maximum bank voltage, and 130,000,000 amperes maximum current.*

on themselves. Although there will be no ends from which the plasma can leak away, losses to the walls will be possible and methods are being developed to minimize them. Experiments are under way to test the feasibility of establishing a fairly stable toroidal theta pinch (see page 77). It is expected that ultimately the magnetic fields will be programmed so as to provide distinct shock-heating and compression phases.

The linear theta pinch is remarkably free from gross plasma instabilities that would drive the plasma as a whole to the walls of the tube. This is indicated clearly by the laser interference patterns in Photo 6, taken at various times during the quiescent phase. The number of interference rings produced by the plasma decreases, indicating a decrease in density due to losses, but there is no appreciable change in location or circular cross section of the plasma. Furthermore, other observations show that, at least at temperatures of about 1,000,000°K, the loss of plasma by diffusion across the magnetic fields lines is approximately classical and is very much less than would result from Bohm diffusion. A similar situation is expected to exist at the higher temperatures required for a nuclear fusion reactor.

Although the linear, high-beta theta pinch appears to have little or no hydromagnetic instability, theory suggests that

2.4 μsec

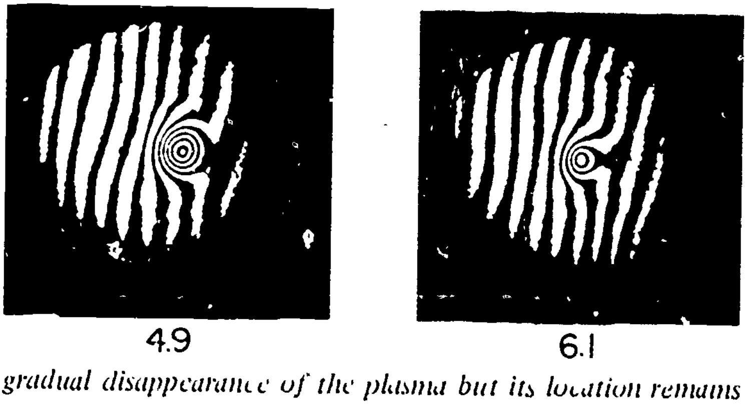
3.6

Photo 6. *Laser interferograms of a theta pinch at successive times (in millionths of a second) after formation. The decrease in the number of interference rings indicates the* such instability may occur in a toroidal theta pinch. Various methods are being considered whereby this type of instability can be controlled when a toroidal chamber is used to eliminate escape of plasma from the ends.

In view of the success of the high-beta theta pinch, there has been a revival of interest in the Z pinch, using the same fast magnetic-compression concept to obtain high-beta plasmas. Experiments were first made by passing an electric current through a straight tube in such a manner that a rapidly increasing poloidal magnetic field was produced. The results have been so promising that a toroidal, high-beta Z pinch system has been built. Hydromagnetic instabilities are expected, just as in the theta pinch, but it is hoped that they can be overcome.

Stellarator Systems

It would seem, at first thought, that a simple way of confining a plasma in a torus would be by means of a toroidal field obtained in the manner shown in Figure 7a. Apart from losses by diffusion across the field lines, the electrically charged particles might be expected to spiral endlessly around the lines of the magnetic field. Unfortunately, this is



4.9 6.1

gradual disappearance of the plasma but its location remains unchanged.

not the case. Because the inner circumference of the torus is shorter than the outer circumference, the coils carrying the electric current must be closer on the inside than on the outside. Consequently, the magnetic field is strongest near the inner circumference and it becomes progressively weaker in the outward direction. In other words, the field is nonuniform (inhomogeneous) over the minor cross section of the torus. In view of the arguments developed earlier, it is evident that the plasma as a whole will drift toward the outer wall, that is, in the direction of the weaker magnetic field. Confinement is thus not possible.

In a ring-shaped tube or, in fact, in a closed tube of any shape, such as an oval or race track, that lies in one plane, each line of force closes upon itself as it is followed around the tube. In all such tubes, the magnetic field is inhomogeneous, and plasma drift must take place. It has been shown, however, that if the magnetic field is distorted or twisted in such a way that the lines of force do not close upon themselves after making one complete circuit, the plasma drift will be greatly reduced or even eliminated. This is the basic principle of the *stellarator* system.

In the earlier models of the stellarator, the required result was achieved by twisting the tube into the shape of a figure eight, somewhat like a pretzel, so that it was no longer in one plane. Later, it was realized that the same result could be achieved in a closed planar tube by using two sets of magnetic field coils. One set, called the *confining field coils* (Figure 13), is of the simple type for producing a toroidal field (compare Figure 7a). The other, indicated as the *helical (stabilizing) windings*, with current flowing in opposite directions in alternate turns, provides the required twist. These windings also provide a degree of stabilization against hydromagnetic instability. For convenience in adding various pieces of equipment, stellarators have generally been constructed in the form of a race track, but this is not essential. In fact, circular (toroidal) chambers may be less subject to diffusion losses.

In the operation of a stellarator, formation and heating of the plasma are generally accomplished in three stages. First, a radio-frequency discharge is used to preionize the deuterium (or other) gas in the tube. The resulting weakly ionized plasma is confined by the magnetic fields, and a toroidal current is then induced from outside by means of a transformer with an iron yoke (see Figure 10). The ionization of the plasma is thereby increased, and its temperature is raised by resistance heating to about 1,000,000°K. For reasons that will be apparent shortly (page 56), this approaches the maximum possible for resistance heating. Hence, subsequent increase of temperature must be attained in other ways, such as ion cyclotron heating or magnetic pumping.

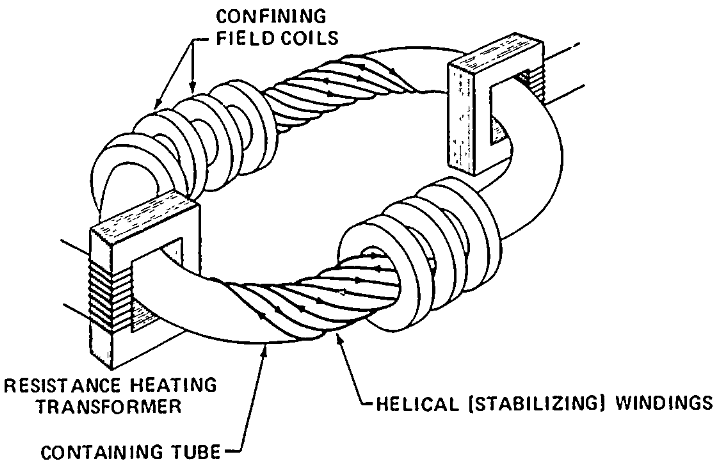


Figure 13. *Representation of a racetrack (planar) stellarator. (The confining field coils and the helical windings go around the entire tube, but parts are omitted in the diagram for simplicity.) The field coils produce the toroidal magnetic field, and the helical windings, with current passing in opposite directions in adjacent turns, provide the twist for stabilizing the plasma.*

In stellarators and similar devices in which the magnetic field lines are twisted in the manner indicated above, there is an upper limit to the toroidal current that can be passed through the plasma. This limiting current is known as the *Kruskal-Shafranov limit*, after M. D. Kruskal of the United States and V. D. Shafranov of the U.S.S.R. who predicted it independently. If this limit is exceeded, the plasma develops a hydromagnetic instability called the *kink instability* (see Figure 14). Suppose that a small kink (actually a helical distortion) develops in the plasma, as indicated in Figure 14. The lines of force of the encircling magnetic field are closer together on the inside (bottom) than on the outside (top) of the kink. The field strength is thus greater on the inside, and, as a result of the difference in field strength, the kink is distended even more. This continues until the pinched plasma is so badly distorted that it touches the walls of the vessel, as in Photo 4, or breaks up entirely.

