# CHAPTER 10

## NUCLEAR ENERGY

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Nuclear energy has suffered a severe blow to its reputation during the last several decades in comparison with its post World War II image as the solution to the world’s energy problems. After the demise of the Cold War, the problems of nuclear proliferation and potential “dirty bombs” as terrorist weapons became a concern. However, nuclear accidents, and in particular, the Fukushima earthquake and tsunami incident have challenged the very safety of nuclear power. On the other hand, many benefit from the medical uses of radioisotopes in medicine. The nuclear chemistry and science behind these and other related topics are discussed in this chapter.

Questions Answered in This Chapter

1. What are the sources of nuclear energy?
2. What are the consequences of the nuclear fission process?
3. What are the function and structure of the various parts of the nuclear reactor?
4. What are the ways in which a reactor can go out of control?
5. What are the problems of the disposal of radioactive reactor materials and the various methods proposed to deal with these problems?
6. What are the problems with the development of a fusion power reactor?
7. In what ways are radioactive nuclei used in medical and commercial applications?
8. What naturally occurring radiation can be dangerous to home residents?
9. What is the scientific basis for nuclear weapons?
10. What are the consequences of fallout from a nuclear and from a “dirty” bomb?
Introduction

Nuclear energy currently supplies about 5-6% of the total primary energy expended and about 18% of the electricity generated in the world from over 400 nuclear reactors. A little over one hundred nuclear reactors generate approximately 20% of the electrical energy of the United States. In some countries, nuclear power is a more significant source of electricity than in the US, e.g., France (78%), Belgium (60%), Sweden (43%), South Korea (36%), and Japan (??%). However, in the U.S., there have been no new nuclear plants completed since 1995, although several are under construction.

A significant advantage of electricity generation using nuclear power is that it does not give off any greenhouse gases such as carbon dioxide. The uranium fuel is relatively plentiful in the United States, so utilizing this fuel would relieve the US of its reliance on imported oil. If one particular type of reactor is used, an almost unlimited amount of fuel can be generated. If the development of fusion reactors were successful, the fuel for such reactors, water from any source, is unlimited.

However, the future of nuclear power in the US is uncertain, especially since the Fukushima accident, because of the inherent dangers in the operation of nuclear reactors and the difficulties with storage of the nuclear wastes resulting from reactors. There are also serious technical problems in nuclear reactors that are causing early retirement of some of these reactors. The anticipated lifetime of nuclear reactors was 40 years. However, 81 nuclear reactors have been retired from service up to 1994, with an average service of 17 years per reactor. It is estimated that the costs of operating and maintaining these reactors exceeds the costs of replacing them with non-nuclear generating stations. Costs of decommissioning retired plants and disposal of nuclear wastes are escalating. However, many reactor operators are requesting and receiving extensions of their operating licenses.

Nuclear fusion and fission have been used as the basis for creating nuclear weapons. The most notorious are those dropped over Japan during World War II and the far more destructive hydrogen or H-bombs tested by the US in the Pacific Ocean. Currently there is concern about proliferation of nuclear weapons of mass destruction and their potential use by terrorists. The potential for destruction with a modern, easily-disguised nuclear weapon in a densely populated area is staggering.

The potential medical consequences of exposure to radioactive natural radon gas in buildings is being addressed more seriously because of the negative consequences resulting from exposure of the lungs to radon and smoking. On the positive side, the uses of radioactive nuclei in nuclear medicine is now an integral part of medical practice. The use of radiation to sterilize food has had a controversial history, but the US FDA has added irradiated beef and pork products to other previously approved irradiated foods.
Nuclear Energy

The reason for the large amounts of energy available from nuclear reactions is the conversion of mass into energy. Einstein was the first to recognize that mass and energy were inter-convertible. He stated this unexpected finding in a fundamental equation, \( E = mc^2 \). In the Einstein equation, \( E \) is the energy released when a certain mass \( m \) of nuclear material is transformed into another form of energy, and \( c \) is the speed of light. When the total mass of the products of a nuclear reaction is less than the total mass of the reactants, this loss in mass must be revealed among the product nuclei as either thermal energy of the products or electromagnetic energy, that is, as x-rays or gamma rays (\( \gamma \)-rays). The fate of these energetic products is generally to produce heat in the medium slowing them down or energetic chemical reactions leading to damage in the absorbing materials in the case of x-rays and \( \gamma \)-rays.

According to calculations using the Einstein equation, the amounts of energy available from very small losses in mass are very large, much larger than those released from the combustion of fossil fuels. Therefore chemicals containing nuclei that can take part in nuclear reactions are high on the list of potential fuels for generating electrical power. However, the “burning” of nuclear fuel in a nuclear reactor is a highly complex and challenging task.

There are two basic types of nuclear reactions that can be used to convert nuclear energy directly into another form of energy. In the fission process, a heavy nucleus (uranium or plutonium) is split into lighter weight fission fragments, with the simultaneous release of neutrons and large amounts of kinetic energy contained in the fission fragments and neutrons. In the fusion process, light nuclei are fused to make a more stable, heavier nucleus, usually the very stable helium-4 nucleus, again accompanied by very energetic gamma rays and high kinetic energy of the fusion products. Smaller amounts of heat energy are released (Fig 10-1) in the fission process than in the fusion process, which is responsible for the energy released by the sun and other stars (Chapter 2).

The reason for the large amounts of energy given off by the fission and fusion processes is the much greater stability of the product nuclei than the reactant nuclei in these two general nuclear reactions. In the case of fission, the two lighter fission products are more stable than the heavy uranium or plutonium nuclei. Thus the cold fission fragments are of lower nuclear energy than the unstable uranium nucleus and the cold helium nucleus is at a very much lower nuclear energy level than the cold nuclei that were fused to form the very stable He-4 nucleus. Because of these differences, a fusion event releases much more thermal energy than a fission event.

Thus, of two types of nuclear power, it would be more desirable to develop fusion power. However, the technical problems with fusion are far greater than those encountered in the controlled fission process. In fact, they are so great that a prototype nuclear fusion reactor has not yet been produced despite the many decades
of research on the fusion process. On the other hand, nuclear reactors based upon the fission principle are currently in wide use around the world.

**Nuclear Fission Fuel**

The U-235 nuclear fuel is a rare isotope of naturally occurring uranium, which is primarily U-238. There is not enough U-235 contained in mined and processed uranium to sustain a nuclear chain reaction. In order to enrich the natural uranium with the U-235 fuel isotope, one has to either separate this isotope from the more abundant U-238 isotope and then mix the U-235 with ordinary uranium to make nuclear fuel rods or enrich the amount of U-235 in the uranium. The enrichment process is the choice for large scale production of fission fuel. Large amounts of energy and technical expertise are needed to acquire a sufficient enrichment of the U-235 isotope. There are a number of different methods used to separate these isotopes. Click the following button to go into detail about these methods and problems with uranium mining: A-10-5

After reconsidering problems with nuclear waste storage and the possibility of terrorists acquiring weapons grade nuclear fuel, there is renewed interest with thorium...
(Th) fuel. This thorium fuel is used to “breed” a U-233 isotope, which can be used as a fission fuel. The advantages of this fuel are that the fission byproducts are shorter lived and there is less risk of proliferation when using thorium fuel. We will discuss this technology below, but first let us investigate the nature of the fission process itself.

The Fission Process

Although the U-235 nucleus does not fission spontaneously, the U-236 nucleus does. U-236 can be created by adding to a U-235 nucleus a neutron whose energy is equal to that of its surroundings. That is, this neutron must be at the same temperature as the U-235. It is also called a “slow” or a “thermal” (local temperature) neutron.

\[ n \text{ (thermal)} + \text{U-235} \rightarrow \text{U-236} \quad (10-1) \]

When the U-236 nucleus fissions, it breaks apart into two smaller, unequal size radioactive nuclei, designated fission products, plus, on average, between two and three neutrons (n). There is a broad range of different fission product pair nuclei, so we designate them as fission products F1 and F2. (Because the atomic number of uranium is 92, the sum of the atomic numbers of F1 and F2 must equal 92.)

\[ \text{fast} \quad \text{U-236} \rightarrow \text{F1} + \text{F2} + 2-3 \text{n (fast)} + \text{ENERGY!} \quad (10-2) \]

Where is this abundant amount of “ENERGY!” indicated in the above equation located? Both the fission products F1 and F2 as well as the neutrons released carry all of this energy as kinetic energy, the energy associated with rapid movement through space. Thus, all of these particles are moving exceedingly fast at the moment of fission. F1 and F2 nuclei give up their kinetic energy relatively rapidly in the form of thermal energy (heat) to the medium through which they are moving. This is the first of three sources of heat resulting from the fission process: (1) heat from the slowing down of fission products F1 and F2; (2) heat from the slowing down of fast neutrons; (3) heat from the radioactive decay of the fission products.

Both F1 and F2 are unstable nuclei and therefore they are both radioactive. Each nucleus emits a series of negatively charged beta (\( \beta \)) rays (fast electrons) and gamma (\( \gamma \)) rays, leaving behind a nucleus with an atomic number (Z) one unit higher for each beta ray emitted. For example, if one of the fission products, F1, were iodine-133 (I-133), it would be highly radioactive and therefore unstable and emit beta rays until it forms the stable non-radioactive isotope cesium-133 (Cs-133). The mass number (133) remains the same because the sum of the number of protons and neutrons remains the same in each new succeeding element during this radioactive decays:

\[ \text{I-133 (Z = 53)} \rightarrow \text{Xe-133 (Z = 54)} + e^- (\beta \text{ ray}) + \gamma\text{-ray} \quad (10-3) \]
\[ \text{Xe-133 (Z = 54)} \rightarrow \text{Cs-133 (Z = 55)} + e^- (\beta \text{ ray}) + \gamma\text{-ray} \quad (10-4) \]
\[ \text{Cs-133 (Z = 55)} \text{ stable, non radioactive} \quad (10-5) \]
Beta rays are very fast moving, and therefore high-energy, electrons that interact primarily with other electrons in the medium through which they travel. As these fast electrons interact with matter through which they travel, they lose their kinetic energy and slow down, increasing the thermal energy of the absorbing matter. Gamma rays (γ-rays) are also converted into heat energy because they excite or eject fast electrons from the medium through which they pass. In turn, these fast electrons create heat in the same manner as beta rays. In words, the surroundings are heated because of the slowing down of the beta rays and absorption of gamma rays.

