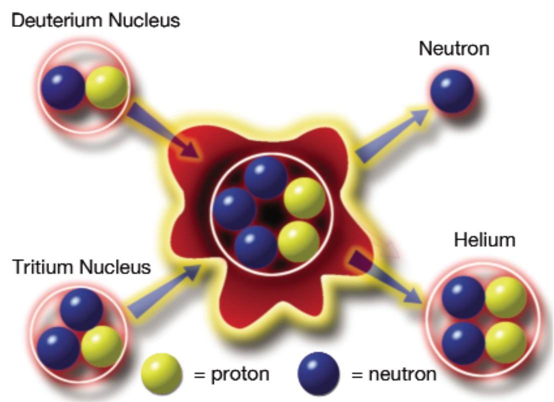
about Plasmas
from the Coalition for Plasma Science

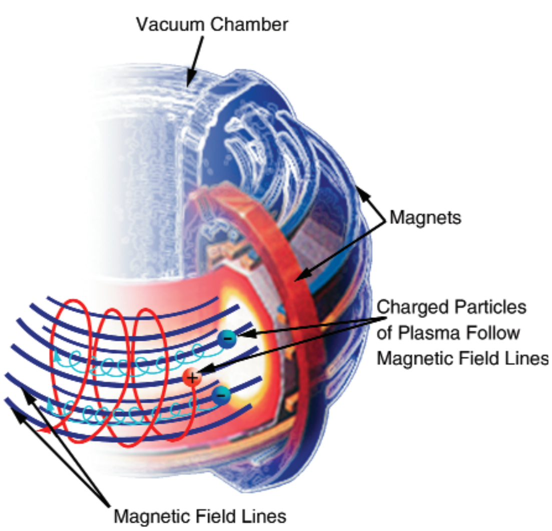
Fusion

Most energy experts agree that, as world electrical energy consumption continues to grow, fossil fuels (oil, coal and gas) will either become too scarce or too polluting to rely upon after the next few decades. If this is true, there are only three noncarbon alternative energy sources – renewable fuels, fission and fusion – and we will need to create vast new energy supplies to power the future.

Fusion, the energy source of the sun and other stars, is a nuclear reaction process that can convert small quantities of matter into significant amounts of energy. Fusion occurs when the nuclei of two light atoms, such as deuterium and tritium, merge to form a heavier nucleus. Since nuclei have positive charges, they tend to repel each other. Consequently, they need high particle energies in order to collide and fuse. During the fusion process, some of the mass involved in the reaction is converted directly into a large amount of energy. For example, the amount of deuterium in one gallon of sea water would yield the energy equivalent of 300 gallons of gasoline.



Fusion takes place when two small atoms combine to form a larger one, releasing substantial energy. The fusion fuel mixture anticipated for first-generation power plants is composed of the hydrogen isotopes deuterium and tritium, each reaction producing a helium nucleus and a neutron. The goal is to convert the neutron energy into electricity.



In a tokamak, spiraling charged particles at temperatures of over one hundred million degrees Celsius — a temperature ten times hotter than the sun — follow magnetic field lines. They seldom hit the walls of this doughnut-shaped metal confinement device, whose surface is near room temperature.

To create a significant amount of electricity, large numbers of nuclei need to become highly energized so they can fuse. In the process of gaining energy – i.e., through heating – electrons are stripped away from the atoms. The resulting collection of electrically-charged particles forms a plasma, a state of matter with unique properties, especially in its interaction with electric and magnetic fields. For a useful amount of fusion to occur, a plasma must be hot and dense. Increasing heat speeds up the nuclei in the plasma, while increasing density adds more nuclei to a given space. These two factors increase the chance that two nuclei collide and fuse.

Creating a practical device that will confine and control a plasma at temperatures and densities high enough to make nuclei fuse has been the primary challenge for fusion researchers. In a star, the large stellar mass has sufficiently high gravitational forces to hold together the fusion fuel. This, along with the very high temperature of the stellar interior, provides the conditions required for fusion energy production. In a laboratory, however, holding the fuel together – confining it – is a huge challenge.

