Quite apart from the safety of reactors themselves is the issue of what to do with the wastes they produce. Even if old fuel rods are processed to separate out the uranium and plutonium they contain, what is left is still highly radioactive. Although a lot of the activity will be gone in a few months and much of the rest in a few hundred years, some of the radionuclides have half-lives in the millions of years. At present over 15,000 tons of spent nuclear fuel is being stored on a temporary basis in the United States.

Burying nuclear wastes deep underground currently seems to be the best long-term way to dispose of them. The right location is easy to specify but not easy to find: stable geologically with no earthquakes likely, no nearby population centers, a type of rock that does not disintegrate in the presence of heat and radiation but is easy to drill into, and not near groundwater that might become contaminated. Studies continue on suitable sites with a view to beginning waste burial early in the next century.

12.11 NUCLEAR FUSION IN STARS

How the sun and stars get their energy

Here on the earth, 150 million km from the sun, a surface 1 m^2 in area exposed to the vertical rays of the sun receives energy at a rate of about 1.4 kW. Adding up all the energy radiated by the sun per second gives the enormous total of 4×10^{26} W. And the sun has been emitting energy at this rate for billions of years. Where does it all come from?

The basic energy-producing process in the sun is the fusion of hydrogen nuclei into helium nuclei. This can take place in several different reaction sequences, the most common of which, the **proton-proton cycle,** is shown in Fig. 12.25. The total evolved energy is 24.7 MeV per ${}^4_2$He nucleus formed.

Since 24.7 MeV is 4×10^{-12} J, the sun's power output of 4×10^{26} W means the sequence of reactions in Fig. 12.25 must occur 10^{38} times per second. The sun consists

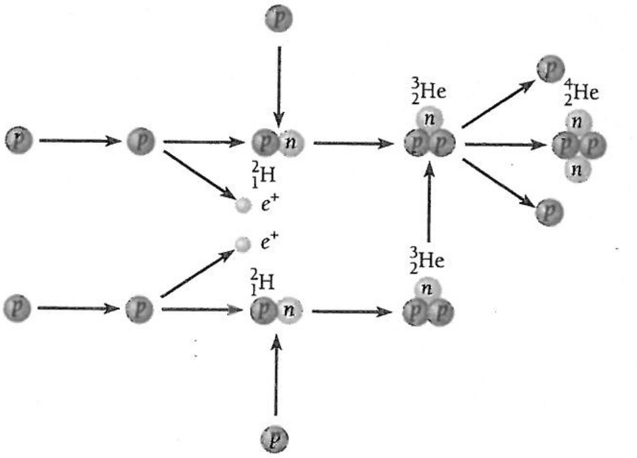


Figure 12.25 The proton-proton cycle. This is the chief nuclear reaction sequence that takes place in stars like the sun and cooler stars. Energy is given off at each step. The net result is the combination of four hydrogen nuclei to form a helium nucleus and two positrons.

of 70 percent hydrogen, 28 percent helium, and 2 percent of other elements, so plenty of hydrogen remains for billions of years of further energy production at its current rate. Eventually the hydrogen in the sun's core will be exhausted, and then, as the other reactions described below take over, the sun will swell to become a red giant star and later subside into a white dwarf.

Self-sustaining fusion reactions can occur only under conditions of extreme temperature and density. The high temperature ensures that some nuclei have the energy needed to come close enough together to interact, and the high density ensures that such collisions are frequent. A further condition for the proton-proton and other multistep cycles is a large reacting mass, such as that of the sun, since much time may elapse between the initial fusion of a particular proton and its eventual incorporation in an alpha particle.

The core of the sun is believed to be at a temperature of about 15 million K, which allows the proton-proton cycle to occur there. The same is true for many other stars. Still other stars have hotter interiors, and in them the **carbon cycle** predominates. This cycle proceeds as shown in Fig. 12.26. The net result again is the formation of an alpha particle and two positrons from four protons, with the evolution of 24.7 MeV. The initial $^{12}_{6}\text{C}$ acts as a kind of catalyst for the process, since it reappears at its end.