Thus, the net result of a fission of a U-235 nucleus is the creation of two highly radioactive nuclei, which heat up their surroundings because of the transformation of kinetic energy into thermal energy (heat) from the slowing down of the fast fission products and from the slowing down or absorption of the beta and gamma rays emitted by the fission products. Additional heat is provided by the transformation of kinetic energy of the fast neutrons into heat as they slow down. Very large amounts of heat are available from these fission processes. It is this heat that is utilized in the nuclear reactor to generate power.

**Nuclear Reactors**

*Components of the nuclear reactor and its chain reaction*

The fission reactions (10-1) and (10-2), representing the fissioning of U-236, would together form a chain reaction if the neutrons involved had the same energy. Reaction (10-1) can only proceed if the reaction involves a slow (thermal) neutron. Yet the neutrons resulting from the fission process are far from thermal. Therefore to create a chain reaction in most current nuclear reactors, one of the critical components must be material that will slow down the fast fission neutrons. This material is called a moderator, because its role is to moderate the speed of the fast neutrons produced in equation (10-2), shown in equation (10-6).

\[
[U-236 \rightarrow F1 + F2 + 2-3 \text{ n (fast)} + \text{ENERGY!} \ (10-2)]
\]

\[
n (\text{fast}) + \text{moderator} \rightarrow n (\text{thermal}) + \text{moderator (heated)} \ (10-6)
\]

With the presence of a moderator near the location of the fission reactions, the combination of equations (10-1), (10-2), and (10-6) form a nuclear chain reaction because the thermal neutrons ["n(thermal)""] produced following fast neutron
moderation in reaction (10-6) can be used to initiate another fission process in reaction (10-1).

For every fission process, there are released, on average, between two and three fast neutrons. If every one of these fast neutrons is moderated and reacts with a U-235 nucleus, a rapidly escalating chain reaction would result (Figure 10-4), with corresponding rapidly increasing amounts of thermal energy released, resulting in a sudden, escalating temperature. If this temperature buildup is exceedingly fast, there can suddenly be a high enough temperature to vaporize any material. The resulting localized hot gases expand suddenly, causing an explosion. This is the principle behind the atomic bomb. However, not all thermalized neutrons react with U-235 nuclei in a nuclear reactor, so that the reactor is designed to maximize the number that do react and to prevent an escalation with an out-of-control chain reaction.

Figure 10-4  Scheme of an escalating chain reaction in which more than one neutron per fission leads to an increasing number of fissioning U-236 nuclei with increasing time. All fast neutrons released from the fission process must be moderated (slowed down) in order to proceed in the chain process.
A sustained, steady state release of heat from the reactor is desired, so part of any nuclear reactor must be a sensitive device to carefully control the rate of the nuclear chain reaction. This is achieved by inserting and withdrawing **control rods** into the reactor to remove unwanted excess neutrons. When the reactor is generating power at a steady rate, the number of thermal neutrons generated in the reactor should remain at a constant level. Control rods are constructed from metal that is impregnated with either boron (B) or cadmium (Cd). Each of these elements strongly absorbs neutrons, and therefore is capable of decreasing the rate of reaction (10-1), which controls the rate of the chain reaction. There are also emergency control rods and solutions with the same elements that are quickly injected to shut down the reactor quickly in the event of an emergency. Figure 10-5 indicate the scheme of one of the major type of US reactor, the pressurized water-cooled reactor (PWR). 10-1 lists the components and functions of a typical PWR.

The large amount of heat generated by the nuclear fission events is used to heat water that passes by or through channels in the hot fuel rods. This intense heat causes the liquid water to turn into steam that is used to turn electrical turbines to produce electricity. The nuclear reactor resides inside a tightly sealed, pressurized vessel that can contain the operating pressures of thousands of pounds per square inch pressure. These pressures elevate the boiling point of water to over three hundred degrees Celsius so that the water doesn’t vaporize at the high temperatures within the reactor core.

**Problems with nuclear reactor fuel rods**

**During shutdown.** While the fuel rods are in the reactor core, reactor operators and the general public are shielded from intense fission product gamma radiation by thick concrete shielding. Because the fuel rods are highly radioactive, they deliver large amounts of heat to their surroundings, heat that is used to generate power while the reactor is running. However, when the reactor is shut down, heat is still released despite cessation of the fission reactions.

The heat from the fission product-containing fuel rods continues to be generated and, depending on the level of fission product content of the fuel rods, this heat must be carried away from the reactor core. Otherwise, the core temperature will rise to temperatures high enough to melt the core. Cooling is accomplished by forced water circulation through the core during shutdown. Every reactor has redundant cooling systems. That is, there are at least two independent cooling systems so that if one fails, the other will be able to take over. However, all cooling systems depend on having electricity available, so backup generators are also part of the reactor safety system. There are even backup batteries for the backup generators, but these do not last very long when they are in use.
Table 10-1 Pressurized Water Reactor Systems

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<tr>
<th>Component</th>
<th>Subsystems</th>
<th>Function</th>
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<tr>
<td>Reactor Core</td>
<td>Fuel rods</td>
<td>holds uranium fuel</td>
</tr>
<tr>
<td></td>
<td>Moderator</td>
<td>slows fast neutrons</td>
</tr>
<tr>
<td></td>
<td>Control rods</td>
<td>controls chain reaction</td>
</tr>
<tr>
<td></td>
<td>Safety rods</td>
<td>shuts down reactor</td>
</tr>
<tr>
<td></td>
<td>Coolant (water)</td>
<td>removes heat from rods</td>
</tr>
<tr>
<td></td>
<td>Reflector (neutrons)</td>
<td>conserves neutrons</td>
</tr>
<tr>
<td></td>
<td>Reactor vessel</td>
<td>container for reactor core</td>
</tr>
<tr>
<td>Heat Exchanger</td>
<td>Primary loop</td>
<td>cools reactor core</td>
</tr>
<tr>
<td></td>
<td>Secondary loop</td>
<td>delivers heat to turbine</td>
</tr>
<tr>
<td>Emergency cooling</td>
<td>–</td>
<td>cools core in emergency</td>
</tr>
<tr>
<td>Containment bldg.</td>
<td>–</td>
<td>contains all of the above</td>
</tr>
<tr>
<td>Steam Generator</td>
<td>–</td>
<td>turns water to steam</td>
</tr>
<tr>
<td>Turbine</td>
<td>–</td>
<td>generates electricity</td>
</tr>
<tr>
<td>Cooling tower</td>
<td>heat exchanger</td>
<td>condenses steam</td>
</tr>
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Figure 10-5 Diagram of the components found in a typical pressurized water nuclear reactor (PWR).
Meltdown of the reactor core. The above circumstances lead to a critical safety problem. Water and electrical power must be always available to circulate the water through the reactor. If one or the other of these is not available, the temperature of the core of the reactor containing large amounts of fission products will heat up continuously and will ultimately reach a temperature which will cause a melting of the reactor core and its contents, an event designated as a core meltdown, sometimes known as the “China syndrome” because of the possibility of the core melting through the reactor vessel and melting down into the ground. This would potentially lead to disastrous consequences if the descending reactor material were to strike an aquifer causing a steam explosion. A reactor meltdown event involving loss of water coolant and melting of more than half of the reactor did occur in 1979 at the Three Mile Island nuclear reactor in Pennsylvania (see below for details). Core meltdowns in at least three reactors have been reported in the Fukushima Daiichi reactor complex caused by the losses of power during the major March, 2011 Japanese earthquake and tsunami (see below for details).

Fuel rod storage. During nuclear reactor operation, fission products and very long-lived transuranic (elements with atomic numbers larger than those of uranium) products build up in the fuel rods, lowering the efficiency of the reactor. At some point, fuel rods must be removed from the reactor, stored in a water-filled pool while the short-lived fission fragments decay, and a critical decision made about the long-term storage fates of these “hot” rods.

There are two possible ultimate fates for the fuel rods. In the “once-through” or open-cycle option, the fuel rod is stored first in a cooling-down period in pools next to the reactor, while short half-life fission products decay, and then the fuel rods are stored in a permanent underground waste site (see below) for on the order of a hundred thousand years. The other option, the closed-cycle process, is to cut up and dissolve the fuel rod in strong acid and chemically separate the unused uranium, trans-uranium elements, including plutonium, from the lighter fission fragments. Both the recovered U-235 and plutonium can be reused in the construction of new reactor fuel rods, while the much shorter-lived fission fragments can be stored for a shorter period of time (on the order of hundreds years) than in the open-cycle option. Plutonium-239, a nuclear bomb-ready fuel can be recovered during this process. For this reason, the U.S. is limited by law to using only the open-cycle option, but other countries use the closed-cycle process, which is highly complex, dangerous and more costly than the open-cycle process. France, Russia, United Kingdom, China, and Japan recycle their nuclear fuel. The U.S., Sweden and Finland do not.