There have been many severe losses arising from Bohm diffusion in much of the stellarator work. At one time it was thought that this behavior might be characteristic of all stellarator systems, but such is not the case. By increasing the plasma temperature and by taking care in the construction of the toroidal magnetic field coils to avoid nonuniform regions, confinement times in stellarators have approached the values

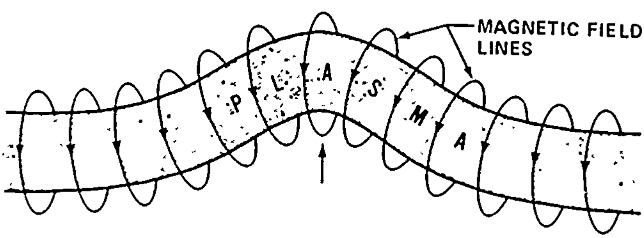


Figure 14. *The kink instability in a plasma. (The plasma is actually in the form of a spiral which is shown here in a two-dimensional representation.)*

expected from neoclassical diffusion. Since there is essentially no compression of the plasma, stellarators are low-beta devices.

Tokamak Systems

Since about 1969, when results of considerable consequence for controlled fusion were reported from the U.S.S.R., there has been widespread interest in the *tokamak* concept. The tokamak is a low-beta toroidal system with features of both the stabilized *Z* pinch and the stellarator. The plasma is contained in a metal-walled torus and toroidal and poloidal fields are applied, the former by coils surrounding the torus and the latter by inducing a current that flows around the torus (Figure 15). This is similar to the stabilized low-beta pinch system (page 42), the difference lies in the relative strengths of the two magnetic fields. In the tokamak, the toroidal field is much stronger than the poloidal field (about 10 to 1), whereas in the *Z* pinch the reverse is true (less than 1 to 1). The tokamak is similar to the stellarator in that the magnetic field is twisted so that the lines do not close on themselves after a single circuit. However, in the tokamak the twist is produced by the combination of toroidal and poloidal fields and can be varied, whereas in the stellarator it is achieved by means of the fixed helical windings.

By varying the toroidal and poloidal magnetic fields independently, a region of exceptional plasma stability was discovered in the tokamak. A low-beta plasma, with a density approaching 5×10^{13} particles per cubic centimeter, was confined for about one-fiftieth (0.02) of a second. The Lawson $n\tau$ product was thus almost 10^{12}, this was achieved in 1972 and is the largest value attained so far in a high-temperature plasma. The ion temperature, which determines the fusion rate, was about 5,000,000°, although the electron temperature was higher. There is no evidence of Bohm diffusion and the confinement times correspond to

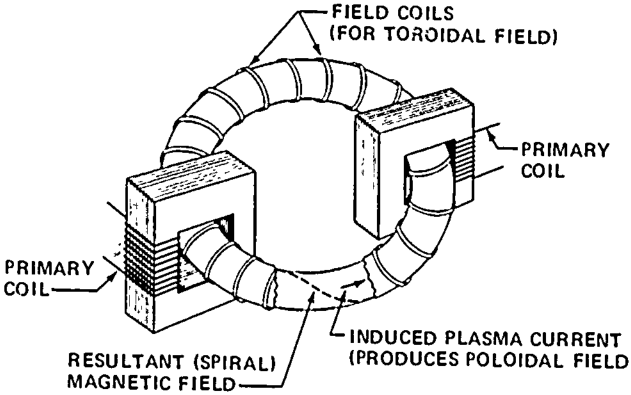


Figure 15. *Representation of a common type of tokamak. The current in the field coils generates a toroidal magnetic field (not shown): the plasma current induced by current in the primary coils produces a poloidal magnetic field (not shown). These two fields combine to form a spiral magnetic field, as shown, which stabilizes the plasma. (In some tokamaks, the plasma current is induced by current in primary coils running around the major circumference of the torus, i.e., perpendicular to the toroidal field coils.)*

neoclassical (or classical) diffusion. Since 1969, various experimental tokamak devices have been built in several countries, including the United States. (See Photo 7.)

The ion and electron temperatures mentioned above result from resistance heating by the toroidal current induced in the plasma. In this type of heating, the energy is first absorbed by the electrons and is then shared with the ions by collisions; this explains why the electron temperature is greater than the ion temperature. The temperatures attained in tokamak experiments have been higher than expected from calculated values of the plasma resistance. This anomalous (larger) resistance is attributed to minor turbulence, perhaps due to microinstabilities, in the plasma.

As in the stellarator, the toroidal current, which heats the plasma and also generates the poloidal field in the tokamak, must be kept below the Kruskal-Shafranov limit in order to avoid hydromagnetic (kink) instability. To achieve maximum resistance heating, the limit should be as large as possible. According to theory, this can be achieved by increasing the toroidal magnetic field strength and decreasing the aspect ratio of the torus (see Figure 9). The smallest practical aspect ratio is about 3, but with such a fat torus, it would be difficult to attain a strong toroidal field; hence, a compromise would be necessary.

Although the tokamak concept appears to be a promising approach to controlled nuclear fusion, there are many problems still to be solved. The problem of increasing the

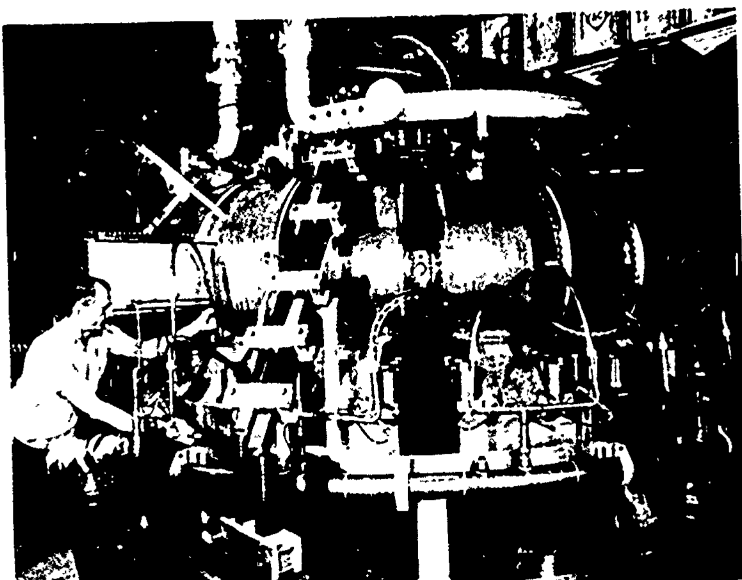


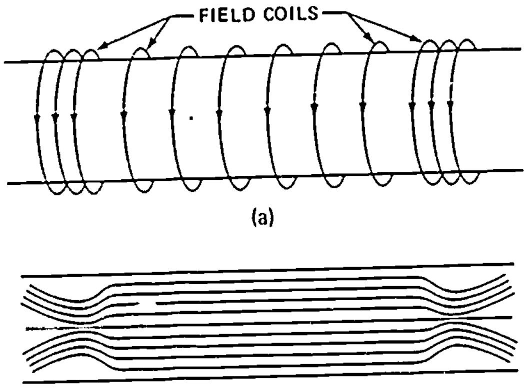
Photo 7. *The Model ST (Symmetric Tokamak) at Princeton Plasma Physics Laboratory. This device was made by reconstructing the Model C stellarator.*

Lawson $n\tau$ product at least a hundredfold is obvious, and there are two others that should be considered. First, the plasma temperature that can be reached by resistance heating is probably 10,000,000° at the very most, partly because of the decrease in the plasma resistance at high temperatures and partly because of the Kruskal-Shafranov limit on the current strength. Further heating will thus be necessary to attain the temperatures required for a nuclear fusion reactor. Several methods of heating are being studied; these include plasma turbulence, magnetic compression, and the injection of high-energy neutral atoms.

