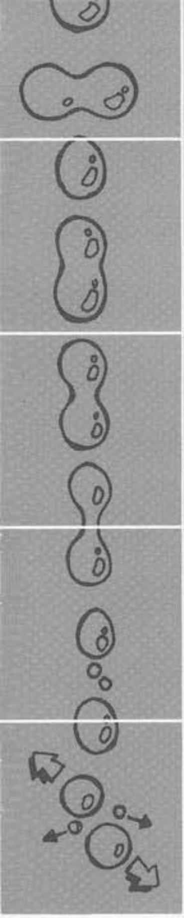

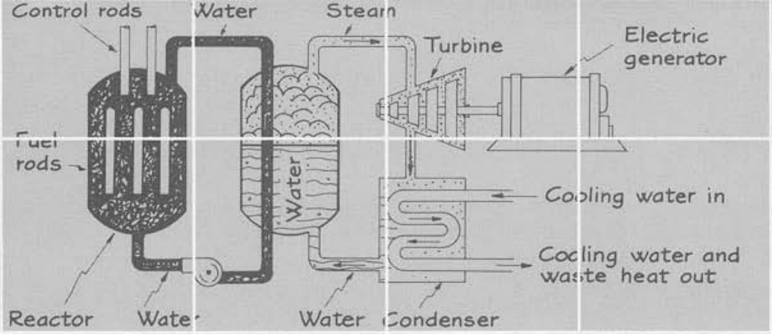

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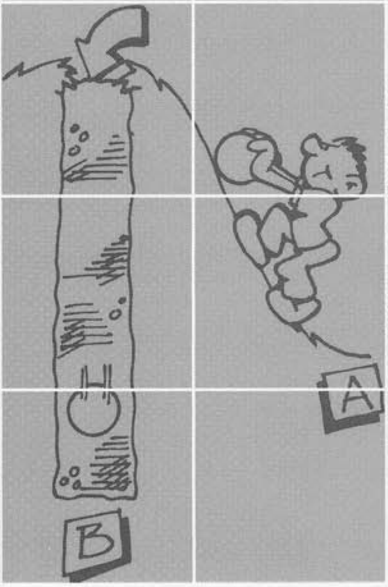
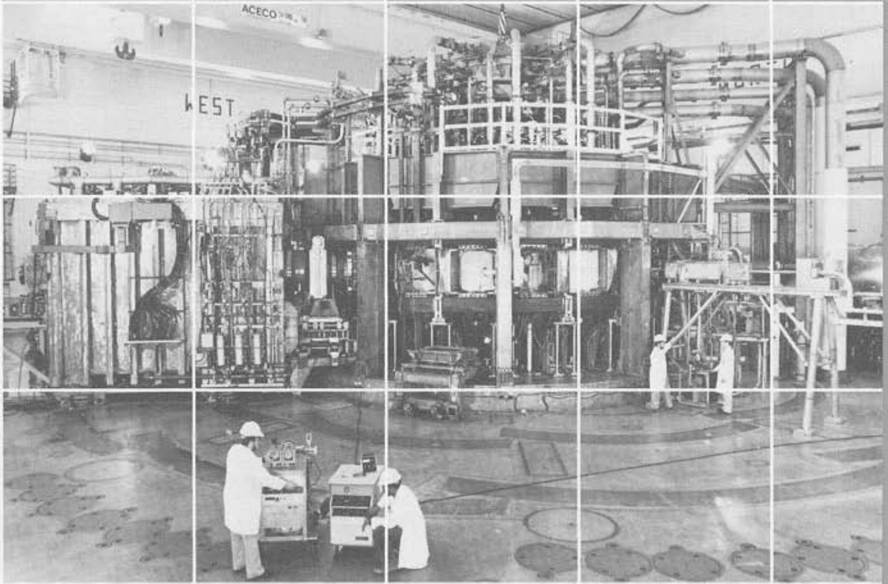




Nuclear Energy

The discovery of radioactivity in 1896 showed that energy stored in the nucleus could be released as the kinetic energy of radioactive particles. Thirty years later people eyed these reactions as a source of useful energy—energy to heat homes, to power tools, and to drive assembly lines. Scoffed at by some eminent physicists, nuclear power seemed at first an idle dream. The radiation emitted in most reactions carries little energy. The reactions themselves are not easily controlled and, in many cases, require more energy to induce than they release. Within a decade, however, fission and fusion reactions were discovered. Both produce enormous amounts of energy, more energy per kilogram of matter than had ever been imagined. The awesome release of this energy in atomic and hydrogen bombs converted the idle dreams into reality. Shortly after the first bombs, nuclear power plants were producing electrical energy. This final chapter turns to nuclear reactions and the risks and benefits we create as we reshape the landscape once more.

The energy released or absorbed in nuclear reactions arises from the different *binding energies* associated with each nucleus. Reactions that transform a loosely bound nucleus into a more tightly bound one release energy into the environment. Two processes, *nuclear fission* and *nuclear fusion,* accomplish this and release significant amounts of energy. Both processes are considered

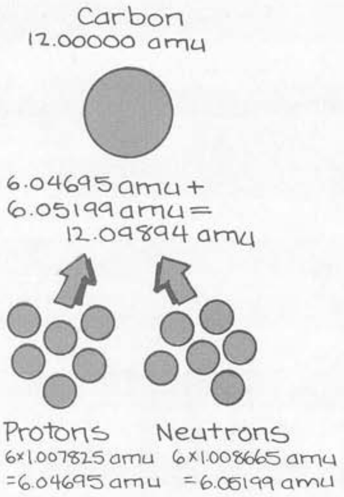


Figure 22-1

When nucleons combine to form a nucleus, the mass of the individual nucleons is greater than the final nucleus.

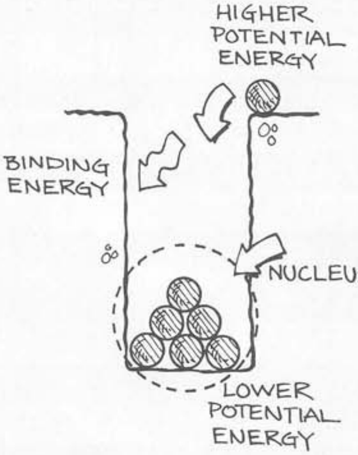


Figure 22-2

When a nucleon enters a nucleus, it gives up energy in a way that is similar to a rock falling in a well.

important alternative energy sources as the world's supply of fossil fuels dwindles. As the use of nuclear processes increases, the biological effects of alpha, beta, and gamma radiation becomes the subject of increasing interest.

BINDING ENERGY

If we compare the mass of a nucleus with the sum of the masses of its individual particles, we find that the two values do not agree. Figure 22-1 shows such a comparison for carbon. The carbon nucleus has a mass that is 0.098940 amu less than the sum of the masses of its six protons and six neutrons. There is a similar loss of mass, called **mass defect,** in all nuclei except hydrogen 1. We know that mass can disappear only by being changed into energy. When protons and neutrons combine to form a nucleus, some of their mass must be converted to energy and released. We now consider why this must happen.

Mass Decrease and Binding Energy

Since nucleons are attracted to one another by the strong nuclear interaction, energy must be supplied to pull them apart. If we were to pull a nucleon out of the nucleus, we would have to give it energy. A nucleon in a nucleus can be compared to a rock lying at the bottom of a well (Figure 22-2). The rock is attracted to the bottom by its gravitational interaction with the earth. To pull it out, we must supply it with some gravitational potential energy—the same amount it lost when it fell to the bottom of the well. A nucleus is a sort of "nuclear energy well." When nucleons bind to one another to form a nucleus, they fall into a nuclear well and lose some energy. To pull them out, we must supply the same amount of energy that they lost. This energy is called the *binding energy* of the nucleons.

The energy that a rock loses when it drops to the bottom of a well is determined by the strength of the gravitational interaction and by the depth of the well. Similarly, the energy that a nucleon loses when it binds to other nucleons is determined by the strength of the strong nuclear interaction and the distances between nucleons in the nucleus which is formed. Each kind of nucleus has a specific **binding energy**—the amount of energy lost when its nucleons came together. This is the same amount that would be needed to pull them apart.

