How nuclear fusion creates unlimited energy potential

In their efforts to harness fusion energy, scientists are quite literally creating miniature suns on earth.

The U.S. Office of Fusion Energy describes fusion as "the energy of the stars—the fundamental energy process of the universe."

Their description continues: "Our sun is a gigantic fusion reactor that continuously converts hydrogen to helium through a complex chain of fusion reactions and releases the resulting energy in the form of heat and light. Fusion occurs in the sun because tremendous gravitational forces squeeze and heat its substance to about 15 million degrees Centigrade. The pressure and the temperature working together break the atoms apart and allow the nuclei, driving into each other, to fuse. All the sun's energy is produced by the fusion process."

The plasma principle

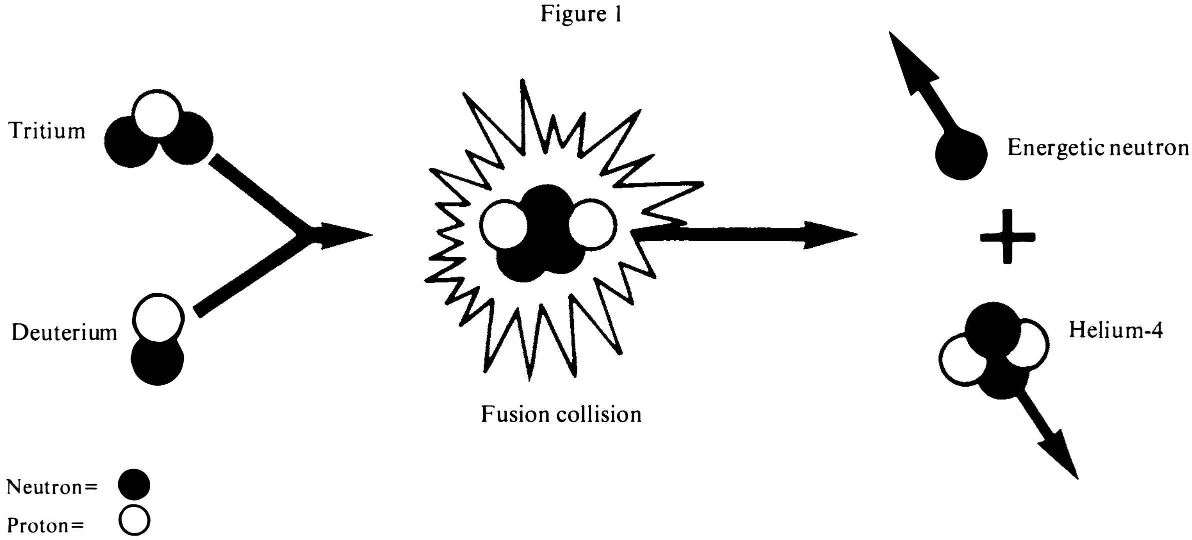
Nuclear fusion is the basic process by which the universe derives its active energy and material. In general terms, the nuclei of lighter elements are fused to form the nuclei of heavier elements, and in the process, large amounts of energy are generated (see Figure 1).

To achieve this, the mutual electrical repulsion of the two positively charged nuclei must be overcome. That is, the electric potential barrier between the nuclei must be penetrated. This is accomplished by giving a sufficient relative velocity to the two nuclei so that there is some chance they will penetrate the barrier. Since temperature is a measure of the average velocity of a group of atoms, the speed required for penetrating the barrier is translated into a temperature condition for the reaction.

At the very high temperatures required for fusion reactions, the atoms in the fuel lose their electrons; this is called ionization. Very hot, ionized gas is a plasma.