A second major problem is associated with the very low beta values in a tokamak device. At low beta, the fusion energy generated per unit volume of a reactor would also be low. This means that the smaller the beta value, the larger would be a reactor designed to produce a certain amount of power. Furthermore, when beta is low, losses from synchrotron radiation (page 18) become large. With existing tokamaks, long confinement times are associated with low-beta plasmas, but possibilities are being studied for increasing beta without significant decrease of confinement. Beta should be increased by decreasing the aspect ratio of the torus, but this will mean some sacrifice in the magnitude of the resistance heating current. An optimum tokamak design can result only from a balance among several factors.

Magnetic Mirror Systems

In its simplest form, the *magnetic mirror* arrangement consists of a number of coils wound around a straight tube with the coils being closer at the ends than in the middle (Figure 16a). If the same current is passed through each coil, the magnetic field generated is stronger at the ends, leading to the result shown earlier in Figure 6. The lines of force are closest where the field is strongest, as indicated in Figure 16b. The stronger magnetic fields at the ends serve to slow down and, under certain conditions, turn back the



(b)

Figure 16. *Representation of a simple magnetic mirror system: (a) shows the windings of the field coils, and (b) indicates the form of the lines of force.*

charged particles that might otherwise escape. As seen earlier, the stronger magnetic fields at the ends can thus act as mirrors for the reflection of the charged particles in a plasma.

As a charged particle spirals along a magnetic field line and enters the mirror region where the field is stronger, a force begins to act on the particle that tends to push it back toward the central region. The rate of motion of the particle parallel to the field lines, or $v_{\parallel}$ (see Figure 4), is thus reduced, and the separations between successive turns of the spiral path become smaller and smaller. If the magnetic field in the mirror region is strong enough, it will first bring the particle motion along the field lines to a stop and then reverse it. In other words, the particle is reflected back into the region of weaker magnetic field. Such a particle will spiral back and forth, after successive reflections at the two ends, so that it is trapped between the magnetic mirrors.

Not all the charged particles in a plasma will undergo reflection in the mirrors. For example, a particle with all its velocity parallel to the field lines in the region between the mirrors, i.e., with $v = v_{\|}$ in Figure 4, will move straight along the field lines, without spiraling, and escape through the mirror. For a particle to be reflected and trapped between the mirror fields, it must have an appreciable velocity component $v_{\perp}$ perpendicular to the lines of force in the central region. Particles with smaller values of $v_{\perp}$ will escape. The greater the strength of the magnetic field in the mirror regions relative to that in between, the smaller the value of $v_{\perp}$ for which reflection is possible. Thus, the stronger the mirror fields, for a given strength in the central region, the greater the proportion of charged particles that can be trapped.

Another way of viewing the situation is to think of the particles as moving in a magnetic valley (central region) between two peaks (mirror regions), as depicted in Figure 6. If a particle has sufficient velocity in the right direction as it approaches a peak, it will, in a sense, go right over and escape. But if the velocity is sufficient only to take it part of the way up the peak, it will fall back to the valley. Particles in this category are trapped. The direction of approach to the peaks is clearly important; if it is head-on, escape will be easier than if the particle, with the same velocity, is moving at an angle. Moreover, the higher the peaks (the mirror fields), with respect to the valley, the more difficult it will be for particles, even those approaching almost head-on, to escape.

Resistance heating in a magnetic mirror system does not seem to be practical; consequently, other plasma heating techniques must be used. An initial plasma may be created by electron cyclotron heating or by the use of microwave radiation. Subsequent heating bv means of high-energy neutral atoms appears to be a promising approach. In addition, heating has been achieved by magnetic compression. This can be done by changing the magnetic fields in one or both of two ways. First, by increasing the strength of the field in the central region, the plasma is compressed toward the axis of the tube and is thus heated. The magnetic field in the mirror region should be increased at the same time to retain the same trapping characteristics. The second method, which may be combined with the first, is to bring the magnetic mirror fields rapidly closer together. The plasma is then squeezed into a smaller space and is heated.

In the earlier magnetic mirror experiments hydromagnetic instability was a problem, but it has now been solved. Theoretical studies indicated that a plasma would be stable if it could be confined by a magnetic field that had a minimum strength in the center and increased outward in *all* directions. Such an arrangement is called a *magnetic well* or a *minimum-B configuration*, since *B* is the symbol commonly employed to represent the strength of a magnetic field. In 1961 the Russian physicist M. S. Ioffe showed that such a configuration could be achieved in a mirror system by placing a number of conductors, generally referred to as "Ioffe Bars", parallel to the central axis of the tube containing the plasma and passing currents in opposite directions through adjacent conductors (Figure 17). Since the magnetic well concept was introduced, hydromagnetic instability has been virtually eliminated in magnetic mirror devices. (See Photo 8.)

An ingenious scheme for producing in a simple manner a mirror field that includes a magnetic well is known as the "baseball"-(or "tennis-ball"-) seam coil, so named because its winding is shaped like the seam of a baseball or tennis ball, as seen in Figure 18. The general configuration of the magnetic field generated by passing an electric current through the coil is also shown. The mirror fields, which are at right angles to each other, occur where the turns in the coil come close together. The central region is a magnetic well from which the field strength increases outward in all directions. Plasma confinement systems have been constructed with magnetic fields produced by baseball-seam coils. The plasmas were found to behave as expected in the suppression of the hydromagnetic instability. The baseball-seam coil system is one possibility of confinement in a nuclear fusion reactor. (See Photo 9.)

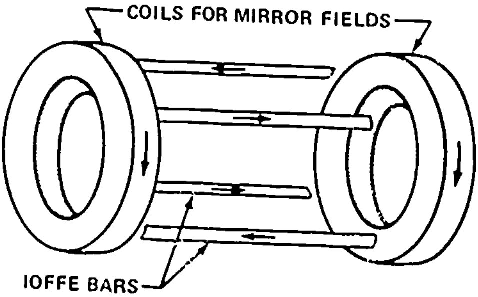


Figure 17. *Representation of four Ioffe bars in a magnetic mirror system: currents flow in opposite directions in adjacent bars. The magnetic field, produced by the currents in the mirror field coils and in the Ioffe bars combine to form a minimum-B (or magnetic-well) field in which the strength increases from the center outward in all directions.*

Photo 8. *Part of the 2X II magnetic mirror experiment for confining and heating plasmas at the Lawrence Livermore Laboratory in California. It includes the magnetic well concept to achieve plasma stability.*

As a result of painstaking researches, both theoretical and experimental, several plasma microinstabilities have been identified in mirror systems, and methods have been developed for controlling them. The procedures include avoidance of impurities in the hydrogen-isotope plasmas, suitable variations in the strength of the magnetic field, and a relatively short distance between the mirrors. As a result of these and other measures, Bohm diffusion does not occur, and the loss of plasma across the magnetic field lines approaches that corresponding to classical diffusion.

Plasma temperatures as high as 200,000,000° have been reported by the injection of energetic neutral atoms into a mirror system. The maximum value of the Lawson product attained, although not in the same experiment, is about 2×10^{11}. This moderate value is mainly the consequence of the low-beta characteristics of the plasmas employed in most