Because of the problems of very long lived radioactive wastes and the production of plutonium when using U-238/U-235 fission fuel, there has been a search for an alternate fission fuel. Thus far the only viable alternative seems to be the use of thorium as a substitute for U-235. We now examine the pros and cons of using this fuel for producing fission energy.
**Thorium as a fission fuel for nuclear reactors**

Thorium is about three times more abundant than uranium in the United States. Nearly all thorium is found in nature as a single isotope, Th-232. However, Th-232 is not directly fissionable by thermal neutrons. Instead, the following series of reactions ensues when Th is bombarded with thermal neutrons:

\[
\text{beta decay} \quad \text{beta decay}
\]

\[
\text{Th-232} + \text{thermal n} \rightarrow \text{Th-233} \rightarrow \text{Pa-233} \rightarrow \text{U-233 \ (fissionable isotope)}
\]

Thus, we have to make or “breed” the U-233 in a breeder reactor that supplies the needed thermal neutrons that bombard and are absorbed by a Th-232 “blanket” that surrounds the reactor to create enough U-233 to achieve a critical U-233 reactor. Unfortunately, that initial startup reactor is fueled by a U-235/238 mixture, which is one of the disadvantages of the use of thorium fission fuel. Thus, some very long-lived trans-actinides and bomb material, such as Pu-239, are formed in the process of making Th-233. However, these are far less quantities than in a U-235 reactor. For more information, click the following button: C-10-12 C-10-12

**Chemical waste storage and transmutation**

In addition to the waste contained in power reactor fuel rods, there is a large volume of highly radioactive waste from nuclear bomb production. How should all of these radioactive wastes be stored for anywhere from hundreds to hundreds of thousands of years? Some schemes would encase the hot fuel in glass or ceramic logs encased in stainless steel. Others would adsorb radioactive elements to solids. Each of these materials would be encapsulated in metals that would be designed to withstand corrosive water in the presence of oxygen.

Transmutation is a term applied to a waste treatment proposal that irradiates radioactive waste with high-energy protons or other appropriate nuclear particles with the goal of transforming the long-lived actinide radioisotopes (nuclei with atomic numbers 90 and above) into either non-radioactive isotopes or shorter-lived isotopes. This would necessarily be a very expensive and highly technical process. It probably would not be able to handle the large volume of radioactive waste already awaiting disposal.

**The Yucca Flats nuclear storage facility**

The long-term storage of spent fuel rods and other high level nuclear waste is both a scientific and political problem. The political problem is in what political subdivision to store the wastes and the scientific problem is to find a location that is secure for the length of time that the fuel elements are radioactive and dangerous.
Fuel rods for nuclear reactors are generally filled with zirconium-clad U-235 enriched uranium oxide pellets doubly clad in welded stainless steel jackets. After the reactor has produced power for a number of years, the fuel rods become brittle from the continual fast neutron bombardment of the metal cladding and reactor components, increasing the probability of leakage of fission fragments from the fuel rods and requiring the retirement of these fuel rods from use. These spent fuel rods are intensely radioactive and must be transferred to water-filled storage pools on the reactor site where the radiation level is diminished. However, because there are radioactive products in the fuel rods (96% of which are U-235 and U238) with half-lives on the order of from hundreds of years (~3-4% of total isotopes) to many thousands of years (~1% of total isotopes). If they are not recycled, these radioactive fuel rods must be stored for a period of about ten times the half life of the longest lived radioactive isotope, a period of more than 100,000 years. There are literally thousands of fuel rods in storage pools at over 130 different sites awaiting the creation of a long-term storage facility. In 31 states, there are many thousands of tons of highly radioactive fuel rod waste from today’s U.S. generating plants already awaiting permanent storage. When all of the current nuclear plants reach the end of their lifetime, there will be over 140,000 metric tons of waste.

The twin problems of reactor safety and storage of high-level radioactive waste has caused severe problems for the nuclear industry in the United States. The history of the issue of high-level radioactive waste disposal has been full of emotional, political, and scientific battles and is likely to continue into the future. Creation of a permanent storage site has been plagued by the NIMBY problem - “Not In My Back Yard!” After decades of scientific study and political turmoil, a national, high-level storage site had been selected for radioactive waste generated by commercial nuclear power reactors at Yucca Mountain in Nevada. The proposed Yucca Flats facility would have easily reached its capacity (77,000 metric tons) even before its often-delayed opening date (2017) but with the assumption is that it would have to expand its capacity. However, the Obama administration cancelled the Yucca Flats facility and has appointed a commission to come up with a new plan for the disposal of high level radioactive waste. Some opponents of this move say that Congress can reverse this decision. Thus, there is still controversy over and opposition to the selection of this site. In addition, there is controversy over the modes of transportation (rail vs. truck) of the wastes from nuclear reactors from all parts of the country to Yucca Mountain.

**Fission product decay**

Each of the many hundreds of different fission product nuclei goes through a well-defined sequence of beta decay events. The early products are formed quickly, but toward the end of the decay chain sequence, the radioactive decay processes slow down to such a point that some of the final decays have comparatively long lifetimes. A **half-life** ($t_{1/2}$) (Fig. 10-6) is the characteristic time it takes for half of a given large number of radioactive isotopes to decay, leaving behind half of the radioactive radioisotopes. That half then takes the same time ($t_{1/2}$) for half of the remaining radioisotopes to decay, and so forth. In some ways, it’s like taking a trip to a certain
destination in a series of jumps, with each jump being between your present location to a point exactly halfway between you and your destination.

A fission product decay sequence illustrating the variety of half-lives of fission products is the decay of antimony-131 (Sb-131) into tellurium (Te), iodine (I) and finally xenon (Xe):

\[ ^{131}\text{Sb} \xrightarrow{\beta^-} ^{131}\text{Te} \xrightarrow{\beta^-} ^{131}\text{I} \xrightarrow{\beta^-} ^{131}\text{Xe} \] (stable)  

You can see that three different beta particles (\(\beta^-\)) are emitted from nuclei during these decay processes for every Sb-131 fission fragment formed. The decay rates are very fast in the first decay of Sb-131 (t\(_{1/2}\) \(\approx\) seconds), slower for second decay of Te-131 (t\(_{1/2}\) = 25 minutes), and slowest for the decay of I-131 (t\(_{1/2}\) = 8 days).

---

**Half-life of a radioactive isotope**

The half-life of a radioactive isotope is defined as the time for one-half of a certain large number of radioisotopes to decay. For each half-life interval, at any time and for any number of nuclei, the number of radioisotopes will be reduced by a factor of two for that interval. For example, in 2 half lives, the number will be reduced by \(1/2 \times 1/2 = 1/4\).

---

**Example 10-1** Calculation of the number of remaining radioisotopes

If there are 800,000 I-131 nuclei (half life = 8 days) present at a certain time t, how many of these nuclei will have decayed at the end of t + 16 days later?

At the end of a period of 8 days, exactly one half-life for the I-131 isotope, there will be half of the 800,000 I-131 isotopes left or 400,000. In 2 x 8 days = 16 days, or two half lives, there will be 1/4 of the original number of I-131 isotopes left or 200,000. This means that 600,000 of the original 800,000 will have decayed. In three half-
lives, 3 x 8 = 24 days, there will be 1/8 (1/2 x1/2x 1/2) of the isotopes left, or 100,000.

**Major Nuclear Plant Accidents**

There have been three major peacetime reactor accidents. The first was the Three Mile Island incident in 1979 near Harrisburg, PA. The second was in 1986 at the Chernobyl reactor complex near Kiev in the Ukraine of the then Soviet Union. The most recent was in 2011 in the Fukushima Daiichi complex that resulted from a very large earthquake and resulting tsunami wave caused a major nuclear disaster. In the following sections we detail the causes and consequences of each of these accidents and some lessons learned from them.

**The Fukushima Daiichi Power Complex Meltdowns**

On March 11, 2011 the fourth largest earthquake ever recorded since 1900 struck the Pacific Ocean floor east of Fukashima, Japan. Its 9.0 magnitude on the Richter scale caused a massive tsunami wave to start moving toward the shoreline of Fukashima, where the Daiichi nuclear reactor complex awaited, with its six reactors. Three of these were in operation immediately before the earthquake, but were immediately shut down successfully by the effects of the quake. The shaking caused a sudden “station blackout.” The entire nuclear reactor complex lost all power, including the pumps that were supposed to be circulating water through the scalding hot fuel rods containing rapidly decaying fission products. At this point, all the fuel rods in three shut down reactors were putting out around 7% of full reactor power as heat, causing heat to build up rapidly because no water was being pumped through or around them. As expected, backup diesel fueled pumps kicked in and started cooling the reactor. The 18.7 foot high seawalls protecting the plant awaited the anticipated oncoming tsunami wave.

Half an hour after the earthquake, the tsunami waves came surging, first at 13 feet and the next massive wave at an unprecedented 50 feet! Not only did the second wave overwhelm the protective seawalls, but the conductive seawater shorted out electrical connections in the backup pumps and eventually shut them all down. Now there were no pumps left to cool the reactors or the fuel storage areas. Efforts to get grid electrical power to the cooling pumps failed for a critical period of 9 days. During this time water was boiling off, increasing the pressure inside the closed reactor systems, threatening to cause it to burst and cause a steam explosion. Reactor operators were hesitant to open valves to relieve the pressure by letting off steam from the reactor. This was because they did not know whether any of the fuel elements had been uncovered, without cooling water.

The problem was that if they were not covered with water, the temperature of the fuel rods would increase to temperatures over 2,000°F at which time the
zirconium (Zr) cladding on the fuel elements would undergo the following chemical reaction:

$$\text{Zr(metal)} + 2\text{H}_2\text{O} \rightarrow \text{ZrO}_2 \text{ (solid)} + 2\text{H}_2 \text{ (hot gas)}$$  

(10-xx)

This hot hydrogen was dangerous both within the containment vessel and, if vented to relieve the pressure, within the reactor building. The hydrogen in either case could react explosively in the presence of any oxygen inside the reactor containment vessel or in the reactor building:

$$2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O} + \text{Energy!}$$  

(10-xx)

The operators had to open the relief valves in the steam line (Fig. 10-8), allowing the steam to enter the reactor building.

