Module 11

Nuclear Chemistry, Radioecology, and Stewardship

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Key Terms and Concepts

- atomic Bomb
- atomic number
- chain reaction
- cosmic rays
- critical mass
- curie
- electron
- free radical
- fuel rods
- gamma rays
- gray
- half-life
- ionizing radiation
- isotopes
- mass number
- neutron
- nuclear fission
- nuclear reaction
- nucleus
- plasma
- proton

- rad
- radioactivity
- sievert
- transmutation

Learning Objectives/Outcomes

Upon completion of this module, you should be able to

1. explain the three types of radiation emitted from atomic nuclei.
2. identify radiation as a normal part of the environment.
3. explain what nuclear reactions and equations are.
4. describe how radiation and its effects are measured.
5. define the concept of half-life.
6. explain the process of fission and nuclear waste.
7. explain atomic bombs and fallout.

Overview

The first controlled release of the awesome energies locked in the nuclei of atoms was surely one of the crucial events in the history of humankind. The explosion of the atomic bomb in 1945 demonstrated this enormous destructive power. Not only was it a big step in understanding and manipulating nature, but the sheer magnitude of its potential effects means that all humankind shares and will share the dangers and benefits. The unveiling of nuclear energy as well as the devastation of Hiroshima and Nagasaki pointed to the future dangers from the radioactive nuclei produced by the fission process, which can affect all life on the planet. The future use or non-use of nuclear chemistry in the Arctic depends on a collective wisdom. Chernobyl and Amchitka have left a legacy that the circumpolar North has to deal with. Yet, nuclear chemistry and energy may be part of the equation necessary to achieve a sustainable future for the peoples of the North.

Radioactivity, the phenomenon of an unstable nucleus breaking down and giving off very energetic radiation, was discovered by Antoine Henri Bequerel during his studies on X-rays and fluorescence in uranium. Marie Curie gave it the name radioactivity. The first practical use was that of X-rays in medical imaging. Nuclear radiation can destroy cells and tissues and cause death. However, cell death can be useful in fighting cancer. Since nuclear radiation is all around us in the environment—some of it artificially produced—we need to be aware of both its benefits and burdens.

Lecture

Nuclear Chemistry and Radioactivity

The basic building block of matter is the atom. Evidence based on a century of research showed us that the atom is composed of three basic particles: a proton with a positive charge, an electron with a negative charge, and a neutron with no charge. The protons and neutrons in an atom are located in a very small volume called the nucleus. The electrons are found moving about outside the nucleus. Each atom is characterized by the number of its electrons, its protons, and its neutrons. If the atom is neutral, that is, if it has no net, overall charge, the number of electrons equals the number of protons. An element may be distinguished from another by the number of protons its individual atoms contain; this number of protons is called the atomic number. Each element, then, is characterized by an atomic number equal to its number of protons. For instance, hydrogen (H) has atomic number 1; and it has one proton in its nucleus. Radon (Rn), has atomic number 86, and 86 protons in its nucleus. Each type of atom has a different number of protons in its nucleus.

Atoms of a given element contain the same number of protons but may contain different numbers of neutrons in the nucleus. Atoms that contain the same number of protons but different numbers of neutrons are called isotopes. Unstable isotopes are radioisotopes. Different radioisotopes have different decay products (i.e., breakdown products).

Hydrogen (H) has three isotopes: protium, deuterium, and tritium. All have one proton, but 0, 1, or 2 neutrons, respectively. Since they are neutral atoms, the number of electrons equals the number of protons. Each isotope has its own symbol, which is the atomic symbol plus a left subscript denoting the atomic number, and a left superscript denoting the mass number [$^{2}_{1}H$]. The mass number equals the sum of the number of protons and the number of neutrons. Most elements have several isotopes, which occur naturally on Earth; usually the isotopes of an element differ in their relative abundance, that is, they are not found in equal amounts. For instance, of all hydrogen atoms in the world, 99.985% are $^{1}_{1}H$ and 0.015% are $^{2}_{1}H$; and only trace amounts of $^{3}_{1}H$ exist.

Protons and neutrons are held together by forces that are very strong. These forces are different than the more familiar electrostatic forces, like the ionic bond, because large numbers of protons, each bearing a positive charge, and similar numbers of neutrons, bearing no charge, are held in stable aggregation in a very small volume. There are limits to the stability afforded by these nuclear forces. The phenomenon of radioactivity, observed by Bequerel before the details of nuclear structure were known, is evidence for the long-term instability of some large aggregations of nuclear particles. When a nucleus does adjust from a less stable to a more stable condition by radioactive emission, the energies involved are very large. The energies of nuclear reactions are hundreds of thousands times as much as those associated with the molecular rearrangements encountered in ordinary chemical reactions.

