CHAPTER 4. NUCLEAR CHEMISTRY

Isotopes, Radioactive or Not

All elements exist in more than one isotopic form. As we have learned in Chapter 3, isotopes of an element have the same number of protons and electrons, but different numbers of neutrons. Isotopes of an element differ slightly in mass because of the contributions of the neutrons to their masses. Their chemical activity, determined by the electrons, remains the same.

To a person unacquainted with basic atomic theory, the word "isotope" often has a sinister connotation. The loudly proclaimed statement "This room is full of isotopes!" might be enough to clear the room of occupants, because most people hear of isotopes only in connection with radioactive isotopes. Only a small proportion of naturally occurring isotopes, however, are radioactive. These radioactive nuclei are unstable, and decay by emitting radiation. All elements found in natural sources with atomic numbers greater than 83 are radioactive. What does our chemical knowledge tell us of radioactive isotopes?

First, it is important to emphasize that radioactivity is a property of the nucleus. This fact, first recognized by Marie Curie, means that it is totally independent of chemical properties, those which deal with chemical reactions and hence with electrons. Reading about the treatment of radioactive waste, one may learn the seemingly comforting fact that the waste is "neutralized," referring to the fact that any acidic and hence corrosive properties of the material have been removed. But chemical reactions cannot touch the nucleus, and so radioactive properties cannot be altered by chemical means.

Types of Radiation

Radiation produced by radioactive isotopes is of several different types, each with characteristic properties (Table 4-1). The radiation observed by Curie emanating from radium and used by Rutherford's group to probe atomic structure was of the type called **alpha particles**. Alpha particles have a mass of 4 amu and a charge of +2. They are identical to helium atoms stripped of their electrons. Not all radioactive nuclei, however, are alpha emitters. Beta particles are nuclear radiation with a negative charge and a mass equal to that of an electron. They are indistinguishable in their properties from electrons, but they come from the nucleus, not the electron energy levels. Gamma radiation, the third form of nuclear radiation, differs from the others in that it has no mass, but only energy.

Radiation Type	Radiation Symbol	Mass Number	Charge
Alpha	α or ${}_{2}^{4}He$	4	2+
Beta	β or ${}_{-1}^{0}e$	0	1-
Gamma	γ	0	0

Radioactive Substance	Half-Life
Iodine-131	8.1 days
Strontium-90	28 years
Krypton-85	10.27 years
Plutonium-239	24,000 years

Half-Life

Both the type of radiation and the rate at which radiation is emitted from the nucleus are characteristics of individual radioactive isotopes. The rate at which a radioactive substance decays is described by its **half-life**, the time required for half the substance to decay. To understand the concept of half-life, first let us examine what happens when a radioactive nucleus emits a particle. With the loss of the particle, the identity of the nucleus and hence of its atom is changed. The new element thus formed may be nonradioactive or may be another radioactive isotope. In any case, the original nucleus is no longer present. For that reason, it will no longer emit the characteristic radiation of the original isotope. Eventually, the radioactive isotope will disappear with repeated emissions of radiation, and its characteristic radiation will no longer be evident. How long will this take? The time period can vary from a few seconds to thousands of years. The decay pattern of an isotope, shown in Fig. 4-1, is most simply described by the half-life concept. After one half-life, half the radioactive substance has decayed. At that point, the radioactivity will be half the original value, since the amount of observed radioactivity is proportional to the amount of radioactive substance present. After a second half-life has passed, the radioactivity will be halved again, or will be one-fourth the original radioactivity. In three half lives, again the observed radiation will be halved, leaving one-eighth the original value. The pattern will repeat until the radioactivity is no longer measurable. Table 4-2 shows half-lives of some radioactive isotopes.

Problem example 4-1: The half-life of an isotope of radium is 12 days. If the activity of a sample is 2000 counts per minute, what activity will be measured in 36 days?

In solving problems of this type, making a table like the one below is useful:

Time	Activity
0	2000 cpm
12 days	1000 cpm
24 days	500 cpm
36 days	250 cpm

The table shows that the activity after 36 days is 250 counts per minute.

Problem example 4-2: For an isotope of radium with a half-life of 12 days, how long will it take until a sample which originally contains 5.00 grams of the isotope has decreased to 1.25 g of radium?

Although this problem is phrased differently from the preceding problem it is solved in the same way by setting up a table:

Time	Amount of isotope
0	5.00 grams
12 days	2.50 grams
24 days	1.25 grams

The table shows that after 24 days there will be 1.25 g of radium left.

Nuclear Symbols and Nuclear Reactions

When radioactive isotopes undergo transformations of the nucleus, we need to specify more information to describe these changes than we need for ordinary chemical reactions. In chapters that follow, when writing **chemical equations** that describe the chemical reactions of elements or compounds, we will simply use element symbols like those listed in Chapters 2 and 3. To describe nuclear transformations, we write **nuclear equations**. For nuclear equations, it is necessary to specify both the atomic number and atomic mass for each species so that the correct isotope can be identified.

To familiarize ourselves with the system of notation that describes individual isotopes, let us examine the possible isotopes of the simplest element, hydrogen (Fig. 4-2). The most common isotope of hydrogen has one proton and no neutrons. The atomic mass is always the sum of the number of protons and the number of neutrons, since both protons and neutrons have a mass of 1 amu. Adding up the protons and neutrons for this isotope of hydrogen, 1 + 0 = 1, so the atomic mass of this isotope is 1. The symbol is written as $^{1}_{1}H$. The superscript in this symbol refers to the atomic mass, and the subscript gives the atomic number. In any sample of naturally occurring hydrogen a small amount of another isotope occurs also. It has one neutron in the nucleus as well as one proton.. The atomic mass of this isotope is 1 + 1 = 2 amu, and its symbol is $^{2}_{1}H$. This isotope is sometimes called deuterium, or "heavy" hydrogen. Hydrogen also has a radioactive isotope called tritium, with two neutrons and an atomic mass of 3. Its symbol is $^{3}_{1}H$.

$^{1}_{1}H$	$^{2}_{1}H$	$^{3}_{1}H$
protium	deuterium	tritium

Problem example 4-3: Write the symbol for the isotope of carbon that has 6 protons and 8 neutrons.

> The number of protons gives the atomic number of the isotope, 6, which appears as a subscript. The number of protons plus neutrons gives the atomic mass, 14, which appears as a superscript. The final symbol is $^{14}_{6}C$.

Problem example 4-4: How many protons and how many neutrons in the uranium isotope $^{238}_{92}U$?

The atomic number in the subscript gives the number of protons, 92. The atomic mass in the superscript gives the number of protons plus neutrons, 238. The number of neutrons is 238 - 92 = 146.