Further indicating breaches in the reactor fuel rods and the release of not only fission products but uranium, plutonium, and long lived actinides to the environment. The fifth and sixth reactors, despite being shut down before the earthquake, then started to overheat. Something had to be done to cool all of these reactors. Fire trucks were finally able to make their way through the tsunami-ravaged road access to the reactors,
but their fresh water supplies were exhausted quickly. Finally, in shear desperation, they had to resort to a last ditch cooling effort, one that would destroy all four reactors – they started pumping sea water onto the buildings from a safe distance because of the high radiation levels around the buildings. This effort was supplying water for two different purposes, cooling the reactor containment vessels and providing water for the spent fuel storage cooling pools Fig. 10-7). In order to understand this, we need to examine the reactor building design.

All of the reactors were General Electric Mark 1 of 1960s vintage, the majority being direct copies of the first commercial reactors in the U.S. The reactors are all boiling water reactors (BWR) in which the reactor core containing the fuel rods in the reactor core are covered with water and encased in a sealed metal system (Fig. 10-8). Heat from the hot fuel rods causes the water to boil producing steam. The steam then drives turbines producing electrical power. The lower temperature steam exiting the turbine was then cooled and condensed back to liquid water which was recycled back into the reactor, providing cooling water for the hot fuel rods.

In this design, the spent fuel rods from each reactor are stored in a pool right next to the reactor (Fig. 10-7,10-9). The crane shown in the upper right allowed direct access to the reactor vessel, to be able to unload spent fuel elements in the vessel and move them to the spent fuel pool to the immediate right of the reactor vessel. Following the hydrogen explosions, the top roofs were ripped off and wrecked the buildings’ exteriors (see Fig. 10-xx). There was evidence that the water level in the spent fuel pool had been lowered exposing and not efficiently cooling the resident fuel rods in this pool, leading to fires and explosions within the reactor buildings. It
was hoped that these water streams were both providing water for the cooling pools and containment vessel or the reactor vessels if they were exposed.

Crews were finally able to restore cooling systems with pure water, rather than seawater. It has been established that there were full meltdowns in at least three of the reactors. Evacuation zones have been established in a 20 km radius and there are calls for an even larger area, given the distribution of radioactivity in the surrounding countryside. Food grown in the surrounding countryside has been banned and destroyed because of the radioactive contamination. All six reactors will be decommissioned following the accident, but this may take up to a decade to complete. The amount of radiation released to the air and to the ocean is unknown, but radioisotopes that can be traced to a reactor leak have been found in the western U.S. The contribution of these to background levels is within the statistical variation of the background radiation itself. However, there is concern raised that certain isotopes, such as I-131, which concentrates in the thyroid gland of humans, could be responsible for radiation damage to the very young even at these relatively low doses.

As of this writing, three reactors, perhaps even four, of the reactors are completely out of commission. They are being cooled, but their condition is not known in detail, except for the fact they have suffered catastrophic damage. Parts of one melted fuel assembly in one reactor may have even breached its reactor vessel. One assessor of the damage has offered the opinion that this is the worst industrial accident in history. Time will tell. In hindsight, pre-planning could have perhaps saved all the nuclear reactors, but no planners probably ever imagined a 50 foot tsunami wave from a magnitude 9.0 earthquake. In hindsight, they should have, but if they had, would they have built a 70 foot wall around the plant, and would it have withstood the wave? In hindsight, backup power should have been available originating from a more elevated site, back from the seacoast. Would this have survived the cost cutting process?

Meanwhile, the nuclear power industry has suffered a severe setback. Two countries have indicated that they will phase out all nuclear reactors (Japan and Germany). When added to the Chernobyl and Three Mile Island accidents, there is a building skepticism of nuclear power in the world. Each of these accidents have a unique history and it is interesting to see what we can learn from each. With Fukushima, nature played the major role in the accident. In both the Chernobyl and Three Mile Island accidents, human error played a dominant role in causing the accidents. For more detailed discussions of these accidents, click the following buttons:

[D-10-18 Chernobyl]  [E-10-18 Three Mile Island]

Three Mile Island
And
Chernobyl
reactor
accidents
Lessons learned from the three nuclear reactor incidents

**Reactor safety**

In two of the accidents, human violations of reactor safety rules were either direct causes or could have prevented the accidents. In any future designs, it must be more difficult or even impossible to override these safety features.

Some engineers insist human reactions to emergencies be removed altogether. With computer systems able to sense emergencies instantaneously, they claim that electronic systems be designed to shut down or refuse counterproductive or dangerous commands in most delicate reactor control situations. Diagnostics can be programmed into control systems to analyze any number of unusual or dangerous situations leading to catastrophic consequences and designed to counter or prevent these from happening. Obviously, not all situations leading to a reactor malfunction will be covered, so one needs to be prepared for what to do in such events.

**Fission product release to the environment – what to do**

If the reactor was running just prior to the release accident, time is of the essence. Therefore all non essential employees and nearby general public should move away from the accident area as quickly as possible and as far as possible and await instructions. This is because the highest exposure doses are at the very beginning of the accident. Just before the accident, an operating reactor is creating very short lived, fast-decaying, and therefore intensely radioactive, high exposure dose-producing radioisotopes. These, in turn, form radioactive isotopes with longer half-lives and therefore lower exposure doses. However, the resulting radioisotopes, have even longer lifetimes and cause smaller exposure doses, etc., etc. Some of the fission fragment radioisotopes initiate a chain of ~5-10 successive radioactive decays:

\[
\text{Fission Product } A \rightarrow B \rightarrow C \rightarrow D \rightarrow E \rightarrow F \rightarrow G \text{ (stable isotope; not radioactive)}
\]

(Typical half-lives of products: \( A < B < C < D < E < F < G \), where < means “less than”)

This is illustrated in data taken early from ground measurements at some distance from the crippled reactors taken in the same manner in the same location at the same time every day in Fukushima over several months following the accident (Fig. 10-12). Data are shown in the graph below on the right of Fig. 10-12).

Note in this graph the very rapid falloff of the radiation levels followed by a period of very slow decay, indicating that there are at least two (classes of?) types of radioisotopes decaying, one with a short half-life and the other a very long half-life.
Need for transparency

In all three accidents, there was difficulty in getting information about what was happening inside the reactor. In such situations, it is important to keep the public and government officials informed. For example, in all of these situations, there was administrative fear that an accident would affect employee’s jobs or more generally, affect the nuclear industry. There was also a lack of effective communication between extremely busy and harried employees and press spokespersons. For several days, the Japanese prime minister was not able to find out details about what the true picture of what was actually happening to the Daiichi reactors. Of course one reason was, in many respects, the employees were literally in the dark. The fifty employees who rode out the early days of the catastrophe were under extremely difficult conditions trying to do the impossible and given the worst possible conditions in which to try to accomplish it.

Radiation doses to the general public

It is critical to monitor the area surrounding the reactor(s) for any signs of radioactivity. At the first sign of above background exposure, the general public should be alerted to be ready to move out, to collect medicines, glasses, any critical unique supplies needed to take along to a shelter that might not be readily available. Exposure doses should be published by location on maps if possible that are widely distributed, along with current and predicted wind directions for the next several days. These doses should be compared with a human lethal dose, a maximum allowable dose for the general public for a year, and typical x-ray doses, where 1 Sievert = 100 rem,** and therefore 1 milliSievert = 100 millirems:

Fig. 10-12 Japanese official measuring ground-level radiation as a function of time. Result: graph above.
Typical Radiation Doses

<table>
<thead>
<tr>
<th>Type Situation</th>
<th>Dose(milliSieverts)</th>
<th>Dose(millirem)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lethal dose- 50% of those exposed die</td>
<td>4,000-4,500</td>
<td>400,000–450,000</td>
</tr>
<tr>
<td>Worldwide average natural background</td>
<td>2.4 per year</td>
<td>240 per year</td>
</tr>
<tr>
<td></td>
<td>3.6 (US)</td>
<td>360* (US)</td>
</tr>
<tr>
<td>Maximum allowed dose gen. population</td>
<td>1 mSv above background</td>
<td>100</td>
</tr>
<tr>
<td>Max. dose for nuclear workers</td>
<td>20</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td>(Daichi 250)</td>
<td></td>
</tr>
<tr>
<td>CT scan</td>
<td>20</td>
<td>2,000</td>
</tr>
<tr>
<td>Chest x-ray</td>
<td>0.15</td>
<td>15</td>
</tr>
<tr>
<td>Dental or spinal x-ray</td>
<td>3</td>
<td>300</td>
</tr>
</tbody>
</table>

*Consists of (in mrem): 26 cosmic; 29 terrestrial; 200 radon; internal isotopes (K-40, C-14, etc.) 40; diagnostic X-rays (average) 39; Nuclear medicine – 14; consumer products – 11; other (air travel, nuclear power plants, etc.) – 2

** A rem is a “roentgen equivalent man,” a unit of radiation dose that is defined as a certain specified amount of energy absorbed by one gram of the absorbing material multiplied by the relative effectiveness of the type of radiation. For example, an alpha particle (fast moving helium nucleus) is 20 times more effective in producing biological damage than an x-ray, a gamma ray or beta particle (a fast moving electron).