When nucleons release binding energy, they experience a detectable loss of mass. This loss of mass, which is converted into energy, is the source of the mass defect of nuclei. The binding energy of a nucleus is related to its mass defect by the equation for mass-energy equivalence. For example, the mass defect of the carbon 12 nucleus is 0.098940 atomic mass units (amu), or 1.64×10^{-28} kilograms (kg). Its total binding energy is (mass defect) × (speed of light)^2 $= 1.48 \times 10^{-11}$ joules (J). Since carbon has 12 nucleons, the binding energy of each nucleon is $(1.48 \times 10^{-11}\text{ J})/12 = 1.2 \times 10^{-12}$ J. Each nucleon lost 1.2×10^{-12} J of energy when it united with the others to form carbon. We would have to supply that much energy to pull one nucleon free from a nucleus of carbon.

The Binding-Energy Curve

The total mass defect of the nucleus increases as we progress from lighter to heavier nuclei. We might guess that all nucleons lose about the same mass as they bind into a nucleus. Then, the mass defect would increase in proportion to the total number of nucleons. If this were correct, the carbon nucleus, with 12 nucleons, would have three times the mass defect as helium, with 4 nucleons. A quick check of the actual values for mass defects (Table 22-1) shows that this is not the case. The mass defect per nucleon for carbon is greater than the value for helium. We conclude that the binding energy of each nucleon varies from one nucleus to another.

Table 22-1 lists the mass defect per nucleon and the binding energy of each nucleon for a selection of nuclei. Both quantities increase rapidly from hydrogen 1 to nuclei with 40 to 50 nucleons and then remain fairly constant for nuclei of up to about 100 nucleons. From 100 nucleons on, the binding energy slowly decreases. This pattern, called the **binding-energy curve,** is illustrated graphically in Figure 22-3.

We can explain the binding-energy curve in terms of the attractive force within the nucleus. As the number of nucleons grows from 1 to about 50, so does the attractive force. With the increase in force the nucleons are pulled together more tightly. Thus the binding energy per nucleon increases. As the nuclei get very large, however, the repulsive electrical forces between protons become more important. This repulsive force adds as a vector to the attractive nuclear force, thus decreasing the net force on the nucleons. Thus the energy needed to pull a nucleon from a large nucleus is less than for smaller nuclei. The binding energy per nucleon decreases as the nuclei become very large.

Table 22-1 Mass Defect/Binding Energy Per Nucleon

Nucleus	Mass Defect (amu)	Number of Nucleons	Mass Defect per Nucleon (amu)	Binding Energy per Nucleon (J)
Hydrogen 1	0	1	0	0
Hydrogen 2	0.002388	2	0.001194	1.7796×10^{-13}
Hydrogen 3	0.008556	3	0.002854	4.2508×10^{-13}
Helium 3	0.007195	3	0.002398	3.5746×10^{-13}
Helium 4	0.030376	4	0.007594	11.318×10^{-13}
Lithium 7	0.042130	7	0.006019	8.9710×10^{-13}
Carbon 12	0.098940	12	0.008245	12.2888×10^{-13}
Nitrogen 14	0.112356	14	0.008025	11.9972×10^{-13}
Oxygen 16	0.137005	16	0.008563	12.8008×10^{-13}
Magnesium 24	0.206295	24	0.008596	12.8114×10^{-13}
Argon 40	0.359287	40	0.008982	13.3875×10^{-13}
Vanadium 51	0.466097	51	0.008147	13.0370×10^{-13}
Chromium 52	0.47683	52	0.009170	13.6674×10^{-13}
Iron 56	0.514291	56	0.0091838	13.6880×10^{-13}
Nickel 58	0.52844	58	0.009111	13.5780×10^{-13}
Germanium 72	0.65748	72	0.009132	13.6103×10^{-13}
Zirconium 90	0.81742	90	0.009108	13.5754×10^{-13}
Cadmium 114	1.01797	114	0.008929	13.3091×10^{-13}
Neodymium 142	1.2396	142	0.008730	13.0110×10^{-13}
Hafnium 180	1.519	180	0.008440	12.5794×10^{-13}
Lead 208	1.7121	208	0.008231	12.2683×10^{-13}
Radon 222	1.8351	222	0.008266	12.3571×10^{-13}
Radium 226	1.8590	226	0.008226	12.2963×10^{-13}
Uranium 238	1.884	238	0.007916	11.7988×10^{-13}
Fermium 253	1.9686	253	0.007781	11.5970×10^{-13}

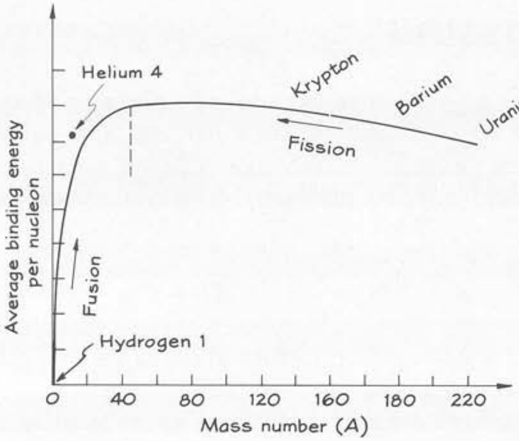


Figure 22-3

The binding energy per nucleon increases rapidly, reaches a peak and then gradually decreases. Fusion describes the process by which we combine lighter nuclei to form heavier nuclei. Fission describes the process by which we split heavier nuclei into light ones. Both processes move nuclei up the binding energy curve—from loosely bound nuclei to more tightly bound ones. Thus energy is released to the environment in both cases.

Binding Energy and Nuclear Reactions

The energy released when a nucleus is formed depends on the binding energy of the nucleus. A nucleus that is tightly bound releases more energy when formed than a nucleus that is less tightly bound. Thus a nuclear transformation that converts a loosely bound nucleus into a tightly bound one releases energy into the environment. We have already seen examples of this type of transformation in our study of radioactivity. When radium changes into radon and an alpha particle, it is changing from a nucleus with a total binding energy of $226 \times (12.2963 \times 10^{-13})\ \text{J} = 2.779 \times 10^{-10}\ \text{J}$ to nuclei with binding energies of $2.743 \times 10^{-10}\ \text{J} + 0.045 \times 10^{-10}\ \text{J} = 2.788 \times 10^{-10}\ \text{J}$. Because the products are bound more tightly, some energy is released in the transformation.

The energy released in radioactive decay is very small because it involves the rearrangement or removal of a small number of nucleons. The new nucleus has only a slightly different binding energy than the original one. But suppose a very heavy nucleus could be split into large fragments forming nuclei in the middle of the binding-energy curve. Or, suppose several very light nuclei combine to form a nucleus in the middle of the binding-energy curve. Both processes occur and release large amounts of energy. The former is called *fission;* the latter, *fusion.*

SELF-CHECK 22A

Can two hydrogen 2 nuclei (mass of each = 2.013553 amu) combine to create one helium 4 (mass = 4.001506 amu) and release energy?

NUCLEAR FISSION

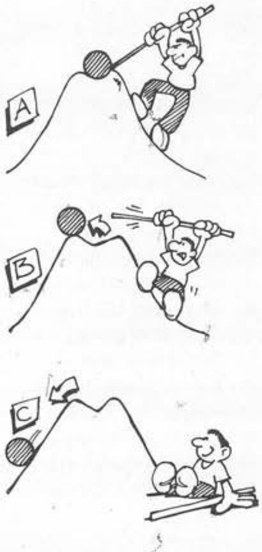


Figure 22-4

Nuclear fission is in some ways like pushing a ball out of a rut at the top of a hill. A small amount of energy invested in the push allows the release of a much larger amount of energy.

One way to create a radioactive isotope is to place an element in front of a beam of neutrons. A nucleus absorbs a neutron and becomes an unstable isotope, which then decays. For example, when a neutron is absorbed by a nitrogen 15 nucleus, it forms nitrogen 16, which undergoes beta decay to become oxygen 16.

$$^{1}_{0}n + {}^{15}_{7}\mathrm{N} \rightarrow {}^{16}_{7}\mathrm{N} \rightarrow {}^{16}_{8}\mathrm{O} + {}^{0}_{-1}e + \bar{\nu}_e$$

The net result of this and other transformations is that an element is changed into the next higher one in the periodic table.