When writing nuclear equations it is possible to use either the Greek letter symbol, for example α for alpha particle, or the nuclear symbol which shows the nuclear charge and atomic mass of the particle, as in $^{4}_{2}He$ for an alpha particle. The latter is preferable, for, as we shall see, the additional information about the charge and mass of the particle are very helpful in balancing the nuclear equation.

Nuclear Equations for Radioactive Decay

Now that we are familiar with nuclear symbols, we are able to interpret nuclear equations that describe nuclear transformations. On the left side of the equation are written the species that are present before the nuclear reaction. Species present after the change occurs are written on the right. To begin with a reaction familiar to us from our study of the discovery of radioactivity, let us write an equation for the radioactive disintegration of radium. Actually, there are several isotopes of radium that are radioactive. This equation describes the disintegration of the isotope with mass 226:

$$^{226}_{88}Ra \quad \text{--->} \quad ^{4}_{2}He \quad + \quad ^{222}_{86}Rn \qquad (4\text{-}1)$$

Although there are no numbers in front of the nuclear symbols for the species present, a "1" is understood to be the coefficient in each case. In other words, one atom of radium produces one alpha particle and one other atom. Notice that both the atomic masses and the atomic charges balance on the two sides of the equation. The atomic mass of 226 on the left side of the equation is balanced by 4 + 222 on the right side. The nuclear charge of 88 on the left side is balanced by 2 + 86 on the right side. The new atom with the element symbol Rn, produced as a product of the nuclear equation, is radon, a gas which is in itself radioactive. A new element that is formed in this way as a product of radioactive decay is often called a **daughter**. The element from which it is formed, in this case radium, is called the **parent**.

Problem example 4-5: Uranium-238 is an isotope of uranium with atomic mass 238. It is very commonly found in rocks and soils in low concentrations. Uranium is an alpha emitter. Write the nuclear equation for the radioactive decay of uranium-238, predicting the identity of the element that is formed. Is this new element radioactive?

To solve this problem, follow the general problem-solving strategy of writing down in an organized way what we already know about the problem. In this case, we know that the starting material is U-238 and that an alpha particle is one of the products. In addition, we know both the atomic masses and the atomic charges of both of these. The atomic charge of the U-238 is not given in the problem. But since uranium is an element, we can look up its atomic number in a periodic table, or in any other list of the elements. Putting all this information into equation form gives us:

$$^{238}_{92}\text{U} \quad \text{-->} \quad ^{4}_{2}\text{He} \quad + \quad ?$$

To find the identity of the "mystery element," we use the fact that both the atomic masses and the atomic charges must balance. For the atomic masses to balance, 238 = 4 + ?, where the unknown number is the mass of the new atom. The new atomic mass must be 234. For the atomic charges to balance, 92 = 2 + ?, where the unknown number is the atomic charge of the new atom. This value, 90, must be the total positive charge on the new nucleus. This is also the number of protons in the new atom, or the atomic number. Our nuclear equation becomes:

$$^{238}_{92}\text{U} \quad \text{-->} \quad ^{4}_{2}\text{He} \quad + \quad ^{234}_{90}?$$

Now to determine the identity of our "mystery element," we have only to remember that the atomic number determines the identity of the element. The element of atomic number 90 is thorium, with symbol Th. The final nuclear equation is:

$$^{238}_{92}\text{U} \quad \text{-->} \quad ^{4}_{2}\text{He} \quad + \quad ^{234}_{90}\text{Th}$$

Since thorium is a naturally found element with atomic number greater than 83, we can predict that it is a radioactive element.

Problem example 4-6: Bismuth-214 decays by beta emission. Write the nuclear equation for this radioactive decay.

Once more we must predict the daughter element in order to complete the equation. We begin as in the alpha decay problem to write the nuclear equation, including all information we know:

$^{214}_{83}\mathrm{Bi}$ --> $^{0}_{-1}\mathrm{e}$ + ?

To find the identity of the daughter isotope, we find its atomic mass and atomic charge. Balancing the atomic mass for the equation, 214 = 0 + ?. The atomic mass of the daughter isotope is 214. Balancing atomic charge, 83 = -1 + ?. The atomic number of the daughter is 84. The nuclear equation becomes;

$^{214}_{83}\mathrm{Bi}$ --> $^{0}_{-1}\mathrm{e}$ + $^{214}_{84}?$

What is the identity of the daughter element? The element with atomic number 84 is polonium. You may recall that this was the first new radioactive element discovered by Marie Curie. The final nuclear equation is:

$^{214}_{83}\mathrm{Bi}$ --> $^{0}_{-1}\mathrm{e}$ + $^{214}_{84}\mathrm{Po}$

Nuclear Equations for Artificial Transmutations

Other types of nuclear transformations besides radioactive decomposition can be described by nuclear equations. For instance, the process through which Chadwick discovered the neutron in 1932 involved the bombardment of beryllium with alpha particles, which produced an isotope of carbon and a free neutron.

$^{9}_{4}\mathrm{Be}$ + $^{4}_{2}\mathrm{He}$ ---> $^{12}_{6}\mathrm{C}$ + $^{1}_{0}\mathrm{n}$ (4-2)

A process like this in which a new element is produced through human intervention is called **artificial transmutation**.

A particularly interesting example of artificial transmutation was produced by Irene Curie, the daughter of Marie and Pierre Curie, and her husband, Frederic Joliot. The Joliot-Curies bombarded aluminum with alpha particles, producing a neutron and an isotope of phosphorus.

$$^{27}_{13}Al + {}^{4}_{2}He \text{ --> } {}^{30}_{15}P + {}^{1}_{0}n \qquad (4\text{-}3)$$

The isotope of phosphorus that was produced from this process, to everyone's surprise, proved to be radioactive, thus providing the first example of **induced radioactivity**. Moreover, this radioactivity was of an unusual nature. The particles emitted had the same mass as an electron, but they had a positive instead of a negative charge. These particles were named **positrons**. The nuclear equation which describes this example of positron emission is as follows:

$$^{30}_{15}P \text{ --> } {}^{0}_{+1}e + {}^{30}_{14}Si \qquad (4\text{-}4)$$

Radioactivity and the Human Body

Alpha, beta, and gamma radiation all can damage human tissue as they pass through it. They are called **ionizing radiation** because they can remove electrons from the molecules of the body, forming electrically charged particles, a process called **ionization**. The most serious consequences of ionizing radiation occur as a result of damage to the DNA molecules which are key to cell formation processes in the body. Altered DNA may result in the formation of cancer cells because of scrambling in the transmission of the genetic code. If DNA in reproductive cells is damaged, future abnormalities in offspring may be the result. If the DNA of a fetus is affected, abnormal development can occur.