Siting of Nuclear Power Plants

Against the objections of a number of opposition groups, nuclear power plants have been located near geologically active faults. In 2007, an earthquake in Japan, which has 55 operating nuclear power plants, caused relatively minor damage to the nearby nuclear reactor buildings, but raised questions about the safety in case of a reactor closer to the earthquake epicenter. Nevertheless, the damage to the world’s largest nuclear reactor complex was enough to shut down the reactor for a year. This event caused a movement to close down a Japanese reactor that is sited directly on a major geological fault line. The Fukushima Daiichi nuclear reactor complex incident was interesting in that the reactors appeared to have survived the major earthquake, but did not survive the ravages of the tsunami and the resulting station blackout. Had there been reliable backup power, the complex would probably have survived with relatively minimal damage. U.S. and other power plants around the world are being reviewed in the light of the Fukushima incident.

The Future of Nuclear Power Reactors

The Three Mile Island and Chernobyl accidents effectively stopped the building of new nuclear power plants in the United States, but did not hamper the development of these plants in other countries around the world. European nations continued to build
reactors to the point that France now obtains around 70% of its electrical energy from nuclear reactors. A number of reactors are currently under design and construction in Asia. Some 60 reactors will be built in the next 15 years, according to the International Atomic Energy Agency (IAEA). Sixteen U.S. power companies have expressed interest in building up to 25 reactors in the United States in the future. It is too soon to say what the consequences will be around the world for the nuclear power industry. Japan and Germany have stated their intent to phase out all nuclear reactors in the near term.

Given the fossil fuel-greenhouse gas carbon dioxide connection (Chapter 6), nuclear energy development in the U.S. is again being seriously examined as a stopgap measure until large-scale alternative energy sources can be developed. Even a few environmental activists have begun to study this as a temporary solution to the growing climate change problem.

The governments of South Africa and China have pioneered a smaller (100 vs. 1000 megawatts for current reactors) pebble bed helium-cooled test nuclear reactor, a safer and more economical design that may provide new sources of electrical power in Africa and elsewhere. In addition to generating electricity, the high temperatures of these reactors (~800 degrees C) could be used to drive a chemical reaction that produces hydrogen gas for use in fuel cells (Chapter 11). A downside of the pebble bed reactor is that its nuclear waste is more bulky and cannot be reduced in size for long-term storage. However, South Africa has recently withdrawn from development of these reactors, stating financial and marketing reasons for doing so.

Newer reactor designs promising more efficient and safer electrical power are being developed. Uranium mineral reserves are not sufficient for a greatly expanded world use of nuclear power. Therefore new designs are being generated for reactors that utilize as their fuel either thorium or recycled uranium and transuranium elements found in used reactor fuel rods. These reactors utilize fast neutrons and are therefore called “fast reactors.” Another name is the “fast breeder reactor,” because in theory the reactor can generate more fuel than it burns. Fast neutrons are able to fission U-238, plutonium 239, americium and traces of other transuranic elements. A combination of uranium, plutonium, and transuranics is therefore cast into fuel rods, used to generate electrical power in a fast reactor, while also generating more plutonium and transuranics. The plan is to recycle used fuel rods from the fast reactor, thus making it unnecessary to mine and refine more uranium for the next reactor cycle.

The fuel recycling process separates out fission products (with trace amounts of transuranics) from the uranium and transuranics. The longest-lived waste products in the conventional nuclear reactor fuel elements are the transuranic elements. If these transuranics are recycled as nuclear fuel in fast reactors, this makes the remaining shorter-lived separated fission fragments the only waste that needs to stored. Instead of having to store these wastes from fast reactors for a period of tens to hundreds of thousands of years, the fission fragment waste, with small amounts of transuranics, need only be stored for hundreds of years. There is only one problem: no fast reactors of this type have produced any commercial power and those that have
been built have been plagued with safety problems. A number of billion dollar fast reactor power plants have been shut down and abandoned. However, research and development have continued because of their potential for reducing nuclear waste.

Currently nuclear power is more expensive than other conventional sources, but may become competitive if a carbon tax is included in cost comparisons. Present and past government subsidies for nuclear power research and development are often overlooked in calculating the cost of nuclear power. However, there is still intense resistance to the use of nuclear power because of the nagging problems of nuclear waste storage, nuclear safety, and proliferation problems that are persistent negatives for the use of nuclear power. For the existing U.S. nuclear power plants, many are passing or have passed their anticipated 20-year lifetime, are requesting and being granted extensions of their licenses, some with increased electrical output. Standards for these plants are not as demanding as future designs, so that safety is a clear issue in their continued operation, especially since there are problems of fatigue and failure of materials that have been exposed to high temperatures and levels of radiation for much of their lifetimes. Stringent government regulation of these plants is mandatory to provide safety. One organization, the Union of Concerned Scientists, has criticized the government for not holding operators of nuclear reactors to proper safety standards.

Mining, processing, and fabrication of the uranium into fuel rods requires the expenditure of large amounts of energy, as does the building of the nuclear power plant itself. This relatively large amount of energy is usually supplied by fossil fuels. As easily mined uranium deposits run out, more fossil fuels will need to be burned to mine the poorer uranium ores. There is now debate as to whether it is better to burn this fossil fuel directly to provide electricity. Miners of uranium are exposed to high levels of radioactive radium gas in the uranium mines and statistics show increased cases of lung cancers among the miners, especially among those who are smokers. Claims have been made that radioactive uranium mine tailings and depleted uranium (DU) have not been stored safely and are contaminating nearby ground water.

Another factor that must be considered is the use of nuclear materials from reactors for terrorist activity. Plutonium contained in reactor fuel rods is weapons grade material. The U-235 in fuel rods is not. All used fuel rods contain the makings of a “dirty bomb” and must be guarded.

Sweden, the first nation to alert the world about the Chernobyl radioactive fallout, has decided to forgo nuclear power and to eliminate the use of fossil fuels by 2020. Neighboring Finland, on the other hand, has constructed its fifth nuclear power plant. Clearly, the future of nuclear power is uncertain. In the U.S., the case for nuclear reactors has not been aided by leaks of radioactive water containing tritium, some of which has contaminated ground water supplying neighboring wells. Although this radioactive water does not stay in the body long enough to pose a significant health threat, its long lifetime in standing aquifers and soil does not exactly build confidence in nuclear energy. The Fukushima incident has clouded the future of nuclear energy, but at least in the U.S. seems not to have provided cautious but determination to proceed with development.
Fusion Energy

Of all of the energy sources on the energy wheel, fusion has the greatest potential for providing the largest amounts of energy per reaction. For example, the energy released when a single He nucleus is formed from a nuclear reaction during a high speed collision of a tritium nucleus and a deuterium nucleus (Fig. 10-13) is orders of magnitude larger than that when one molecule of hydrocarbon is burned in a reaction with oxygen to produce carbon dioxide and water. However, there have been continued technological and engineering problems with the design of fusion reactors that are able to produce electricity or other usable forms of energy.

Even though most of our current energy sources owe their existence directly or indirectly to the sun, it has been difficult for scientists to reproduce the nuclear reactions taking place in the sun in such a controlled manner that fusion energy might be harnessed for commercial purposes. Progress in the design of a fusion reactor has been very slow, with critics saying that fusion power is not going to be possible for the next fifty years or so, if it is possible at all. There is an old saying among fusion scientists that “Fusion enerergy is 20 years away and it always will be!” Scientists working in the field point to slow, but continuing, progress toward their goal of a sustainable, controlled fusion reaction liberating more energy in a fusion reaction that is consumed in initiating that reaction. For governments, subsidization of this very expensive program is politically risky since it has a significant possibility of failure. However, large economic rewards may be reaped if controlled fusion is successful because the fusion fuel is so cheap and plentiful. However fusion energy is so expensive that at least one major fusion research project is funded by an international consortium of seven wealthy nations.

Fusion research and engineering are technically exceedingly challenging. The most difficult scientific problem is how to overcome the long-range repulsive force of positively charged particles as they approach one another. The challenge is to provide enough translational energy to positively charged nuclear particles so that they can come close enough together during collisions to achieve close nuclear contact, whereupon a second type of short range, attractive nuclear force can take over and allows nuclear fusion reactions to proceed. The loss of mass in these nuclear reactions shows up in the products of the nuclear reaction as excess translational energy that is subsequently converted into heat, which is then available for use in a conventional electrical generating system. Contemplated fusion reactors are based upon the formation of the highly stable helium-4 isotope, its great stability offering up very

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**Fig. 10-13** Fusion of deuterium and tritium, forming a helium atom and neutron
large amounts of energy during its formation. For more technical details about fusion, click the following button: F-10-24

**Hybrid fusion and fission reactor – transmuting nuclear waste**

The difficulties in constructing a pure fusion reactor have prompted some nuclear scientists to call for a reactor design that utilizes the fast neutrons originating in a fusion reaction and cause them to interact with the remaining U-238, Pu-239, and some other very long-lived actinides that are present in stored, spent fuel rods. When bombarded with fast neutrons, these nuclei react with fast neutrons and fission into two fragments, giving off one or more neutrons. This fission reaction not only provides heat energy, but converts the long-lived waste products in the fuel rods into much shorter-lived fission products. There is abundant fission fuel in these rods. Destroying bomb grade Pu-239 is also highly desirable. Neutrons from fusion reactions could burn up nearly all of the long-lived radioactive waste in a hybrid reactor. However, as in the case of fusion reactors, this hybrid fusion-fission reactor is currently just a glint in the eyes of a few dreamy nuclear engineers.