Radioactivity refers to the instability of certain nuclei that leads them to disintegrate spontaneously with accompanying release of energy in the form of electromagnetic radiation and particles with high speeds. Many of these unstable nuclei occur naturally and give rise to background radiation, which accounts for a high percentage of the radiation a person receives during a year. Each year, living organisms receive a certain dose of radioactivity from cosmic and terrestrial sources. Terrestrial sources include carbon-14, strontium-90, and cesium-37 from uranium and thorium ores. In addition, human exposure in the form of medical X-rays and radioactive materials in the diagnosis and treatment of disease is common. Unstable nuclei can be synthesized by using nuclear reactors. No net changes are produced or destroyed in these reactions, though a neutron sometimes appears to split into a proton and an electron. Because different isotopes have different decay products, it is necessary to include the mass number as a left superscript. The sum of the superscripts indicate the mass is balanced, that is, each side of the equation has the same total. In the following alpha decay reaction, 234 = 234:

$$^{234}{}_{92}\mathrm{U} \rightarrow {}^{230}{}_{90}\mathrm{Th} + {}^{4}{}_{2}\mathrm{He}$$

There are three types of transformation by which a naturally occurring radioactive nuclei can decay: (1) emission of alpha particles (42 He nuclei); (2) beta particles (electrons); (3) or gamma rays (photons of electromagnetic radiation with very short wavelengths and very large energies). The emission of gamma rays (photons of energy) results from the shifting of particles within nuclear energy levels. These same modes of decay can be observed in some nuclei made artificially radioactive by nuclear reactions (induced radioactivity).

One of the characteristics of the radioactivity phenomenon is that the nuclear decay occurs spontaneously. It is not influenced by common variations of the environmental conditions in which the radioactive isotopes exist. Different nuclei disintegrate, or decay, at different rates; the rate of decay is given by the half-life of the nuclei. The half-life is the amount of time it takes a sample of the radioactive nuclei to decay to the point where only half of the original amount remains. The longer the half-life, the longer it takes for a sample to decay. The half-lives of many isotopes are very short and, hence, these isotopes are not found naturally on Earth. One example of an unstable isotope is ${}^{3}_{1}$H. Other radioactive nuclei have very long half-lives. Carbon-14 (${}^{14}_{6}$C), is one of the long-lived radioisotopes (radioactive isotopes) of carbon. It has six protons and eight neutrons in its nucleus. The half-life of ${}^{14}_{6}$C is 5,770 years. Radioactive carbon-14 is used to date ancient objects. The decay reaction is

$$ {}^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}e $$

This is a beta decay reaction and it appears as if a neutron is changed to a proton.

There is no way to predict when any one individual nucleus will spontaneously decay by readjusting itself to a more stable arrangement. Only the statistical behaviour of large numbers of an isotope can be measured with reliability. The decay of all radioactive samples follows a similar pattern in that it always takes a particular period of time for half of the atoms in a sample to decay. The graphic form than this breakdown takes is shown in figure 11.1.

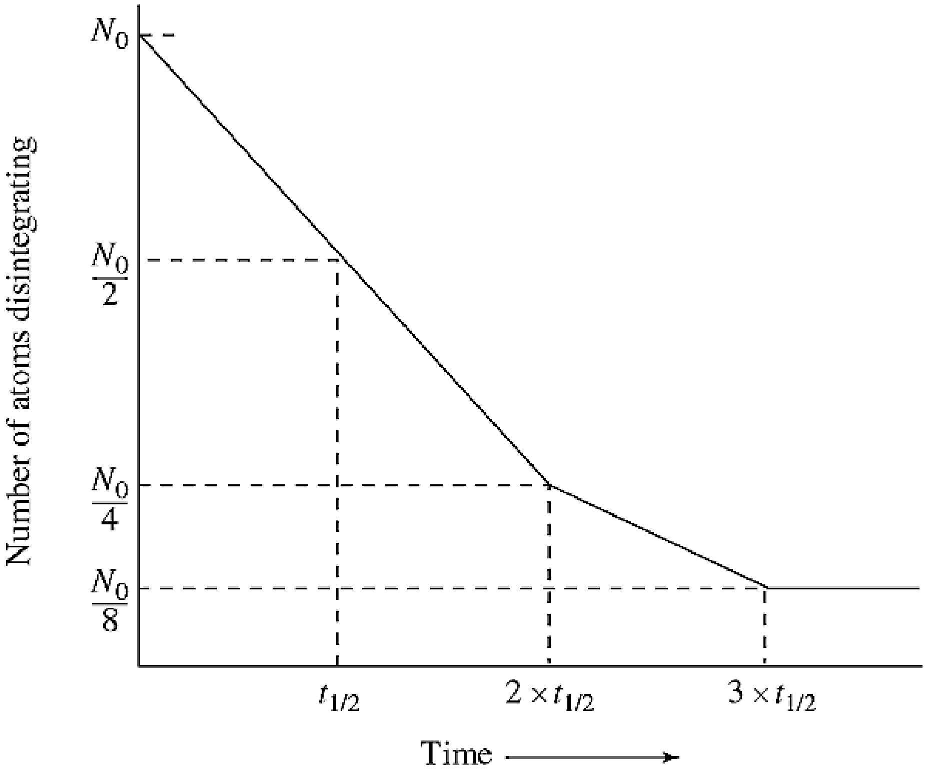

Fig. 11.1 Decay of a radioactive sample. N_0 is the amount of sample in grams and t is time.

The half-life—the time-dependance of the exponential decay of a radioactive source—can be characterized in terms of the mean life: $\tau = t_{1/2}$. For the radioactive source containing initially N_0 radioactive nuclei, this parameter is the time taken for these nuclei to decay to 1/e of their original number, that is, the time taken for N to equal N_0/e.

The detection of radiation is performed by devices that measure the energy of the particles or photons. A swiftly moving charged particle (a or ß particle) or a highly energetic photon (γ ray) will knock the loosely held outer electrons off of atoms or molecules to form ions. These ions can then be manipulated electrically to produce a pulse of electric current that can be recorded. The Geiger counter is a modified cathode ray tube that is best suited to the detection of ß radiation. The amount of radioactivity is measured in disintegrations per second. A curie is equal to 3.7×10^{10} disintegrations per second. Gamma rays are often detected by observing the flashes of fluorescence that they produce when they encounter certain atoms in solid crystals.