There are various approaches to achieving fusion energy. However, two major paths have emerged: magnetic confinement and inertial confinement. In one magnetic-confinement approach, scientists and

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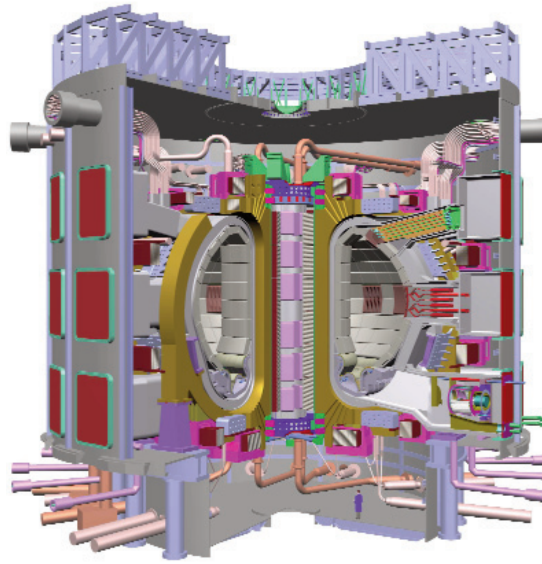
engineers use one type of magnetic "bottle," a doughnut-shaped device called a "tokamak," to hold the fusion fuel. The heating is accomplished using radio waves, energetic particle beams, and the self-heating from the fusion process itself. The largest tokamak presently operating is the Joint European Torus (JET). With deuterium and tritium fuel it has generated a peak fusion power of about 16 Megawatts (MW) and a steady power of about 4 MW for 4 seconds (both somewhat less than the power input).

Work on a significantly larger tokamak has begun. An international partnership involving the European Union (host), Japan, China, India, Russia, South Korea, and the USA is constructing the ITER tokamak in southern France. The goal is to generate 500 Megawatts of fusion power for hundreds of seconds, ten times more than that needed to keep the plasma at the right temperature. ITER will therefore be the first fusion experiment to produce more energy than is used to sustain the fusion process. It will also test a number of key technologies, including the heating, control, and remote maintenance that will be needed for a commercial fusion power station.

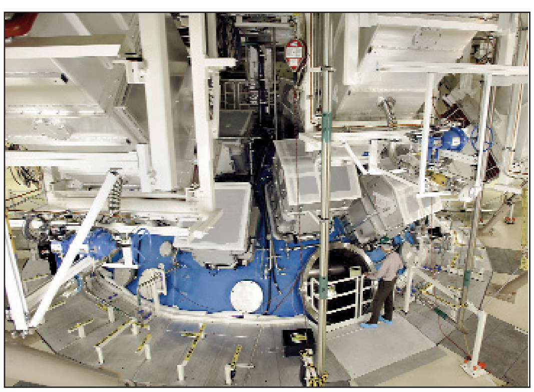


ITER

This schematic of the ITER tokamak shows the scale of the device relative to a person (bottom, right of center, blue).

A second major approach to fusion power, inertial confinement, produces short-duration, extremely dense plasmas by heating and compressing small pellets of fusion fuel. The pellet surface is heated rapidly by an intense pulse of X-rays, ion beams or laser beams, which blasts away the outer layers of the pellet. The resulting shock waves cause the pellet to implode, compressing the fuel pellet into a high-density plasma. The result is a burst of fusion power lasting a billionth of a second. A stadium-sized laser device, the National Ignition Facility (NIF) is nearing completion at the Lawrence Livermore National Laboratory in California. NIF will be capable of demonstrating deuterium-tritium fusion at significant levels in about 2010.

Although fusion is a nuclear process, it differs from the fission process in that there is no radioactive by-product from the fusion reaction – only helium gas and neutrons. The neutrons from the fusion reaction do produce some radioactivity in the surrounding systems, but at low levels that would allow shallow land burial, in contrast to the deep geological disposal necessary for fission by-products. A fusion power station will be an inherently safer system with no potential for a meltdown event. Any malfunction will rapidly eliminate the conditions necessary to sustain the fusion reaction; this will assure a complete and safe shutdown of the fusion process.



When NIF is completed, 192 laser beams will be directed at millimeter-sized targets located at the center of the target chamber (10 meter diameter).

Fusion fuel is also inexpensive compared with fission fuel, but researchers need to show that the additional technical complexity of a fusion system will not make a fusion device more costly or less reliable than other energy sources. Meeting the challenges of fusion energy will require insights and conceptual innovations from a broad range of scientific disciplines. Researchers in fluid mechanics, astrophysics, plasma physics, material science and computer simulations will all contribute to making fusion a practical source of electricity.

For more information:
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Hans Wilhelmsson, *Fusion: A Voyage Through the Plasma Universe*, IOP, 1999.
Yaffa & Shalom Eliezer, *The Fourth State of Matter*, Hilger, Bristol, 1989, (2nd edition, 2001).
JET website: www.jet.efda.org/ • ITERwebsite: www.iter.org/ • NIF website: www.llnl.gov/nif/ • For various approaches to fusion: www.plasmas.org/fusion-alternate.htm

Text: Adapted from *Fusion Energy Science*, Department of Energy; and *Fusion Science: Harnessing the Energy of the Stars*; General Atomics; with additions from Ronald Miller
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Images: General Atomics; ITER; NIF – University of California, Lawrence Livermore National Laboratory, and the U.S. Department of Energy