ation of 135,000 people. Thirty individuals died during the accident or shortly thereafter and data from the Ukraine Radiological Institute suggest that more than 2,500 deaths could be attributed to the Chernobyl accident. In the period 1986–1997 there was a tenfold increase in the number of children contracting thyroid cancer from the ingestion of radioactive iodine in milk from cows that ate contaminated grass. One conclusion of an international conference studying the Ukraine accident was that the main causes of the Chernobyl accident were the coincidence of severe deficiencies in the reactor design and a violation of safety procedures. Most of these deficiencies have been addressed at plants of similar design in Russia and neighboring countries of the former Soviet Union.

Commercial reactors achieve safety through careful design, rigid operating protocol, and thorough emergency-response training of operators. It is only when these variables are compromised that reactors pose a danger. Radiation exposure and the potential health risks associated with such exposure are controlled by three layers of containment. The fuel and radioactive fission products are contained inside the reactor vessel. Should this vessel rupture, the reactor building acts as a second containment structure to prevent radioactive material from contaminating the environment. Finally, the reactor facilities must be in a remote location to protect the general public from exposure should radiation escape the reactor building.

A continuing concern about nuclear fission reactors is the safe disposal of radioactive material when the reactor core is replaced. Even when the uranium and plutonium are separated out and recycled, the remaining waste material contains long-lived, highly radioactive isotopes that must be stored over long time intervals in such a way that there is no chance of environmental contamination. At present, sealing radioactive wastes in waterproof containers and burying them in deep salt mines seems to be the most promising solution.

Transport of reactor fuel and reactor wastes poses additional safety risks. Accidents during transport of nuclear fuel could expose the public to harmful levels of radiation. To minimize these dangers, the Department of Energy requires stringent crash tests of all containers used to transport nuclear materials. Container manufacturers must demonstrate that their containers will not rupture even in high-speed collisions.

Despite these risks, there are advantages to the use of nuclear power to be weighed against the risks. For example, nuclear power plants do not produce air pollution and greenhouse gases as do fossil fuel plants, and the supply of uranium on the Earth is predicted to last longer than the supply of fossil fuels. For each source of energy, whether nuclear, hydroelectric, fossil fuel, wind, or solar, the risks must be weighed against the benefits and the regional availability of the energy source. Thus, thoughtful use of a variety of energy sources *and* increased emphasis on energy conservation methods appear to be logical components of a sensible energy policy.

14.6 NUCLEAR FUSION

In Chapter 13 we found that the binding energy for light nuclei (those having mass numbers less than 20) is much smaller than the binding energy for heavier nuclei. This suggests a process that is the reverse of fission, called **nuclear fusion.** Fusion occurs when two light nuclei combine to form a heavier nucleus. Because the mass of the final nucleus is less than the combined rest masses of the original nuclei, a loss of mass occurs, accompanied by a release of energy. The following are examples of such energy-liberating fusion reactions occuring in the Sun:

$$\begin{aligned} {}^1_1\text{H} + {}^1_1\text{H} &\longrightarrow {}^2_1\text{H} + {}^0_1\text{e}^+ + \nu \\ {}^1_1\text{H} + {}^2_1\text{H} &\longrightarrow {}^3_2\text{He} + \gamma \end{aligned} \tag{14.10}$$

This second reaction is followed by one of the following reactions:

$$\begin{aligned} {}^1_1\text{H} + {}^3_2\text{H} &\longrightarrow {}^4_2\text{He} + {}^0_1\text{e}^+ + \nu \\ {}^3_2\text{He} + {}^3_2\text{He} &\longrightarrow {}^4_2\text{He} + {}^1_1\text{H} + {}^1_1\text{H} \end{aligned}$$

Thermonuclear reactions

These are the basic reactions in what is called the **proton–proton cycle,** believed to be one of the basic cycles by which energy is generated in the Sun and other stars that have an abundance of hydrogen. Most of the energy production takes place in the Sun's interior, where the temperature is approximately 1.5×10^7 K. As we will see later, such high temperatures are required to drive these reactions that they are called **thermonuclear fusion reactions.** The hydrogen (fusion) bomb, which was first exploded in 1952, is an example of an uncontrolled thermonuclear fusion reaction. All of the reactions in the proton–proton cycle are exothermic—that is, they involve a release of energy. An overall view of the proton–proton cycle is that four protons combine to form an alpha particle and two positrons, with the release of 25 MeV of energy.