In the 1930s, Enrico Fermi conducted an exhaustive study of neutron absorption of the various elements. At the time these experiments were conducted, uranium was the last known element in the periodic table. Intrigued with the idea of creating the element with an atomic number one greater than uranium—an entirely new chemical element—Fermi bombarded uranium nuclei with neutrons. In some cases the results were what Fermi expected, but in others nuclei with much smaller masses—nuclei of known elements—were the products of his experiments. Fermi had stumbled across the process of nuclear fission.

Nuclei Split into Smaller Fragments

The process by which massive nuclei split apart to form less massive nuclei is called **nuclear fission.** The most common fission reaction involves isotopes of uranium and plutonium. One example is uranium 236, an unstable nucleus that does not exist naturally. When we manufacture it, we find that it spontaneously transforms into isotopes of much less massive nuclei within 10^{-12} seconds (s). While the uranium 236 can split in many different ways, a common breakup is into barium, krypton, and three neutrons.

$$^{236}_{92}\mathrm{U} \rightarrow {}^{142}_{56}\mathrm{Ba} + {}^{91}_{36}\mathrm{Kr} + {}^{1}_{0}n + {}^{1}_{0}n + {}^{1}_{0}n$$

$$\begin{aligned}(236.045563\ \text{amu}) = (141.912205\ \text{amu}) &+ (90.91891\ \text{amu})\\ &+ (3 \times 1.008665\ \text{amu}) + \text{energy}\end{aligned}$$

This fission releases 2.8×10^{-11} J of energy because uranium 236 is much less tightly bound than the product nuclei, barium 142 and krypton 91.

The fission process involves two fundamental interactions—the strong nuclear and the electrical. Within the nucleus, the strong nuclear force dominates. In order for fission to occur, something must pull the nucleons far enough apart that the strong nuclear attractive force becomes less than the electrical repulsion of the protons. Then the nucleus can split. In some respects this situation is analogous to a ball sitting in a small rut at the top of a hill (Figure 22-4). The ball is quite stable; it will not move unless it receives a small push. Once pushed, the ball rolls all the way down the hill. By adding a small amount of energy to get it started, we enable the ball to give up much more energy when it reaches the bottom. Similarly, adding a little energy to the

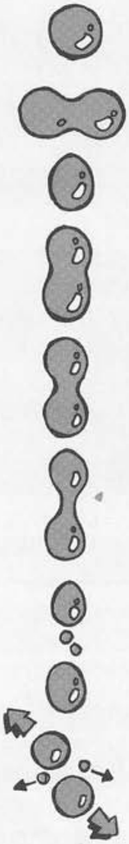


Figure 22-5

By supplying external energy, we can make a spherical drop of water vibrate so that it splits into two spherical fragments and several tiny droplets.

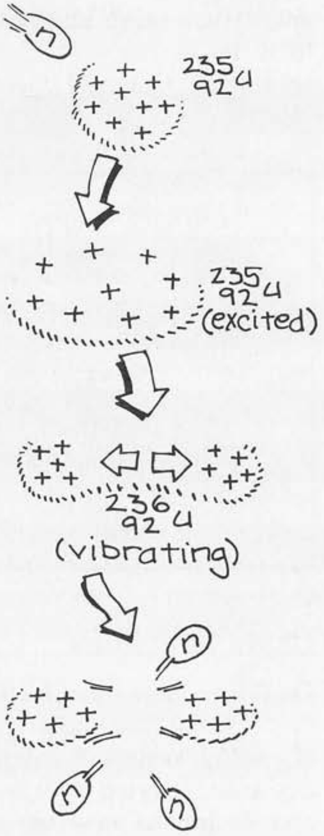


Figure 22-6

A neutron strikes the uranium 235 nucleus, transforming it to uranium 236 in an excited state. After a sequence of vibrations, the uranium 236 nucleus fissions to produce two smaller nuclei and three free neutrons.

nucleus—"pushing" it with the addition of a neutron—enables it to release much more energy in the process of fission.

We can describe the push that initiates a fission reaction by comparing a nucleus with a drop of liquid. The uranium 236 nucleus in its lowest energy state is much like a spherical drop of water. Strong nuclear forces bind the nucleus together in as small a space as possible. If we provide a drop of water with energy by flicking it with a finger, we can make it vibrate (Figure 22-5). If the vibrations match a natural frequency of the liquid drop, they become so large that the drop splits into two spherical fragments and a few tiny droplets. We imagine that much the same process occurs with the nucleus. If the massive nucleus is supplied with a small push, it begins to vibrate. As the vibrations increase, the fragments pull farther and farther apart. Finally, the repulsive electrical force exceeds the attractive nuclear force, and the nucleus splits into two fragments and several neutrons.

How do we push a uranium 236 nucleus? By producing it. If we force a neutron into a nucleus of uranium 235, we can convert uranium 235 into uranium 236. As the neutron is absorbed, it carries enough energy to excite the newly created uranium 236. Once excited, this nucleus can undergo fission. The entire process by which uranium 235 leads to fission is illustrated in Figure 22-6.

The energy released by one fission reaction seems quite small. However, it is about 10^8 times the energy released in a single chemical reaction, such as one carbon atom combining with two oxygen atoms in the burning of fossil fuels. In comparison with other energy-releasing methods, fission provides an enormous amount of energy per reaction.

SELF-CHECK 22B

Another fission reaction involving uranium 236 is:

$$ {}^{1}_{0}n + {}^{235}_{92}\mathrm{U} \rightarrow {}^{236}_{92}\mathrm{U} \rightarrow {}^{90}_{38}\mathrm{Sr} + {}^{135}_{54}\mathrm{Xe} + 10\,{}^{1}_{0}n $$

$$ \begin{aligned} (1.0087\text{ amu}) + (235.0439\text{ amu}) &= (89.9073\text{ amu}) \\ &\quad + (135.9072\text{ amu}) + (10.0867\text{ amu}) + \text{energy} \end{aligned} $$

How much mass is converted to energy? How does the energy released in this transformation compare with that released in the transformation that produces barium 142 and krypton 91?

Chain Reactions

On the average three neutrons are released by each fission reaction. The destiny of these three neutrons determines whether the result is an isolated burst of energy, sustained energy production, or an explosion. The three possibilities are illustrated in Figure 22-7.

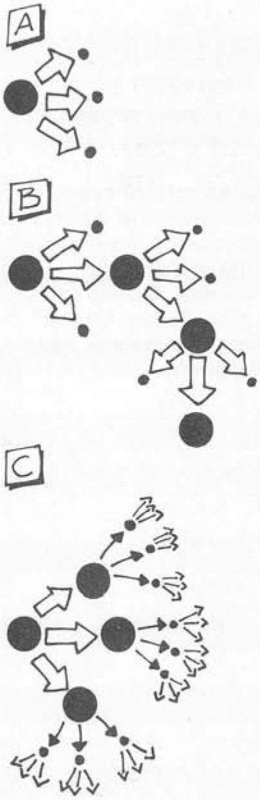


Figure 22-7

Three possibilities exist for the neutrons released from a fission event. **(a)** When no neutrons are absorbed by other uranium 235 nuclei, the reaction stops. **(b)** When one neutron is absorbed by another uranium 235 nucleus, a sustained chain reaction occurs. **(c)** When two or three neutrons are absorbed by other uranium 235 nuclei, an uncontrolled chain reaction occurs.

In (a) the neutrons are simply lost or absorbed by nuclei other than uranium 235. No further fission occurs. In (b) one of the neutrons released by each fission reaction is absorbed by a uranium 235 nucleus. This absorption creates another fission, which produces three neutrons, one of which is absorbed by another uranium 235 nucleus, and so forth. Fission continues at a constant rate. Finally, in (c) two or three of the neutrons released by each fission reaction is absorbed by uranium 235 nuclei. Each fission reaction creates more than one fission reaction and the process grows exponentially. An isolated fission event, such as that shown in (a), provides us with valuable insights into the structure of the nucleus, but it does not give us a useful quantity of energy. **Chain reactions** provide us with enormous amounts of energy, controlled in one case (b) and uncontrolled in the other (c).

The absorption of one neutron per fission event assures us of a sustained chain reaction in which each fission event leads to only one other fission event. Fission proceeds at a constant rate until all the uranium 235 is used up. We can use the energy released to drive electric generators.