**“Low temperature,” “tabletop,” “cold,” and “bubble” fusion**

There have been occasional reports since 1989, given one of the above names, of various experiments that have been carried out at room temperature claiming to have achieved fusion of nuclei. Many of these experiments hinged on the observation of neutrons being given off during the reactions. Many of these experiments have been either difficult to reproduce or to interpret. This is not to say that the scientists, many highly reputable ones, did not observe something unique. A number of scientific reputations have been severely damaged because of the challenge to claims made for having achieved fusion at low temperature. The idea behind most of these claims of successful room temperature fusion is that certain surroundings at the atomic level lower the huge repulsive energies needed to overcome the repulsion between positively charged nuclei and to produce nuclear fusion. The “bottom line” is that, at the time of this writing none of these experiments has been taken to the level of engineering where they might be harnessed for use in a fusion reactor. Indeed, most of the reported reactions are either difficult to reproduce and have not yet been reproduced. Some experiments have produced heat in excess of that expected of any chemical reaction. Many scientists are skeptical that there will ever be successful low temperature fusion experiments, whereas others hold open the possibility that some of these experiments may be on the verge of some new basic discovery that will lead to success with low temperature fusion. Meanwhile, limited, very expensive experiments are continuing at the international level on high temperature fusion research.
Nuclear Weapons and the Problem of Proliferation

The background

Since 1940, about six trillion dollars have been spent on the U.S. nuclear weapons program. During the Cold War with the Soviet Union, the purpose of having these weapons on hair-trigger alert was MAD, mutually assured destruction. The reasoning was that no nation would start a nuclear war knowing this would initiate a devastating counterattack. During this period, there were more than twenty false alarms that threatened to initiate just such world-wide destruction, including one in which a Soviet colonel refused to recommend a counterstrike, correctly suspecting that he was witnessing a false alarm. Despite saving the world from nuclear devastation, he was punished for not following orders. There is a window of fifteen minutes or less to decide whether the U.S. or Russia has ordered a nuclear attack. Once a missile launch has been confirmed on the other side, there are approximately 6 minutes to decide whether to reciprocate with a counterattack, resulting in a wave of unparalleled destruction. Each head of government carries has with him a suitcase with the key to ordering such an attack. There are currently thousands of nuclear weapons on hair-trigger alert in Russia and the U.S. These weapons are programmed to destroy targets in the other’s country. These targets undoubtedly include major cities as well as rocket launch sites.

In 1970 the U.S. signed the Nuclear Non-Proliferation Treaty, which calls for existing nuclear-weapons states to take steps toward disarmament. The Treaty of Moscow Offensive Reduction limits Russia and the U.S. to between 1700 and 2,200 “operationally deployed” warheads by 2012. As of November, 2007, the U.S. had 5,700 and Russia had 5,800 warhead operational (ready to deploy), many of which were still on hair trigger alert. However, the U.S. had 15,000 and Russia had 9,900 stockpiled nuclear warheads. In addition, there are an additional several hundred nuclear weapons in France, the United Kingdom, China, Pakistan, Israel, India, and North Korea.

In the new 2010 START II (Strategic Arms Reduction Treaty) between the U.S. and the Russian Federation replaced the Treaty of Moscow, the number of strategic nuclear missile launchers will be reduced by half. A new inspection and verification regime will be established, but it does not limit the number of inactive stockpiled nuclear warheads, that remain in the high thousands in both the Russian and American inventories. The treaty limits the number of deployed strategic nuclear warheads to 1,550, which is down nearly two thirds from the original STARAT treaty. It will also limit the number of deployed and non-deployed inter-continental ballistic missile (ICMB) launchers equipped for nuclear armaments to 800. The number of deployed ICBMs, SLBMs (Submarine-Launched ballistic missiles) and heavy bombers equipped for nuclear armaments is limited to 700. The treaty allows for satellite and remote monitoring, as well as 18 on-site inspections per year to verify...
limits. These obligations must be met within seven years from the date the treaty enters into force. The treaty will last ten years, with an option to renew up to five years.

Nineteen nations are now known to have programs to develop nuclear weapons or have previously pursued that goal. In total, there are 45 nations are known to have previous nuclear weapons programs, current weapons stockpiles, or the potential to become nuclear weapons holding states. As more nations have acquired nuclear weapons, and extremist groups allegedly have been seeking to obtain nuclear weapons, highly enriched uranium, or bomb grade plutonium (Pu-239), the chances are significantly increased of a single nuclear strike being made where the origin of the weapon is uncertain. It is possible to identify the source of the fissionable material used to construct the nuclear weapon, and there are now attempts to catalog these different materials for faster identification of the material causing a nuclear blast.

The proliferation of nuclear weapons is a major problem. The Non-Proliferation Treaty (NPT) came into force in 1970. Currently there are 189 states party to this treaty. Included among these are the five permanent members of the UN Security Council (United States, Russia, the United Kingdom, France, and China). Four states known or suspected to have nuclear weapons, India, Pakistan, North Korea, and Israel, are not currently signatories to this treaty. The conference is reviewed every five years.

It is worrisome that the security of large amount of fissionable materials in the former Soviet Union has been reported to be less than ideal, and that this material could fall into the hands of those who might use these weapons for either blackmail or for actual attacks. There are also efforts to give former weapons scientists and engineers attractive job offers in other fields to prevent them from offering their skills to non-state entities. One concern is that very early in the nuclear era, the U.S. lent highly enriched uranium to a number of non-nuclear countries for use in new reactors or for scientific and engineering research. It was later realize that this was unwise because of the possibility of its use for constructing nuclear weapons. Some of this highly enriched uranium has been retrieved, but a significant is not accounted for or its return to the U.S. has been refused. One Pakastani nuclear scientist has admitted that he was secretly dealing revealing nuclear weapons secrets to individuals in other non-nuclear countries.

The consequences of a large exchange of nuclear weapon are numerous. Not only would each bomb vaporize a large area, killing many thousands of people in a densely populated area, but would cause a massive firestorm, elevating smoke and particles into the upper reaches of the atmosphere. Simulations of the resulting damage from the detonation of a one megaton nuclear weapon over Manhattan predict the loss of several million lives, mass fires, and radiation exposure. Many other cities would fare just as badly. Climate simulations suggest that the exchange and detonation of a few dozen nuclear weapons would cause significant cooling of the Earth (“nuclear winter”) for many years following the disaster, but these
calculations have been disputed. Nobody is anxious to do the experiment to see who is right.

The world’s nuclear weapons arsenal is aging. Arms experts within the US government and military are pushing for replacement of aging nuclear materials in their current nuclear weapons with new, more reliable nuclear warheads. This has set off a debate as to whether such a program is desirable, necessary, and cost effective, especially if the ultimate goal is nuclear disarmament. A recent budget request has been made to “modernize” the U.S. nuclear arsenal.

**The plutonium problem**

Fissionable nuclear weapons rely on one of two fissionable isotopes, U-235 or Pu-239. The latter isotope is found in all reactors containing uranium fuel. This is the result of the neutron irradiation of U-238, the abundant isotope, giving rise to U-239. This isotope is unstable and beta decays to give neptunium-239, which beta decays to plutonium-239:

\[
\begin{align*}
^{238}_{92}\text{U} + ^1_0\text{n (any energy)} & \rightarrow ^{239}_{92}\text{U} \rightarrow ^{239}_{93}\text{Np} \rightarrow ^{239}_{94}\text{Pu}
\end{align*}
\]  

Pu-239 has a long lifetime (24,000 year half-life). This plutonium isotope is fissionable but differs from U-235 in that it will fission with both fast neutrons and slow neutrons. Thus, there is no need for a moderator and a critical mass of plutonium (as little as one kilogram is sufficient) is all that is necessary to make a fission bomb. However, acquiring this amount of Pu-239 is accomplished by a fairly sophisticated process in which plutonium is separated from highly radioactive fission products in spent reactor fuel rods. This separation process requires skilled workers to operate behind thick barriers using remote controls. Very highly enriched uranium (at least 90% U-235) can also be used as a weapons material.

The deliberate destruction of nuclear weapons is now posing a serious problem. In 1991, the US and Russia agreed nuclear warheads. This amounts to approximating plutonium. Dismantling the nuclear weapons poses little problem in comparison with that of what to do with the plutonium once the bomb is dismantled. With as little as 3 kg of highly enriched uranium or 1 kg of plutonium needed to create a nuclear weapon, there is much concern about the need to tighten the world's defenses against nuclear smuggling and possible terrorism. In 1994, a man was arrested in St. Petersburg, Russia with 3 kg of highly enriched uranium. The density of one kilogram of plutonium is such that it can

![Fig. 10-16 Enough plutonium metal (a critical mass) to make an atomic bomb.]
be contained in one sixth of the volume of the average soft drink can (Fig. 10-16). Therefore the control of nuclear weapons material is an increasingly important international problem. All options thus far considered for getting rid of the plutonium have serious drawbacks for either scientific or political reasons. For example, the plutonium could be used as fuel in special nuclear reactors but non-proliferation treaties forbid this to take place in commercial reactors. Governments could “burn” this plutonium in nuclear reactors just to make it radioactive and too dangerous to be a viable material for proliferation or for terrorists to handle. Another proposed solution is to incorporate this plutonium with high level radioactive waste already scheduled to be vitrified, i.e. incorporated into glass logs. These logs are supposed to be able to withstand long-term weathering and provide indefinite storage in a secure storage site. The latter is easier said than done, since the lifetimes of the radioisotopes are measured in hundreds to thousands of years. What kind of guarantees can be made for political stability in any nation for those time periods?