Fusion Reactions

The enormous amount of energy released in fusion reactions suggests the possibility of harnessing this energy for useful purposes here on Earth. A great deal of effort is currently directed toward developing a sustained and controllable thermonuclear reactor—a fusion power reactor. Controlled fusion is often called the ultimate energy source because of the availability of its fuel source: water. For example, if deuterium were used as the fuel, 0.12 g of it could be extracted from 1 gal of water at a cost of about 4 cents. Such rates would make the fuel costs of even an inefficient reactor almost insignificant. An additional advantage of fusion reactors is that comparatively few radioactive by-products are formed. For the proton–proton cycle described earlier in this section, the end product of the fusion of hydrogen nuclei is safe, nonradioactive helium. Unfortunately, a thermonuclear reactor that can deliver a net power output spread out over a reasonable time interval is not yet a reality, even though research has been in progress since the 1950s. Many difficulties must be resolved before a successful device is constructed.

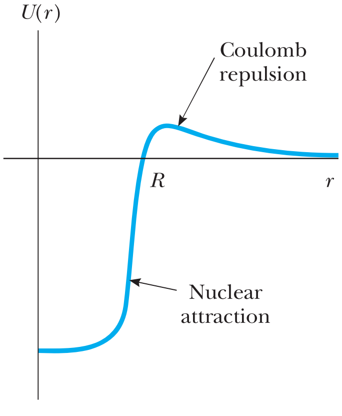


Figure 14.11 Potential energy as a function of separation between two deuterons. The Coulomb repulsive force is dominant at long range, whereas the nuclear attractive force is dominant at short range, where R is of the order of several fermi.

We have seen that the Sun's energy is based, in part, upon a set of reactions in which hydrogen is converted to helium. Unfortunately, the proton–proton interaction is not suitable for use in a fusion reactor, because this reaction requires very high pressures and densities. The process works in the Sun only because of the extremely high density of protons in the Sun's interior.

The fusion reactions that appear most promising for a terrestrial fusion power reactor involve deuterium (${}^2_1\text{H}$) and tritium (${}^3_1\text{H}$):

$$\begin{aligned} {}^2_1\text{H} + {}^2_1\text{H} &\longrightarrow {}^3_2\text{He} + {}^1_0\text{n} \qquad Q = 3.27\text{ MeV} \\ {}^2_1\text{H} + {}^2_1\text{H} &\longrightarrow {}^3_1\text{H} + {}^1_1\text{H} \qquad Q = 4.03\text{ MeV} \\ {}^2_1\text{H} + {}^3_1\text{H} &\longrightarrow {}^4_2\text{He} + {}^1_0\text{n} \qquad Q = 17.59\text{ MeV} \end{aligned} \tag{14.11}$$

As noted earlier, deuterium is available in almost unlimited quantities from our lakes and oceans and is very inexpensive to extract. Tritium, however, is radioactive ($T_{1/2} = 12.3$ yr) and undergoes beta decay to ^{3}He. As a result, tritium does not occur naturally to any great extent and must be artificially produced.