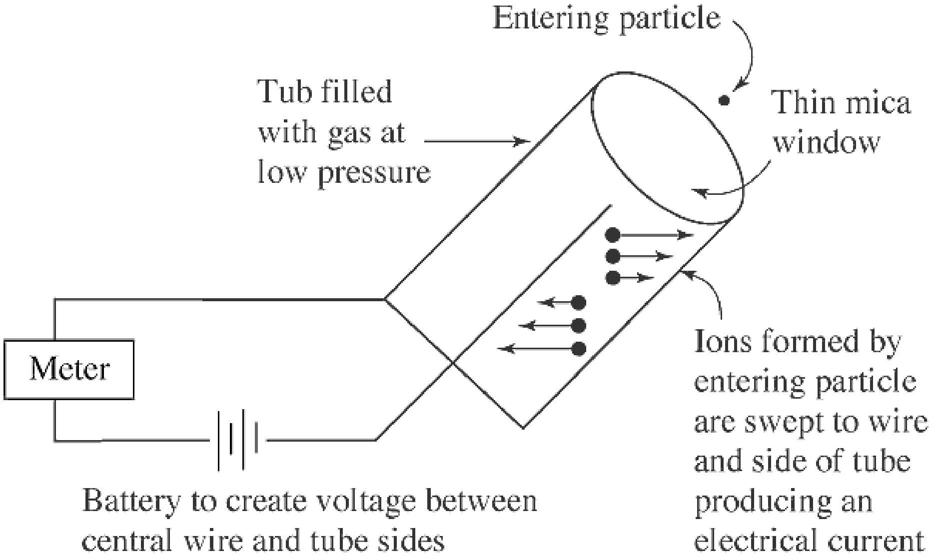

Fig. 11.2 Geiger counter for detecting radiation

Student Activity

Make a poster that will clearly explain the concept of radioactivity to a group of schoolchildren who have no background in science.

Effects of Radioactivity: Health Effects and Waste Stewardship

Health Effects

The damaging effects of radiation on living tissues, as well as on inanimate material, are basically a matter of how the energy of the particle is dissipated. When a high-energy particle or photon encounters a molecule, it disrupts the electronic structure of the bonds. The electrons may be knocked out of the molecule completely, and the molecule may adjust energetically by breaking a bond and fragmenting. This alters the chemical characteristics of the material, many times creating new charged molecules called ions. This is why radioactivity is called ionizing radiation.

Because organisms have a high percentage of water, a sequence of reactions occurs when water is irradiated. The initial step is to make the very reactive fragments H·• and •OH (• is an unpaired electron). A single unpaired electron remains on each; •OH is called the dydroxyl radical. The presence of an unpaired electron, creating a free radical, makes the fragment highly reactive, since the pairing of two electrons constitutes a chemical bond in stable molecules. These fragments bearing a single electron are encountered as transitory intermediates in a variety of reactions. When water is irradiated, immediately following the primary step, two •OH free radicals can combine to form H_2O_2, hydrogen peroxide. This is a reactive chemical tending to give up its extra oxygen to revert to H_2O. The oxygen atom will readily combine with some essential compound converting it into another compound that cannot be used by the cell. If there is dissolved O_2 in the aqueous medium, the H• radical—that is, the other primary free radical—forms the extremely reactive HO_2. This also is highly oxidizing. An oxidizing agent takes electrons from other molecules.

A mammal can repair the damage from the inevitable “background” radiation of normal living circumstances (cosmic rays and the presence of natural radioactivity); but additional radiation may cause irreparable changes in cell metabolism. Two of the greatest health hazards of radioactive waste are the isotopes $^{90}{}_{38}Sr$ and $^{137}{}_{55}$ Cs. The strontium isotope is an energetic beta emitter with a half-life of 28.8 years. The periodic table shows that the element strontium is in Family 2A along with calcium. Because of their chemical similarity, bodily processes will carry both strontium and calcium atoms into bone. The proximity of the emitted beta particles causes deleterious effects on the production of red blood cells by the bone marrow. Cesium-137, also an energetic beta emitter, has a half-life of 30 years. Since cesium is chemically related to sodium and potassium in Family 1A of the periodic table, it would be expected to act as sodium and potassium in a variety of physiological functions.

Marie Curie suffered from anemia and died of leukemia. She was one of the first occupational victims of radiation poisoning. In the last century, industrial workers painting radium on watch dials to make them glow in the dark often developed cancer of the lips. As ionizing radiation, radioactivity is harmful because it has enough energy to knock electrons from an atom to form positively charged ions and free radicals. The degree of damage caused by this ionizing radiation is dependent on factors such as the following:

- the amount of the radiation exposure
- the penetrating power of the radiation
- the distance from the source of the radiation
- whether the source is inside or outside the body
- the type of tissues exposed
- the frequency of exposure

Alpha particles from a source outside the body are the least dangerous, because alpha particles cannot penetrate the skin and enter the body. When an alpha emitter is ingested in contaminated food, or is inhaled by breathing air containing radon gas, damage to internal body tissues can occur. Once inside the body, alpha particles are more damaging than either beta particles or gamma rays because they are more effective in forming ions in the molecules of the surrounding tissues. Alpha particles travel only short distances through tissues and rapidly transfer the bulk of their energy to other molecules, especially water. Beta particles and gamma rays travel farther than alpha particles and transfer their energy over a wider area of tissue. The radiation received per unit area is lower for beta particles and gamma rays, and the ability to form ions is reduced. The greater the penetrating power of a particular source of radiation, the weaker is its ionizing power.

