2. PRINCIPLES OF IONIZING RADIATION

2.1 INTRODUCTION

This chapter provides an overview of the principles of ionizing radiation before a discussion of the health effects in Chapter 3.

The primary purpose of this chapter is to provide public health officials, toxicologists, and other interested individuals and groups with an overall perspective of the health physics and toxicology of ionizing radiation. It contains descriptions and evaluations of radiological and toxicological studies and epidemiologic investigations and provides conclusions, where possible, on the relevance of health physics, toxicity, and toxicokinetic data to public health. A glossary and list of acronyms, abbreviations, and symbols can be found at the end of this profile, along with an index. This profile focuses on "ionizing radiation" (alpha, beta, gamma, x ray) as opposed to "non-ionizing" radiation (radio waves, microwaves, radar, ultrasound, visible light, ultraviolet light), so the term "radiation" without further qualification refers only to ionizing radiation.

"Radioactive material" is defined as any material containing radioactive atoms that emit radiation as they transform into other radioactive or stable atoms. The frequently used terms "radiation," and "ionizing radiation" are defined in this toxicological profile as a specific form of radiation that possesses sufficient energy to remove electrons from the atoms in the tissues that they penetrate (Borek 1993). This process is called ionization and is the reason for the name "ionizing radiation." When this energy is received in appropriate quantities and over a sufficient period time, it can result in tissue damage. The clinical manifestations of radiation can be negligible (no effect), acute (occurring within several hours after very large doses), or delayed or latent (occurring several years after the exposure), depending on the dose and the rate at which it was received and the type of damage produced.

All organisms (i.e., bacteria, plants, or animals, including humans) are exposed each day to some amount of radiation. In the United States, as shown in Figure 1-2, 81% of the dose received from radiation comes from natural sources: 55% from radon; 8% from cosmic radiation; 8% from rocks and soil; and 10% from internal exposures to radiation from the radioactive materials in food and water consumed in the daily diet, such as potassium-40 (^{40}K) (NCRP 1987). The remaining 19% of the daily dose may originate from man-made sources; it is composed of medical x ray exposure (11%), nuclear medicinal exposure (4%), consumer products (3%), and other sources (<1%). This last category includes occupational sources, nuclear fallout, the nuclear fuel cycle radioactive waste, hospital radioactive waste, radioactively contaminated sites, and other miscellaneous sources.

Radiation dose is expressed in units of rad and millirad (mrad) (1 rad = 1,000 mrad), or grays (1 Gy = 100 rad) and milligrays (mGy). For administrative, regulatory, and radiation safety purposes, a unit called the rem or the sievert (Sv) (1 rem = 0.01 Sv) is used. For beta and gamma radiation, 1 rad = 1 rem, while for alpha radiation, 1 rad = 20 rem. For the population of the United States, the average annual total effective dose equivalent (natural and anthropogenic), is approximately 360 millirem (mrem) (3.6 mSv) per year (BEIR V 1990).

A survey of the open literature found comprehensive information and many discussions of the biological and toxicological effects of radiation. Much of the information on these effects was obtained from laboratory animal studies and human epidemiological studies (see Chapters 3, 4, and 5). The human data are mostly from studies of World War II atomic bomb survivors, medical patients exposed to radiation and radioactive material, uranium miners and millers, and radium dial painters. A great deal is currently known about the biological, toxicological and toxicokinetic aspects of radionuclides, as well as the general mechanisms of action of radiation. Although much remains to be learned about the specific mechanisms by which radiation exerts its effects, how these effects can be minimized in living tissues, and what the effects of very low doses of radiation over long periods of time will be (see Chapter 3), we know enough to safely use radioactive materials and radiation in commerce, industry, science, and medicine. For the purposes of this toxicologic profile, discussions on the effects of radiation will be limited to alpha (α), beta (β), and gamma (γ) radiation, since these three types of radiation are the most likely to be encountered at Department of Energy (DOE) National Priorities List (NPL) hazardous waste sites (see Chapter 3, Table 3-1). This profile provides an in-depth discussion of radiation biology and radiation toxicology. Chapters 3 and 5 provide a comprehensive overview of a representative cross-section of the available literature that pertains to the effects of radiation, both in humans and laboratory animals. Data on specific radionuclides were used to demonstrate how toxicological effects can occur, but these effects can also be caused by other radionuclides that emit the same or other types of radiation (see Chapters 3 and 5). Several excellent texts and review documents are currently available in the open literature that provide important background material used in developing other sections of this profile (BEIR IV 1988; BEIR V 1990; Cember 1996; Faw and Shultis 1993; Harley 1991; Roesch 1987; UNSCEAR 1993).