**The depleted uranium problem**

A fairly abundant by-product of the uranium-235 enrichment process is metallic uranium that has been depleted of the U-235 isotope, thus the name “depleted uranium,” often designated as DU, nearly pure U-238. Uranium metal has a very high density of 19 grams per cubic centimeter in comparison with that of lead (11.3 grams per cubic centimeter). Because of its high density, uranium has been incorporated into tank-penetrating ammunition. It is claimed that the explosion melts the uranium and disperses the liquid uranium as an aerosol with very small particles of uranium oxide, a result of the reaction of the hot metal with atmospheric oxygen. It is claimed that the explosion temperatures between 3,000 and 6,000 degrees centigrade turn the oxide into a nanometer-sized ceramic particle. When these nano particles are inhaled, they provide contact radiation (U-238 is an alpha particle emitter) and a source of heavy metal poisoning. Nano-sized uranium oxide is roughly the size of a virus, invisible, able to penetrate the lung-blood barrier and can be carried by the bloodstream throughout the body. Nano particles can reach sensitive targets, including the lymph nodes, spleen, heart, and access to the central nervous system. Furthermore, claims have been made that the inhalation exposure of troops in the Gulf wars to this depleted uranium aerosol has caused serious illnesses. These claims have not been confirmed by the U.S. military as of this writing. Studies of a former industrial plant in Colonie, New York that processed DU showed high residual levels of radioactivity on plant grounds and nearby housing plots. This radioactivity was intense enough to deem it necessary to remove the soil, sometimes to great depths. Unusually high rates of cancer have also been reported among workers in and neighbors of this plant, but the sample population was not enough to draw statistical conclusions.
Nuclear Weapons, Proliferation, and Terrorism

Nuclear weapons

A nuclear weapon is designed to cause a sudden, uncontrolled, very rapidly escalating fusion or fission chain reaction. Very large amounts of heat are released in a very short period of time causing temperatures to increase so rapidly that they cause the vaporization of everything near the nuclear weapon. The resulting intensely hot gas expands exceedingly rapidly, crushing and pulverizing anything in its way, resulting in the familiar mushroom cloud. There were 120,000 deaths in the U.S. bombing of Hiroshima (Fig. 10-17) and another 70,000 who perished in Nagasaki in late 1945. By 1950 there were an additional 800 deaths attributed to the two bombs.

A fission-based nuclear weapon, commonly called an “atomic bomb,” is constructed either from very heavily enriched, weapons grade uranium-235 or plutonium-239, a byproduct of nuclear reactor operation contained in spent fuel rods. The uncontrolled chain reaction leading to an explosion is initiated by the sudden bringing together of two halves of a critical mass of the fissionable material. The critical mass is the amount of material that must be present within a given volume to cause a self-sustaining nuclear explosion. Large amounts of fission products are suddenly created during the explosion. Thus there is not only damage from the explosion itself, but the mushroom cloud is intensely radioactive and spreads this radioactive “fallout” over large areas downwind of the explosion site. The area contaminated depends on the wind speed and the rate at which the debris falls out of the cloud.

The bomb based on the fusion principle is the “hydrogen -” or “H-bomb.” In this device, an atomic bomb is set off to achieve temperatures high enough to initiate the fusion reaction. Significantly larger amounts of damage result from the H-bomb than from the atomic bomb.
There are two weapons that are of concern. The first is the “suitcase” atomic weapon. The amount of fissionable material needed to construct a nuclear A-bomb is surprisingly small: 50 kg (110 lb.) of U-235 and 10 kg (22 lb.) of Pu-239. A plutonium based bomb could indeed be contained in a volume as small as a suitcase and would be difficult to detect. Because of this, one of the most serious problems the world faces is the safety of stores of weapons grade uranium and plutonium. With the advent of the dismantling of nuclear weapons, there are large amounts of fissionable, weapons grade material in storage at facilities whose security is less than needed to protect it from terrorists. Potential clandestine sales of nuclear weapons components to terrorists is also of concern.

Former Senator Sam Nunn of Georgia has reflected on the impact of the possible use of the existing nuclear weapons on the U.S. and the world:

“If Al Qaeda had hit the trade towers with a small crude nuclear weapon instead of two airplanes, a fireball would have vaporized everything in the vicinity. Lower Manhattan and the financial district would be ash and rubble. Tens of thousands of people would have been killed instantly. Those who survived would have been left with no shelter, no clean water, no safe food, no medical attention. Telecommunications, utilities, transportation, and rescue services would be thrown into chaos.

That would have been just the physical impact. If you were trying to draw a circle to mark the overall impact of the blast – in social, economic, and security terms – the circle would be the equator itself. No part of the planet would escape the impact. People everywhere would fear another blast. Travel, international trade, capital flows, commerce would initially stop, and many freedoms we have come to take for granted would quickly be eroded in the name of security. The confidence of America and the world would be shaken to the core.

From my perspective, we are in a race between cooperation and catastrophe.”

The “dirty” bomb is not a nuclear weapon, but a conventional explosive that scatters a radioactive substance over a relatively wide area. Although the radiation exposure to the public may not be great, the cleanup costs and arrangements for decontamination could be very expensive. There would be high costs of keeping large areas off limits for an extended period of time. Most important, the psychological fear of radiation from the general public probably would be out of proportion to the actual danger.
Radiation coming from radioactive fission products and other sources of ionizing radiation is a two-sided coin. One side is a dangerous safety hazard. On the one side, the radiation is widely used in medicine to trace the movement of deliberately created radioisotopes within the body. Gamma rays from isotopes such as cobalt-60, cesium-137, and iodine-131 is used in treating cancer in radiation therapy. As with the waste from nuclear reactors, the medical waste containing long-lived radioisotopes must be stored for long periods of time in isolated regions, and radioisotopes in these wastes must be kept from getting into ground water.

All except the smallest hospitals have Nuclear Medicine Departments. Radioactive isotopes made in nuclear reactors and accelerators are used in these units as tools in medicine to diagnose various diseases, including heart disease and metastatic cancer, that is, cancer that has spread from its original site to other parts of the body. One of the most common uses is in bone scans. In this diagnostic process, radioactive technetium (Tc-99) is injected into the blood stream and makes its way to the crystalline matrix of the bone, in particular where bone is being produced or where there is a large blood supply. If there is an excess of the radioisotope, this is an indication that there is a tumor, including bone metastases from tumors elsewhere in the body (Figure 10-18). The other common radioisotope procedure used in medical diagnostics is in myocardial perfusion. In this procedure, Tc-99 is injected after the patient is stressed to the maximum allowed for their condition. These isotopes localize in the heart muscle and the patient is immediately imaged with a gamma ray camera that can rotate around the patient. Imaging information stored in a computer allows the reconstruction of a three dimensional representation of the heart. Low radioactivity may represent dead tissue and thus damage to the muscles of the heart. It may also represent low blood flow through the arteries feeding into the heart due to narrowing of these arteries.

In medical research, the radiation from isotopes is used to help visualize of certain molecules in the cell on X-ray film in a process called autoradiography. Radioactive tracers are particularly useful when testing drug metabolism. A radioactive carbon isotope, C-14, is used to follow the compounds (metabolites)
formed as the body degrades the drug. If scientists cannot predict what compounds
the body will make from these new drugs, the radioactive tracer helps to track down
all of the metabolites and identify them chemically and determine their toxicity.
Tritium (H-3) is used to help determine blood volume and body water content, in
research on DNA and other biochemical research, cell kinetics studies, life span
studies, and as a tracer in steroids.

Radioactive isotopes (americium-141) are used in smoke detectors, as gauges and
detectors for filling levels in industry, and are used to detect explosives (Nickel-63)
and to sterilize medical equipment (Cs-137).

**Radiation Chemistry & Biochemistry**

What happens to people when they are exposed to radiation from radioisotopes, a
medical X-ray or a gamma-ray radiation unit? The net result is the transfer of kinetic
energy from either a fast-moving, charged nucleus or a fast-moving electron to cells
of the body. This energy transfer causes ionization and excitation of the water and the
various biological molecules in the cell. The net result of this ionization and
excitation is water decomposition and biochemical damage and generation of small
amounts of heat.

When humans are exposed to sources of ionizing radiation or ingest
radioactive particles or contaminated food, the radioactive decay exposes living
tissues to very fast, energetic electrons called “beta particles.” These fast electrons are
ejected from radioactive nuclei at very high speeds, causing chemical damage when
they slow down, releasing energy in the body’s tissue. The damage arises because the
repulsive forces between the fast moving electron and the electrons in the body
molecules eject large numbers of electrons, causing ionization, and electronically
excite exposed biological molecules.

The ionization and excitation of water molecules in the body ultimately
produces free radicals such as H• and •OH as well as low energy electrons. As we
have seen in our discussions of air pollution (Chapter 5), the OH radical is
responsible for oxidizing air pollutants and allowing them to be scrubbed out of the
atmosphere. In biological systems, the OH radical is not as beneficial and is one of
the most damaging radicals known in all of biochemistry.

The OH radical is a very reactive chemical. It alters certain key biological
molecules such as DNA and proteins. This type of damage is known as the indirect
radiation damage effect since the damage is initially to the water molecule. The
“direct effect” is also thought to be an important part of radiation biological damage.
The fast charged particles resulting from alpha particle (fast helium nuclei) decay,
beta particle decay, and gamma ray emission can directly damage sensitive molecules
such as proteins or DNA by causing ionization or electronic excitation of these
biological molecules. Direct effect damage to these molecules can lead to altered
cellular processes. For example, altered cellular processes are reflected in symptoms
such as burns and blisters if there is a large amount of radiation deposited in a small
area of skin in a short period of time. Mutations and other genetic damage arise from
direct as well as indirect effects on such molecules as DNA and RNA. For further discussions of radiation chemistry click the following buttons:

**G-10-33**  **G-10-34**  **Ch10/RadiationChemistry/p.1**

**Is there any way I can avoid exposure to radiation?**

Nobody can avoid radiation completely. We are all radioactive. There are natural radioactive isotopes of potassium-40 (half-life $\approx 10^9$ years), carbon-14 (half-life $\approx 6000$ years), and hydrogen-3 (tritium half-life $\approx 12$ years) the latter two continuously formed by cosmic rays and incorporated into the body through the water we drink. We’re being exposed constantly to radiation from cosmic rays and naturally-occurring radioactivity in common building materials such as brick and stone. When we fly in an airplane, our exposure level to cosmic rays, which are another form of highly penetrating radiation, is comparatively high.