Formation of Heavier Elements

Fusion reactions that produce helium are not the only ones that occur in the sun and other stars. When all the hydrogen in a star's core has become helium, gravitational contraction compresses the core and raises its temperature to the 10^8 K needed for

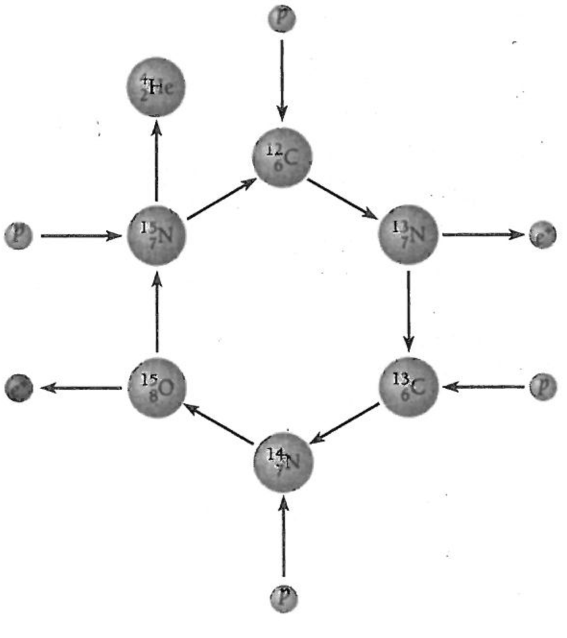


Figure 12.26 The carbon cycle also involves the combination of four hydrogen nuclei to form a helium nucleus with the evolution of energy. The $^{12}_{6}\text{C}$ nucleus is unchanged by the series of reactions. This cycle occurs in stars hotter than the sun.

(AIP Meggers Gallery of Nobel Laureates/AIP Emilio Segre Visual Archives)

Hans A. Bethe (1906–) was born in Strasbourg, then part of Germany but today part of France. He studied physics in Frankfurt and Munich and taught at various German universities until 1933, when Hitler came to power. After 2 y in England he came to the United States where he was professor of physics at Cornell University from 1937 to 1975. He has remained active in research and in public affairs even though formally retired.

Notable among Bethe's many and varied contributions to physics is his 1938 account of the sequences of nuclear reactions that power the sun and stars, for which he received the Nobel Prize in 1967. During World War II he directed the theoretical physics division of the laboratory at Los Alamos, New Mexico, where the atomic bomb was developed. A strong believer in nuclear energy—"it is more necessary now than ever before because of global warming"—Bethe has also been an effective advocate of nuclear disarmament.

helium fusion to begin. This involves the combination of three alpha particles to form a carbon nucleus with the evolution of 7.5 MeV:

$$^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{12}_{6}\mathrm{C}$$

In heavy stars, core temperatures can go even higher, and fusion reactions that involve carbon then become possible. Some examples are

$$\begin{aligned} &^{4}_{2}\mathrm{He} + {}^{12}_{6}\mathrm{C} \rightarrow {}^{16}_{8}\mathrm{O} \\ &^{12}_{6}\mathrm{C} + {}^{12}_{6}\mathrm{C} \rightarrow {}^{24}_{12}\mathrm{Mg} \\ &^{12}_{6}\mathrm{C} + {}^{12}_{6}\mathrm{C} \rightarrow {}^{20}_{10}\mathrm{Ne} + {}^{4}_{2}\mathrm{He} \end{aligned}$$

The heavier the star, the higher the eventual temperature of its core, and the larger the nuclei that can be formed. (The high temperatures, of course, are needed to overcome the greater electric repulsion of reacting nuclei with many protons.) In stars more than about 10 times as massive as the sun, the iron isotope $^{56}_{26}\mathrm{Fe}$ is reached. This is the nucleus with the greatest binding energy per nucleon (Fig. 11.12). Any reaction between a $^{56}_{26}\mathrm{Fe}$ nucleus and another nucleus will therefore lead to the breakup of the iron nucleus, not to the formation of a still heavier one.