One of the major problems in obtaining energy from any fusion reaction is the fact that the Coulomb repulsion force between two charged nuclei must be overcome before they can fuse. The potential energy as a function of particle separation for two deuterons (each with charge $+e$) is shown in Figure 14.11. The potential energy is positive in the region $r > R$, where the Coulomb repulsive force dominates, and negative in the region $r < R$, where the strong nuclear force dominates. The fundamental problem, then, is to give the two nuclei enough kinetic energy to overcome this repulsive potential barrier. This can be accomplished by heating the fuel to extremely high temperatures (about 10^8 K, far greater than the interior temperature of the Sun). At these high temperatures, the atoms are ionized and the system consists of a collection of electrons and nuclei, commonly referred to as a **plasma.**

High temperatures are required to overcome the large Coulomb barrier

EXAMPLE 14.6 The Fusion of Two Deuterons

The separation between two deuterons must be about 1.0×10^{-14} m for the attractive nuclear force to overcome the repulsive Coulomb force. (a) Calculate the height of the potential barrier due to the repulsive force.

Solution The potential energy associated with two charges separated by a distance r is

$$U = k\frac{q_1 q_2}{r}$$

where k is the Coulomb constant. For the case of two deuterons, $q_1 = q_2 = +e$, so

$$U = k\frac{e^2}{r} = \left(8.99 \times 10^9 \,\frac{\text{N}\cdot\text{m}^2}{\text{C}^2}\right)\frac{(1.60 \times 10^{-19}\ \text{C})^2}{1.0 \times 10^{-14}\ \text{m}}$$

$$= 2.3 \times 10^{-14}\ \text{J} = 0.14\ \text{MeV}$$

(b) Estimate the effective temperature required for a deuteron to overcome the potential barrier, assuming an energy of $\frac{3}{2}k_\text{B}T$ per deuteron (where k_B is Boltzmann's constant).

Solution Since the total Coulomb energy of the pair of deuterons is 0.14 MeV, the Coulomb energy per deuteron is $0.07\ \text{MeV} = 1.1 \times 10^{-14}$ J. Setting this equal to the average thermal energy per deuteron gives

$$\tfrac{3}{2}k_\text{B}T = 1.1 \times 10^{-14}\ \text{J}$$

where k_B is equal to 1.38×10^{-23} J/K. Solving for T gives

$$T = \frac{2 \times (1.1 \times 10^{-14}\ \text{J})}{3 \times (1.38 \times 10^{-23}\ \text{J/K})} = 5.3 \times 10^8\ \text{K}$$

Example 14.6 suggests that deuterons must be heated to about 5×10^8 K to achieve fusion. This estimate of the required temperature is too high, however, because the particles in the plasma have a Maxwellian speed distribution, and therefore some fusion reactions are caused by particles in the high-energy "tail" of this distribution. Furthermore, even the particles without enough energy to overcome the barrier have some probability of tunneling through the barrier. When these effects are taken into account, a temperature of "only" 4×10^8 K appears adequate to fuse two deuterons.

The temperature at which the power generation rate exceeds the loss rate (due to mechanisms such as radiation losses) is called the **critical ignition temperature.** This temperature for the deuterium–deuterium (D–D) reaction is 4×10^8 K. According to $E \cong k_\text{B}T$, this temperature is equivalent to approximately 35 keV. It turns out that the critical ignition temperature for the deuterium–tritium (D–T) reaction is about 4.5×10^7 K, or only 4 keV.

Critical ignition temperature

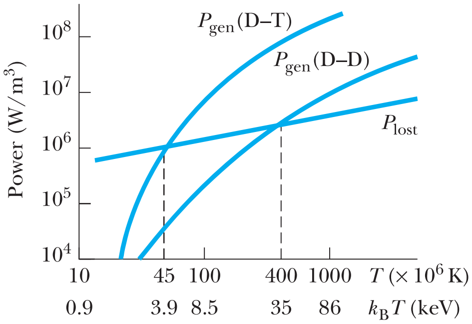


Figure 14.12 Power generated (or lost) versus temperature for the deuterium–deuterium and deuterium–tritium fusion reactions. When the generation rate P_{gen} exceeds the loss rate P_{lost}, ignition takes place.

Figure 14.12 is a plot of the power generated by fusion, P_{gen}, versus temperature for the two reactions. The straight line represents the power lost, via the radiation mechanism known as **bremsstrahlung,** versus temperature. This is the principal mechanism of energy loss, in which radiation (primarily x-ray) is emitted as the result of electron–ion collisions within the plasma.[2] The intersections of the P_{lost} line with the P_{gen} curves give the critical ignition temperatures.