Beta particles, unlike alpha particles, can penetrate the outer layers of skin and clothing and can produce severe burns. They can also cause skin cancer and cataracts. Outside the body, they are more damaging than alpha particles. Gamma rays, because of their great penetrating power, are more dangerous than alpha or beta particles outside the body, but they are less dangerous than the other two inside the body.

X-rays are another type of ionizing radiation. Their penetrating power, and thus their ability to cause tissue damage, lies between that of beta particles and gamma rays.

Body tissues vary widely in their sensitivity to ionizing radiation. Rapidly dividing cells are very vulnerable to radiation. Such cells are found in bone marrow, the lining of the gastrointestinal tract, the reproductive organs, the spleen, and the lymph glands. Embryonic tissue is particularly easily damaged.

Cancer cells, which divide very rapidly, are more easily killed by radiation than are non-dividing healthy cells. While nuclear disintegrations are measured in curies (Ci; 1 Ci is equal to 3.7×10^{10} disintegrations per second). The damage caused by radiation depends not only on the number of disintegrations per second but also on the radiation's energy and penetrating power. Another unit of radioactivity, the rad, measures the amount of energy released in tissue when it is struck by radiation. The rad is being replaced by a new international unit, the gray (1 gray = 100 rad).

An additional unit for measuring radiation is the rem, which takes into account the potential damage to living tissues caused by the different types of ionizing radiation. For X-rays, gamma rays, and beta particles, 1 rad is essentially equivalent to 1 rem; but for alpha particles, because of their greater ionizing ability, 1 rad is equivalent to 10–20 rems. The new international unit to replace the rem is the sievert (1 sievert = 100 rem).

The study of survivors of the bombings during the Second World War of Hiroshima and Nagasaki and of people exposed to fallout from nuclear power plant accidents—such as Three Mile Island near Harrisburg, Pennsylvania, in 1979, and at Chernobyl in 1986—has revealed the effects of short-term doses of radiation given to the whole body (see table 11.1). But there is no agreement on how the effects of these short-term doses can be used to predict the effects of low chronic doses.

Table 11.1: Effects on humans of short-term whole-body exposure to various doses of radiation

Dose (rem)	Effects
<50	Inconsistent effects
50–250	Fatigue, nausea, decreased production of white cells and platelets in blood
250–500	Vomiting, diarrhea, damage to intestinal lining; very susceptible to infections because of low white cell count; hemorrhaging because of impaired clotting mechanism
500–1000	Damage to cardiovascular system, intestinal tract, and brain; death within weeks
1000–10,000	Coma; death within hours at 10,000 rem
100,000	Immediate death

Since the body has the ability to repair radiation damage, many small doses of radiation over a long period of time may produce no lasting effects. A study of survivors of the atomic bomb blasts in Japan found that, although large numbers of those who were closest to the explosions died of cancers, those with limited exposure to the radiation from the bombs were actually living longer than Japanese people who had been far enough from the bombs to avoid exposure. An epidemiological study has shown that US soldiers who participated in nuclear weapons testing in the early 1960s have not had more health problems than veterans who were not involved in the tests. At the present time, there is no agreement on what constitutes a “safe” annual dose of chronic radiation.

Protection against radiation is achieved by having the energy of the particles or photons dissipated by “something else.” Alpha particles are relatively easily stopped because of their bulk and double positive charge. Often a few sheets of paper are sufficient. Beta particles are more penetrating, but usually a few millimetres of a light material such as aluminum or a piece of plywood will absorb them. Gamma rays, since they are not charged particles but photons, are the most difficult to stop. Usually heavy atoms bearing many electrons are most effective. (The gamma photons lose energy by interaction with electrons in atoms.) Lead is most frequently used, although walls of concrete several feet thick are common for large structures needing to be shielded. Contamination of food like fish or milk negates this shielding strategy.

The average dose from all natural sources of radiation is about 300 mrem/yr. It is now recognized that the major natural source is radon, a gas. Radon-222 (half-life of 3.8 days), an alpha emitter, is a naturally occurring product of the decay of uranium-238, a radioisotope of uranium that is present in widely varying concentrations in most soils and rocks. Radon-222 is an odourless, tasteless, inert gas, which, as it escapes from soil and rocks, enters the surrounding water and air. In areas of the North where crustal rocks and soil have high concentrations of uranium-238, radon can seep into homes through basements and, in well-sealed houses, may reach potentially dangerous levels. Inhalation of radon gas can increase the risk of cancer. This effect is because of its alpha- and beta-emitting decay products, which become deposited in the respiratory tract when the gas is inhaled.

Low-level radiation is all around us in the environment. It has been estimated that the average exposure of a member of the US population to ionizing radiation amounts to approximately 300 millirem (mrem) per year (note that a millirem is 0.001 rem). The largest contribution to this average exposure comes from natural sources like radon. The remaining comes primarily from medical procedures, consumer products, and occupational activities. Medical personnel and other people who work near radioactive substances wear badges containing film that is sensitive to radiation, and their exposures are monitored regularly.