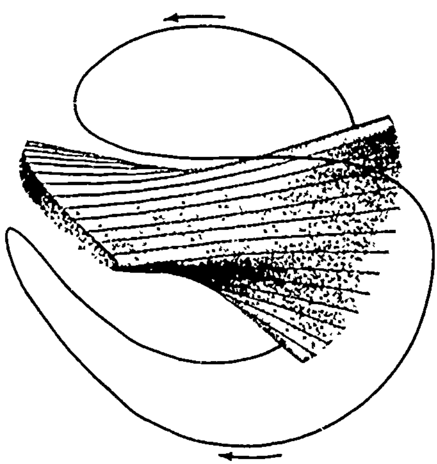
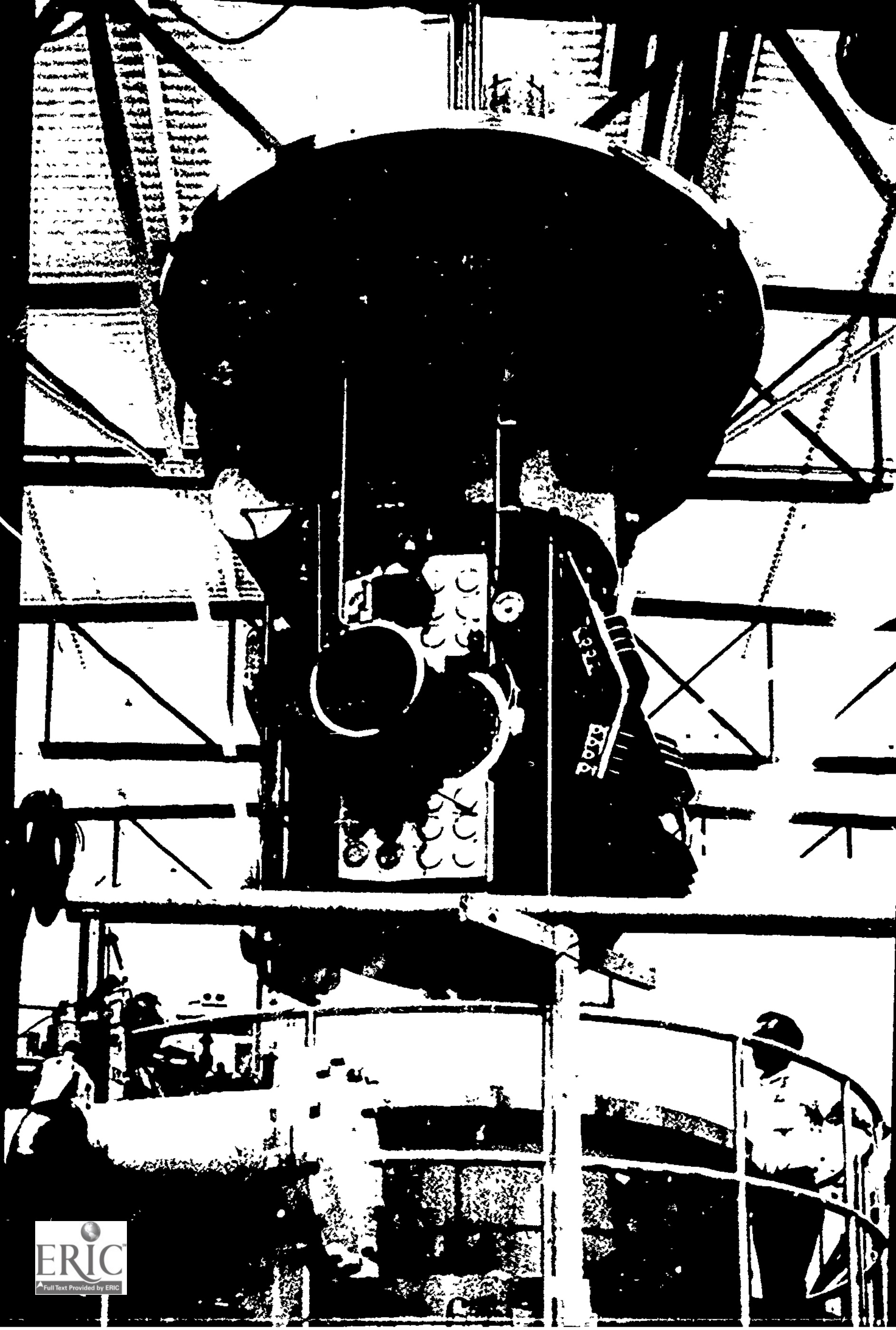


Figure 18. *Magnetic-well field produced by current in a coil shaped like the seam of a baseball (or tennis ball). Two fan-shaped mirror fields are formed at right angles to each other in the regions where parts of the coil come close together.*



magnetic mirror experiments Research is being conducted to discover a means to increase the beta of the confined plasmas, and the early observations appear to be promising.

Even if all instabilities could be suppressed, magnetic mirror systems would still suffer from the loss of plasma by escape through the mirrors. In a thermonuclear plasma, it is inevitable that a fraction of the particles will have substantial velocity components parallel to the magnetic field lines. Such particles will not be trapped by the mirrors. Because of the resulting loss of energy, it is possible that the temperature required for self-sustaining nuclear fusion may be higher in mirror systems than in other types of magnetic confinement. Consideration is being given to the possibility of decreasing escape of plasma through the mirrors by applying radio-frequency fields.

Internal-Ring Systems

Internal-ring devices are toroidal systems in which one or more conducting (metal) rings are suspended either mechanically or by magnetic levitation within the torus (Figure 19). The ring circumference is parallel to that of the toroidal chamber. These systems generally contain one or four rings; the latter are called octopole devices. Current may be induced in the rings from outside by making them serve as secondaries of a transformer. Single-ring devices have been constructed with superconducting rings, so that once current is induced, it persists as long as the required low temperature

Photo 9. *In the upper part of the photograph is the Baseball II superconducting magnet, which is the largest magnet of this type ever built for fusion research. Underneath is the vacuum chamber in which the magnet is now sealed at the Lawrence Livermore Laboratory.*

is maintained (see page 67). Alternatively, as in the D. C. octopole, direct-current leads are connected directly to the rings. (See Photo 10.)

Passage of current through the rings generates poloidal fields in the usual manner. In one-ring devices, windings around the torus also provide a toroidal magnetic field. Such a field may or may not be included with octopole arrangements. Plasma is injected into or generated within the torus and it tends to form a sleeve around the ring (or rings).

The internal-ring systems are not intended as prototypes for nuclear fusion reactors. Their main purpose is to study plasma stability and instabilities. It has been found that when the poloidal magnetic field is produced by current flowing in a metal ring rather than the plasma, it is a relatively simple matter to achieve stability. The diffusion rates are then very close to those expected from classical considerations. By varying the experimental conditions, the requirements for stability can be determined. Furthermore, by disturbing the magnetic fields in various ways, the factors that lead to instabilities can be understood.

Figure 19. *Sections through a torus with (a) one suspended conducting coil and (b) four suspended coils (octopole).*

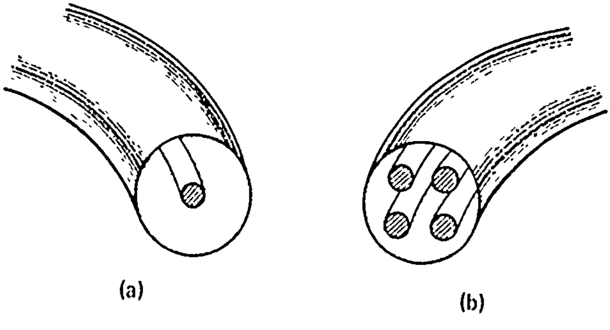


Photo 10. *Interior of the D. C. octopole device at Gulf General Atomic. Four conducting rings are supported mechanically within the torus.*

NUCLEAR FUSION REACTORS WITH MAGNETIC CONFINEMENT

Toroidal Confinement System

There is a feeling among plasma physicists that the scientific possibility of nuclear fusion as a means of generating useful power will probably be established in the early 1980s. Consequently, some thought is being given to the form that a fusion reactor might take. The following description indicates the general outlines of a steady-state, toroidal magnetic confinement reactor in which the energy is produced by the deuterium tritium nuclear reaction.* Systems of other types have been studied and two of them will be described in later sections.

*A steady-state reactor is one that operates continuously rather than in pulses.

We mentioned on page 12 that some 80% of the energy of the D–T reaction is carried by the neutrons. Since these particles are not electrically charged, they are not confined by a magnetic field. Consequently, when D–T fusion has occurred, the high-energy neutrons will escape from the plasma. The helium nuclei produced in the fusion reaction will remain in the chamber and their energy will ionize and heat the incoming deuterium–tritium gas. Eventually, the helium gas will be discharged as a completely innocuous material that may, however, be used in the operation of the fusion reactor (see below).