The absorption of more than one neutron per fission results in an uncontrolled chain reaction. One neutron initiates one fission event, which produces three neutrons that initiate three fission events, which produces nine neutrons that initiate nine events, and so forth. The progression is 1; 3; 9; 27; 81; 243; . . . . The number of fission events very quickly becomes enormous, and a devastating quantity of energy is released, as documented by the atomic bombs dropped on Nagasaki and Hiroshima, Japan, in 1945.

Which of these processes occurs depends primarily on the number of uranium 235 nuclei near the fission event. Natural uranium consists of 0.7% uranium 235 and more than 99% uranium 238. This concentration of uranium 235 is not sufficient to produce a chain reaction. But, if we artificially increase the fraction of the uranium 235 to 3% of the total, an average of one neutron released by each fission will be absorbed by another uranium 235 nucleus. A sustained reaction will occur. If we increase the fraction of uranium 235 to 97%, almost all the released neutrons will be absorbed by uranium 235 nuclei. The number of fission reactions will grow exponentially, and an uncontrolled chain reaction will occur. Thus the ratio of material that can undergo fission to material that cannot determines the outcome of a fission event.

Even if the material contains 97% uranium 235, it may not explode. If it contains a very large surface area, the material may allow many of its neutrons to escape from it without encountering another uranium 235 nucleus. Designers of fission weapons use this factor. Masses of 97% uranium 235 are constructed to have a shape and density that allow most of their neutrons to escape. These masses are placed in close proximity. To cause an explosion, they are driven together by ordinary explosives such as TNT. Then, the shape, mass, and density of the uranium 235 reaches the place where an explosion occurs. The uranium 235 is said to have reached a **critical mass.**

SELF-CHECK 22C

Describe the progression of fission events if only two neutrons from each fission are absorbed by uranium 235 nuclei.

Fission Reactors

Today, more than 20% of our electrical energy is generated by nuclear **fission reactors.** As shown in Figure 22-8, the design and operation of these

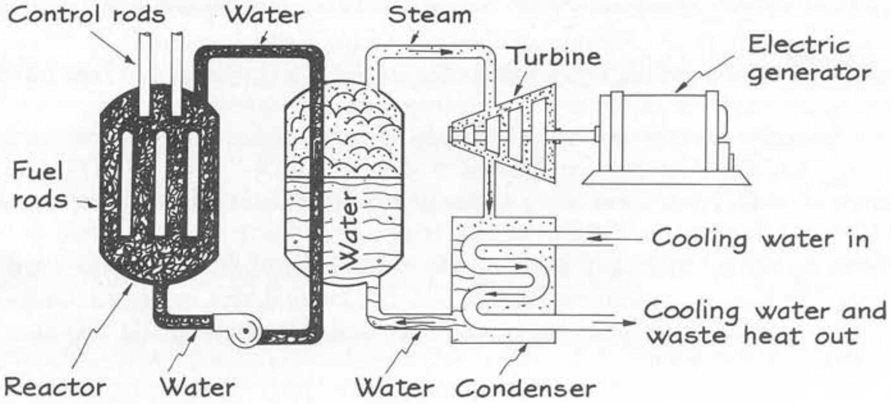


Figure 22-8
A schematic view of a typical fission reactor.

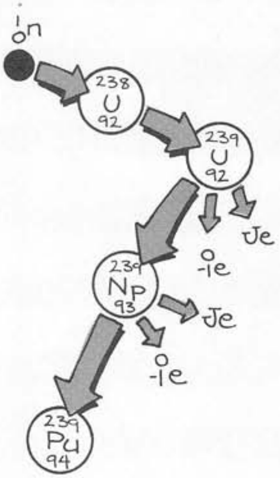


Figure 22-9

In breeder reactors, uranium 238 goes through a series of decays to produce plutonium 239, a fissionable nucleus.

generating plants are very similar to that of fossil fuel plants. Both use thermal energy to produce steam; the difference is the process used to produce the thermal energy. Fossil fuels are replaced by fission reactors. Chemical potential energy is replaced by nuclear potential energy.

The reactor itself contains three components: the nuclear fuel, the control rods, and water used to transfer the thermal energy from the reactor to the generator. The nuclear fuel consists of uranium in which the fraction of uranium 235 has been artificially increased to 3%. The control rods are made of a material that readily absorbs neutrons and does not undergo fission. They are used to control the number of neutrons by absorbing and removing some of them from the fuel. Water, which surrounds the nuclear fuel, absorbs the thermal energy generated by the fission process. This heated water transfers its thermal energy to a second water system and then returns to the fuel elements. The second water system operates the electrical generator in a conventional fashion. (Two isolated water systems are required because the water circulated near the nuclear fuel can become radioactive.)

Because only 0.7% of natural uranium is uranium 235, this isotope must be considered a very limited resource, like gas, coal, and oil. If we were to rely strictly on uranium 235 reactors for production of electrical power, we would very quickly end up in the same position with respect to fission fuel as we are with fossil fuels. Therefore, another fission process, using the more abundant uranium 238 isotope, is being developed as a commercial energy source. Called a **breeder reaction,** this process transforms uranium 238 into plutonium 239, which undergoes fission when it absorbs a neutron (Figure 22-9).

The fission of plutonium provides both the nuclear energy for heating the water system and neutrons needed to turn uranium 238 into plutonium 239. This process breeds its own fuel. To create the plutonium 239, some of the uranium 238 must be placed near a source of a large number of neutrons. The most abundant source today is a nuclear reactor. When uranium 238 is placed in a nuclear reactor, it absorbs neutrons, and plutonium is produced. This is the basic idea of the breeder reactor.

The design of a breeder reactor involves two regions. In the first, fission of either uranium or plutonium is taking place. Energy released in these fission processes is used to produce electricity. Surrounding the energy-producing area is a supply of uranium 238. As neutrons leave the fission area, they are absorbed by uranium 238 nuclei. The plutonium that is produced by this process is taken to a special processing plant, where it is chemically separated and turned into fuel for the energy-producing part of a reactor.

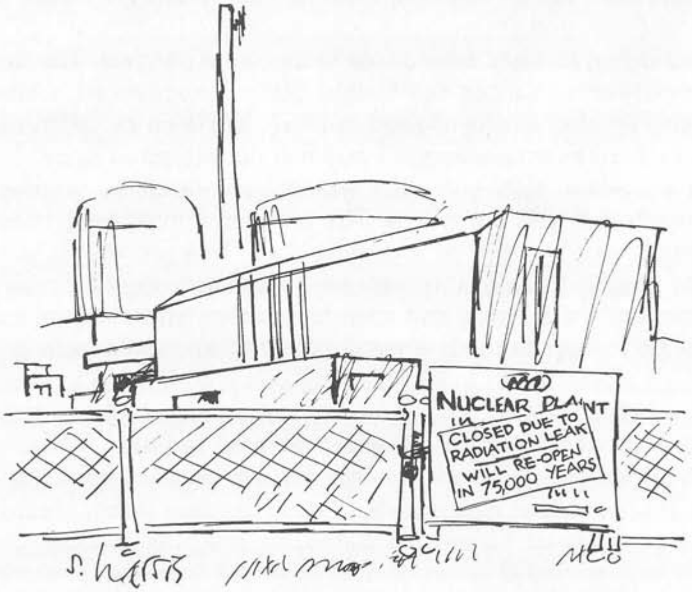
Breeder reactors hold the promise of being a seemingly inexhaustible energy source. The nuclear fissions in these reactors produce 100 million times as much energy per atom as the chemical reactions involved in burning coal or oil. In addition, if they become commercially cost-effective, they would create more fuel than they use. In spite of this overwhelming step forward in energy technology, fission reactors of all kinds come under heavy criticism. To see why, we must consider the advantages and disadvantages of this energy process.

Benefits and Risks of Fission Reactors

Fission reactors have two major advantages: availability of fuel and absence of chemical pollutants. The energy source for fission reactors is not a fossil fuel and, at present, does not come from foreign sources. Uranium is mined and processed within the United States, and the breeder process makes use of the abundant isotope uranium 238. Because they use nuclear rather than chemical processes, fission reactors do not release the chemical pollutants that are so objectionable in burning fossil fuels. In this respect, nuclear fission reactors are much cleaner than conventional power plants.