Student Activity

Do a literature search on modern concepts of the health effects of radioactivity.

Radioactive Waste Stewardship

An issue that must be faced for the use of nuclear power in the Arctic is the essential requirement that radioactive waste products from reactor operations be isolated from the biological environment. The legacy of cold war with Amchitka and disposed nuclear naval ships is not only a current risk but also raises the issues of intergeneration ethics. The chief source of radioactive waste is the fission product nuclei. To a lesser extent, some radioactivity is present in spent coolant, either gas or liquid, and in any structural parts of a reactor that may have had to be replaced. This induced radioactivity is the consequence of the absorption of neutrons by a wide variety of nuclei.

Hundreds of different radioactive product nuclei are produced by nuclear fission reaction. This occurs because they are usually neutron-rich isotopes of naturally occurring elements. There are more neutrons in a $^{235}{}_{92}U$ nucleus than can be accommodated in stable isotopes of the elements produced by fission. The unstable fission product nuclei will readjust by beta and gamma emissions. Many of these readjustments are highly energetic and have short half-lives. A short storage period behind heavy shielding renders them harmless. However, there are some radioisotopes that have very long half-lives. Long half-lives result in an increased risk of exposure and the danger of ingestion by a living organism.

The uranium fuel for a reactor is usually in the form of a solid, either a metal or its oxide, encased in an aluminum container. When the spent fuel is removed from the reactor, a series of chemical reactions is used to separate the unused uranium and isolate the complex mixture of fission products. Since the activity of the fission products occurs with the decay characteristics typical of all radioactivity: the only recourse against risk is to be sure that the storage of the material is secure and isolated from organisms. This is relatively simply accomplished for short periods of time (up to a year) in well-shielded tanks for liquids.

During this time the great majority of the isotopes with short half-lives decay to harmless levels. The long-lived ones persist; a practical “rule” is that 20 half-lives must pass before the residue of a decaying isotope is safe for biological exposure. Over that period, a sample will have decayed to about one-millionth of its original radioactivity. This requires a storage time of about 600 years for the hazardous $^{90}{}_{38}Sr$ and $^{137}{}_{55}Cs$.

Sufficient sites must be found for the storage of nuclear wastes. These facilities must be impervious to geological change for up to a thousand years. If abandoned salt mines are used, the action of water in the ground is minimal. Salt, an extremely water-soluble compound, would never have been deposited if geological conditions were such that water was seeping through the surrounding rock. Concentrated highly radioactive fission waste in solid form encased in non-porous ceramic material can be deposited in such sites for centuries. In contrast, consider the geological and hydrological instability of an island such as Amchitka in Alaska.

The problem of radioactive waste disposal, not only of the highly active fission products but also of the slightly contaminated process water or even trash from reactor plants, is complex. This may require the setting up of a monitoring system independent of the organizations operating power reactors. An example of such an independent organization is the Consortium for Risk Evaluation with Stakeholder Participation (CRESP), whose reports are public.

Atomic bombs are weapons that produce their energy by a nuclear chemistry reaction. There are two types: hydrogen and fission. For example, the H-bomb is based on a reaction similar to that of the sun: $4\ {}^{1}_{1}H + 2\ {}^{0}_{-1}e \rightarrow {}^{4}_{2}He$ + energy. This is the fusion process for hydrogen. The energy released in both processes is called thermonuclear energy.

Even before the first fission bomb was exploded, scientists predicted that it would produce temperatures like those on the sun and stars. A fusion bomb was built by arranging potentially fusible nuclei inside a fission bomb. The high temperature and compression then would trigger the super explosion. Such a device was built and first tested over an atoll in the Pacific Ocean in 1952. A variety of fusion reactions occur between species of low atomic mass, such as the three isotopes of hydrogen, ${}^{1}_{1}H$, ${}^{2}_{1}H$, and ${}^{3}_{1}H$. They are held in compact form by being chemically combined with lithium, which itself enters into fusion reactions. The ratings of these “H”-bombs are usually expressed in megatons, implying the explosive force of millions of tons of TNT, a “conventional” explosive. The first fission bombs rated in the kiloton range (thousands of tons of TNT).

Student Activity

Do a literature search and make a poster on nuclear waste storage alternatives.

Radioecology and Ethical Issues of Nuclear Energy

Sources of Transboundary Nuclear Weapons Material

Two major periods of worldwide radioactive fallout upon northern Alaska ecosystems occurred: the first and most sustained was during the extensive testing of fission weapons and development of fusion devices in 1946–1959; and the second was during 1961–1964, reflecting atmospheric nuclear weapons test regimes of the former Soviet Union, Great Britain, and the United States. Pulses of further stratospheric fallout deposition occurred during 1965–1970, following nuclear weapons tests of France and the People's Republic of China.

Distribution and ecological relationships of these contaminating events have been extensively documented in several major studies. Also, two major books have discussed these issues: *The Firecracker Boys*, by Dan Oneill (1994), and *Amchitka and the Bomb*, by Dean W. Kohlhoff (2002). Continuing studies in both areas have resulted in many other reports.