The toroidal reaction chamber will be surrounded by a "blanket" of molten lithium, either in elemental form or as a salt (Figure 20) for breeding tritium. The blanket shell would probably be made of a refractory metal, such as niobium, vanadium, or molybdenum, although stainless steel is also a possibility. The energetic neutrons enter the blanket and interact with the lithium nuclei to produce tritium; this is removed as gas and returned to the reaction chamber. At the same time, the neutrons deposit their energy in the lithium, which will thus be heated to temperatures up to about 1100°C (2000°F). The lithium blanket will be surrounded by

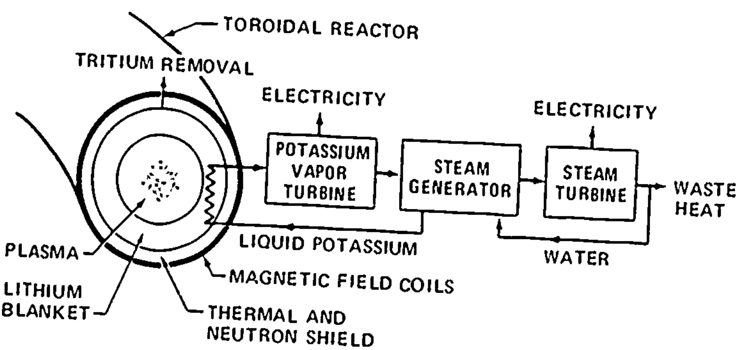


Figure 20. *Section through a torus showing the basic principles of a possible fusion reactor.*

a thermal insulator, which can also absorb stray neutrons, and finally by the magnetic confinement coils.

The heat deposited in the blanket by the neutrons can be transferred to potassium by passing liquid potassium through pipes immersed in the lithium. The potassium will boil and the hot vapor will be used to drive a turbine-generator for the production of electricity. The potassium vapor exhaust from the turbine will be of sufficiently high temperature to produce steam from water by way of a water potassium vapor heat exchanger. The steam will be employed in a conventional turbine to generate more electricity. Another possibility would be to circulate a gas, such as helium, through the lithium blanket. The hot gas would then be used to operate a gas turbine. Instead of circulating the liquid potassium or helium gas through pipes within the lithium blanket, the transfer of heat may occur outside the blanket (see page 66).

Maintenance of the strong magnetic fields would normally require considerable amounts of electric power. A possible way to decrease the power requirements would be to use *superconducting magnets.** When certain metals and alloys are cooled to extremely low temperatures, usually less than 10°K (i.e., 263°C below the freezing point of water), they become superconductors. Once a flow of current has been started in a superconductor, it will continue indefinitely in a closed circuit, even after the source of the current is removed. Magnets constructed with superconducting coils have already been used in controlled fusion (and other) research, although their dimensions and field strengths are small compared with those for a reactor. It is of interest that liquid helium is commonly used to maintain the temperature required for superconductivity.

The use of superconducting magnets would permit an overall decrease in power requirements, but energy would be needed to operate the refrigeration machinery for keeping

*See *Cryogenics*, another booklet in this series.

the magnets at a low temperature. A fusion reactor system, as outlined above, would thus have an extremely hot region in the interior and an extremely cold region on the exterior. The problems of thermal insulation would thus be difficult to handle.

Environmental Aspects

By taking advantage of the high temperature in the lithium blanket to introduce a potassium "topping" cycle preceding the usual steam-water cycle in the operation of the turbine-generators, more than 50% of the energy deposited in the lithium by the neutrons could be converted into electricity. This conversion efficiency may be compared with the maximum of about 40% for the most efficient fossil-fuel or nuclear fission power plants. A nuclear fusion reactor would thus release less heat to the environment.

During normal operation, tritium is the only radioactive material that could escape, either into the air or water, from a fusion reactor. Special precautions would be taken to keep leakage to the lowest practicable levels. In any event, the system would be designed to prevent loss of lithium and potassium. Since most of the tritium would be present in the lithium, the escape of tritium would be minimized at the same time.

After a period of operation, the niobium (or other) vessel containing the lithium will have to be replaced because of damage that the high-energy neutrons caused. As a result of neutron capture, the discarded niobium will have become radioactive and means will have to be found for disposing of it safely. After a few years, however, the activity will have decayed sufficiently for it to be refabricated by means of remote-handling techniques. If vanadium were used instead of niobium to contain the lithium, the problems would be greatly decreased since the radioactivity caused by neutrons is quite small.

The most serious hazard from a fusion reactor plant would probably arise from a fire because both lithium and potassium burn readily in air. The amounts of deuterium and tritium present in the reaction chamber at any time are so small that the energy released in an accident would not be important. *There is certainly no danger of a thermonuclear explosion.* The total energy liberated if *all* components of the system were consumed in a fire would be about the same as from a large tank of fuel oil. Use of the molten salt, lithium beryllium fluoride ($LiBeF_4$), in place of elemental lithium, as has been suggested, would greatly reduce the fire hazard. The main danger associated with a fire would be the release of tritium, but normal operations would be directed at keeping the amount of tritium as small as possible.

Direct Conversion Reactor

We have seen that, because of the loss of charged particles through the ends of magnetic mirror confinement systems, the operating temperatures will have to be higher than for closed systems. Advantage may be taken of the high temperature to convert fusion energy directly into electricity. At the same time, the energy of escaping particles would be recovered. In the D-D reactions, that would occur if deuterium alone were used in a fusion system, almost 67% of the energy released is carried by the charged particles. In the reaction between deuterium and helium-3 the amount is 100% since charged particles are the sole reaction products (page 13), although in practical systems there would be neutrons from D-D reactions.

If plasma temperatures exceeding 1000 million degrees K could be attained in a mirror system, both the D-D and D-^{3}He reactions could take place. The latter would be especially favorable for the direct conversion of fusion energy into electricity. Helium-3 is extremely rare in nature and there is no simple way in which it can be made, as tritium can be. However, helium-3 is a product of one of the D–D reactions and this would provide the helium-3 for the D–^{3}He reaction.

On the assumption that the conditions for the D–^{3}He (or even the D–D) reaction could be realized in a magnetic mirror system, the energy of the charged particles could be converted into electricity in the following manner (Figure 21). The charged particles, consisting of positively charged nuclei and negatively charged electrons, emerging from the ends of the cylindrical reaction chamber would first be expanded into a broad beam by a magnetic field. The charged particles are guided and directed outward by the gradually weakening field. Since the electrons are lighter than the ions, they are more easily deflected and they would be collected at an electrode, called the "charge separator", which is grounded.

The ions would continue on and pass through a series of "decelerating electrodes"—three are shown in Figure 21—

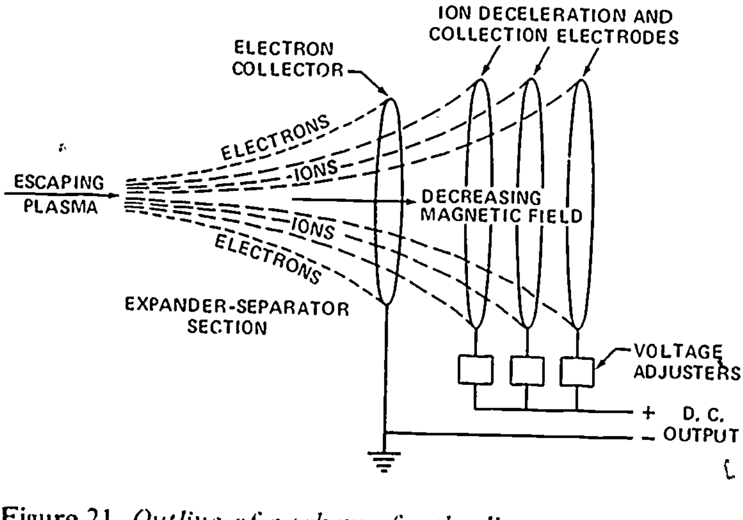


Figure 21. *Outline of a scheme for the direct conversion into electricity of the energy carried by the charged particles escaping from a magnetic mirror fusion reactor.*

where they would be collected and their positive charges deposited. The nuclei with the lowest energies are most easily decelerated and are collected at the first electrode: those of higher energy would be collected at subsequent electrodes. The voltages at the decelerating electrodes will steadily decrease and appropriate multipliers and dividers will be required to bring them to the same final output voltage. In the system just described direct current will be generated: the charge separator would constitute the negative pole and the decelerating electrodes the positive pole.