The major disadvantage of fission reactors is the radioactive material they produce. The neutrons released from the fission reactions interact with all parts of the reactor, producing a variety of nuclear transformations. The radioactive byproducts of these reactions range from probably harmless to lethal. Reactors are built with thick concrete and steel walls to absorb the radioactive emissions. These designs are so effective that the environmental radiation surrounding a nuclear fission plant is, in fact, less than that surrounding a coal-burning plant. (Coal contains minute quantities of radioactive material.) Because the fuel contains only 3% uranium 235, it cannot become an atomic bomb, which could cause vast destruction and harmful radiation. The issue, then, is not proper shielding from the nuclear pollutants or nuclear explosions. The major concerns are long-term storage of the radioactive waste products and protection against accidents and sabotage.

Every few years the uranium 235 in the reactor fuel is depleted to the point where it will not sustain a chain reaction. The material left in the fuel elements includes cesium 137 and strontium 90 as well as isotopes of plutonium and uranium. These products are highly radioactive and dangerous to living things. The huge quantities involved, the dangers in their radioactive emissions, and their relatively long half-lives mean that we must find places to



store the waste products for more than 10,000 years. Storage sites must be geologically stable (no earthquakes for at least 10,000 years) and must be isolated from any ground water.

Some studies have proposed salt mines in the southwestern United States, which seem to meet both these criteria. If these sites prove satisfactory, then highly radioactive material must be transported there from all over the country. Of course, traffic accidents must be avoided. Further, residents of the region must be convinced that no harm will come to them or their environment from storage of the radioactive wastes. Finally, we as a society must answer the question of who will watch over these materials for the next 10,000 years—a time much longer than any civilization has survived on this planet.

Storage is a long-range problem; a more immediate problem is accidents. Reactors are complex mechanical and electronic machines—things can and do go wrong. One of the most serious possible accidents is called *loss of coolant*. In this situation, the cooling water does not circulate and cool the fuel. Heat builds up rapidly and, if the situation is not corrected, the fuel becomes hot enough to melt metal. The floor of the building in which the fuel is contained could melt, and radioactive material could escape. In the worst situation the extremely hot material would melt through the rock below the reactor until it hit water. The water would turn to steam and move upward into the air, carrying radioactive materials with it. Large areas of land could be covered with a dangerous radioactive material.

The worst possible accident has not occurred, but some very serious ones have. The most well-known incident occurred at the Three-Mile Island Reactor in Pennsylvania, where malfunctioning equipment caused a loss of coolant. The reactor fuel became extremely hot. For several days a complete meltdown of the reactor was possible. Finally, the fuel was cooled sufficiently that it would not melt through the building floor. However, in the process the reactor was destroyed.

Breeder reactors are susceptible to the same dangers. The first commercial breeder reactor built in the United States experienced a loss-of-coolant accident shortly after it was opened in 1967. While no radiation escaped, the reactor was permanently damaged and has not operated since.

The abundant plutonium that would be created by large-scale use of breeder reactors is also a concern. The plutonium must be processed chemically before it can be used as a nuclear fuel. This processing would require large-scale plants. Such plants can be built; however, two problems exist. First, plutonium is very toxic and must be handled with extreme care to avoid accidental poisoning. Second, a small group of knowledgeable people could steal enough plutonium to build a nuclear weapon. If large amounts of plutonium were being shipped from breeder to processing plants and back, the possibility of an accident or theft would increase greatly.

Nuclear fission can supply energy for our future. It is doing so successfully now. Proponents of fission fuels point to the past safety record of nuclear power plants. Even at Three-Mile Island, no one was seriously injured. The risks, they say, are small when compared to the benefits. The critics, on the other hand, state that one serious accident or theft of fuel could be devastating. They feel that the risks are much too great for the benefits received. As with all technological advances, this one has both advantages and disadvantages. The disadvantages always lead us to look for new solutions.

NUCLEAR FUSION

The sun releases some 240×10^{26} J of energy each minute, more energy than can be explained in terms of the energy released in ordinary chemical reactions. Ninety-nine percent of the sun's mass is hydrogen and helium. A look at the binding-energy curve (Figure 22-3) tells us what process must be involved in this enormous output of energy.

The binding energy per nucleon increases from hydrogen until it reaches a peak around iron, nickel, and cobalt. It then levels off and gradually decreases. The largest change in binding energies occurs as we move from hydrogen and its isotopes to helium 4. The binding energy of helium 4 is more than six times that of hydrogen 2. Thus, when hydrogen nuclei combine to make helium, large amounts of energy can be released.

Nuclei Combine into Heavier Elements

The process by which lighter nuclei join together to form heavier nuclei and release energy is called **nuclear fusion.** A combination of experimental and theoretical work has identified several fusion reactions that occur with lighter elements.

The most common fusion process begins with four hydrogen 1 nuclei and eventually transforms them into a helium 4 nucleus. (Since helium has only two protons and four hydrogens have four, two of the protons transform into neutrons. Two positively charged particles, called positrons, are also created. The positron is identical to an electron except that it has a positive charge. Its symbol is ${}^{0}_{+1}e$.) The hydrogen-to-helium fusion reaction is:

$$
\begin{aligned}
{}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} &\rightarrow {}^{4}_{2}\mathrm{He} + {}^{0}_{+1}e + {}^{0}_{+1}e \\
4.03130\ \text{amu} &= 4.00260\ \text{amu} + 0.000549\ \text{amu} \\
&\quad + 0.000549\ \text{amu} + \text{energy}
\end{aligned}
$$

The total mass of the four hydrogen nuclei is 4.03130 amu. The total mass of the helium nucleus and the two positrons is 4.003698 amu. A total of 0.027602 amu has been converted into energy—4.12×10^{-12} J. This energy arises from the large difference in binding energies in the nuclei.

Fusion does not normally occur on earth because of the electrical repulsion between the positively charged hydrogen nuclei. At a separation distance of more than 10^{-12} meters (m), the attractive nuclear interaction is essentially zero and the repulsive electrical interaction is dominant. To overcome this force, the hydrogen nuclei must have sufficient kinetic energy to move within 10^{-13} m where the nuclear attraction overwhelms the electrical repulsion.

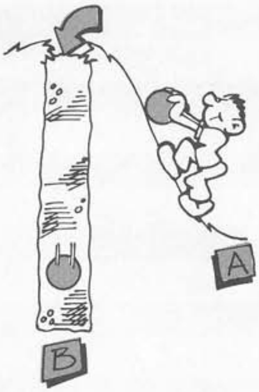


Figure 22-10

Nuclear fusion in some ways is like a ball that must roll uphill in order to fall into a well. Though the ball's gravitational potential energy at position A is greater than at B, the ball will not move until we give it a push.

This situation is somewhat analogous to rolling a ball into a deep well when the well is located at the top of a hill (Figure 22-10). Sitting at the bottom of the hill, the ball has a greater gravitational potential energy than it would have if it were at the bottom of the well. To reach the bottom of the well, however, the ball has to gain additional gravitational potential energy. Giving the ball a push can provide it with enough kinetic energy to reach the top of the hill and drop into the well. When it reaches the well bottom, it converts to other energy forms both the difference in gravitational potential energy between its starting point and the bottom of the well and the kinetic energy we gave it. Once the ball is located at the bottom of the well, it requires a lot of energy to get it out. The ball has given up energy and is more tightly bound than it was at the start.

When two hydrogen nuclei try to fuse, the hill they must overcome is the electrical repulsion between the two positive charges. To overcome this barrier, a hydrogen nucleus must be moving at a speed of about 10^5 m/s. When an environment produces hydrogen nuclei at these speeds, fusion will occur.

Fusion reactions have been produced on a small scale by accelerating hydrogen nuclei to the proper speed and then hurling them at targets of matter. While this process does produce fusion and provides knowledge about the process, it delivers much less energy than is required to accelerate the hydrogen. On a much larger scale, the huge temperatures and pressures in the sun sustain fusion reactions, which provide us with our solar energy.

On earth, large-scale fusion energy is produced in the hydrogen bomb. For a fusion bomb to explode, the hydrogen nuclei must move toward one another very rapidly. This motion is accomplished by surrounding the hydrogen with another bomb, usually a fission weapon. When the external bomb explodes on all sides at once, it drives inward (implodes) the hydrogen nuclei. The nuclei meet in the middle while traveling at tremendous speeds, and many fusion events occur so rapidly that a violent explosion occurs. Though the energy production is enormous in this case, it is so fast that it is uncontrollable and, except as a military threat, useless to us.