The dangers of radioactivity were not known at first to the researchers who gave us our knowledge of radioactivity and atomic structure. But the consequences of radiation exposure soon became apparent. Those who met Marie Curie noticed the radiation burns on her hands, and her death from leukemia was caused by her exposure to radiation. In the 1920's workers who were painting luminous numbers on luminous watch dials with radium-containing paint suffered from radiation poisoning when they wet the paint brushes with their tongues, introducing the radioactive substance into their bodies.

The effects on human tissue that has been exposed to nuclear radiation differ depending on the type of radiation. Some types of radiation are more penetrating than others. Alpha radiation, the most massive form of radiation, is the least penetrating form. Even a sheet of paper is adequate to produce shielding from alpha radiation. For that reason there must be direct exposure of the tissue to the alpha source in order for damage to occur.

Beta particles are more penetrating than alpha particles. Wood or metal sheets, however, can provide adequate shielding. Gamma radiation is most penetrating, and hence potentially most damaging, of all. As shown in Chapter 2, they are even higher in energy and hence more penetrating than x-rays. Heavy lead shielding is necessary for protection from gamma rays.

Measurement Units for Radiation

The traditional unit for measuring radiation is the **curie**, defined as 3.7×10^{10} nuclear disintegrations per second. The SI unit for radiation measurement is the becquerel, equal to one disintegration per second. The Becquerel, like other SI units in radiation chemistry, is in less common usage than the older units.

The traditional unit for measuring the absorbed dose of radiation is the **rad**, which measures the amount of radiation energy absorbed by matter or tissue at a specific exposure point. The most useful traditional unit for measuring radiation exposure, however, is the **rem**. This unit takes into account the fact that different types of radiation cause differing types of biological effects. For that reason the rem is used as a unit when the biologic effects of exposure to radiation are being compared.

Radon in Our Homes

The Environmental Protection Agency has warned that the most deadly form of indoor air pollution may be radioactive radon gas. Where does this dangerous substance come from? To understand the process of radon formation, we must use all the knowledge of radioactive processes we have learned.

In equation 4-1 we learned that the decay process of radium produces not only an alpha particle, but also an atom of radon:

$^{228}_{88}Ra \quad \text{--->} \quad ^{4}_{2}He \quad + \quad ^{222}_{86}Rn \quad (4\text{-}1)$

We can say, therefore, that radon is a daughter of the parent nucleus radium. The radon gas that appears in at least one in ten American homes is produced as a disintegration product of radium. What is the source of the radium parent nuclei? Actually, the radon and the radium are only links in a long series of disintegrations known to radiochemists as **the uranium series**.

The uranium series of radioactive nuclei begins with uranium-238, a common component of many natural rock formations, with a half-life of 4.51×10^9 years. In problem example 4-5 we investigated the disintegration of this atom to form Thorium-234.

$^{238}_{92}U \quad \text{-->} \quad ^{4}_{2}He \quad + \quad ^{234}_{90}Th \, (4\text{-}5)$

Thorium itself is radioactive. It emits a beta particle, forming protoactinium-234. In a long chain of successive decays, one radioactive nucleus after another is formed. The radium nucleus which produces the radon daughter is formed as a part of this long series of parents and daughters. Radon, yet another radioactive nucleus, goes on to produce more links in the chain of the uranium series.

Both radon and its daughters are sources of radioactive hazard. Radon, being a gas, mixes with the other gas molecules of the air and spreads far from its source. How far it spreads will depend on the air currents in its vicinity. Often, for instance, the rising column of heated air in a house can create a suction on the basement, drawing up radon-containing air that has originated in rock formations near the basement. Occupants of the house breathe the radioactive radon gas into their lungs. Radon is continually decomposing into daughters which are radioactive solid substances. Thus radioactive exposure in the lungs occurs both from radon and, more importantly, from the penetrating radiation of its daughters, and this exposure appears to be a significant cause of lung cancer. Like some other forms of air pollution, radon appears to act much more potently as a cancer-causing agent in lungs which have been exposed to cigarette smoke.

Factors influencing indoor radon concentrations are sufficiently complex that each home needs to be tested in order to determine its level of radon concentration; similar homes side by side may have widely differing levels. The average indoor radon level is 1.5 picocuries per liter of air. Though authorities differ on the exact correlation of radon levels with lung cancer deaths, an estimate by the National Council on Radiation Protection predicts 9 deaths due to lung cancer for every 1,000 people who are continuously exposed at a level of 4 pCi/L. Studies indicate that energy-efficient homes in New York State have an average radon concentration in their basements of 6 pCi/L, with levels as high as 24 pCi/L found in Pittsburgh, and Northwestern states reporting values as high as 92 pCi/L. Once high radon levels are discovered, action can be taken to inhibit flow of the radon gas to the living areas of the home. These measures can vary from very simple ones like filling cracks in the basement to more complex structural modifications.

Medical Uses of Radiation

Radioactive isotopes are widely used in medicine both for treatment and for diagnosis. High-energy gamma sources like cobalt-60 are effective when used to destroy tumors, because the fast-growing cancer cells are especially susceptible to radiation damage. Side effects may occur as other rapidly-growing cells are affected as well. Bone marrow cells may be affected in their ability to produce infection-fighting white blood cells. Nausea and diarrhea may result from damage to intestinal cells. This weighing of possible side-effects against positive, therapeutic effects is a common medical dilemma. Often, however, the seriousness of the illness, as in cancer therapy, makes the life-saving treatment a welcome alternative.

Use of radioisotopes in diagnosis of illness is a complex subject, because the isotope used varies with the illness and the part of the body that is involved. The general technique involves finding a chemical which will appear in concentrated form in the part of the body that is under study. Then a molecule is made that incorporates a radioactive isotope into that chemical. The isotope then can be traced in the body through its radioactive emanations.

The thyroid gland, for example, takes up iodine from the bloodstream as part of its natural function. If a patient drinks water containing the radioactive isotope iodine-131, the substance quickly concentrates in the thyroid gland, which is located in the neck. Radioactive imaging of this area shows whether the thyroid is functioning normally. The amount of radioactivity involved is so small as to be of minimal risk. Technetium-99^m is a gamma emitter which has seen wide uses as a diagnostic tool that has been incorporated into a variety of molecules, enabling it to produce images in a number of different areas of the body. The letter *m* in its symbol stands for *metastable*, a term for gamma emitters, which emit radiation in the form of energy without changing atomic number or atomic weight.