The direct conversion process would have environmental and other advantages. In the first place, it should be possible to convert into electricity up to 90% of the charged-particle energy produced by fusion. Thus, much less waste heat would have to be released to the environment. Incidentally, this high conversion efficiency would result in a decrease in the Lawson $n\tau$ criterion. which is based on a 33% efficiency. Furthermore. most of the tritium formed in one of the D–D reactions would be consumed by the D–T reaction and very little would be present in the system at any time. Finally. fewer neutrons. and with lower energies. would be produced than in the fusion of deuterium and tritium nuclei. Hence. damage and radioactivity in structural materials would also be considerably less. Another material, other than lithium. could be used to absorb the neutrons, since the breeding of tritium would not be required. There would not only be a larger choice of structural materials, but the fire hazard could be decreased.

INERTIAL CONFINEMENT

Heating by Laser Beams

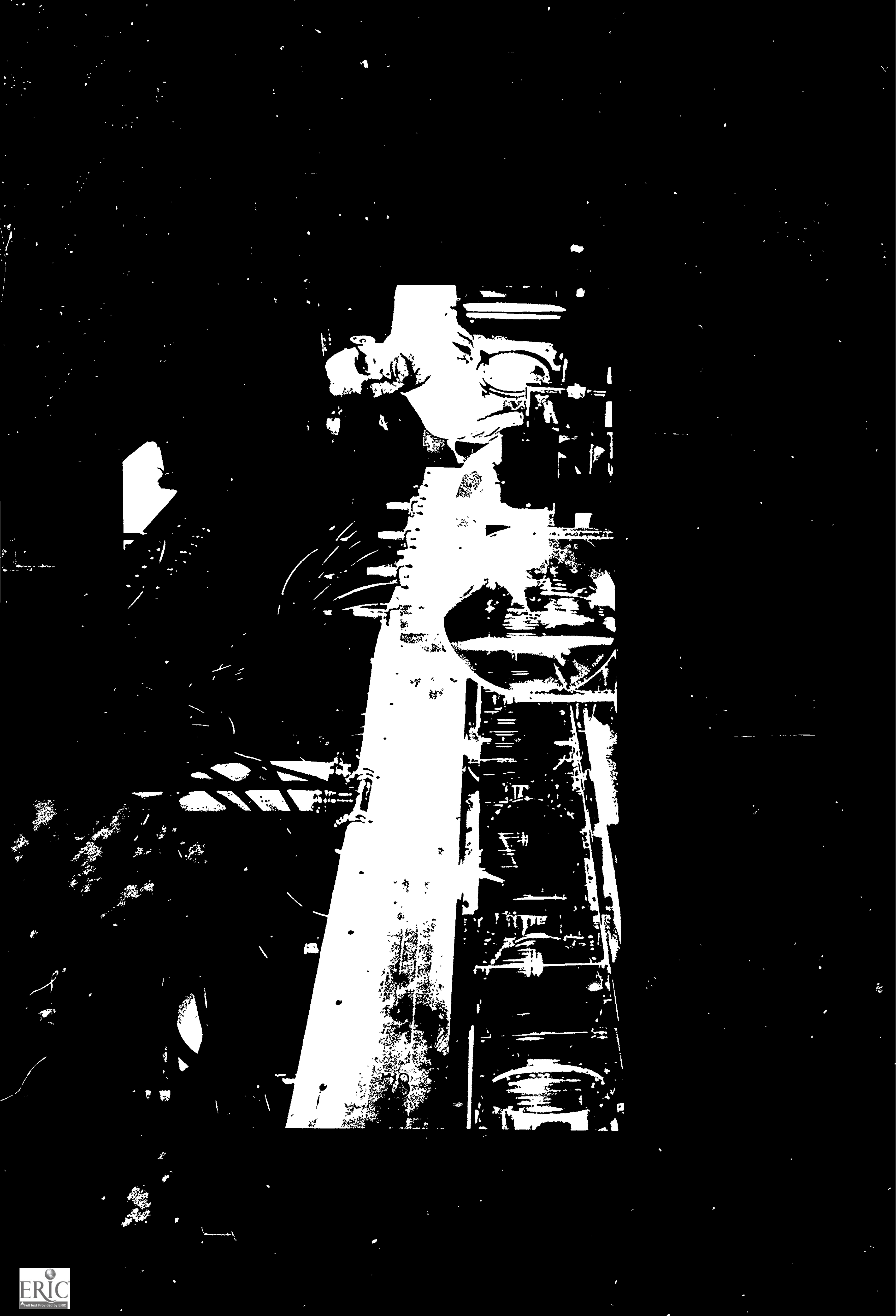
The basic idea of *inertial confinement* is that a pellet of a deuterium–tritium mixture would be heated very rapidly to thermonuclear temperatures. Such a system could produce energy from plasmas with densities much greater than those for which magnetic fields could be used for confinement. When an incident pulse of high-intensity laser energy is absorbed by the pellet, a plasma is formed from the outer surface material. The resulting "blow-off" causes the remaining pellet mass to implode (i.e., to move very rapidly inward). The converging shock pressure compresses and heats the material to a state in which the D–T reaction occurs rapidly. Thereafter, the tremendous pressures generated by the fusion energy explode the pellet. Most of the energy from the interaction of deuterium and tritium nuclei is carried by the neutrons produced, and this would be removed in a convenient manner, as will be described shortly, and used to generate electricity. A new deuterium–tritium pellet would then be introduced and the process repeated and so on.

Laser-fusion reactions would occur so rapidly that inertial forces would provide adequate confinement for the reacting nuclei. For such confinement to be possible, the considerable amount of energy required to heat the solid to temperatures in the vicinity of 100,000,000°K would have to be delivered (and absorbed) in the extremely short period of a fraction of a nanosecond, that is, in less than a billionth part (10^{-9}) of a second. The only presently known ways in which this might be done is by means of pulsed laser beams* or focused beams of high-energy electrons. The major activities related to inertial confinement for nuclear fusion are presently concerned with the use of lasers.

Laser beams can be readily controlled and focused onto very small areas, thereby permitting efficient irradiation of pellets that might be 1 millimeter (i.e., about ¹⁄₂₅ inch) or less in diameter. Lasers can deliver large amounts of energy in

*See *Lasers* another booklet in this series.

Photo 11. *A short-pulse neodymium glass laser having an energy of up to 200 joules is shown at the Lawrence Livermore Laboratory.*



very short times, although not yet in the quantities that would be required for nuclear fusion.

Laboratory experiments have established the fact that nuclear fusion reactions can indeed be induced by the action of lasers on solid deuterium. However, the amount of energy released is only a small fraction of that in the laser beam. More powerful lasers with shorter pulses are required and efforts are being made to achieve this objective. One possibility being studied for increasing the power is to focus several individual laser beams onto the solid pellet of reacting material.

Calculations have shown that if the laser pulse is properly shaped in time, the pellet is more highly compressed. At the very high densities that can be reached in this manner, the laser energy required to attain fusion conditions should be greatly decreased.

Laser-Fusion Reactor

The major immediate problem in connection with laser fusion is concerned with the development of lasers capable of repeatedly delivering large amounts of energy in very short and properly shaped pulses. A solution does not seem to lie outside the realm of technological possibility.