This toxicological profile contains tables that summarize the effects of radiation for both humans and laboratory animals (see Observed Health Effects from Radiation and Radioactive Material tables in Chapter 8). In radiation biology, the term "dose" has a very specific meaning. The term "dose" used in these tables refers to the amount of radiation energy absorbed per unit mass by the organ, tissue, or cell; dose is typically expressed either in grays (Gy) or in rad (1 Gy = 100 rad). For example, estimation of the dose to lung tissue or specific cells in the lung from a given exposure to plutonium-239 (^{239}Pu) is

accomplished by modeling the sequence of events involved in the inhalation, deposition, clearance, and transformation of ^{239}Pu within the lung. While based on the current understanding of lung morphometry and experimental data for other radionuclide toxicokinetics, different models make different assumptions about these processes, thereby resulting in different estimates of dose and risk coefficient. The units of measure in the studies that describe the health effects of radiation vary from one report to another. Some studies reported the amount of radioactive material introduced into the body (curies [Ci] or becquerels [Bq] where 1 Ci = 37 billion Bq) when describing the biological effects related to radiation, while other authors reported units of absorbed dose (rad, Gy) or dose equivalent (rem, Sv). Although the units did differ among the many reports, attempts were made to standardize the reporting of doses in units of rad in order to minimize confusion and provide a basis by which dose responses could be determined and evaluated.

An understanding of the basic concepts in radiation physics, chemistry, and biology is important to the evaluation and interpretation of radiation-induced adverse health effects and to the derivation of radiation safety principles. This chapter presents a brief overview of radiation physics, chemistry, and biology and is based to a large extent on the reviews of Eichholz (1982), Hendee (1973), Early et al. (1979), Faw and Shultis (1993), Harley (1991) and Roesch (1987).

2.2 HISTORY, BACKGROUND INFORMATION, AND SCIENTIFIC PRINCIPLES OF IONIZING RADIATION

2.2.1 Historical Perspective on Ionizing Radiation

Ionizing radiation has been present since the earth was created. Before the 1890s, there were only natural sources of radiation such as radiation from cosmic sources, and radioactive material inside the body and in rocks, soil, and air. Much of the radiation exposure was in the form of low-level cosmic and terrestrial radiation. Since radiation cannot be observed using any of the five senses, humans were not aware of its existence.

About 1,800,000 years ago, the only known natural "nuclear reactor" operated for about 100,000 years in the uranium-rich soil around what is now Oklo, Gabon. The first known use of uranium occurred in 79 AD, when Roman artisans were producing yellow-colored glass in a mosaic mural near Naples; this activity produced low levels of radiation. The first reports of adverse health effects that were probably related to radiation from inhaled radon gas and its radioactive progeny occurred around 1400 AD, when a

mysterious malady resulted in the deaths of miners at an early age in the mountains around Schneeberg and Joachimsthal in the Sudetenland (The Czech Republic). This mysterious disease was known as "mountain sickness" and is now believed to have been lung cancer. When mountain sickness was first described, radon was not known and was not linked to the disease until the 1920s, when radon gas was identified as a cause of lung cancer.