Nuclear Fission

A turning point in human history arrived with the discovery of the nuclear transformation known as **nuclear fission**. On January 6, 1939 Otto Hahn and Fritz Strassman published in a German scientific journal that, in performing experiments that they hoped would produce artificial radioactivity like the Joliot-Curies had observed, they had produced a new kind of artificial transmutation. In this reaction, called nuclear fission, uranium bombarded with neutrons had split into two elements with much smaller nuclei, isotopes of barium and krypton. Three neutrons were produced as well, as shown in the nuclear equation:

$$^{235}_{92}U + ^{1}_{0}n \dashrightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n \quad (4\text{-}6)$$

Political events were moving very rapidly in Nazi Germany in early 1939. Hitler was soon to seize Czechoslovakia and Poland. Lise Meitner, a prominent physicist, was almost sent to a concentration camp by the Nazis because she was Jewish. Instead she fled from Germany and shared with friends in Stockholm what she felt was the urgent implication of the fission experiment. In addition to the observed fission products, an unexpected amount of energy had been released. Meitner had done a mathematical analysis that showed that this massive energy release was consistent with an equation developed by Albert Einstein as part of his theory of relativity in 1905. According to Einstein, mass and energy were not totally separate after all. Energy was not without mass; its mass was simply so very small it could not be measured. The relationship between mass and energy was given by the equation

$$E = mc^2 \qquad (4\text{-}7)$$

where c, the speed of light, is a very large number, 3.00×10^{10} cm/sec. Squaring this number gives a huge number, 9.0×10^{20}. This means that the amount of mass associated with even a large amount of energy is immeasurably small. The large size of the conversion factor means also that the conversion of even a very small amount of mass into energy would result in the result of quantities of energy hitherto unknown to man.

News of the fission results travelled quickly throughout the scientific world, and laboratories rushed to confirm the results. Before Meitner had arrived in Stockholm in her flight from Germany the Joliot-Curies had already performed the experiment. Robert Frisch, another German refugee working in Bohr's laboratory, confirmed the results as well, as did several American laboratories. Enrico Fermi, a professor at Columbia University who was a refugee from fascist Italy, recognized another important aspect of the new type of nuclear reaction. In addition to barium and krypton isotopes, the reaction produced three neutrons. If these neutrons reacted with other uranium atoms, more fission could result in a "chain reaction". The energy produced could then rapidly multiply with incredibly large amounts of energy released. A single pound of uranium could release as much as energy as forty million pounds of TNT, and would do so spontaneously once the chain reaction was started. Fermi's theory had immense implications. But why hadn't this chain reaction occurred in the many laboratories in which the fission reaction had been performed?

Figure: Each of the three neutrons produced in the fission of U-235 can start another nuclear fission reaction if it encounters another atom of U-235; hence a chain reaction can occur. Each fission reaction releases energy, so that the chain reaction can quickly produce an immense amount of energy: the "atomic bomb."

Neils Bohr and a former student, John Wheeler, proposed at a scientific meeting on February 17, 1939, that two conditions had to be met before the chain reaction could occur. First, the isotope of uranium that undergoes fission, uranium-235, needed to be obtained in pure form. This meant separating this isotope from the other forms of uranium with which it naturally occurred. Second, the reacting neutrons had to be "slow neutrons." The neutrons which are emitted from the uranium nucleus in the fission reaction would have to be passed through a substance called a **moderator** such as graphite in order to slow them down. Only weeks after the first fission reaction had occurred, the world was aware of its immense potential for producing explosive energy, and the manner in which it might be done was known.

By 1940 information about the nuclear fission reaction was no longer being publicly shared. Hitler had conquered Czechoslovakia, which was a source of uranium ore. The Belgian Congo, with its important deposits of uranium, was soon expected to fall under his control. German scientists had been directed to produce an "atom bomb" based on the fission reaction, and Allied scientists felt urgent pressure to develop the technology first. At the suggestion of President Roosevelt, American and British scientists collaborated on the venture, which became known as the Manhattan Project. When France fell to Hitler in June of 1940, Frederic Joliot remained there to work for the resistance, but sent to the British laboratories in Cambridge 165 quarts of heavy water. The hydrogen atoms in heavy water are made of heavy hydrogen or deuterium, the isotope with one neutron in the nucleus. Joliot suggested that it would be useful as a moderator to produce slow neutrons.

The first nuclear reactor, called a **pile** because of the large pile of 12,400 pounds of graphite bricks which served as a moderator, was set up by Fermi on the floor of the squash court underneath the stands of Stagg Field at the University of Chicago. It successfully produced a controlled chain reaction as predicted. It also produced as a by-product plutonium, a man-made element which undergoes nuclear fission as easily as uranium-235. Uranium-238, the more common but non-fissionable isotope of uranium, captured one of the slow neutrons, starting a series of nuclear reactions that produced plutonium:

$$ {}^{238}_{92}\mathrm{U} \quad + \quad {}^{1}_{0}\mathrm{n} \quad \text{-->} \quad {}^{239}_{92}\mathrm{U} \qquad (4\text{-}8)$$

$${}^{239}_{92}U \longrightarrow {}^{239}_{93}Np + {}^{0}_{1-}e \qquad (4\text{-}9)$$

$${}^{239}_{93}Np \longrightarrow {}^{239}_{94}Pu + {}^{0}_{1-}e \qquad (4\text{-}10)$$

Because it was another element and not just another isotope of uranium, plutonium was much more easily purified by separating it from the mixture of the pile. Secret plants at isolated sites in Oak Ridge, Tennessee, and Hanford, Washington purified uranium-235 and plutonium in large quantities. The secret results of the experiments on the nuclear fission chain reaction became known to the world on August 6, 1945, when an atom bomb containing both plutonium and uranium-235 was dropped on Hiroshima, Japan.

Atomic Power from Nuclear Fission

The fission reaction which created the atomic bomb used in World War II is the same that occurs in our nuclear power plants today. Uranium is usually used as nuclear fuel, and boron or cadmium **control rods** are inserted adjustably to absorb excess neutrons and control the speed of the chain reaction. Water, heavy water, or graphite is used as a moderator to slow down the neutrons. However, the uranium-235 used in nuclear power reactors is enriched to only about 3% from the abundance of less than 1% in naturally occurring uranium ores. A atomic bomb requires much purer U-235, about 90% pure.

Figure: In a nuclear power plant the heat generated from nuclear fission is used to produce electrical power, instead of using heat generated from coal. Control rods which absorb neutrons are used to control the chain reaction, and a moderator (usually water or heavy water) is used to slow the speed of the neutrons.

Nuclear Energy: What Are the Prospects?