Radioactive fallout from weapons testing consists of many nuclear fission products, unexpended fissile material such as uranium-235 (^{235}U), plutonium-239 (^{239}Pu), and a variety of activation products resulting from neutron capture by materials contained in the nuclear devices or in the environment of the explosions. The type and composition of a nuclear device markedly affects the kinds of radioactivity produced; while the location, size, and height of the detonation determine the quantity of radioactivity released to the environment. Two natural radionuclides of atmospheric origin, Hydrogen-3 (^{3}H), and carbon-14 (^{14}C), were produced in significant amounts by nuclear detonations; the 1961–1962 test series of the United States and USSR increased Earth's reservoir of ^{3}H and the ^{14}C by 10%–15%.

Seasonal injection of stratospheric fallout occurs in the upper boundary of the troposphere at about 40°–50° N latitude. Regions with high rainfall accelerate deposition; because of this, northern regions, such as southeast Alaska and southern Canada, have received most of the fallout on the North American continent. Northern Alaska, for example, has received about one-quarter as much fallout per unit area as the lower United States. For Alaska, the highest fallout Cesium-137 (^{137}Cs) was observed in caribou samples from southern high rainfall areas (57°–59° N latitude, 120 cm annual rainfall); median values in caribou from central areas (64°–66° N latitude, 57 cm rainfall); and lowest values were in northern areas 67°–70° N latitude, 30 cm rainfall).

The total fission product mixture resulting from a thermonuclear explosion produces some 80 or 90 different primary radioactive fragments. These fragments decay to form daughter nuclides, many of which are radioactive. The total inventory may comprise up to 200 radioactive species shortly after the explosion, but only a small fraction of these persist for more than a few hours because of their short physical half-lives. About 15 fission product radionuclides are considered of potential biological exposure significance, though only some have nutrient element analogs and are assimilated into the food chain.

Several fallout radionuclides were routinely measured in tundra ecosystem components during an intensive sampling conducted during 1964–1968, including Potassium-40 (^{40}K), Manganese (^{54}Mn), Zinc-65 (^{65}Zn), Strontium-90 (^{90}Sr), Ruthenium-106 (^{106}Ru), Cesium-137 (^{137} Cs), and Cerium-Praseodymium-144 (^{144}Ce-Pr). ^{65}Zn and ^{106}Ru were rapidly lost from lichens into lower soil horizons, while ^{54}Mn was translocated at a slower rate; and the ^{144}Ce-Pr occurred as a nearly uniform label throughout strata and moved deep into the soil. Iron-55 (^{55}Fe) that originated as an activation product in worldwide fallout was measured in Anaktuvuk Pass *nunamiut* during the peak fallout year of 1964 and was found to be eight times the concentration in residents of the State of Washington.

Similarly, the concentration in caribou at that time was eight times that of cattle at comparable locations. Body burdens in the people were 0.06% of the recommended maximum permissible amount and began to decline as fallout levels declined. Some amounts of ^{55}Fe and low levels of Sodium-22 (^{22}Na), and Cesium-134 (^{134}Cs) were measurable in caribou-dependent populations.

^{137}Cs has received most attention because it is easily measured by gamma spectrometric methods. It has a relatively long physical half-life (30 yrs) and is concentrated at successive levels of food webs similar to its chemical analog, ^{40}K. ^{90}Sr is important because it also has a relatively long half-life (28 yrs) and concentrates in bone similarly to its chemical analog calcium-40 (^{40}Ca). Both radionuclides contribute to increased radiation exposures of circumpolar populations associated with caribou/reindeer harvesting.

Plutonium-239 and -240 ($^{239, 240}$Pu), as well as other actinides from worldwide fallout, were measured in lichens and other Alaska tundra ecosystem components during 1967–1979. Peaks occurred in 1968, 1972, 1974, and 1976 that correlated well with periods of high-yield (>200 kilotons) nuclear tests by France and the People's Republic of China. This demonstrated a 1–2 year stratospheric residence time of the test debris. Both ^{238}Pu and $^{239, 240}$Pu showed the same pattern of concentrations, with ^{238}Pu consistently 10% of the $^{239, 240}$Pu values. Americium-241 (^{241}Am) inventories in soils were 9.2 femtocuries per square metre (fCi/m^2) (0.34 mBq/m^2), or 6.4% that of inventories in lichen communities at Anaktuvuk Pass in 1975; in 1976, ^{241}Am inventories of the lichen communities at that location were 23%–28% of $^{239, 240}$Pu inventories. These radionuclides are considered to be of minor importance because they are of low solubility. Poor Pu absorption by ingestion leads to only low levels being transferred through food webs. The long physical half-lives of these isotopes, however, assure their continuing concern.

Worldwide Atmospheric Testing Fallout in Northern Alaska Ecosystems

Radionuclides measured in northern Alaska originated primarily from two major periods of nuclear weapons tests, in 1952–1959 and 1961–1964, during which periods the United States, Britain, and the former Soviet Union conducted extensive series of high-yield (>200 kt) experiments in the atmosphere. Those two periods were followed by smaller fallout contributions form French tests in 1966 and Chinese tests in 1967; India conducted an underground test of a small (10–15 kt) device in May 1974 and the United States performed underground tests on Amchitka in 1965, 1969, and 1971. No detectable fallout on Alaska landscapes resulted from these last four events.

An earlier period of worldwide fallout during the period 1952–1960 is inferred by comparing fallout deposition in New York during that period, to that at Fairbanks during 1960–1979. The initial values of 18–26 nCi/m^2 (666–962 Bq/m^2) in lichen carpets apparently represented a new “background” remaining from the 1952–1958 period of worldwide fallout that occurred prior to the onset of fallout from the later test series.