SELF-CHECK 22D

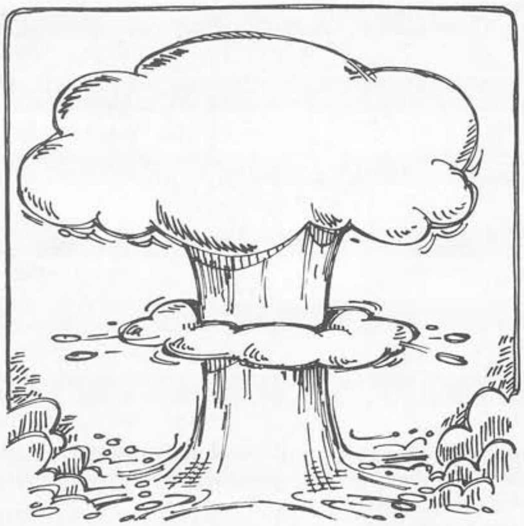
A second fusion reaction that has been observed involves deuterium (hydrogen 2):

$$ {}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} + 0.64 \times 10^{-13}\ \mathrm{J} $$

$$ 2.013553\ \text{amu} + 2.013553\ \text{amu} = 3.016050\ \text{amu} + 1.007276\ \text{amu} + \text{energy} $$

Explain why less energy is released in such a reaction than in the fusion of four hydrogen 1 nuclei.

THE BOMB



When Enrico Fermi first created a nuclear fission, he did not realize that he had done so. He knew that he had produced a new nucleus but did not know what it was. In 1938 two German chemists, Otto Hahn and Fritz Strassman, separated barium in the products of an experiment in which uranium had absorbed a neutron. They communicated their results to Lise Meitner, who had fled Germany and was working with Niels Bohr in Copenhagen. She analyzed the results and realized that the energy released in a single transformation was enormous compared to any other interaction. Soon afterward, Bohr came to the United States and discussed these conclusions with Fermi, Einstein, and others. At the urging of Leo Szilard, Einstein wrote a letter to President Franklin Roosevelt in which he stated "... it may become possible to set up a nuclear chain reaction in a large mass of uranium by which vast amounts of power ... would be generated." While Einstein was a pacificist, he was very concerned about what would happen if Hitler used this type of energy. Thus he described to Roosevelt the possibility that a fission bomb could be created.

This letter began one of the most concentrated efforts in the history of science and technology. When it was completed, two nuclear bombs had been dropped on Japan and had ended World War II. Since that time "the bomb" has become a part of our lives. We can only hope that, some day, people will learn better ways to discuss their differences than by threatening wholesale destruction. Maybe, then, the bomb will be as useless as some of the inventions we have described in this book.

Fusion Reactors

Nuclear fusion devices that produce energy in a controllable manner are called **fusion reactors.** Their design must deal with two related difficulties: temperature and containment. To drive the nuclei close enough to initiate fusion, we must heat the hydrogen nuclei to temperatures of about 10^8 K. Once at that temperature, the hydrogen nuclei must be contained. Unfortunately, all known materials melt at temperatures far below that required for fusion, so containment of the material must be accomplished by other than traditional methods. While physicists and engineers are studying several processes, they are currently devoting much attention to two of them: magnetic containment and laser-induced fusion.

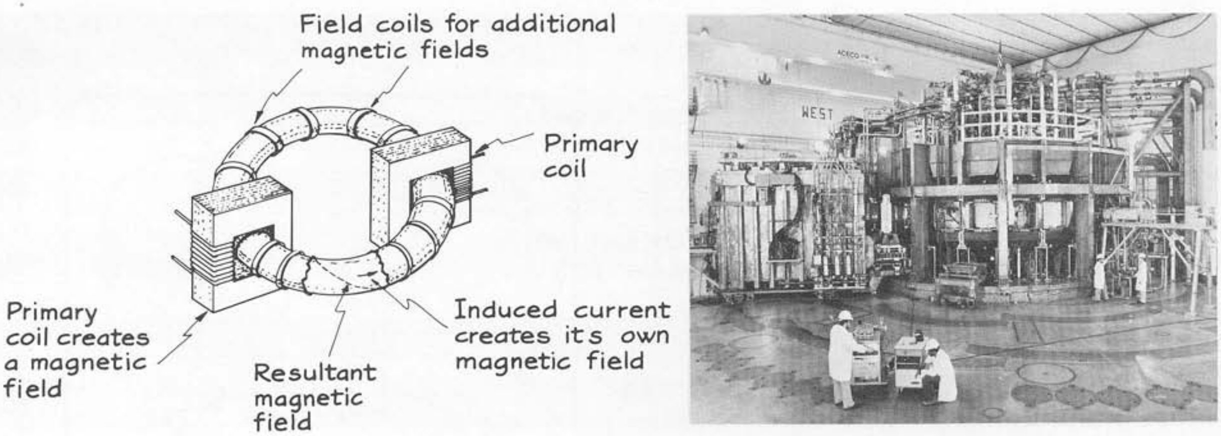


Figure 22-11

One magnetic confinement system, the tokamak, uses several magnetic fields. The field from the primary coil induces a current in the plasma. In turn, the plasma produces a magnetic field. All fields combine to produce a spiral field that contains the charged nuclei.

Magnetic containment takes advantage of the electrically charged nature of material at very high temperatures. Material raised far above its boiling point moves into a fourth state of matter, the plasma state. In a plasma all the electrons have been stripped from their nuclei, and the material is a swarm of positively charged nuclei and free electrons. Because a magnetic field deflects charged particles, it should be able to confine the electrically charged plasma.

Very complicated magnetic fields, which are created by a careful arrangement of current-carrying wires plus the magnetic field of the plasma itself (Figure 22-11), are arranged so that the charged particles always feel a force toward the inside of the plasma. Such a containment device is integrated into an electrical generating plant as illustrated in Figure 22-12. The intense heat generated by fusion is first absorbed by potassium and used to drive one generator, then transferred to water and used to drive a steam generator. This entire process is still under development.

Laser-induced fusion begins not with a very hot plasma, but with frozen hydrogen isotopes, hydrogen 2 and hydrogen 3. A pellet of the frozen material is placed in the path of a very intense laser beam. The laser light is directed toward the pellet equally from all directions. The amount of energy transferred to the pellet is enough to vaporize the surface layer of the hydrogen

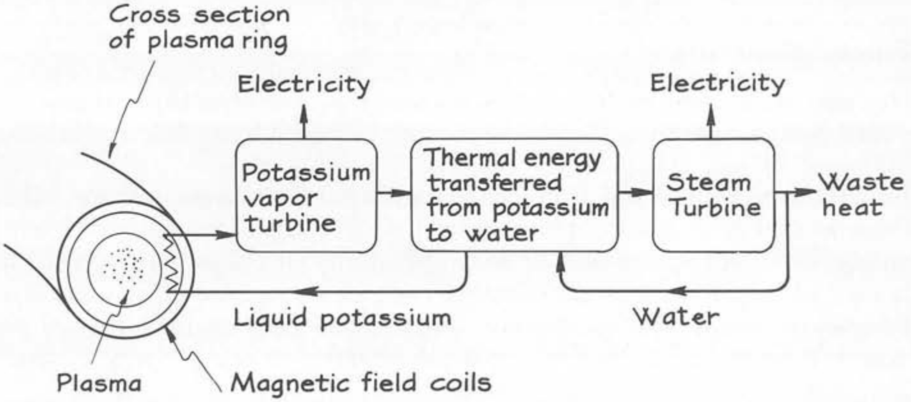


Figure 22-12

A possible magnetic confinement electrical generating system.