At the end of World War II the horrors of the atomic blasts at Hiroshima and Nagasaki had made clear to scientists and nonscientists alike the potential for massive destruction that atomic fission had loosed upon the world. Prominent nuclear scientists campaigned for controls on the use of the destructive power of nuclear energy and the development of technologies for its peaceful use. In 1947 an Atomic Energy Commission was established, placing atomic energy under civilian rather then military control. "Atoms for Peace" became the hopeful slogan as the potential of atomic power as a new energy source began to be realized. The first use of the new power source, however, was in Navy submarines. Submarines with nuclear power could stay underwater without need for refueling, and would not require the large quantities of oxygen needed for fuel combustion. In 1955 the first atomic-powered underwater vessel, the Nautilus, was launched. In 1957 the first American power plant began to operate in Shippingport, Pennsylvania, three years after the first Russian atomic power station. By 1988 7.1% of the total energy supply of the United States was provided by nuclear energy; 79.4% of the total French energy output was nuclear, and 67.2% of the Japanese output. Yet in the U.S., 116 planned nuclear plants have been canceled since 1973 -- more than are presently operating-- and no new plants have been ordered since 1978. Nuclear power plants have a lifetime of only twenty to thirty years, after which they are decommissioned, or shut down. Operating a nuclear plant beyond this point is considered unsafe because the constant bombardment of neutrons on metals causes **embrittlement**, a change in the physical properties of the metal that might result in cracking of the reactor vessel under stress. Have the prospects for nuclear power become questionable?

Photo:Yankee Rowe managers descent a spiral staircase at the nation′s oldest commercial reactor, which has shut down permanently. (Color photo, Boston Globe).

The major advantage of nuclear power has always been its viability as an alternative to fossil fuels. This feature is especially important to those countries, like Japan and France, without significant fossil fuel reserves. Awareness of the problems of fossil fuel emissions, notably global warming from carbon monoxide, acid rain from the oxidized sulfur impurities when coal is burned, and photochemical smog and carbon monoxide from auto exhaust, has made alternatives to burning fossil fuels even more desirable. Nuclear power, however, has serious disadvantages, as well, and these have been more resistant to technological solutions than the early proponents of nuclear energy foresaw.

Nuclear radiation is extremely hazardous to the human body. Massive doses of ionizing radiation from a nuclear reactor can destroy enough body tissue to cause death in days. This fact was demonstrated very early in the history of nuclear power in a tragic accident at Los Alamos, New Mexico, on May 26, 1946, when a piece of equipment accidentally slipped and a nuclear explosion was imminent. The Canadian scientist Louis Sloton separated the fissionable material with his bare hands, saving the lives of those about him, and died of radiation poisoning nine days later at the age of thirty-five. Exposure to lower levels of radiation can be damaging, as well. The action of low-level ionizing radiation on the DNA inside the cells of the body has a long-term effect which in a large population can cause a significant increase in cancer-related deaths over time. The magnitude of this effect is controversial, because in order to know the number of deaths caused by a given type of exposure, a large population with this level of exposure must be studied over a long period of time. A recent study of workers at the nuclear facility at Oak Ridge, Tennessee, looked for statistical correlation of radiation exposure and death through 1984 for 8,318 men hired between 1943 and 1972. The study showed that the risk of dying from cancer increased by almost 5% for each rem of radiation exposure. These figures are almost tenfold higher than those found from another long-term study of the effects of radiation exposure, based on data from Japanese survivors of atomic bomb explosions.

Awareness of possible radiation exposure in populations around nuclear reactors increased among the general public after an accident in 1979 at the Three-Mile Island nuclear power plant near Harrisburg, Pennsylvania. Mechanical failures and operator error resulted in a loss of coolant water, partially uncovering the reactor's core and causing a partial meltdown of the core. Though the containment building which surrounds the reactor successfully contained most of the resulting radiation emissions, a small amount of radioactive gases escaped into the atmosphere; the exact quantity released is unknown. In 1986 a massive nuclear explosion at the Soviet Chernobyl nuclear power plant north of Kiev drew international attention as the resulting release of radioactive materials poisoned crops and livestock as far north as Scandinavia. Herds of reindeer that constituted the main food supply of Laplanders north of the Arctic Circle were contaminated as prevailing winds carried radioactive substances hundreds of miles from the explosion, depositing them on the foraging areas of the livestock. The Soviet plant did not have the containment systems of those built in the United States, and flammable graphite was incorporated into its core design. Moreover, most of the safety systems of the plant had been turned off by its operators as they conducted an unauthorized safety experiment. Nevertheless, the massive contamination of land and crops for hundreds of miles around the reactor were a sobering example of the perils of radiation exposure. At least 50 tons of volatile radioactive particles-- ten times the fallout at Hiroshima-- were spread over Byelorussia, western Russia, and the Ukraine. While the iodine 131 and other short-lived radioactive elements have died out, residual gamma radiation from cesium and other longer-lived radioactive elements will persist for a generation, so the final toll of increased death rates from radiation exposure will not be known for many years.

What are the risks of radiation exposure from accidents at currently existing nuclear power plants? Reactor safety is a controversial issue; there is currently no officially accepted study of nuclear power plant safety. A 1985 study by the Nuclear Regulatory Commission estimated that there is a 45% chance of a complete core meltdown within the next twenty years. In a worst-case scenario such a meltdown, the study estimates, up to 100,000 deaths would result in the first year,and 400,000 cancer deaths would ultimately occur. The probability of this worst-case scenario is probably very slight, though to opponents of nuclear power any such risk is unacceptable. Considering the tragedy of the victims of Chernobyl, it is difficult to disagree. Yet experts estimate that coal-generated electricity, from the major type of electrical power plant being built today, results in the loss of about 10,000 lives each year, through mining and transportation accidents and respiratory illnesses caused by air pollution. The choices between coal and nuclear power in this respect are more complex than most people realize. In determining acceptable risk, however, most people do not examine the actual probabilities of death and disease.

Instead, they tend to choose the familiar risk over the unfamiliar one. Moreover, highly publicized incidents involving large numbers of people, as in Chernobyl or an airplane crash, tend to give a strong impression of risk. More people died of air-pollution related respiratory illnesses in 1986 than died in that year at Chernobyl, and far more people die in auto accidents each year than die in airplane crashes. Yet the average person considers nuclear reactors more dangerous than air pollution, and fears air travel more than auto travel. With regard to generating electrical power, regardless of public perception, neither coal nor nuclear power is risk-free.

Nuclear accidents are not the only possible source of radiation, however, from nuclear power plants. As each plant operates, radioactive wastes are generated. Table 4-2 shows the half-lives of some of the radioactive products of a nuclear fission plant.