Confinement time

In addition to the high temperature requirements, there are two other critical parameters that determine whether or not a thermonuclear reactor will be successful: the **ion density,** n, and **confinement time,** τ. **The confinement time is the period for which the interacting ions are maintained at a temperature equal to or greater than the ignition temperature.** The British physicist J. D. Lawson has shown that the ion density and confinement time must both be large enough to ensure that more fusion energy is released than is required to heat the plasma. In particular, **Lawson's criterion** states that a net energy output is possible under the following conditions:

Lawson's criterion

$$\begin{aligned} n\tau &\geq 10^{14}\ \text{s/cm}^3 \qquad (\text{D–T}) \\ n\tau &\geq 10^{16}\ \text{s/cm}^3 \qquad (\text{D–D}) \end{aligned} \tag{14.12}$$

Figure 14.13 is a graph of $n\tau$ versus the so-called **kinetic temperature** $k_B T$ for the D–T and D–D reactions.

Lawson arrived at his criterion by comparing the energy required to heat the plasma with the energy generated by the fusion process. The energy E_h required to heat the plasma is proportional to the ion density n; that is, $E_h = D_1 n$. The energy generated by the fusion process, E_{gen}, is proportional to $n^2\tau$, or $E_{gen} = D_2 n^2 \tau$. This can be understood by realizing that the fusion energy released is proportional to both the rate at which interacting ions collide, n^2, and the confinement time, τ. Net energy is produced when the energy generated by fusion, E_{gen}, exceeds E_h. When the constants D_1 and D_2 are

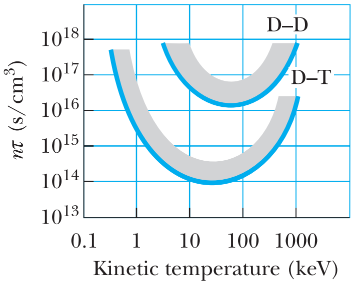


Figure 14.13 The Lawson number $n\tau$ at which net energy output is possible versus temperature for the D–T and D–D fusion reactions. The regions above the curves represent favorable conditions for fusion.

---

[2] Cyclotron radiation is another loss mechanism; it is especially important in the case of the D–D reaction.

calculated for different reactions, the condition that $E_{\text{gen}} \geq E_h$ leads to Lawson's criterion.[3]

In summary, the three basic requirements of a successful thermonuclear power reactor are

Requirements for a fusion power reactor

- The plasma temperature must be very high—about 4.5×10^7 K for the D–T reaction and about 4×10^8 K for the D–D reaction.
- The ion density must be high. A high density of interacting nuclei is necessary to increase the collision rate between particles.
- The confinement time of the plasma must be long. To meet Lawson's criterion, the product $n\tau$ must be large. For a given value of n, the probability of fusion between two particles increases as τ increases.