Since the situation appears promising, preliminary designs have been proposed for nuclear fusion power reactors utilizing inertial confinement with laser heating. The main structure of the reactor would be a large chamber capable of withstanding the repeated explosions occurring when deuterium tritium pellets are heated by a laser beam (Figure 22). A pellet would be injected into the vessel and when it reaches the center a powerful pulsed laser beam would be focused onto it for a period of about a nanosecond or less. After the lapse of a few seconds, another pellet would be injected and heated, and so on.

The neutrons produced in the D T reaction, carrying some 80% of the fusion energy, would be taken up by lithium. The basic scientific principles from now on would be the same as for a fusion reactor with toroidal magnetic confinement (page 66), although the design of the system would be different. The lithium might be introduced into the reaction chamber as a film of liquid covering the interior surface or as a swirl of droplets (or both). The energy of the neutrons would be deposited in the lithium and at the same time tritium would be generated for subsequent use in the fusion reaction.

The heated lithium would be drawn off from the bottom of the reaction chamber, passed through a heat exchanger, and then returned at a lower temperature. The heat removed in the heat exchanger would be used to produce steam (or possibly a hot gas) for operation of a turbine-generator in the usual manner.

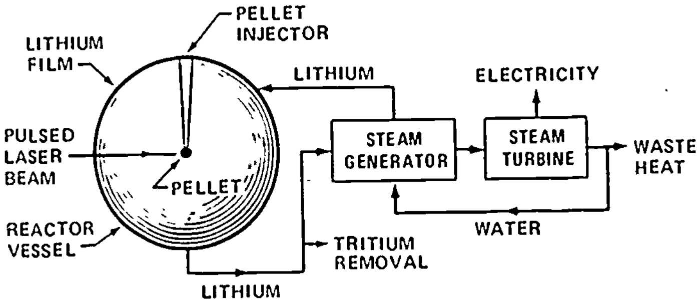


Figure 22. *Basic principles of a conceptual spherical (or approximately spherical) reactor utilizing laser fusion of deuterium tritium pellets.*

NUCLEAR FUSION RESEARCH PROGRAMS

Support by U. S. Government and Industry

The study of controlled fusion in the United States was begun in 1951 and 1952 at the Los Alamos Scientific Laboratory in New Mexico, and at what are now the Lawrence Livermore Laboratory and the Lawrence Berkeley Laboratory, which are both in California, and the Princeton Plasma Physics Laboratory in New Jersey. A substantial program was started at the Oak Ridge National Laboratory in Tennessee in 1955, although there had been an interest in controlled fusion in earlier years. Except for a small amount of research and development, the Berkeley Laboratory is no longer a major contributor in this area, but at the other four laboratories the U. S. Atomic Energy Commission (AEC) supports research aimed at the ultimate development of a reactor for obtaining useful energy from controlled fusion. In addition, the AEC has sponsored both theoretical and experimental research on high-temperature plasmas at several universities. The National Science Foundation, the National Aeronautics and Space Administration, and the Department of Defense also finance plasma physics research, which is somewhat related to controlled fusion.

Electrical utilities have provided some support for controlled fusion studies although to a much smaller extent than the AEC. In 1957, the Texas Atomic Energy Research Foundation, a consortium of private utility companies, started a project in conjunction with what is now Gulf General Atomic in La Jolla, California. Some 10 years later, the financial support was transferred to the University of Texas. Work at Gulf General Atomic is being continued with help from the AEC. In recent years, several utilities have been contributing to the cost of plasma research at a number of universities. Private industry is also supporting laser fusion research and a company named KMS Fusion, Inc., has been formed exclusively for this purpose.

Historical Outline

Studies of the low-beta Z pinch were started in 1951 and 1952 at the Los Alamos Scientific Laboratory and at the Lawrence Berkeley and Livermore Laboratories. This work has now been largely abandoned in the United States although interest continues in other countries (e.g., the United Kingdom's large ZETA device). Preliminary experiments, which led to the high-beta (shock heated) theta-pinch system, were originally made at Livermore in 1954 and a more promising approach began the following year at the Naval Research Laboratory in Washington, D. C. The concept was taken up by the Los Alamos Scientific Laboratory around 1956 and developed into the successful Scylla linear theta pinch in which definite controlled fusion on a small scale was first achieved in 1957. A toroidal theta-pinch device, called Scyllac (for Scylla closed), has been constructed at Los Alamos. (See Photo 12.) Following the encouraging results with shock heating in Scylla, the same principle was used in a linear Z pinch. Subsequently, a toroidal high-beta Z pinch was placed in operation at the Los Alamos Scientific Laboratory.

The investigation of magnetic mirror confinement was initiated at the Lawrence Livermore Laboratory in 1951 and at the Oak Ridge National Laboratory around 1955. Studies of this aspect of controlled nuclear fusion have continued at both of these laboratories. At Livermore the work has been mainly concerned with the stability, confinement, and heating of low-beta plasmas. At Oak Ridge, on the other hand, the major interest is in the production of high-temperature, high-beta plasmas for confinement by magnetic mirrors.

The stellarator concept originated with L. Spitzer at Princeton University in 1951 and several devices based on the figure eight and other forms of the stellarator principle were constructed. These activities culminated in the completion in 1961 of the large (overall length 40 feet) Model C stellarator at the Princeton Plasma Physics Laboratory. Plasma confinement in this system was limited by Bohm diffusion and after the encouraging results with the Russian tokamak, the Model C stellarator was converted into a tokamak system and renamed the ST device. (See Photo 7.) Studies of stellarators have been terminated at Princeton, at least for the present, but they are still in progress in countries other than the U. S.

In addition to the ST tokamak, other systems based on the tokamak principle have been constructed since 1970 at Princeton and elsewhere in the United States at the following locations: Oak Ridge National Laboratory, Massachusetts Institute of Technology, University of Texas, and Gulf General Atomic. (See Photo 13.)

Studies of plasma stability by using internal-ring conductors developed from the linear "hard-core" system at the Lawrence Livermore Laboratory in 1958. Current passing through a metal rod running around the axis of a cylinder produced a poloidal magnetic field. In the following year, the toroidal Levitron with an internal ring, levitated by means of a pulsed alternating magnetic field, was constructed at the same laboratory. Other toroidal systems with internal rings have been built recently at Livermore, Princeton, the University of Wisconsin, and Gulf General Atomic.

In 1962, the study of laser fusion was started on a small scale at the Lawrence Livermore Laboratory with the support of the AEC. Interest in the work derived from the potential of this technology to military applications. About 5 years later, the activity was extended to the Sandia Laboratory, Albuquerque, which performs weapons-related work for the AEC, and in 1970 to the Los Alamos Scientific Laboratory. Lasers with large outputs, suitable for nuclear fusion, are also being developed by the Department of Defense at the Naval Research Laboratory. The AEC is supporting all of the U. S.

Photo 12. *An arc of the toroidal theta-pinch Scyllac device at Los Alamos Scientific Laboratory. (Scyllac consists of three such sectors.)*

*A steady-state reactor is one that

Photo 13. *The ORMAK is a fusion research device based on the tokamak principle at Oak Ridge National Laboratory in Tennessee.*

Government effort directed at achieving controlled fusion by laser methods. Related studies, wholly or partly supported by industry, are being conducted at the United Aircraft Research Laboratory and at the University of Rochester, and KMS Fusion, Inc., was formed in 1970 to exploit an approach to laser fusion.

United States Programs

The major programs of controlled nuclear fusion in the United States are summarized in the accompanying table. In addition, theoretical and experimental activities on a smaller scale are being conducted at several universities.