Then how do nuclides beyond $^{56}_{26}\mathrm{Fe}$ originate? The answer is through the successive capture of neutrons, with beta decays when needed for appropriate neutron/proton ratios. The neutrons are liberated in such sequences as

$$\begin{aligned} {}^{1}_{1}\mathrm{H} + {}^{12}_{6}\mathrm{C} &\rightarrow {}^{13}_{7}\mathrm{N} + \gamma \\ {}^{13}_{7}\mathrm{N} &\rightarrow {}^{13}_{6}\mathrm{C} + e^{+} + \nu \\ {}^{4}_{2}\mathrm{He} + {}^{13}_{6}\mathrm{C} &\rightarrow {}^{16}_{8}\mathrm{O} + {}^{1}_{0}n \end{aligned}$$

Neutron-capture reactions in a stellar interior can build up nuclides as far as $^{209}_{83}\mathrm{Bi}$, the largest stable nucleus, but no further. The density of neutrons there is not sufficient for them to be captured in rapid enough succession by nuclei of $A > 209$ before such nuclei decay. However, when a very massive star has reached the end of its fuel supply, its core collapses and a violent explosion follows that appears in the sky as a supernova. During the collapse neutrons are produced in abundance, some by the disintegration of neutron-rich nuclei into alpha particles and neutrons in collisions and some by the reaction $e^- + p \rightarrow n + \nu$. The huge neutron flux lasts only a matter of seconds, but this is sufficient to produce nuclei with mass numbers up to perhaps 260.

A supernova explosion, which occurs once or twice per century in a galaxy of stars like our own Milky Way, flings into space a large part of the star's mass, which becomes dispersed in interstellar matter. New stars (and their planets, such as our own) that come into being from this matter thus contain the entire spectrum of nuclides, not just the hydrogen and helium of the early universe. We are all made of stardust.

12.12 FUSION REACTORS

The energy source of the future?

Enormous as the energy produced by fission is, the fusion of light nuclei to form heavier ones can give out even more per kilogram of starting materials. Nuclear fusion promises to become the ultimate source of energy on the earth: safe, relatively nonpolluting, and with the oceans themselves supplying limitless fuel.

On the earth, where any reacting mass must be very limited in size, an efficient fusion process cannot involve more than a single step. Two reactions that may eventually power fusion reactors involve the combination of two deuterons to form a triton and a proton,

$$^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} + 4.0\ \mathrm{MeV} \tag{12.28}$$

or their combination to form a $^{3}_{2}\mathrm{He}$ nucleus and a neutron,

$$^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + {}^{1}_{0}n + 3.3\ \mathrm{MeV} \tag{12.29}$$

Both D-D reactions have about equal probabilities. A major advantage of these reactions is that deuterium is present in seawater and is cheap to extract. Although its concentration in seawater is only 0.015 percent, this adds up to a total of about 10^{15} tons of deuterium in the world's oceans. The deuterium in a gallon of seawater can yield as much energy through fusion as 600 gallons of gasoline can through combustion.

The first fusion reactors are more likely to employ a deuterium-tritium mixture because the D-T reaction

$$^{3}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}n + 17.6\ \mathrm{MeV} \tag{12.30}$$

has a higher yield than the others and occurs at lower temperatures. Seawater contains too little tritium to be extracted economically, but it can be produced by the neutron bombardment of the two isotopes of natural lithium:

$$^{6}_{3}\text{Li} + ^{1}_{0}n \rightarrow ^{3}_{1}\text{H} + ^{4}_{2}\text{He} \tag{12.31}$$

$$^{7}_{3}\text{Li} + ^{1}_{0}n \rightarrow ^{3}_{1}\text{H} + ^{4}_{2}\text{He} + ^{1}_{0}n \tag{12.32}$$

In fact, plans for future fusion reactors include lithium blankets that will make the tritium they need by absorbing neutrons liberated in the fusion reactions.