It was not until the discovery of mystery rays or "x rays" in 1895 that people began to be aware of the almost magical presence of these invisible "rays" that could allow us to see inside the body. In the summer of 1894, Wilhelm Roentgen began experiments with cathode ray tubes; on November 8, 1895, he observed that a few crystals of barium platinocyanide, which were lying on a table, produced a fluorescent glow. He subsequently discovered that some unknown component ("X") from the cathode ray tube could also penetrate solid substances, and that "x rays" had the same effect on a photographic plate as visible light. What followed was the first "Roentgen exposures," or "Roentgenograms," which were photographs that were able to show the shapes of metal objects locked in a wooden case and the bones inside his wife's hand. A month after his discovery, Roentgen sent a manuscript about his extraordinary findings to the Physical-Medical Association in Wuerzburg, titled *Concerning a New Kind of Ray: Preliminary Report*. Other periodicals such as *Nature* and *Science* published the report in the following year, and Roentgen received wide acclaim for his discovery, both in the scientific and lay communities, in the years to come. Others quickly found practical applications for x rays (also called "Roentgen rays"). In 1896, the first diagnostic x ray in the United States was performed by E. Frost. Within the next 2 years, the first x ray picture of a fetus *in utero* was taken; this was followed by the first use of an x ray in dentistry. Adverse health effects due to exposure to x rays were soon reported. These included a report by Thomas Edison asserting that eye injuries can be produced by exposure to x rays, and a report by Daniel identifying alopecia and erythema (skin reddening) 3 weeks after he radiographed the head of Edison's assistant, Mr. Dudley.

Roentgen's discovery of x rays was followed by Henri Becquerel's discovery of radioactivity in November 1896. Becquerel found that photographic plates that were lying near pitchblende (a uranium ore) were exposed despite being sealed in light-tight envelopes. The exposure, he found, was due to radiations emitted from the pitchblende. Subsequent studies showed that there were three uniquely different radiations, which he called alpha, beta, and gamma. Later, it was shown that Roentgen's x rays and Becquerel's gamma rays were the same kind of radiation.

After these discoveries, scientific interest in the properties of radiation increased dramatically. Radioactive thorium (Th) was discovered by Schmidt in 1898. A few months later, Marie and Pierre Curie isolated polonium (Po) from pitchblende, a variety of the mineral uraninite (largely UO_2), that occurs as a constituent of quartz veins and is a source of radium (Ra) and uranium (U). The Curies later isolated radioactive ^{226}Ra from pitchblende and explained the natural transformation of an unstable atom of a higher atomic number to one of a lower atomic number, referred to as transformation or "decay." The Curies ultimately coined the word "radioactivity." In the years to come, other notable scientists contributed to this new area of science: Villard discovered gamma rays; Rutherford discovered radioactive gas emanating from thorium and coined the term "half-life" and used alpha particles to develop a new theoretical model of the atom (Friedlander et al. 1964); Planck created quantum theory; Einstein discovered mass-energy relationship and photoelectric effect; and Hess reported the existence of "cosmic rays" (ionizing radiation) at high altitudes.

In 1904 Ernest Rutherford said, "If it were ever possible to control at will the rate of disintegration of radio-elements, an enormous amount of radiation could be obtained from a small amount of matter." This statement expressed the obvious implications for the use of radionuclides (in particular uranium and plutonium) in generating large amounts of electric energy in nuclear reactors and in the production of nuclear weapons approximately 40 years later. The use of the "atomic bomb" (this term is somewhat of a misnomer since it is the nucleus from which this energy derives) would make an important contribution to ending the second World War. Much scientific research was required to move from theory to application. "The Manhattan Project" was the code name for the project responsible for taking many of the theoretical ideas on atomic energy proposed since Roentgen's discovery and applying them in a real-world application that would result in the creation of the first atomic weapon.

The Manhattan Project was named for the Manhattan Engineering District of the U.S. Army Corps of Engineers, because much of the early theoretical research on the potential of nuclear energy was done at Columbia University and because the Manhattan District of the U.S. Army Corps of Engineers was located near Columbia University in New York City. Initiated by President Roosevelt on the recommendation of several physicists who had fled Europe, the program was slowly organized after nuclear fission was discovered by German scientists in 1938. Many U.S. scientists began to express the fear that the Germans, under their dictator Adolf Hitler, would attempt to build a fission bomb which would pose a serious threat to the world. It was subsequently decided that the United States must be the