A correlation of worldwide fallout deposition with precipitation deposited in a geographic region by careful soil sampling has been demonstrated. Inventories of ^{137}Cs in surface (top 5 cm) soils in northern Alaska during 1975–1979 declined at an effective halftime of 3.9±1.4 yr, including minor increases owing to fallout deposition during snow-free summer months. Much of the radionuclide loss from surface soil is a combination of surface erosion during snowmelt and percolation to depths >5 cm. Sampling below lichen carpets showed 5% of ^{137}Cs and 15% of ^{90}Sr inventories were in the humus layer and 3%–4% of both radionuclides were in the organic mineral soil. These values represent integrated fallout deposition over several years. Plutonium in surface soils at northern Alaska and northern Greenland decreased at 0.4–0.5%/yr.

Student Activity

Borrow a Geiger counter from your local school, college, or health centre and measure radiation levels in building materials, rocks, and food items (such as a banana). What did you observe?

Ethical Aspects

Humankind's ability to release the awesome energies of the atomic nucleus has, more than any other single event, brought science into the life of all people. This was a large jump in our considerations of the age-old struggles of conscience with a reverence for life. In the many years since the first mushroom cloud, the field of ecology has shifted our understanding of risk. Initially, the only role for nuclear energy was an offensive weapon of war. Consideration of nuclear energy has the dimension of using a uniquely important resource to meet the energy demands of sustainable economy at peace.

The first issue was with the direct question of whether the use of such a life-destroying weapon has any justification, even in war. This issue was first raised by the Manhattan Project scientists themselves in July 1945, prior to the first fission explosion. Their opinions suggested that the bomb be used for demonstration rather than tactical purposes to convince the Japanese that the war must end. This was judged impractical by those in command; the war was brought to an end with a devastation of an "enemy" people, which may well have saved the lives of thousands of allied military personnel. The sheer magnitude of the effect of a weapon made clear that war could destroy humankind. Those arguing the deterrent effects of the threat of nuclear capability convinced policy-makers. An ecological end of the human race was later forecast. Few incidental scientific goals could be claimed for the detonation of the fusion bomb in 1952.

Another issue was the issue of secrecy. Nearly a decade was required to prove the contention that knowledge revealed by research cannot be other than the property of all. The obvious fact that no nuclear bombs have been exploded over an enemy is a mark of progress.

Humankind's next issue of increasing awareness of the significance of nuclear energy came during the 1950s, when the dangers of fallout from nuclear explosions became the focus of concern. Fallout is the presence of radioactive fission products in the atmospheric dust and rain, which is an unavoidable part of the planet's weather. Any high-altitude fission explosion produces it. A near-ground explosion is worse, since atoms in the earth and ocean swept up in the mushroom cloud are made radioactive by the many neutrons released in the blast.

Some have argued that a fusion bomb is a "cleaner" explosion than is a fission bomb. The argument is based on the fact that the bulk of energy comes from the synthesis of relatively small stable nuclei in contrast to the middle-sized radioactive fission product nuclei. This is true, even though some fission products are inevitably produced by the triggering fission explosion. However, the very large number of neutrons released will react with the nitrogen atoms of the air to produce carbon-14. Normally, cosmic ray neutrons in the atmosphere accomplish the reaction: ${}^{1}_{0}n + {}^{14}_{7}N \rightarrow {}^{14}_{6}C + {}^{1}_{1}H$.

This carbon eventually becomes ${}^{14}CO_2$, which is photosynthesized by plants into mammalian foodstuffs, and thus enters the body. There it acts as a very long-lived ß emitter. In a living animal or plant, this activity amounts to many million emissions per day. Any large increase in the number of neutrons in the atmosphere to make more ${}^{14}_{6}C$ ultimately leads to an increase in bodily radiation, since carbon is the chief element in all bodily tissue. The following reactions suggest how C-14 can be spread in the food chain:

$$6\,{}^{14}CO_2 + 6\,H_2O \xrightarrow{\text{chlorophyll}} {}^{14}C_6H_{12}O_6 + 6\,O_2$$

$${}^{14}C_6H_{12}O_6 \xrightarrow{\text{enzymes}} 2\,{}^{14}C_2H_5OH + 2\,{}^{14}CO_2$$

$${}^{14}C_2H_5OH + 3\,O_2 \longrightarrow 2\,{}^{14}CO_2 + 3\,H_2O$$

Nuclear testing in the atmosphere had possible long-lasting dangers. Immediate damage to cells and even worse prospects of genetic damage to future generations must be recognized as a possibility. The accident at Chernobyl supported this projection. The opinions of scientists often vary. Often extrapolations of possible effects had to be made from very incomplete data on the ultimate deleterious genetic consequences of radiation absorption. Chemist and Nobel laureate Linus Pauling extensively advocated a cessation of nuclear armament testing. He was awarded a Nobel Peace Prize in 1963; he is the only double Nobel laureate. Edward Teller, the scientific leader of the fusion bomb project, vigorously defended the view that the potentially harmful effects of fallout radiation were minimal in comparison to the deterrent effects superior nuclear armaments had on the possibility of armed world conflict. Since there were few unequivocal facts, the debate could not be settled. The positive result of the controversy was the cessation of above-ground testing by major world powers (France and China accepted), and the establishment of more extensive research programs by many nations on the biological effects of small doses of radiation.