At the required temperatures, a fusion reactor's fuel will be in the form of a **plasma,** which is a fully ionized gas. **Breakeven** occurs when the energy produced equals the energy input to the reacting plasma. **Ignition,** a more difficult target, occurs when enough energy is produced for the reaction to be self-sustaining.

A successful fusion reactor has three basic conditions to meet:

1 The plasma temperature must be high so that an adequate number of the ions have the speeds needed to come close enough together to react despite their mutual repulsion. Taking into account that many ions have speeds well above the average and that tunneling through the potential barrier reduces the ion energy needed, the minimum temperature for igniting a D-T plasma is about 100 million K, which corresponds to an "ion temperature" of $kT \sim 10$ keV.

2 The plasma density n (in ions/m^3) must be high to ensure that collisions between nuclei are frequent.

3 The plasma of reacting nuclei must remain together for a sufficiently long time τ. How long depends on the product $n\tau$, the confinement quality parameter. In the case of a D-T plasma with $kT \sim 10$ keV, $n\tau$ must be greater than roughly 10^{20} s/m^3 for breakeven, more than that for ignition (Fig. 12.27).

Apart from stellar interiors, the combination of temperature, density, and confinement time needed for fusion thus far has occurred only in the explosion of fission ("atomic") bombs. Incorporating the ingredients for fusion reactions in such a bomb leads to an even more destructive weapon, the "hydrogen" bomb.

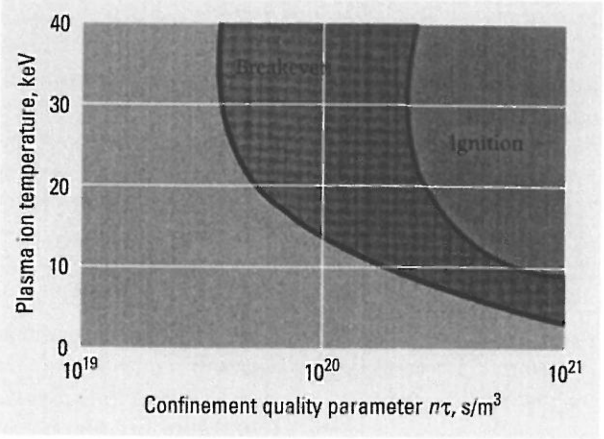


Figure 12.27 Conditions for breakeven (energy output equals energy input) and for ignition (a self-sustaining reaction) in a fusion reactor. Existing reactors have come close to breakeven; the projected International Thermonuclear Experimental Reactor is intended to reach ignition.

Confinement Methods

The approach to the controlled release of fusion energy that has thus far shown the most promise uses a strong magnetic field to confine the reactive plasma. In the Russian-designed **tokamak** scheme, the magnetic field is a modified torus (doughnut) in form (Fig. 12.28). Because the field lines of a purely toroidal field are curved, an ion moving in a helical path around its field lines will drift across the field and escape. To prevent this, a tokamak uses a poloidal field whose field lines are circles around the toroid axis. The poloidal field is produced by a current set up in the plasma itself by the changing field of an electromagnet in the center of the toroid. This current also heats the plasma; once the plasma is sufficiently hot, the current needs little help to continue.

The most powerful tokamaks today have attained plasma temperatures of 30 keV and confinement quality $n\tau$ values of 2×10^{19} s/m^3. In 1993 the Tokamak Fusion Test Reactor in Princeton, New Jersey, produced a record 6.2 MW of fusion power for 4 s with a D-T plasma. The input power was 28 MW. Breakeven and ignition will probably have to wait for the planned International Thermonuclear Experimental Reactor (ITER), which is intended to start operating in 2005.