first country to harness this new technology in order to maintain the future balance of world power. In 1942, General Leslie Groves was chosen to lead the Manhattan Project. He immediately purchased a site at Oak Ridge, Tennessee, and constructed the facilities to extract and purify the ^{235}U isotope fuel needed to power the weapon. He also secured a 550-square mile site in Eastern Washington State, later called the "Hanford Works," for the highly secret reactor production and chemical refinement of plutonium metal. The first plutonium in gram quantities was produced in early 1945 by the Hanford "B" reactor, which has been designated a National Historic Site. Groves appointed theoretical physicist Robert Oppenheimer as director of a weapons laboratory built on an isolated piece of land at Los Alamos, New Mexico. In 1945, ^{235}U of adequate purity was shipped to Los Alamos and was used in the testing in the first of two prototype weapons. In the first prototype, one subcritical piece of uranium was fired at another subcritical piece down a gun barrel; the combined pieces formed a supercritical, explosive mass. The second prototype was constructed using plutonium. In the plutonium prototype, the plutonium was surrounded with explosives to compress it into a superdense, supercritical mass far faster than could be done in a gun barrel. The result was tested (Pu weapon only) at Alamogordo, New Mexico, on July 16, 1945, and was the first detonation of an atomic-type weapon. Two more atomic weapons were subsequently manufactured in the United States and detonated over Hiroshima and Nagasaki, Japan, in August 1945. The use of these devices, the most destructive weapons at the time, quickly brought the war in the Pacific to an end, thus saving Allied and Japanese soldiers who would have been lost in a ground invasion of the Japanese mainland using only the conventional weapons of the time.

The two bombs detonated over Japan in the final days of World War II were made from two different types of explosive material. The Hiroshima bomb was made from the highly enriched ^{235}U, extracted from ore containing the much more abundant isotope ^{238}U. This bomb, which was released over Japan's seventh largest city on 6 August 1945, contained approximately 60 kg of highly enriched uranium; its detonation destroyed 90% of the city. The explosive charge for the bomb detonated over Nagasaki 3 days later was provided by about 8 kg of ^{239}Pu, which caused a similar amount of destruction.

Both atomic devices were detonated in the air over the cities. The devastating effects of the bombs depended essentially upon the blast, shock, and heat released at the moment of the explosion, causing immediate fires and destructive blast pressures. Since the bombs were detonated about 600 meters above the ground, only a relatively small proportion of the radioactive fission products was deposited on the ground near the "ground zero" point below the site of detonation. Some deposition occurred in areas near

each city due to local rainfall soon after the explosions, specifically at positions a few kilometers to the east of Nagasaki and in areas to the west and northwest of Hiroshima. Generally, the majority of the fission products were carried into the upper atmosphere by the heat generated by the explosion. When the fallout returned to earth, it contributed to global human radiation exposure.

In Hiroshima, with a resident civilian population of about 250,000 people, an estimated 45,000 died on the first day after the bombing and an additional 19,000 died during the subsequent 4 months. In Nagasaki, with a resident population of about 174,000, an estimated 22,000 died on the first day and an additional 17,000 deaths were reported within the next 4 months. Actual totals may be higher due to unrecorded deaths of military personnel and foreign workers. Teratogenic effects on fetuses were severe among those heavily exposed, resulting in many birth deformities and stillbirths over the next 9 months. No genetic damage has been detected in the survivors' children and grandchildren, despite careful and continuing investigation by the Radiation Effects Research Foundation (RERF), which is a joint Japanese-U.S. foundation. Since then, some of the surviving adults developed leukemias and other cancers (see Chapter 3). The major source of radiation dose to the population in both cities was from the penetrating gamma radiations. The study of the Japanese survivors has proven to be an important historical confluence for major health effects studies at low doses. Prior to World War II, radiation mutagenesis, teratogenesis, and carcinogenesis studies developed along separate lines. The study of the atomic bomb survivor populations allowed these separate lines of research to converge with studies in a single population.