There has been a developing awareness of what may be termed a population morality. This applies not only to the past problem of accidental fallout but also to the problem of isolating radioactive wastes from reactors and sites like Amchitka. The actual increase in radiation dose attributed to human-induced nuclear radiations is small. However, the issue is whether we have a moral right to cause any increase at all. The effect on even one unidentifiable human being by our calculated action is putting the “brother’s keeper” role in a new perspective. The same concern is now the basis for the ever-increasing awareness of other ways in which we have contaminated our environment.

Nuclear power is another resource at our disposal that can be used for the benefit of all humankind. All of our stockpiles of plutonium, now ready for insertion in missile warheads, could make electricity. France and the United States are working to reprocess weapons-grade plutonium into a product suitable for power plants. The many uses of radioactive isotopes in medicine, industry, and research can be multiplied many orders of magnitude if we have the proper waste storage and stewardship programs.

Another issue is nuclear power plants that produce pollutants. During the nuclear reactions, which yield heat, materials are produced that are quite radioactive and, hence, pose a pollution threat of their won. These radioactive materials can be divided into two categories: (1) those that escape directly into the environment; (2) and those that must be stored until enough half-lives have passed. Controversy has arisen over the location and methods of containing the nuclear wastes until they are safer. The use of salt mines, burial inside stable mountains, and concrete bunkers (with continuous cooling by water) appear to provide the most likely depositories for these materials.

The radioactive materials that escape into the environment are basically ^{85}Kr and tritium, ^{3}H. The isotope ^{85}Kr is produced as a product of nuclear fission and is contained within the nuclear fuel but escapes as a gas once the fuel is removed from the reactor for storage. Most ^{85}Kr found in the environment comes from nuclear power production. Tritium is produced from a secondary reaction between neutrons and hydrogen atoms in the reactor. The amount of tritium in the environment will increase. Only a small amount of the decay products from ^{85}Kr are damaging.

Lastly, another ethical concern is the association of nuclear material with weapons of mass destruction (WMD), either as atomic bombs or “dirty bombs.” Some reactors produce not only energy by using heat from the U-235 reaction, but also plutonium that could be used as WMD. These reactors that produce plutonium are breeder reactors. A breeder reactor is designed to allow the heat developed to be converted into electrical power; in addition, the extra neutrons not needed to maintain the fission chain reaction convert non-fissionable atoms into fissionable ones. Such a reactor is said to convert stable atoms into fissionable ones. One such conversion is the reaction we have already discussed: $^{238}_{92}\mathrm{U} \rightarrow {}^{239}_{94}\mathrm{Pu}$. Another possible conversion is the similar reaction starting with the thorium to make fissionable $^{233}_{92}$U:

$$^{232}_{90}\mathrm{Th} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{233}_{90}\mathrm{Th} \rightarrow {}^{0}_{-1}\beta + {}^{233}_{92}\mathrm{U}$$

Student Activity

Initiate a discussion group on ethical aspects of the continued use of radionuclides for purposes of health, defence, and energy production.

Study Questions

1. What are the three types of radiation emitted from atomic nuclei?
2. Clearly explain the meaning of half-life in radioactive decay.
3. What is the difference between radionuclide fission and fusion?
4. Provide some examples of how radiation and its effects are measured.

Glossary of Terms

atoll	a ring-shaped coral reef enclosing a lagoon.
atomic bomb	a fission device that releases large amounts of energy, including radiation.
atomic number	the number of protons in the nucleus of an atom of an element.
chain reaction	a self-sustaining nuclear reaction.
cosmic rays	energetic particles, primarily high-energy protons that bombard Earth from space.
critical mass	the amount of fissionable material necessary to sustain a chain reaction; the amount needed to make an atomic bomb.
curie	a measure of radioactivity.
electron	a subatomic particle with a negative charge of one (-1) and a small negligible mass.
free radicals	highly reactive but uncharged chemical species that can be atoms or a group of atoms having an odd number of electrons.
fuel rods	the steel tubes that contain pellets of uranium or plutonium that form the core of a nuclear reactor.
gamma rays	high-energy form of electromagnetic radiation given off by many radioactive substances.
gray	a unit of radiation effects equal to 100 rad.
half-life	the time required for half of the atoms originally present in a sample to decay.
ionizing radiation	radiation capable of dislodging an electron from an atom or molecule and thus making it into an ion or free radical.

isotopes	atoms of an element that contain the same number of protons but a different number of neutrons; atoms of the same element with different masses.
mass number	the sum of the number of protons and neutrons in the nucleus of an atom.
neutron	an electrically neutral subatomic particle found in the nuclei of atoms.
nuclear fission	a nuclear reaction in which a heavy nucleus splits spontaneously or on impact with another particle, with the release of energy.
nuclear reaction	a reaction that either splits or fuses isotopes and generates radioactive species.
nucleus	the very small, dense, positively charged central core of an atom; composed of neutrons and protons.
plasma	the fourth state of matter; high-temperature ionized particles.
proton	a stable elementary particle with a positive electric charge, equal in magnitude to that of an electron, and occurring in all atomic nuclei; a subatomic particle with a mass of 1AMU and a charge of +1.
rad	a unit for measuring the amount of radiation absorbed by living tissue, no matter the type.
radioactivity	the particles and energy released by the nucleus as it undergoes nuclear decay.
radioisotope	an isotope of an element that is unstable and tends to gain stability by giving off radiation.
sievert	a unit of radiation dosage equal to 100 rem.
transmutation	conversion of one kind of atomic nucleus to another.

Supplemental Reading

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