Notable among these products is plutonium-239, with a half-life of 24,000 years, which is produced when neutrons from the fission reaction enter into a nuclear reaction with the uranium 238 which constitutes about 90% of the uranium in the reactor core. The sequence of nuclear reactions which produces plutonium 239 is as follows:

$$^{238}_{92}U + {}^{1}_{0}n \text{ --> } {}^{239}_{92}U \qquad (11\text{-}1)$$

$$^{239}_{92}U \text{ --> } {}^{0}_{-1}\beta + {}^{239}_{93}Np \qquad (11\text{-}2)$$

$$^{239}_{93}Np \text{ --> } {}^{0}_{-1}\beta + {}^{239}_{94}Pu \qquad (11\text{-}3)$$

The very long half life of the plutonium-239 means that the radioactive waste from the nuclear power plant must be safely contained for at least 240,000 years, or ten half-lives of this substance. The current plan in the United States is to solidify the waste and store it in a remote underground facility at Yucca Mountain in southwestern Nevada. Critics point out that no site can be guaranteed free of earthquakes or other disturbances for thousands of years, and that any solution for disposal of nuclear waste poses a risk for future generations. For now the waste generated at each plant is stored on-site, so any plan for disposing at a remote facility will involve shipping quantities of radioactive material cross-country. Putting the problem of radioactivity from nuclear plants in perspective, the exposure to radioactivity from the radioactive contents of a nuclear power plant is estimated to be 0.001 millirem per year, as compared with 2 millirem per year on a coast-to-coast jet flight or 35 rem per year from the cosmic rays that surround us (Table 4-3).

Nevertheless, the continuing unsolved problem of the safe disposal of nuclear waste must be considered as a serious drawback to nuclear power as a source of electricity.

Photo:A spent fuel bundle stored underwater glows blue at the Vermont Yankee Nuclear Power Station in Vernon, Vt. (Color photo, Boston Globe)

It must be recognized that nuclear fission is not a renewable source of electrical energy. The fission reaction depends, as we learned in Chapter 4, on the availability of fissionable uranium 235. Like the supply of fossil fuels, the supply of uranium 235 from uranium mines will one day be exhausted, a problem that is exacerbated by the fact that only 0.71% of naturally occurring uranium is the fissionable U-235 isotope. One possible way of extending the fuel supply for fission reactors is by using plutonium 239, which is fissionable, and which, as we have seen, is produced as a by-product in nuclear reactors. Special nuclear reactors called **breeder reactors** have been designed that produce usable quantities of plutonium 239 while they operate. Breeder reactors were once considered the energy supply of choice for the future. Serious problems, however, have limited the number of breeder reactors that have been put into production. Construction of the only breeder reactor planned for the United States, at Clinch River, Tennessee, has been halted. One of the problems with the breeder reactor is the design of the reactor. "Fast" neutrons are needed for the production of plutonium, so liquid sodium is used as a coolant instead of water or graphite in the reactor. Sodium reacts explosively if it comes into contact with water; the prospect of highly radioactive sodium metal being involved in a nuclear accident increases tremendously the potential for a massive explosion of radioactive material. Another objection to breeder reactors is the nature of plutonium. Plutonium 239, in addition to being a radioactive substance with the very long half-life of 24,000 years, is chemically toxic. Perhaps worst of all in terms of its potential for causing large-scale fatalities, plutonium 239 can be used to make nuclear weapons, and obtaining fissionable plutonium from a breeder reactor is much simpler than obtaining fissionable quantities of uranium 235 from uranium ore.

The availability of fissionable plutonium from breeder reactors has led to the problem of **nuclear proliferation**, the growth in the number of countries with the potential to use nuclear weapons. The Soviet Union has roughly 30,000 nuclear weapons, the United States 20,000, France 600, Britain 300, and China 300. No other countries admit to having nuclear weapons, but Israel, South Africa, India, and Pakistan are all believed to possess them. By furnishing developing countries like India with the technology to build breeder reactors so they can become self-sufficient with respect to energy, the United States has unfortunately increased the potential for the production of nuclear weapons. The more widespread nuclear weapons become, the greater the possibility that nuclear explosion and radiation release will occur through war, accident, or terrorism. By 1978 approximately 320 kilograms (700 pounds) of plutonium 239 were missing and unaccounted for in the United States. Whether this loss represents simply clerical errors or theft is unknown. Certainly the danger of fissionable plutonium falling into terrorist hands increases as its availability around the world becomes more widespread.

C & E News photo of workers transporting plutonium: The availability of fissionable plutonium from breeder reactors has led to the problem of nuclear proliferation, the growth in the number of countries with the potential to use nuclear weapons.

Nuclear Fusion

While nuclear fission reactions involve the splitting of large nuclei into smaller pieces, **nuclear fusion** reactions involve the joining together of small nuclei to make bigger ones. In that respect these two types of nuclear processes are opposites. They have in common, however, one very important characteristic. In both fission and fusion reactions, vast quantities of energy are liberated. This energy, as we have learned, comes from the conversion of a small amount of mass into energy as predicted by Einstein's equation $E = mc^2$.

The sun's energy is generated by fusion reactions in which hydrogen atoms are converted to helium atoms at temperatures of over 100,000,000 degrees Celsius. Some possible types of fusion reactions are described by the following nuclear equations:

$$4\ {}^{1}_{1}\mathrm{H} \ \text{-->}\ {}^{4}_{2}\mathrm{He} + 2\ {}^{0}_{+1}\mathrm{e} \tag{4-11}$$

$${}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \ \text{-->}\ {}^{3}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} \tag{4-12}$$

$${}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \ \text{-->}\ {}^{3}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \tag{4-13}$$

$${}^{3}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \ \text{-->}\ {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} \tag{4-14}$$

Fusion energy has the potential of being a limitless source of clean energy for mankind. It does requires not require uranium, nor does it produce long-lived radioactive wastes as fission does. Water, one of the most abundant substances on the planet, contains the hydrogen which is the fuel of fusion. The isotope deuterium, or heavy hydrogen, required for most of the fusion reactions listed above, is one of the naturally occurring isotopes of hydrogen. The practical problems of producing usable energy from fusion, however, have not been solved. How can the required temperature of one hundred million degrees Celsius be achieved? And once achieved, how can so much energy be contained? Any known solid substance from which a containment vessel could be constructed would vaporize at such temperatures. Even its atoms would disintegrate, because at this temperature electrons become stripped from their nuclei, forming the electrically charged gas called a **plasma**.

Sadly, the only purpose for which we have been able to use the vast energies of fusion has been destruction. The hydrogen bomb, or "H-bomb," derives its energy from fusion. A fission atomic bomb, or "A-bomb," provides the high temperatures necessary for fusion and thus provides the trigger. In 1952 the United States exploded the first hydrogen bomb at a test site on a remote Pacific island. Other tests followed, confirming the possibility of inducing fusion reactions. Fusion reactions have also been attained in a laboratory setting. The problem of containing fusion has proved to be more intractable. The leading magnetic fusion technology currently is the **tokamak**, in which a momentary fusion reaction is contained within a magnetic field. One such fusion reactor, the Joint European Torus (JET), located in Culham, England, is now at 80% of the break-even point at which more energy is released by the reactor than is required to operate it. Several laboratories in the United States, including the Princeton Plasma Physics Laboratory, the Massachusetts Institute of Technology, General Atomics, and the Lawrence Livermore National Laboratory are conducting tokamak physics experiments as well. An alternative possibility that is being investigated is the use of lasers to create fusion temperatures inside tiny glass beads about 0.1 mm in diameter filled with frozen deuterium and tritium.