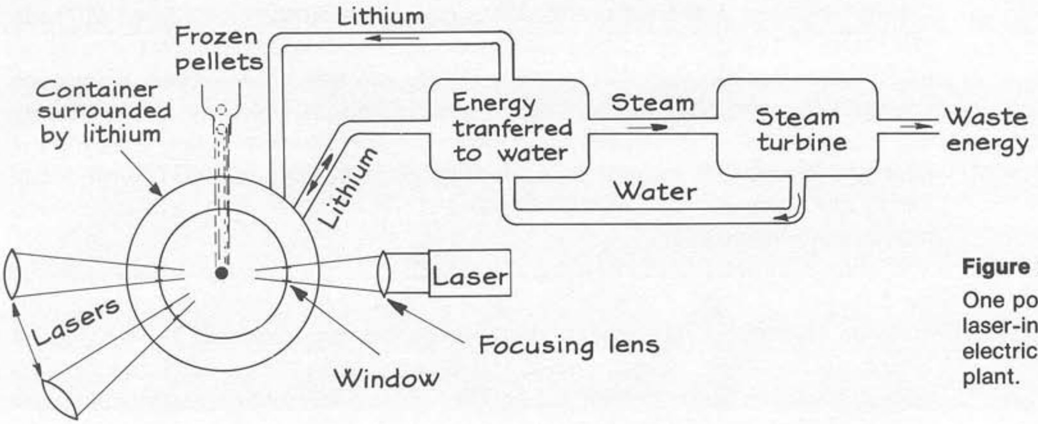


Figure 22-13
One possibility for a laser-induced fusion electrical generating plant.

isotopes. This sudden vaporization creates a shock wave that causes an implosion as it travels toward the center. As the pellet collapses in upon itself, the temperature of the isotopes rises to 10^8 K and fusion begins. A proposed power plant based on this idea is shown in Figure 22-13. Because of the range of temperatures involved, this process is sometimes called the "snowball-in-hell" approach to energy generation. This process, too, is still in the experimental stage.

Risks and Benefits of Controlled Fusion

In discussions of fusion reactors two concepts—scientific break-even and thermodynamic break-even—are frequently mentioned. These terms refer to breaking even on energy. A **scientific break-even** is reached when the

energy released in the fusion reactions equals the energy consumed in creating them. Since the efficiency of converting the released nuclear energy to useful energy is necessarily less than 100%, scientific break-even is not good enough. We need **thermodynamic break-even,** in which the useful energy (for example, electrical energy) derived from the fusion reaction exceeds the energy consumed in creating it. Both magnetic containment and laser-induced fusion are approaching scientific break-even but are far from achieving thermodynamic break-even.

The magnetic fields needed to maintain magnetic containment must be very large. To keep them large, the electrical current to the primary coils must be enormous. At present, this electrical energy exceeds the energy released by the fusion. Additionally, the plasma leaks. Soon after the process begins, particles begin to leak out and the plasma current gradually collapses. New designs are needed to overcome this leakage.

The lasers required for laser-induced fusion are not ordinary grocery-store scanning lasers. They must produce large beams capable of reaching a power output of 10^{14} watts. One such laser, called SHIVA, has been built, but the energy consumed to produce its beam is far greater than the energy output of the beam.

Once these technical difficulties are overcome, then the advantages and disadvantages of fusion reactors are derived from comparisons with conventional power plants. Questions of fuel, efficiency, and safety become paramount.

One of the primary advantages of fusion reactors will be the cost and availability of fuel. The essential fuel in most fusion reactors, hydrogen 2 (deuterium), is found in ordinary water. The amount of deuterium in ocean water will produce one billion times the energy stored in the world's fossil fuel energy reserves. And, it is relatively inexpensive to separate.

Compared to fossil fuel power plants, fusion reactors should be much more efficient. The Carnot efficiency of a system increases as the difference between its high and low temperature increases (Chapter 12). Fusion reactors, because of their high operating temperatures, should be more efficient than the 35% efficiency of a typical conventional power plant. However, we have yet to learn how to handle large quantities of materials at these enormously high temperatures.

The most prevalent disadvantage of fusion reactors is the radiation that will accompany the reactions. The fusion of deuterium into helium releases neutrons, which interact with the walls and other reactor components to create other transformations. As components of the reactor need to be replaced, storage of large quantities of radioactive materials becomes a problem. In addition, the fusion process produces hydrogen 3 (tritium). Tritium is naturally radioactive, emitting low-energy electrons and antineutrinos. Outside the body, these radiations are not particularly harmful, but when they are generated inside our bodies, they can be dangerous. Since tritium can replace hydrogen in water and food, it must be handled extremely carefully. Any contamination of drinking water with tritium could be a very serious matter.

Fusion reactors are still decades away, but researchers are optimistic. Once the technology is mastered, a demonstration plant must be built and operated successfully. Only then will fusion reactors be built on any large scale. The most optimistic scientists predict that we will not see a commercial nuclear fusion power plant until the second or third decade of the 21st century.

NUCLEAR RADIATION AND THE HUMAN BODY

Until rather recently, post-World War II, our knowledge of the effects of radiation on the human body was meager at best. Early scientists had noticed the direct effects—severe burns on their hands as a result of handling radioactive materials. In most cases, however, the burns healed quite normally. Marie Curie and her daughter, Irene, both of whom performed many experiments with radioactive materials, died from leukemia. While we cannot be certain that their diseases were induced by their unusually large exposures to radiation, we know from experiments that there is a direct link between blood and bone disorders and unusually large radiation doses.

Victims of the Nagasaki and Hiroshima bombings have provided us with information on the effects of massive radiation on a large population. The people nearest the explosion suffered burns and tissue damage primarily related to the amount of energy released by the explosion. The same fatal effect would have resulted from an equivalent release of energy by a nonnuclear explosion. Survivors far from the blast had few immediate symptoms. Over many years, however, they showed patterns of illnesses that unveiled long-term internal damage done by nuclear radiation. In addition, they bore an unusually large number of deformed children, showing that their genetic material had been damaged by radiation.

Radioactive products interact with living tissue through two processes: direct collisions and electrical interactions. Neutrons and gamma rays carry no electrical charge and consequently interact with the atoms in our bodies via direct collisions. Through these collisions, they transfer energy to the electrons and often knock them free from their atoms. Because the electrons hold atoms together in molecules, these collisions can alter the molecular structure of millions of molecules in living cells. Alpha and beta particles both carry electric charge. They do not need to collide directly with atoms in order to interact with them. The electrical attractions and repulsions can cause molecules to be altered.

Interactions with both charged and uncharged particles lead to changes in the structure of matter. In living tissue, several things can happen. First, a cell can be damaged, die, and be replaced by a new cell. This is the least harmful effect of radiation. A more serious situation arises when a damaged cell survives but does not function properly. In some cases the cell repairs itself through natural processes, but in others the altered cell persists. The change in function is most serious when it is the result of damage to DNA, the genetic material. DNA molecules carry the codes for all the structure and activities of the cell and are passed from one cell generation to the next. Altering these molecules causes descendants of the original cell to be altered

Table 22-2 Typical Applications of Radioactive Isotopes

Isotope	Half-life	Important Uses
$^{3}_{1}H$	12 years	Traces water and organic substances.
$^{14}_{6}C$	5600 years	Studies of organic processes such as metabolism.
$^{24}_{11}Na$	15 hours	Studies of biochemical processes.
$^{32}_{15}P$	14 days	Studies of bone growth and treatment of blood diseases.
$^{60}_{27}Co$	5.3 years	Used in cancer therapy.
$^{131}_{53}I$	8 days	Treats and studies thyroid diseases.

in form and function. These altered cells may stop reproducing, or they may start to reproduce at an enormous rate, as is the case for cancer cells. Extensive cell damage is generally fatal to the entire organism. Finally, radiation can damage the genetic material of the reproductive cells in ways that do not appear until the next generation is born. These alterations can range from inconsequential to lethal.

Not all interactions between radioactivity and living cells are bad. As we gain more experience with the biological effects of radiation, we are able to direct radiation to therapeutic purposes. A summary of some important applications is included in Table 22-2. Controlled use of radiation allows us to kill cancer cells selectively. Radioactive isotopes that can circulate through the blood system are important in the diagnosis of heart and circulatory problems and thyroid, liver, and kidney ailments. The list of applications continues to grow as our understanding of biological processes increases.

Step by step we have explored our earth. We have examined the atoms and molecules from which it is constructed and the nuclei and electrons from which atoms and molecules are constructed. With each step we have gained knowledge—knowledge that has deepened our perceptions of ourselves and the altered landscape we share. As demonstrated by the concepts we build and the uses to which we put our knowledge, we have chosen to be active, not passive, observers. In so choosing, we accept both the risks and the benefits associated with change.

