Fusion Power

For centuries, the way in which the sun and stars produce their energy remained a mystery to man. During the twentieth century, scientists discovered that they produce their energy by the fusion process.

$E=mc^2$, Albert Einstein's familiar formula, provided the basis for understanding fusion. Einstein's theory that mass can be converted into energy was further explored by other physicists who discovered two practical methods for achieving this conversion.

One method is fission in which heavy atoms, such as uranium, are split, thus releasing the internal energy that holds the atom together. Fission energy is being used commercially in the United States and elsewhere to produce electricity. The other method of transforming mass into energy is fusion in which light atoms, such as those of hydrogen, are fused or joined.

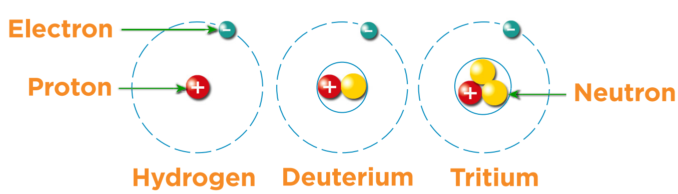
An atom is the smallest portion of an element that can exist, while retaining the characteristics of that element. The lightest atoms are those of the element hydrogen, and the heaviest atoms occurring naturally in significant quantity are those of uranium.

Atoms, although extremely small, have an internal structure. Every atom consists of a central nucleus, carrying nearly all the mass of the atom, surrounded by a number of negatively charged electrons. The nucleus of an atom has a positive electrical charge that is balanced by the negative charge of the electrons. Consequently, in its normal state, the atom as a whole is electrically neutral.

All atomic nuclei contain even smaller particles called protons and all except one form of hydrogen also contain neutrons. The protons have a positive electric charge, and the neutrons have no charge. The protons are thus responsible for the electric charge of the nucleus. Each atomic species is characterized by the number of protons and neutrons in the nucleus.

Fusion Reactions

Many different nuclear fusion reactions occur in the sun and other stars, but only a few such reactions are of practical value for potential energy production on earth. These all involve forms (isotopes) of the element hydrogen. Three isotopes of hydrogen are known: they are hydrogen (H), deuterium (D), and tritium (T).



The nuclei of all three isotopes contain one proton, which characterizes them as forms of the element hydrogen. In addition, the deuterium nucleus has one neutron and the tritium nucleus has two neutrons. In each case, the neutral atom has one electron outside the nucleus to balance the charge of the single proton.

To produce net power, fusion reactions must take place at high temperatures. The power production process which can occur at the lowest temperature and, hence, the most readily attainable fusion process on earth is the combination of a deuterium nucleus with one of tritium.

The products are energetic helium-4 (^{4}He) the common isotope of helium (which is also called an alpha particle), and a more highly energetic free neutron (n). The helium nucleus carries one-fifth of the total energy released and the neutron carries the remaining four fifths. This and other fusion reactions are listed below:

D + D	→	^{3}He	+	n	+	3.2 MeV*
D + D	→	T	+	p	+	4.0 MeV
D + T	→	^{4}He	+	n	+	17.6 MeV
D + ^{3}He	→	^{4}He	+	p	+	18.5 MeV

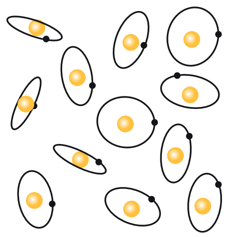
* Million electron volts. An electron volt is a unit of energy equal to the energy acquired by an electron passing through a potential difference of one volt. The electron volt is also used to express plasma temperatures. 1 MeV = 1.52×10^{-16} Btu = 4.45×10^{-20} kW h.

Since nuclei carry positive charges, they normally repel one another. The higher the temperature, the faster the atoms or nuclei move. When they collide at these high speeds they overcome the force of repulsion of the positive charges, and the nuclei fuse. In such collisions, energy is released.

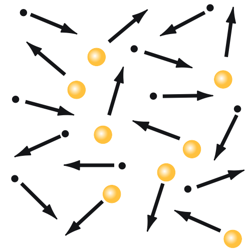
The difficulty in producing fusion energy has been to develop a device that can heat the deuterium-tritium fuel to a sufficiently high temperature and then confine it for a long enough time so that more energy is released through fusion reactions than is used for heating.

In order to release energy at a level of practical use for production of electricity, the gaseous deuterium-tritium fuel must be heated to about 100 million degrees Celsius (°C). This temperature is more than six times hotter than the interior of the sun, which is estimated to be 15 million °C.

High as these temperatures are, they are readily attainable. The problem is how to confine the deuterium and tritium under such extreme conditions. A part of the solution to this problem lies in the fact that, at the high temperatures required, all the electrons of light atoms become separated from the nuclei. This process of separation is called ionization, and the positively charged nuclei are referred to as ions. The hot gas containing negatively charged free electrons and positively charged ions is known as plasma.



Gas



Plasma

Because of the electric charges carried by electrons and ions, plasma can, in principle, be confined by a magnetic field. In the absence of a magnetic field, the charged particles in plasma move in straight lines and random directions. Since nothing restricts their motion, the charged particles can strike the walls of a containing vessel, thereby cooling the plasma and inhibiting fusion reactions. But in a magnetic field, the particles are forced to follow spiral paths about the field lines.

Consequently, the charged particles in the high-temperature plasma are confined by the magnetic field and prevented from striking the vessel walls.