Photo:Tokamac reactor

The United States, the Soviet Union, and the European Atomic Energy Community are all currently conducting fusion research. In addition, ITER, the International Thermonuclear Experimental Reactor, is now in the planning stage, with participation from Europe, the United States, the Soviet Union, and Japan. Even the most optimistic observers, however, foresee no commercial applications of fusion energy until the year 2040, and major experimental breakthroughs will have to be made before commercial energy from nuclear fusion is a reality. the potential for a clean, unlimited energy resource is so great that it remains a focus of energy research.

Background Radiation

Clearly, we should protect ourselves from unnecessary exposure to the damaging effects of radiation. It is not possible, however, to reduce radiation exposure to a zero level. Even without man's contributions, the natural world contains sources of radioactivity which we encounter every day.

Cosmic rays originating in our sun and other galactic sources are present throughout outer space. Most of the cosmic radiation which enters our atmosphere consists of positively charged particles, predominantly protons. The atmosphere acts as a protective screen as the cosmic rays interact with its molecules. Some cosmic rays, however, penetrate to the earth's surface where they form a part of the background radiation we are exposed to every day. Recent studies have shown that airline employees who spend a large proportion of their time flying at high altitudes show the effects of their exposure to increased amounts of cosmic radiation.

Nuclear reactions of cosmic rays with molecules in the upper atmosphere produce slow neutrons, which are absorbed by the nuclei of nitrogen, which is the major component of the atmosphere. The nuclear equation for this process shows that the product is an isotope of carbon, carbon-14:

$$^{1}_{0}n \quad + \quad ^{14}_{7}N \quad \text{-->} \quad ^{14}_{6}C \quad + \quad ^{1}_{1}H \qquad (4\text{-}15)$$

Carbon-14 is a radioactive isotope which is a beta emitter:

$$^{14}_{6}C \quad \text{-->} \quad ^{0}_{-1}e \quad + \quad ^{14}_{7}N \qquad (4\text{-}16)$$

The radioactive carbon becomes incorporated into the carbon dioxide of the atmosphere, is incorporated into plants through the process of photosynthesis, and is finally ingested and incorporated into the bodies of animals and humans. Hence, the carbon-containing molecules which form most of our bodies are radioactive... to a very small degree, about 0.8% of our carbon atoms. This radioactive property of the carbon-containing molecules of all living plants and animals is the basis for an ingenious method for determining the age of any material which once was alive, like wood or bone. As soon as the plant or animal dies, it ceases to incorporate new sources of carbon. Its proportion of radioactive carbon-14 slowly diminishes as the carbon-14 nuclei decay. The half-life of C-14 is 5730 years, enabling scientists to date objects which are thousands of years old. In 1988, for example, a small piece of the shroud of Turin, reputed to be Christ's burial robe, was tested,and found to date from the year 1200 at the earliest. (These results have been questioned by other scientists who maintain the sample was mixed with more modern material.) Along with other forms of dating from other radioactive substances like uranium, radiocarbon dating is an indispensable source of information for archaeologists.

Photo: ancient artifacts like this ....have been dated by measuring the radioactivity emitted by C-14.

Carbon is not the only radioactive isotope we encounter daily. Potassium is one of the chief minerals found in our bodies, and 0.012% of natural potassium is the radioactive isotope potassium-40. We have already mentioned the common occurrence of uranium-238 in rocks and soils, and the accompanying presence of the members of its decay series including radon. Table 4-3 shows some of the radiation levels associated with various contributions to the naturally occurring radiation we encounter every day, known as

background radiation.

Radiation and Risk

Background radiation introduces us to a concept we will encounter repeatedly as we learn about exposure to risk. Frequently it is impossible to eliminate all sources of a hazard, in other words to produce a climate of zero risk. In the case of radiation exposure as in other types of risk we encounter, a thorough understanding of the issues involved is essential in evaluating risk and taking sensible precautions against unnecessary harm.

Examination of Table 4-3, which shows average exposures to radiation from some common radiation sources, reveals some interesting facts, especially in relation to common perceptions of risks from radiation. Cosmic rays, an everyday source of exposure most people are unaware of, ranks high in level of radiation exposure, and nuclear power plants, a source of popular anxiety, rank lowest. Cosmic rays and medical X-rays are similar in magnitude as radiation sources for the average person, yet there are important differences between these two types of radiation source. As we have seen, it is impossible to eliminate totally all sources of low-level radiation like cosmic rays or naturally-occurring radioactive isotopes like carbon-14 and potassium-40. Nevertheless, with proper understanding, we can identify and eliminate or minimize unnecessary sources of risk.

Source	Milirem Per Year
Cosmic rays	35
Medical X-rays; therapy	35
Building materials	34
Soil	11
Foods	25
Air	5
Coast-to-coast jet flight	2
Nuclear power plant	0.01

High levels of radon in the home, release of radioactive isotopes into the atmosphere, and unnecessary x-rays are all sources of radiation we should be able to control.

Photo: nuclear power plant (left), jet plane (right). Caption: Which is a greater source of exposure to radiation, regular jet flights or a regular proximity to a nuclear power plant? Most people would guess incorrectly.

CONCEPTS TO UNDERSTAND FROM CHAPTER 4

Radioactivity is a property of the nucleus.

There are three types of natural radiation, alpha, beta, and gamma radiation. Their symbols and properties are described in Table 4-1.

The half-life of a radioactive isotope is the time it takes for half the sample to disappear through radioactive decay.

Both nuclear mass and nuclear charge are conserved in a nuclear equation.

Radioactivity can damage human tissue. The most serious consequences occur as a result of damage to DNA molecules which are key to cell formation processes in the body.

Alpha radiation is the least penetrating form of ionizing radiation. Gamma radiation is the most penetrating form.

The uranium series of radioactive decay involves not only radon, but a series of radioactive daughter molecules.

Nuclear fission reactions are nuclear processes which produce lighter atoms from heavier ones.

Nuclear fusion reactions are nuclear processes which produce heavier molecules from lighter ones.

The relation $e = mc^2$ implies that small amounts of mass lost in nuclear processes are converted to large amounts of energy.

We are exposed every day to background radiation from a variety of sources, both natural and man-made.