ITER

ITER represents the final step before practical fusion power stations become a reality. Sponsored by the United States, the European Community, the Commonwealth of Independent States (the countries of the former Soviet Union), and Japan, ITER is expected to cost about $7.5 billion and to generate 1 GW from D-T reactions. The tokamak torus will be around 12 m in diameter and have an elliptical cross section 8.4 m high. Superconducting magnets will confine the plasma with fields as high as 11 T, and the plasma current should reach 25 million A. About 80 percent of the energy released in D-T reactions is carried off by the neutrons they produce, and these neutrons will be absorbed in ITER by lithium pellets inside stainless-steel tubes that surround the torus. Circulating water will carry away the resulting heat from the tubes, and the tritium that is formed will be flushed from the tubes by streams of helium gas.

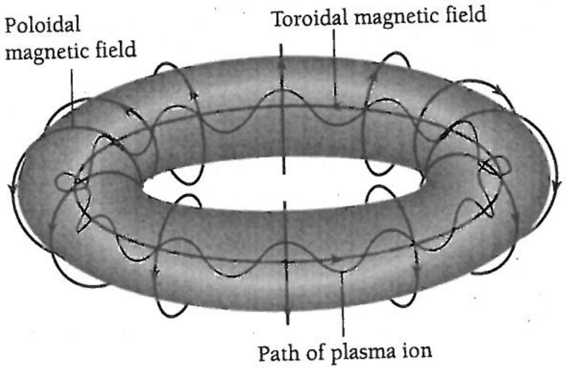
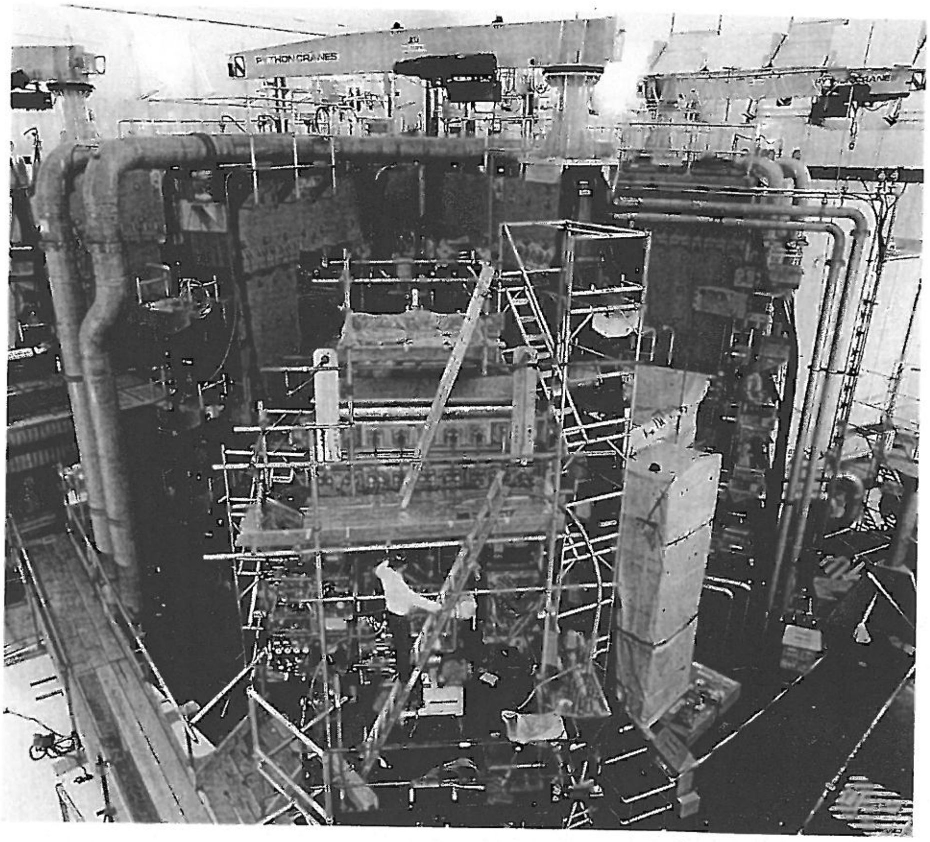


