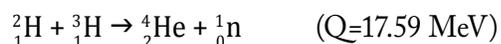
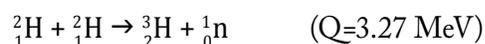




The deuterium-tritium target pellet at the National Ignition Facility.



The fuel for nuclear fusion is extremely abundant. Hydrogen is the most plentiful element in the universe, and its isotopes can be harvested from ordinary water. The deuterium supply within the world's oceans represents more available energy than the world's supply of fossil fuels or uranium. Thirty liters of seawater contain 1 gram of deuterium, from which the energy equivalent of 10,000 liters of gasoline can be extracted through fusion. Tritium has a very low natural abundance because it is radioactive with a half-life of about ten years. However, tritium can be synthesized through the reaction of lithium-6 with a neutron, which produces tritium and an alpha particle. This process is known as "breeding."

On paper, fusion offers a number of advantages over fission for the purposes of power generation. We have already discussed how fusion reactions have a higher energy density than fission reactions, meaning more energy can be extracted per unit mass of fuel. Furthermore, unlike fission reactors, fusion reactors have no risk of meltdown because there is no "supercritical" reaction rate—subsequent fusion events do not rely on the product, like in fission chain reactions. Nuclear fusion also produces no air pollution (the only byproduct is helium) and produces no radioactive waste.

Unfortunately, there are a number of challenges to overcome before fusion can become a reliable power source. The greatest challenge to controlled nuclear fusion is the extremely high temperature necessary to en-

sure that nuclei are energetic enough to fuse. As we have seen, hydrogen fusion in the Sun requires temperatures of at least ten million kelvin. Temperatures of this magnitude are difficult to achieve and maintain in a laboratory or power plant.

Achieving a single fusion reaction is not enough, however; a fusion reactor, like a fission reactor, must be self-sustaining. **Fusion ignition** refers to the point at which a fusion reaction becomes self-sustaining. That is, the energy released by the fusion reactions continues to heat the fuel, and the external energy that was used to heat the fuel can be turned off—much like lighting a piece of paper with a match. Although it has not yet been achieved, reaching fusion ignition is considered an important first step toward harnessing fusion energy.

Fusion reactors require not only extremely high temperatures, but also a sufficiently high density of nuclei to ensure that fusion reactions will occur with a great enough frequency. When atoms are heated past their ionization energy, their electrons are no longer bound to the nucleus. A collection of superheated atoms forms a cloud of positively charged nuclei and negatively charged electrons called a **plasma**. Two parameters for describing the characteristics of a plasma are the plasma ion density,  $n$ , and the plasma confinement time,  $\tau$ . According to Lawson's criterion, proposed by J. D. Lawson in 1957, a fusion reactor is capable of producing a net output of power as long as the product of  $n$  and  $\tau$  takes the following values:

$$n\tau \geq 10^{14} \text{ s/cm}^3 \quad (\text{deuterium-tritium fusion})$$

$$n\tau \geq 10^{16} \text{ s/cm}^3 \quad (\text{deuterium-deuterium fusion})$$

In order to achieve the appropriate Lawson's criterion, confining the high-density and high-temperature plasma poses the greatest challenge. Containment of high-temperature plasma poses a challenge because ordinary structural materials vaporize at temperatures above several thousand degrees. Therefore, scientists must utilize nonmaterial containment methods to generate and store plasmas.

The two primary techniques for containing plasmas are magnetic confinement and inertial confinement. Magnetic confinement relies on the fact that the trajectory of charged particles, such as the ions within a plasma, can be bent using strong magnetic fields. A "magnetic bottle" is a magnetic field configured in such a way that moving particles will be reflected backward, and thus contained, when they encounter areas of greater field strength. A **tokamak** is a toroidal (doughnut-shaped) device that confines a plasma using a combination of two magnetic fields. The tokamak was developed in the former Soviet Union following World War II.