Nuclear power plants use the transformation of matter into energy in the nuclear fission reaction as a source of energy. The release of harmful radiation through plant accidents or from long-lived radioactive waste are among the disadvantages of nuclear power.

Embrittlement is a process by which the structural metals in a nuclear reactor become weakened with time because of neutron bombardment.

Breeder reactors are a form of nuclear power plant which generate fissionable plutonium.

The availability of fissionable plutonium from breeder reactors has led to the problem of nuclear proliferation, the growth in the number of countries with the potential to use nuclear weapons.

Controlled nuclear fusion may be a major source of unlimited, non-polluting energy, but major research progress must be made before fusion has commercial applications.

FACTS TO LEARN FROM CHAPTER 4

All elements found in natural sources with atomic numbers greater than 83 are radioactive.

A process in which a new element is produced through human intervention is called artificial transmutation.

Artificial transmutation which produces a radioactive element is called induced radioactivity.

Particles resulting from induced radioactivity which have a positive charge and the mass of an electron are called positrons.

Bombardment of U-235 with slow neutrons produces a fission reaction which releases great amounts of energy (Eqn. 4-6) and which has the potential for a chain reaction.

SKILLS TO LEARN FROM CHAPTER 4

Be able to predict how much radioactive material is left after a given number of half-lives.

Be able to balance nuclear equations.

PROBLEMS TO SOLVE USING CONCEPTS, FACTS, AND SKILLS FROM CHAPTER 4

Name______________________________ Date ____________

4-1. Why would "cold fusion" or room-temperature fusion reactions be desirable? What might be the commercial applications of such a process?

4-2. Fill in the blanks on the following table.

Name	Nuclear symbol	Atomic mass	Atomic charge
Alpha particle			
		approx. 0	-1
	$^{1}_{0}\mathrm{n}$		
Positron			

4-3. Write an example of a nuclear reaction that describes nuclear fission.

4-4. Write an example of a nuclear reaction that describes nuclear fusion.

4-5. Supply the missing symbol in the following nuclear equations:

$^{11}_{6}\mathrm{C}$ --> $^{11}_{5}\mathrm{B}$ + ?

$^{14}_{7}\mathrm{N}$ + $^{1}_{0}\mathrm{n}$ --> $^{14}_{6}\mathrm{C}$ + ?

4-6. Supply the missing symbol in the following nuclear equations:

a. ? --> $^{1}_{0}\mathrm{n}$ + $^{24}_{11}\mathrm{Na}$

b. $^{1}_{1}H$ + ? --> $^{4}_{2}He$

4-7. Write nuclear equations for:

a. The alpha decay of $^{232}_{90}{}^{Th}$

b. The alpha decay of $^{228}_{88}Ra$

4-8. Write nuclear equations for:

a. The beta decay of $^{3}_{1}H$

b. The beta decay of $^{40}_{19}K$

4-9. Write the nuclear equation for positron emission by sulfur-31.

4-10. Technetium 99, used in diagnostic medical imaging, has a half-life of 6.0 hours. How much will be left of a 1.0 gram sample after one day?

4-11. Remains of an ancient campfire were found to contain one-fourth the carbon-14 content of living wood. How old is the campsite? Hint: find the half-life in the chaper.

4-12. Tell whether each statement refers to nuclear <u>fission</u> or <u>nuclear fusion</u>.

a. An example of this process occurs on the sun.
b. Long-lasting radioactive byproducts are formed.
c. Nuclear power plants use this principle.
d. Neutrons are an important part of this reaction.

e. We do not currently have the technology to harness this process.

4-13. List some positive benefits and negative outcomes which can result from the commercial use of radioactive elements. What do you think would be the reaction of Marie Curie to the uses of radioactivity today?

4-14. Which element in the uranium series is most likely to a source of dangerous levels of radioactivity in the US today? Why?

4-15. How do we know which homes have dangerous levels of radon gas? What can be done about excessive radon in the home?

4-16. List the types of radiation from naturally occurring radioactive sources, giving appropriate forms of shielding for each.

4-17. What are cosmic rays? Are they cause for concern? Is everyone equally exposed to them?

4-18. Name the most common sources of background radiation. Which of these is most important?

Consult the half-life values in Table 4.2 in answering questions 19-21: Show your work!

4-19. Breeder reactors produce nuclear fuel in the form of plutonium-239, a highly toxic substance. If radioactive waste becomes contaminated with this isotope, how long will it take for 75% of the plutonium to disintegrate through radioactive decomposition?

4-20. Nuclear fission of uranium-265 can split in a number of possible ways, each with different fission products. One of the possible decay products is strontium-90, a radioactive isotope of the Group 2 element strontium. Because of its chemical similarity of the Group 2 element calcium, strontium-90 is especially hazardous to humans and other living species if ingested, since it can be deposited in the bone along with calcium. Testing of atomic fission weapons in the 1950's resulted in the release of strontium-90 into the atmosphere, with consequent deposition on vegetation and incorporation into the milk supply. What fraction of the strontium-90 produced in 1955 had disappeared through radioactive decay by 1983?

4-21. After the explosion of the nuclear power plant at Chernobyl, Russia in April 1986, radioactive iodine-131 was implicated in thyroid abnormaliites and cancers found in children exposed to the fallout. Will residual iodine-131 remaining from the explosion still be a concern to residents of the polluted areas in 1996?

4-22. Is the final death toll from the Chernobyl disaster known at this time? Explain your answer.

4-23. Discuss the advantages and disadvantages of the breeder reactor.

4-24. Compare the dependence on nuclear power of the United States, France, and Japan. What do you think accounts for the disparities?

4-25. Recently an expert on nuclear power stated: "Older nuclear power plants have been upgraded repeatedly, so that they are safer than when they were first put into service." Can you think of same facts which might challenge this statement?

4-26. What is nuclear proliferation? In your judgment, is it an important problem?

4-27. Do you think any countries should be prohibited from having breeder reactors? Why, or why not?

SOME INFORMATION SOURCES FOR NUCLEAR CHEMISTRY

"Crucibles, the Story of Chemistry from Ancient Alchemy to Nuclear Fission," Fourth Ed., Bernard Jaffe, Dover Publications, 1976.

"Your Good Health," Wm. J. Bennett, Steven E. Goldfinger, and G. Timothy Johnson, eds.,Consumers Union, 1989.

"What You Need To Know To Live with Chemicals," Ralph I Freudenthal and Susan Loy Freudenthal, Hill and Garnett Pub. Inc.,1989.

"Nuclear and Radiochemistry," 3rd ed., G. Friedlander *et al.*, Wiley-Interscience, 1981.

"Archaeological Chemistry: Organic, Inorganic, and Biochemical Analysis," M.V. Orna, Ed., American Chemical Society: Washington, DC, 1996.