CHAPTER SUMMARY

The mass of a nucleus is always less than the sum of the masses of its constituents. This difference in mass, called the *mass defect,* is related to the binding energy that holds the nucleus together. The principle of mass-energy equivalence relates the mass defect and *binding energy* by the equation: binding energy = (mass defect) × (speed of light)^2. The binding energy per nucleon is not the same for all nuclei. Nuclei with atomic mass numbers that range from 50 to 100 have the largest binding energies per nucleon and are more tightly bound than either more massive or less massive nuclei. Nuclear reactions that transform loosely bound nuclei into more tightly bound nuclei release energy to the environment. The energy release can occur in two ways. A very massive nucleus can split to form smaller nuclei, and light nuclei can combine to form a more massive one.

The process by which massive nuclei split apart to form less massive nuclei is called *nuclear fission*. In a typical example a neutron penetrates into a uranium 235 nucleus, which then becomes an excited uranium 236 nucleus. This nucleus vibrates and splits into barium 142, krypton 91, and three neutrons. The uranium 236 can split into other products as well; however, on the average three neutrons are released per fission event. The neutrons released by the fission can be simply lost or they can be absorbed by other uranium nuclei to induce other fissions. The absorption of one neutron per fission assures us of a sustained *chain reaction,* which can be used to produce useful energy. The absorption of more than one neutron per fission results in an uncontrolled chain reaction, the process in the nuclear fission bomb. Fission reactors, which provide nuclear energy for generating electricity, use sustained chain reactions fueled by uranium 235 or by plutonium 239.

The process by which lighter nuclei join together to form heavier nuclei is called *nuclear fusion*. One possible reaction involves the fusion of four hydrogen 1 nuclei into one helium 4 nucleus and two positrons. To overcome the electrical repulsion between positively charged nuclei, the hydrogen nuclei need to be hurled at one another at speeds close to 10^5 m/s. While controlled fusion has been produced in the laboratory, the energy required to induce the controlled reaction has, thus far, exceeded the energy released. Fusion reactors are still decades away.

The products of radioactive decay can interact with living cells either by direct collision or through the electrical interaction. Damage to cells can range from inconsequential to fatal for the organism. Radioactive isotopes have also proven to be beneficial, particularly in diagnosing and treating illnesses.

ANSWERS TO SELF-CHECKS

22A. The mass of hydrogen 2 is 2.013553 amu. Thus the total starting mass is 2×2.013553 amu $= 4.027106$ amu. The final mass is that of one helium 4, 4.001506 amu. Because the final mass is less than the initial mass, energy can be released.

22B. The masses of the neutron and uranium 235 nucleus sum to give a total mass of 236.0526 amu before the fission. The strontium 90, xenon 135 nuclei and the ten neutrons sum to give a total mass of 235.9012 amu after the fission. The difference between the masses before and after fission is 236.0526 amu $-$ 235.9012 amu $=$ 0.1514 amu. This mass difference is less than that for the process that produces barium 142 and krypton 91. Thus, the energy released in this fission is smaller.

22C. One neutron initiates one fission event that produces two neutrons, which initiate two fission events that produce four neutrons, which initiate four fission events, and so on. The progression is 1, 2, 4, 8, 16, 32, 64, ... The reaction is uncontrolled.

22D. The mass before the fusion is 2 × 2.013553 amu = 4.027106 amu. After the fusion the total mass is 3.01650 amu + 1.007276 amu = 4.023326 amu. The mass difference is 0.003780 amu, which is less than the mass difference for the four hydrogen 1 fusion.

PROBLEMS AND QUESTIONS

A. Review of Chapter Material

A1. Define each of the following:
Mass defect
Binding energy
Binding energy per nucleon
Nuclear fission
Sustained chain reaction
Uncontrolled chain reaction
Fission reactors
Nuclear fusion
Fusion reactors
Scientific break-even
Thermodynamic break-even

A2. Describe the process by which you could use the binding-energy-per-nucleon characteristic of each isotope to predict whether a reaction would proceed on its own.

A3. Use Figure 22-3 to explain why the process of nuclear fission releases energy.

A4. Describe the liquid-drop analogy used to understand the process by which a heavy nucleus splits into two smaller fragments.

A5. Distinguish between a sustained chain reaction and an uncontrolled chain reaction.

A6. Describe the operation of a nuclear fission reactor.

A7. What are two advantages to fission reactors?

A8. Why do the radioactive byproducts of nuclear fission pose a problem to us?

A9. Use Figure 22-3 to explain why the process of nuclear fusion releases energy.

A10. What two problems must be addressed in the design of fusion reactors?

A11. Distinguish between scientific break-even and thermodynamic break-even.

A12. Describe the two processes by which radioactive products interact with living tissue.

B. Using the Chapter Material

B1. What is the total binding energy of iron 56?

B2. Could chromium 52 spontaneously transform into argon 40 and carbon 12? Explain your answer.

B3. If a hydrogen 1 nucleus fused with a vanadium 51 to produce chromium 52, how much energy would be released?

B4. Would the fusion of hydrogen 2 and iron 56 to produce nickel 58 release energy?

B5. Explain why nuclei which undergo fusion must be at very high temperatures.

B6. How many neutrons would be released if uranium 236 fissioned into barium 141 and krypton 91?

B7. Suppose a fission reaction which did *not* release any free neutrons existed. Would that process be useful for production of electrical energy? Why or why not?

B8. How much mass is converted to energy in the reaction:

$$^{235}_{92}\mathrm{U} + ^{1}_{0}n \rightarrow ^{110}_{46}\mathrm{Pd} + ^{110}_{46}\mathrm{Pd} + 16^{1}_{0}n$$

The masses are: $^{235}_{92}\mathrm{U}$ = 235.0439 amu; $^{1}_{0}n$ = 1.008665 amu; and $^{110}_{46}\mathrm{Pd}$ = 109.9052 amu.

B9. Will the reaction in Question B8 release more or less energy than the one given in Self-Check 22B?

B10. For the fission reactor and the fusion reactor, describe the changes in types of energy involved as the process goes from nuclear to electrical energy.

B11. Calculate the amount of energy released if 0.001 kg of mass were converted completely to energy.

C. Extensions to New Situations

C1. An unusual "fusion" reaction occurs when ordinary matter combines with material called *antimatter*. The antimatter of any particle is essentially identical to the particle, except that the electric charges of the matter and antimatter are opposite.

a. Why can matter combine with antimatter when the particles are moving at very low speeds? (Recall the nature of the electric interaction between opposite charges.)

b. What is the total electric charge of the products of a matter-antimatter collision?

c. When an electron and an antielectron (positron) combine, the product is electromagnetic energy (which has zero mass). The electron and positron have masses of 9.11×10^{-31} kg each. How much mass is converted to energy in this process?

d. What is the total energy released?

C2. Why would tritium create a much more serious problem if it were in drinking water than if it were in rocks?

C3. At some time in the future, the government research groups will need to choose between magnetic-containment or laser-fusion research. What type of information would you want if you had to make this decision? (Include both scientific and other information.)

C4. Suppose you had to make the decision to build a breeder reactor. What type of information would be useful to help you make that decision?

C5. If there were only two choices—fission or fusion—for future generation of electrical energy, which would you prefer? Why?

C6. One model suggested to explain the source of energy emitted by the sun is the carbon cycle, in which carbon undergoes nuclear transformations including fusion. Complete the steps of the cycle using the periodic table included in Chapter 21.

$$
\begin{aligned}
{}^{12}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H} &\rightarrow (\qquad) + \gamma \\
(\qquad) &\rightarrow {}^{13}_{6}\mathrm{C} + {}^{\;\,0}_{+1}e + \nu \\
{}^{13}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H} &\rightarrow (\qquad) + \gamma \\
(\qquad) + {}^{1}_{1}\mathrm{H} &\rightarrow {}^{15}_{8}\mathrm{O} + \gamma \\
{}^{15}_{8}\mathrm{O} &\rightarrow (\qquad) + {}^{\;\,0}_{+1}e + \nu \\
(\qquad) + {}^{1}_{1}\mathrm{H} &\rightarrow {}^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He}
\end{aligned}
$$

C7. One fusion reaction that might occur in the sun is shown below. Use the information given in Table 22-1 to predict whether energy will be absorbed or released by the reaction.

$${}^{4}_{2}\mathrm{He} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{7}_{3}\mathrm{Li} + \gamma$$

D. Activities

D1. Find out what types of nuclear reactors, if any, your local electrical utility has in operation. Learn about any future plans for nuclear power plants.

D2. Talk to someone who works around radiation (for example, an X-ray technician). Learn what they do to guard against biological damage.