**Radon in the home**

There is some concern about radiation coming from a naturally occurring radon radioisotope that is evolved as a gas in the ground in certain regions. Radon is a chemically inert noble gas that works its way up through the soil. Both of the U-238 and U-235 isotopes as well as another naturally occurring, long-lived radioactive isotope, thorium-232, form long chains of radioactive decay products that end with the formation of stable isotopes of lead. Each of these chains produces a gaseous radon isotope. One of the decay products in the U-238 chain is radon-222, which has a half-life of about 4 days (Fig. 10-19).

In regions where there is uranium in the soil or in mineral deposits, radon produced by radioactive decay is continually escaping from the ground. Because of the large volume of the atmosphere, the radioactive radon emerging from the ground into the atmosphere is quickly diluted to relatively harmless concentrations. However, houses are built on top of and basements are surrounded by earth. There are nearly always cracks in concrete slabs, foundations, and retaining walls that allow radon gas to leak through. Concrete, itself, is also permeable to radon gas. Thus, radon can build up in the basements or ground floors to surprisingly high levels in some cases because of the lack of ventilation to the outside. More modern houses are especially “tight” for energy-saving purposes, yet allow radon to build up.

![Radon in the home](image)

**Figure 10-19** Radioactive decay chain following the formation of Rn-222. Only radon in this series is a gas.
Radioactive radon-222 gas emits an energetic alpha particle and forms solid polonium-218, an unstable isotope which decays during a series of subsequent radioactive decay products into a stable isotope of lead (Figure 10-19). Thus, while the radon enters the lungs as a gas, if it decays while in the lungs, it quickly becomes a radioactive chemical species that is a solid, not a gas, and therefore remains in the lung going through the rest of its radioactive decay chain while remaining in the lungs. In this decay process, there are large amounts of locally deposited radiation energy from the highly energetic alpha and beta particles. This can cause damage to DNA in lung tissue that ultimately can lead to lung cancer. Statistics are now clearly showing a linkage between radon exposure and lung cancer: the larger the radon exposure, the greater the risk of lung cancer. There appears to be no minimum exposure level that is free of risk, although there are some scientists who debate this assumption.

Individuals are exposed to this radon irradiation in varying levels, depending upon the location of their home, the level of radon in their homes, the time of their exposure to radon and other pertinent factors. While there is still controversy over the "action" levels at which remediation (correction) of the radon problem is recommended, there is no controversy about two items. First, if the radon level in any region of you home is over 20 picocuries per liter (pCi/L, where 1 pCi/L equals 2.22 disintegrations of a radioactive nucleus per minute in a one liter volume of air), action should be taken to reduce radon gas from these levels to a lower value, preferably below 4 pCi/L. Second, if there is a smoker in the household, there is a definite relationship between smoking and radon. That is, smokers who are exposed to higher radon levels will definitely experience increased probability of contracting lung cancer. Radon levels are measured in a two-stage procedure. The first stage is a passive device that is exposed to the ambient air and adsorbs radon from that air. If the radon desorbed from this device indicates high levels (greater than 4 pCi/L) of radon, then further testing by a certified radon contractor is recommended. Radon provides the largest contribution to the radiation exposure burden for humans.
We live in a world surrounded by natural as well as artificial sources of radiation. Some scientists proposed that life evolved, or at least evolution was accelerated, by the exposure of early living systems to high levels of radiation. On the other hand, there are increasingly popular theories that identify the body's continual exposure to radiation as one of the prime causes of the aging processes because of the free radicals induced by the ionization and excitation of key biological molecules and cellular water.

Whether you are for or against nuclear power plants, regardless of their fate, radiation is part of everyone's life. We must learn to live with it and deal with it with understanding.

**Summary**

1. **What are the sources of nuclear energy?**

   Isotopes of hydrogen are unstable in comparison with the He-4 nucleus. When isotopes of H are able to fuse to form a He-4 nucleus in a nuclear reaction, there is a large amount of energy given off in the fusion reaction. In a similar way, certain uranium isotopes are unstable and when they fission, they release large quantities of energy in the fission reaction products.

2. **What are the consequences of the nuclear fission process?**

   Fission of U-235 is induced by thermal (slow) neutrons and causes a fissioning of the resulting U-236 nucleus into fission fragments and one or more neutrons. Both the fission fragments and neutron products from this reaction have very high translational kinetic energy.
3. What are the function and structure of the various parts of the nuclear reactor?

The function of a commercial nuclear reactor is to generate electricity from the energy given off during fission reactions of uranium. Reactor fuel rods contain the fissionable U-235 isotope. The moderator slows down fast neutrons so they can engage in a chain reaction. Control rods help control the rate of this chain reaction by absorbing unwanted neutrons. In pressurized water reactors, pressurized water circulates through the fuel rods carrying heat to a heat exchanger, which causes water in a linked system to turn to steam, which turns the blades of an electricity-generating turbine.

4. What are the ways in which a reactor can go out of control?

Two: (a) a loss of cooling water, which allows heat buildup to the point that it can melt the reactor core; (b) an escalating chain reaction, causing sudden evolution of heat, with consequences of a sudden accompanying pressure buildup, such as rupture of reactor vessel.

5. What are the problems of the disposal of radioactive reactor materials and the various methods proposed to deal with these problems?

The fuel rods are both thermally hot and intensely radioactive for long periods of time. After short-term storage (years) in cooling pools, there should be long term storage (a minimum of tens of thousands of years) in a secure, isolated, geologically-inactive storage facility.

6. What are the problems with the development of a fusion power reactor?

The chief problem is achieving and sustaining the exceedingly high temperatures necessary to induce a self-sustaining fusion reaction in which the heat released from the fusion reaction maintains the high temperature and releases more energy than used to initiate the fusion reaction.

7. In what ways are radioactive nuclei used in medical applications?

Radioactive isotopes are used to pinpoint the location of diseases in the body and to irradiate and destroy cancerous tissues.

8. What naturally occurring radiation can be dangerous to home residents?

In certain regions, naturally occurring, radioactive radon gas seeps into basements and ground floors of buildings and tends to concentrate there if measures are not taken to vent it. Especially if smokers occupy the building, there is a danger of inducing lung cancer.
9. What is the scientific basis for nuclear weapons?

A nuclear weapon is designed to induce a very fast-escalating nuclear reaction whose result is the exceedingly rapid release of heat of fission or fusion that suddenly vaporizes its surroundings and explodes with disastrous consequences.

10. What are the consequences of fallout from a nuclear weapon and from a “dirty” bomb?

A fission weapon releases vast quantities of highly radioactive fission products that mix with the explosion debris to form “fallout.” A “dirty” bomb uses a non-nuclear explosion to disperse radioactive material over a wide area.

**Review Questions**

1. Describe in some detail the mechanism by which the fission process provides usable heat in a nuclear reactor.

2. What is an isotope? Why are isotopes important when considering nuclear energy fuel sources?

3. Why is U-235 used as nuclear fuel rather than U-238? Which of these two isotopes is more abundant in nature?

4. In the nuclear reactor, what is a moderator? a control rod?

5. Was the nuclear chain reaction controlled in the Chernobyl incident? Was it controlled in the Three Mile Island incident?

6. What is the chemical nature of nuclear “fallout”?

7. What are the two different types of sources of heat in a nuclear reactor?

8. Which is potentially the more abundant energy source, fission or fusion? Why?

9. Why is nuclear fusion so difficult to achieve?

10. What does the term “cold fusion” connote?

11. Define half-life?

12. High level radioactive waste from reactors is becoming a serious problem. What is the problem?

13. Summarize the advantages and disadvantages of nuclear power?
14. Nuclear disarmament poses certain problems regarding the disposal of weapons grade material. What are they?

15. Describe four uses of radioisotopes in medicine.

16. What are the properties of ionizing radiations such as alpha, beta, and gamma radiation that cause damage in biological and other systems?

17. Why is it difficult to prove that ionizing radiation caused a particular cancer?

18. Why is it difficult to escape from exposure to ionizing radiation?

19. What are the dangers posed by radon in the home?

20. In what ways can terrorists make use of nuclear devices?

Problems

21. Using the following nuclear masses, 
\[ ^0_1 n - 1.008665; \ ^1_1 H - 1.007825; \ ^2_1 H - 2.01355; \ ^3_1 H - 3.01605; \ ^4_2 He - 4.00260 \]

calculate the mass loss in the following nuclear fusion reaction:
\[ ^2_1 H + ^3_1 H \rightarrow ^4_2 He + ^0_1 n \]

22. Fill in the blanks in the following nuclear equations:
(a) \[ ^2_1 H + ^3_1 H \rightarrow _____ + ^0_1 n \]
(b) \[ ^6_3 Li + _____ \rightarrow ^3_1 H + ^4_2 He \]
(c) \[ ^{235}_{92}U + ^0_1 n \rightarrow ^{118}_{47}_____ + ^{115}_{45}_____ + 3^0_0 n \]

Group and Individual Projects

23. Have a debate on the topic: Should nuclear power plants be eventually shut down entirely or should the nuclear power industry be strengthened and used to provide carbon dioxide-free electric power plants? Be sure to list carefully the pros and cons of each of the two positions and give a timetable for each side.

24. Search the internet and your local library for information on the following subjects: nuclear power, nuclear reactors, nuclear waste, fission, fusion,
Chernobyl, Three Mile Island, nuclear medicine, radiation (alpha, beta, and gamma), radon, nuclear terrorism, dirty bomb.

Readings (to be updated)

5. Nuclear power plants showing their age, Robert Pollard, Union of Concerned Scientists, Dec. 1995,