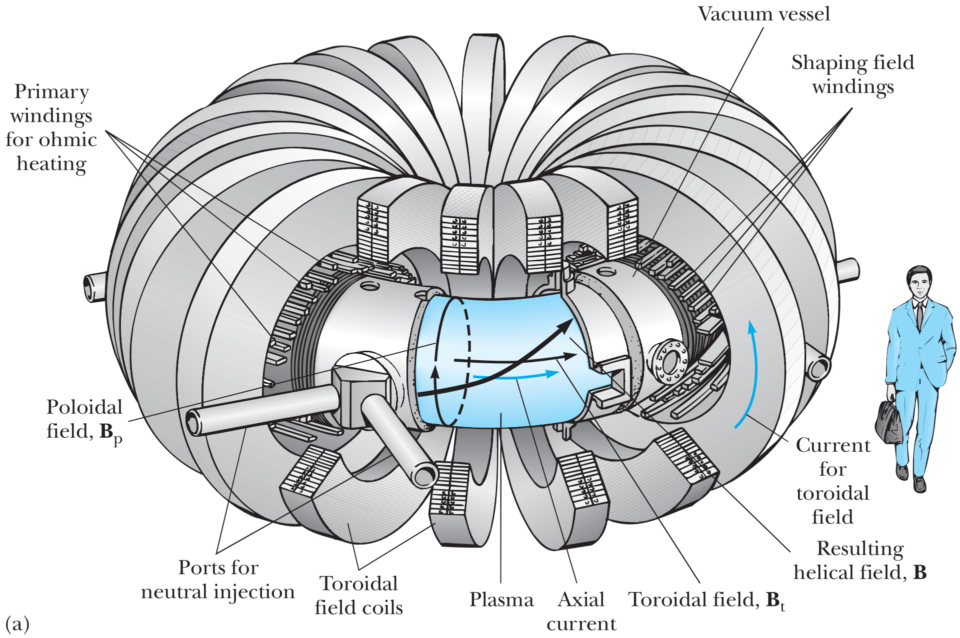
Current efforts are aimed at meeting Lawson's criterion at temperatures exceeding the critical ignition temperature. Although the minimum plasma densities have been achieved, the problem of confinement time is more difficult. How can a plasma be confined at 10^8 K for 1 s? Two basic techniques for confining plasmas are under investigation: magnetic field confinement and inertial confinement.

Magnetic Field Confinement

Many fusion-related plasma experiments use **magnetic field confinement** to contain the charged plasma. Figure 14.14a shows a device called a **tokamak,** first developed in Russia. A combination of two magnetic fields is used to confine and stabilize the plasma: (1) a strong toroidal field, produced by the current in the windings, and (2) a weaker "poloidal" field, produced by the toroidal current. The toroidal current heats the plasma in addition to confining it. The resultant helical field lines spiral around the plasma and keep it from touching the walls of the vacuum chamber. If the plasma comes into contact with the walls, its temperature is reduced and heavy impurities sputtered from the walls "poison" it and lead to large power losses. One of the major breakthroughs in the 1980s was in the area of auxiliary heating to reach ignition temperatures. Experiments have shown that injecting a beam of energetic neutral particles into the plasma is a very efficient method of heating the plasma to ignition temperatures (5 to 10 keV). Radio-frequency heating will probably be needed for reactor-size plasmas. Figure 14.14b shows a cutaway view of the Princeton Tokamak Fusion Test Reactor. When it was in operation, the Tokamak Fusion Test Reactor (TFTR) reported central ion temperatures of 510 million degrees Celsius, more than 30 times hotter than the center of the Sun. The $n\tau$ values in the TFTR for the D–T reaction were well above 10^{13} s/cm^3 and close to the value required by Lawson's criterion. By the late 1990s, tokamaks in England and Japan were reporting reaction rates of 10^{18} D–T fusions per second and $n\tau$ values of 5×10^{13} s/cm^3 at temperatures of 30 keV. Direct measurements showed that the output energy slightly exceeded the input energy to the plasma for brief periods.

---

[3] Note that Lawson's criterion neglects the energy needed to set up the strong magnetic field that is used to confine the hot plasma. This energy is expected to be about 20 times greater than the energy required to heat the plasma. Consequently, it is necessary to have a magnetic energy recovery system or to make use of superconducting magnets.



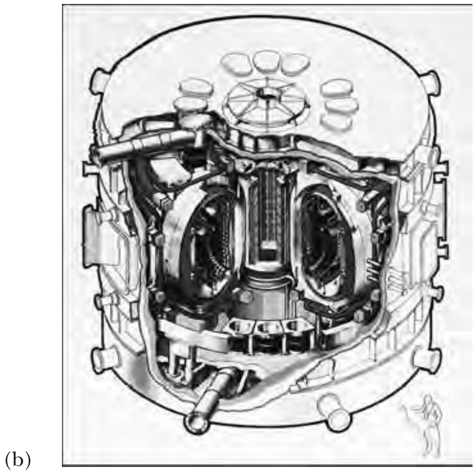


Figure 14.14 (a) A schematic diagram of a tokamak used in magnetic confinement. The total magnetic field $\mathbf{B}$ is the superposition of the toroidal field $\mathbf{B}_t$ and the poloidal field $\mathbf{B}_p$. The plasma is trapped within the spiraling field lines as shown. (*Adapted from* McGraw-Hill Encyclopedia of Science and Technology, *New York, McGraw-Hill Book Co., 1987.*) (b) A cutaway view of the TFTR. (*Courtesy of Princeton Plasma Physics Laboratory*)