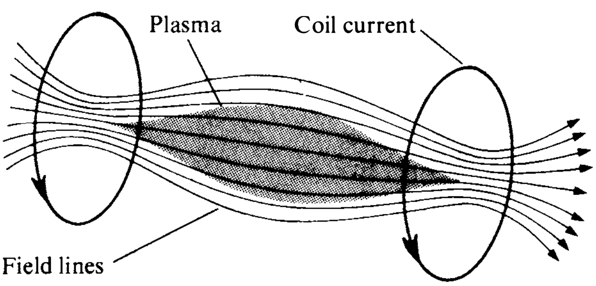
Most matter in the universe exists in the plasma state, sometimes referred to by scientists as the fourth state of matter—gas, liquid, and solid are the other

Figure 1



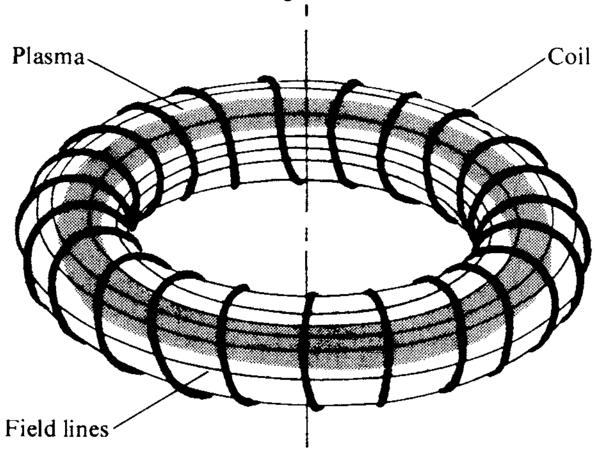
To produce net power, fusion reactions must take place at high temperatures. The power production process that can occur at the lowest temperature, and hence the one most easily attained on earth, is the fusion of a deuterium nucleus with one of tritium. The products are energetic helium-4 and a more highly energetic free neutron. The helium carries one-fifth of the total energy released, the neutron the remaining four-fifths.

Figure 2



There are two main types of systems for magnetic confinement of plasma, one a closed system, as in the toroidal configuration employed in tokamak devices, the other an open-ended configuration like the simple "mirror" system above.

Figure 3



three. Plasma is not a single state, but rather an infinite continuum of higher-order states. These higher-order states can be measured in terms of their energy-density, and the efficiency with which the energy is organized and transformed is the most crucial feature of plasma states. Although neutral molecules may still exist within the sea of charged plasma particles, molecular and atomic forces no longer determine the essential relations of the macroscopic structure of the plasma. This leads to a higher-order relationship between the microscopic motions of the plasma particles and the overall macroscopic configuration and energy relations of the plasma as a whole.

In addition to temperature, there is also a density condition for fusion reactions. The rate at which fusion reactions will proceed is determined by the density of the fuel nuclei, expressed in the number of nuclei per cubic centimeter. It also depends on the likelihood of a specific type of fuel to react at a temperature high enough for the barrier to be penetrated and fusion to occur. For example, deuterium-tritium fuel will undergo fusion more readily than other types of fuel.

The temperature at which there will be significant amounts of nuclear fusion reactions is the threshold plasma temperature, and it is very high—in the sun, 15 million degrees, and in temperatures recently achieved in the Princeton laboratory, 80 million degrees Centigrade. Yet the reaction energy output from nuclear fusion is quite large compared to the energy input. For example, in the case of the fuel deuterium and tritium, the heavy isotopes of hydrogen, there is a maximum energy gain—energy out divided by energy in—of about 1,800.

This energy output shows up in the reaction products. The deuterium-tritium reaction generates a helium nucleus, with an energy of 3.5 million electron volts (MeV) and a neutron with 14.1 MeV. If a portion of this output energy can be used either to maintain the reacting fusion fuel or to heat other "cold" fusion fuel above the threshold temperature, then there can be an infinite energy gain—as long as the density of the reactant nuclei is maintained.

To achieve significant amounts of fusion energy output, both the original energy used to ignite the fusion fuel and the fusion energy generated must be confined to the fuel at the same time that the density of the fuel is maintained.

The fuel can lose its energy by dissipating to a very low density at which the fusion reaction is essentially stopped; the fuel could lose its energy thermally to its physical surroundings; or the fuel could lose its energy by radiating it away in the form of electromagnetic energy, primarily X-rays. These must be prevented by the right balance of temperature, density, and confinement time.