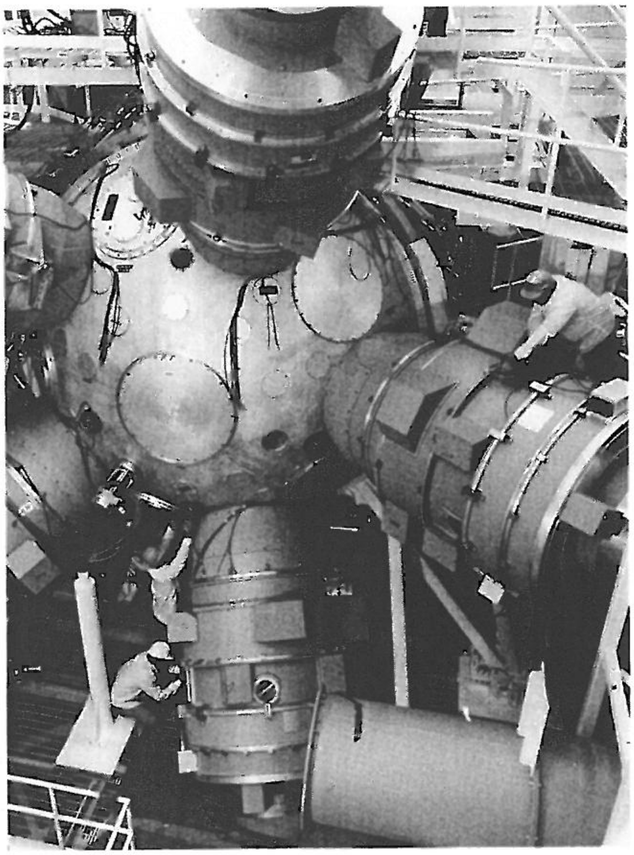
Figure 12.28 In a tokamak, combined toroidal and poloidal magnetic fields confine a plasma.



The Joint European Torus is an experimental tokamak fusion reactor at Culham, England. (*Jerry Mason/Science Photo Library/Photo Researchers*)

An entirely different procedure, called **inertial confinement,** uses energetic beams to both heat and compress tiny deuterium-tritium pellets by blasting them from all sides. The result is, in effect, a miniature hydrogen-bomb explosion, and a succession of them could provide a steady stream of energy. If ten 0.1-mg pellets are ignited every second, the average thermal output would be about 1 GW and could yield 300 MW or so of electric power, enough for a city of 175,000 people.

Laser beams have received the most attention for inertial confinement, but electron and proton beams have promise as well. The beam energy is absorbed in the outer layer of the fuel pellet, which blows off outward. Conservation of momentum leads to an inward shock wave that must squeeze the rest of the pellet to about 10^4 times its original density to heat the fuel sufficiently to start fusion reactions. The required beam energy is well beyond the capacity of today's lasers, though perhaps not of future ones. Particle beams are closer to reaching the needed energy but are much harder to focus on the tiny fuel pellets. Research continues, but magnetic confinement seems closer to the goal of a working fusion reactor. Conceivably the middle of the next century will see the start of a new era in energy supply for the world.



The world's most powerful laser, located at the Lawrence Livermore National Laboratory in California, is used in inertial confinement experiments. Its output of 60 kJ per nanosecond (10^{-9} s) pulse is divided into 10 beams that are directed at tiny deuterium-tritium pellets in an effort to induce fusion reactions in them.

on the tiny fuel pellets. Research continues, but magnetic confinement seems closer to the goal of a working fusion reactor. Conceivably the middle of the next century will see the start of a new era in energy supply for the world.