One of the new generation of fusion experiments is the National Spherical Torus Experiment (NSTX), shown in Figure 14.15. Rather than the donut-shaped plasma of a tokamak, the NSTX produces a spherical plasma that has a hole through its center. The major advantage of the spherical configuration is its ability to confine the plasma at a higher pressure in a given magnetic field. This approach could lead to development of smaller, more economical fusion reactors.

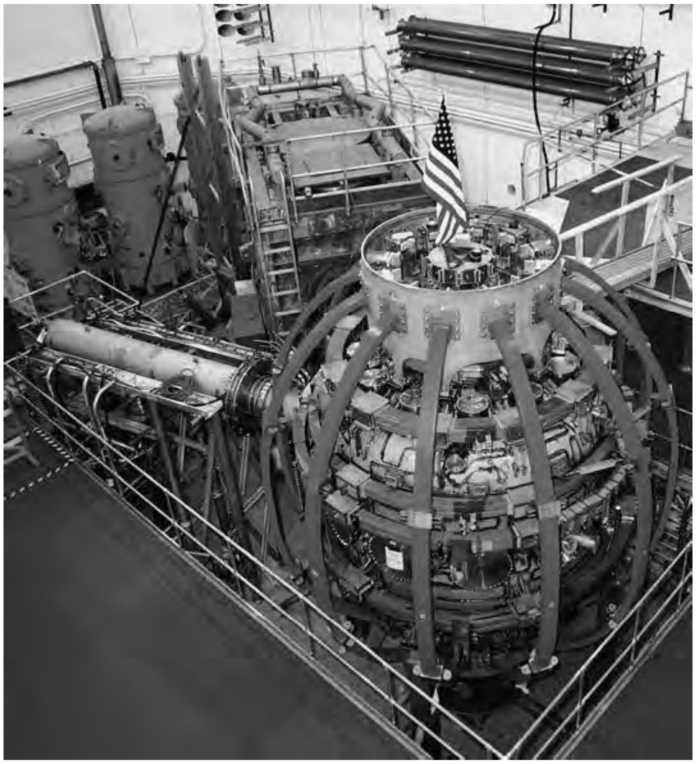


Figure 14.15 The National Spherical Torus Experiment (NSTX) that began operation in March 1999. (*Courtesy of Princeton Plasma Physics Laboratory, Princeton University*)

An international collaborative effort involving Canada, Europe, Japan, and Russia is currently under way to build a fusion reactor called ITER (International Thermonuclear Experimental Reactor). China and the United States began to participate in program activities in early 2003. This facility will address the remaining technological and scientific issues concerning the feasibility of fusion power. The design is completed, and site and construction negotiations are under way. If the planned device works as expected, the Lawson number for ITER will be about six times greater than the current record holder, the JT-60U tokamak in Japan. ITER will produce 1.5 GW of power, and the energy content of the alpha particles inside the reactor will be so intense that they will sustain the fusion reaction, allowing the auxiliary energy sources to be turned off once the reaction is initiated.

Inertial Confinement

The second technique for confining a plasma, called **inertial confinement,** makes use of a D–T target that has a very high particle density of 5×10^{25} particles/cm^3, or a mass density of about 200 g/cm^3. In this scheme, the confinement time is very short (typically 10^{-11} to 10^{-9} s), and so, because of their own inertia, the particles do not have a chance to move appreciably from their initial positions. Thus Lawson's criterion can be satisfied by combining a high particle density with a short confinement time.