At a high density, the fusion reaction proceeds at a high rate, and so large amounts of energy can be generated in a short time. At lower densities, the energy must be confined within the fuel for longer periods of time.

The right balance also depends on the fuel. For deuterium-tritium fuel, temperatures must be maintained above 50 million degrees Centigrade, and the product of density and confinement time must be greater than 30 trillion nuclei per cubic centimeter per second, in order to generate minimal net energy. For significant net energy generation, these figures must be increased by a factor of 2 or 3.

These three factors—temperature, density and confinement time—are not entirely independent. Experiments have shown that plasma confinement time increases with increasing temperature under some conditions, and that at different levels, confinement time increases with density. This corresponds to the transformation of the microscopic structure of a plasma in a way that tends to maintain or further the process itself.

In other words, the successful fusion plasma is *self-organizing*. The essential problem is to discover which configuration of forces acting on a plasma can most efficiently induce the desired self-ordering behavior in the plasma. That particular configuration is the one that will give the most energy output with the least energy input.

Two approaches

There are two basic approaches to confining the fusion plasma: magnetic confinement and inertial confinement.

In a typical fusion reactor of the first sort, the fusion plasma is kept in place by configurations of magnets that exert forces on the fusion plasma in which the reactions take place. This magnetic confinement technology is well under development, and features two types of devices, each with a different geometry: an open system or magnetic mirror system, and a closed system shaped like a doughnut, called the tokamak.

The world's largest tokamak is now being built at Princeton, and has been designed with the idea that it will produce more energy than has to be put in to get the fusion reaction going. This is the critical measurement—breakeven—in which a net return on the energy invested is realized (see Figures 2, 3).

The second basic approach, inertial confinement, allows the magnetic coils to be eliminated. This approach is often called laser fusion, although other methods in addition to laser beams are used to ignite the fusion fuel, for example, ion beams and electron beams.

In inertial fusion the primary force confining the fusion fuel is the inertia of the fuel mass itself. The fusion fuel is heated to fusion temperatures and undergoes significant amounts of fusion before blowing up. To achieve this, the fusion fuel must be compressed to a very high density at which the fusion reaction proceeds at a sufficiently rapid rate.

Inertial confinement uses a tiny hollow pellet—so small that it can't be seen with the naked eye—filled with deuterium and tritium, the fuel. The spherical pellet is then irradiated with a laser beam or some other beam. This force heats and compresses the pellet to produce a burst of energy before the pellet flies apart. What is involved is essentially a miniature explosion, the same process that occurs in the H-bomb.

The most efficient type of inertial fusion implosion is one that is *isentropic*; that is, one in which the largest portion of the implosion energy goes into compressing the fuel.

Types of magnetic confinement

In magnetic confinement approaches to fusion, there is an almost infinite variety of plasma/magnetic field configurations that can be formed for sustaining a plasma in fusion conditions. The most important distinctions are: 1) whether the magnetic fields are internally or externally generated; 2) whether the plasma is primarily heated by: internally generated fusion energy, plasma currents, shock implosion, or external heaters such as intense beams of electromagnetic radiation (radio frequency or microwaves heating), ions, electrons, high-energy neutral molecules (neutral beam heaters), or preheated blobs of plasma shot from plasma "guns"; 3) whether the configuration is pulsed or steady-state and continuous; 4) whether the plasma/magnetic field configuration is open-ended or closed; 5) how the magnetic field is used to confine the hot plasma; and 6) the geometry of the plasma currents and magnetic fields.

The object of scientists is to set up a system in which relatively crude energy input is transformed via the plasma's own response into higher quality energy (more intense electric and magnetic fields, for example) that in turn permits a higher-order plasma structure to be generated.

The scientific principles involved are well on the way to being understood. The technology required to apply those principles is in sight. As Dr. Stephen O. Dean reported in the October issue of *Fusion* magazine: "We can now say with confidence that success is assured. To use a popular phrase, success is 'in the bag.' "