Foreign Programs

Studies aimed at the realization of controlled fusion as a source of useful power were started in the United Kingdom and in the U.S.S.R. at about the same time as in the United

CONTROLLED FUSION PROGRAMS IN THE UNITED STATES

Pinch (High-Beta) Systems
- Los Alamos Scientific Laboratory (Scylla; Scyllac; Toroidal Z-pinch, ZT-1)

Tokamak Systems
- Princeton Plasma Physics Laboratory (Symmetric Tokamak, ST; Adiabatic Toroidal Compressor, ATC; Princeton Large Tokamak, PLT)
- Oak Ridge National Laboratory (ORMAK)
- Massachusetts Institute of Technology (Alcator)
- University of Texas (Texas Turbulent Torus, TTT)
- Gulf General Atomic (Doublet II)

Magnetic Mirror Systems
- Lawrence Livermore Laboratory (2X II, Baseball II)
- Oak Ridge National Laboratory (ELMO)
- United Aircraft Research Laboratory

Internal-Ring Devices
- Princeton Plasma Physics Laboratory (Floating Multipole, FM-1)
- University of Wisconsin (Levitated Octopole)
- Gulf General Atomic (D. C. Octopole)

Laser Fusion in Pellets
- Lawrence Livermore Laboratory
- Los Alamos Scientific Laboratory
- Sandia Laboratories, Albuquerque
- Naval Research Laboratory
- University of Rochester
- United Aircraft Research Laboratory
- KMS Fusion, Inc.

States. In fact, the pinch effect in a plasma was first reported from the United Kingdom in 1951, although previously it had been predicted theoretically by American physicists. For several years, all nuclear fusion studies were classified because some might have weapon-related applications. However, in 1958, the United States, the United Kingdom, and the U.S.S.R. agreed to declassify all work on controlled fusion and this agreement appears to have been honored. There have been extensive exchanges of information and personal visits of scientists between these three countries. After the publication in 1958 of the previously unavailable reports on controlled fusion, several other countries started their own research programs.

For some time, the U.S.S.R. has devoted substantially more manpower than any other country to studies of controlled fusion. In recent years, the effort in the U.S.S.R. has been more than twice as great as in the United States, which is roughly the same as in West Germany. Substantial programs on nuclear fusion are under way in the United Kingdom, Japan, France, Italy, and the Netherlands, with smaller efforts in Australia, Czechoslovakia, Denmark, Israel, Poland, Sweden, and Switzerland.

The major activities on controlled nuclear fusion outside the United States are summarized in the table; there are also several smaller programs that are not mentioned.

CONCLUSION

The objective of controlled nuclear fusion research is to develop a major economic source of energy that should be readily available to all mankind. This development is most likely to occur first by way of the reaction between deuterium and tritium nuclei. The basic fuel materials will then be deuterium and lithium; the tritium will be obtained by the interaction of neutrons with the latter element. The quantity of deuterium in the oceans and other water bodies is virtually inexhaustible and the lithium that can be extracted from heavy brines and minerals (e.g., pegmatites) should be adequate for several hundred years. If it should ultimately prove necessary, the lithium in seawater could be extracted

CONTROLLED FUSION PROGRAMS IN OTHER COUNTRIES

Pinch Systems
- United Kingdom (high-beta and low-beta)
- U.S.S.R. (high-beta)
- Germany (high-beta)
- Netherlands (high-beta)

Stellarator Systems
- United Kingdom
- U.S.S.R.
- West Germany
- Japan

Tokamak Systems
- U.S.S.R.
- West Germany
- France
- Italy
- Japan

Magnetic Mirror Systems
- United Kingdom
- U.S.S.R.
- France

Laser Fusion in Pellets
- U.S.S.R.
- France
- Italy
- Germany
- Japan
- Israel

for an acceptable price. However, before terrestrial sources of lithium are exhausted, the conditions for fusion of deuterium nuclei alone (or of deuterium and helium-3) should be achieved. In this event, lithium will no longer be required.

The cost to the consumer of electricity generated by nuclear fusion cannot be predicted with any certainty, largely because all the technological problems are not yet known. However, it is clear that the fuel materials will be very cheap in relation to the amount of energy that can be obtained from them. The best estimates at present indicate that electric power from nuclear fusion will be competitive in price with power from other major sources, such as coal and nuclear fission.

Research on magnetically confined plasmas since the early 1950s has revealed many problems relating to the attainment of controlled fusion on a useful scale. Extensive theoretical and experimental researches have led to a better understanding of plasma instabilities and how they can be controlled. If, as is not improbable, additional instabilities should become apparent, plasma physicists have the means for studying them and for learning how to deal with them

The general consensus is that there is no fundamental reason why the conditions of plasma temperature, particle density, and confinement time required for practical nuclear fusion cannot be achieved, conceivably early in the next decade. Such an achievement would establish scientific feasibility. The realization of laser-fusion with solid reacting materials would represent an important alternative to the confinement and heating of plasmas in a magnetic field.

Even if the scientific feasibility of nuclear fusion can be established, there will still be many technological difficulties to be overcome before fusion can be used as an economic source of electric power. This might possibly require another 10 to 20 years. But the rewards of a successful outcome would be so great as to be worth almost any effort made to achieve it. The solution of the problems of controlled nuclear fusion has been well described as one of the greatest scientific and technical challenges of the 20th century.

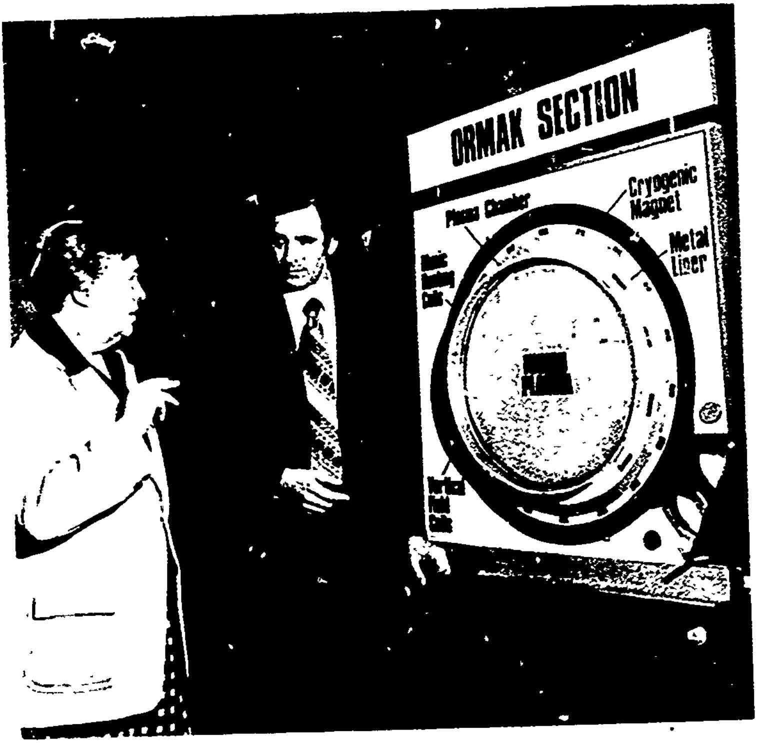


Photo 14. *Dr. Dixy Lee Ray, Chairman of the Atomic Energy Commission, and Dr. Robert L. Hirsch, Director of the AEC's Division of Controlled Thermonuclear Research, discuss recent progress in the ORMAK experiment at the Oak Ridge National Laboratory.*

READING LIST

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MOTION PICTURES

Available for loan without charge from the USAEC Film Library-TIC, P. O. Box 62, Oak Ridge, Tennessee 37830.

To Bottle the Sun, 5½ minutes, color, 1973. The principles of fusion are explained. Various research projects are discussed as well as the problems that must be overcome before fusion reactors are a reality.

A Superconducting Magnet for Fusion Research, 22 minutes, color, 1971. Intense magnetic fields are generally agreed to be the most promising means of confining hydrogen-isotope plasma to produce controlled fusion on earth. As part of this research a 13-ton superconducting magnet has been built for the Baseball-II neutral beam injection experiment at the Lawrence Livermore Laboratory in California. This film describes the general concept of the experiment, the winding and installations of the magnet system, and initial testing of the new fusion research facility.

PHOTO CREDITS

Cover courtesy Lick Observatory

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