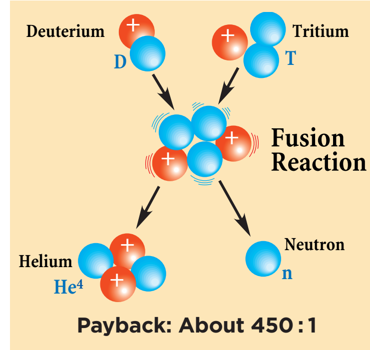
To produce substantial net power from fusion reactions, the following condition, known as the ignition condition, must be achieved: the product of the energy confinement time, τ seconds, and the plasma density, n particles (ions or electrons) per cubic centimeter, at a temperature of 100 million °C is such that $n\tau$ must be greater than 3×10^{14} cm^{-3} sec. In an operating fusion reactor, part of the energy generated will serve to maintain the plasma temperature as fresh deuterium and tritium are introduced. However, in the start-up of a reactor, either initially or after a temporary shutdown, the plasma will have to be heated to 100 million °C.

In present magnetic fusion experiments, insufficient fusion energy is produced to maintain the plasma temperature. Consequently, the devices operate in short pulses and the plasma must be heated afresh in every pulse.

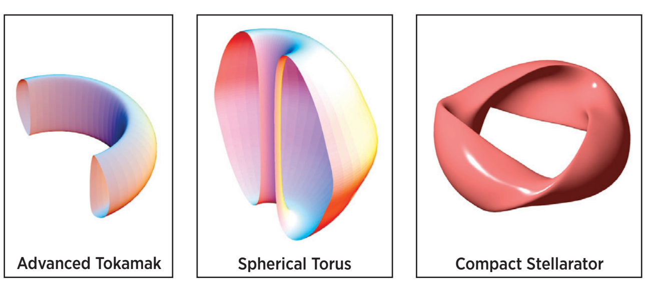
Since the plasma is an electrical conductor, it is possible to heat the plasma by passing a current through it. This is called ohmic (or resistive) heating. It is the same kind of heating that occurs in an electric light bulb or in an electric heater.

The heat generated depends on the resistance of the plasma and the current. But as the temperature of heated plasma rises, the resistance decreases and the ohmic heating becomes less effective. For example, the maximum plasma temperature attainable by ohmic heating in a tokamak is 20-30 million °C. To obtain still higher temperatures, additional heating methods must be used.

Neutral-beam injection involves the introduction of high-energy (neutral) atoms into the ohmically heated, magnetically confined plasma. The atoms are immediately ionized and are trapped by the magnetic field. The high-energy ions then transfer part of their energy to the plasma particles in repeated collisions, thus increasing the plasma temperature.



In radio-frequency heating, high-frequency waves are generated by oscillators outside the vacuum chamber. If the waves have a particular frequency (or wavelength), their energy can be transferred to the charged particles in the plasma, which in turn collide with other plasma particles, thus increasing the temperature of the bulk plasma. Radio-frequency waves may also be used to drive the plasma current.



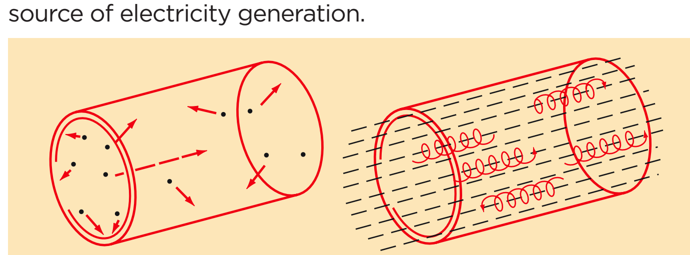
Many different plasma configurations have been studied. Presently, the advanced tokamak, the spherical torus, and the compact stellarator are of particular interest.

Advantages of Fusion

As a source of energy, fusion would have many advantages:

- The major fuel, deuterium, can be readily extracted from ordinary water, which is available to all nations. The surface waters of the earth contain more than 10 million million (10^{12}) tons of deuterium, an essentially inexhaustible supply. The tritium required would be produced from lithium, which is available from land deposits or from seawater that contains thousands of years' supply. The worldwide availability of these materials would thus eliminate international tensions caused by imbalance in fuel supply.
- The amounts of deuterium and tritium in the fusion reaction zone will be so small that a large uncontrolled release of energy would be impossible. In the event of a malfunction, the plasma would strike the walls of its containment vessel and cool.
- Since no fossil fuels are used, there will be no release of chemical combustion products because they will not be produced. Thus there will be no contribution to global warming or acid rain.
- Similarly, there will be no fission products formed to present a handling and disposal problem. Radioactivity will be produced by neutrons interacting with the reactor structure, but careful materials selection is expected to minimize the handling and ultimate disposal of such activated materials.
- Another significant advantage is that the materials and by-products of fusion are not suitable for use in the production of nuclear weapons.

The abundance of raw materials, their wide distribution, and the environmental acceptability of fusion are augmented by the expectation that fusion energy will also be an economical source of electricity generation.



At left: Motion of charged particles without magnetic field, and at right with magnetic field.

The Princeton Plasma Physics Laboratory is operated by Princeton University under contract to the U.S. Department of Energy. For additional information, please contact: Office of Communications, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08543; Tel. (609) 243-2750; e-mail: pppl_info@pppl.gov or visit our web site at: www.pppl.gov.