The atomic bombs used in Japan in 1945 and the bombs tested during the following 7 years used ^{235}U or ^{239}Pu. The explosive power of the Hiroshima bomb was about 15 kilotons (equivalent to 15,000 tons of trinitrotoluene [TNT]) and that of the Nagasaki bomb was approximately 25 kilotons. For comparison, the total TNT equivalent explosive power of all atmospheric weapon tests made by the end of 1951 was approximately 600 kilotons.

After 1951, the atomic bombs being tested included hydrogen bombs, which became more sophisticated and had explosive effects about a thousand times greater than those of the Hiroshima and Nagasaki type bombs; by the end of 1962, the total of all atmospheric tests had risen from the 1951 value of 0.6 million tons of TNT equivalent, to about 500 million tons of TNT equivalent. This vast increase in scale was due to the testing of the “thermonuclear” weapons or (hydrogen bombs or “H-bombs”), which depended not on the fission of a critical mass of fissile material alone, but on a two- or three-stage process initiated by a

fission reaction. Briefly, the hydrogen bomb uses the same process that the sun uses to release its tremendous amounts of energy. In the hydrogen bomb, the nuclei of two light atoms (usually hydrogen) are fused together to form a heavier atom, helium. A fission reaction, in which a heavier atom is split into lighter ones, generates the energy to trigger the fusion reaction. The United States exploded its first hydrogen bomb in November 1952 at Eniwetok Atoll in the South Pacific. Atomic weapons development by the United States and other nations continues in the 1990s.

The development of the “atomic bombs” has frequently received more attention than the peaceful use of atomic energy and radiation. Peaceful uses of radiation have also been developed quite successfully. An important application has been in the generation of safe, controlled and long-term power sources for the civilian population. On December 20, 1951, the first usable electricity produced from nuclear energy was manufactured at the National Reactor Testing Station, now called the Idaho National Engineering and Environmental Laboratory (INEEL), in Idaho Falls, Idaho. The electricity produced lit four light bulbs across a room of the Experimental Breeder Reactor I (EBR-I). In 1953, these scientists demonstrated that a reactor could create more fuel than it used, "breeding" fuel from ^{238}U as it created electricity with ^{235}U. EBR-I operated as a research reactor until 1963, at which time EBR-II became active; EBR-II is now a historical monument. In July 1955, Arco, Idaho, became the first U.S. town to be powered by nuclear energy, supplied by power from the Borax-III reactor, an early prototype of a boiling water-type nuclear reactor. The Sodium Reactor Experiment in Santa Susanna, California, generated the first power from a civilian nuclear reactor on July 12, 1957, using sodium instead of water as the primary coolant. The first large-scale nuclear power plant in the world began operating in Shippingport, Pennsylvania, in December 1957. Today, nearly 25% of the electricity generated in the United States (75% in Maine and Illinois and 50% in South Carolina) comes from nuclear power. Other countries generate much larger proportions of their electricity with nuclear energy. In oil-poor countries, such as France, 80% of the electricity is generated with nuclear energy and in Japan nuclear energy accounts for 30% of the electricity generated. Other countries using nuclear power include Canada (17%), Germany (29%), Sweden (47%), and the former Soviet Union (42%) (USNRC 1997b). Although nuclear reactors continue to be used as a source of power for many states and countries, public concerns about nuclear reactor safety have intensified due to well-publicized accidents (see Chapters 4 and 6). However, only two of these accidents involved nuclear power reactors: Three Mile Island and Chernobyl. At Three Mile Island, although the reactor melted down, no one was overexposed or injured, and there was no significant contamination outside the

containment and auxiliary buildings. At Chernobyl, the reactor melted down, causing serious public health consequences which could have been prevented if the reactor design had included a containment building.

Medical uses of machine-produced radiation and radionuclides emitting radiation have also been developed that play a significant role in medical diagnosis and treatment. Controlled amounts of radiation in the form of x rays have been used for a century, and beta particles have used more recently, as an aid in the diagnosis and treatment of diseases in humans and animals. Today, much is known about the health effects of high doses of x rays, as well as other radiation; however, this has not always been the case. In 1947, doctors in Israel and many other countries treated ringworm of the scalp with up to 400 rad (4 Gy) of x rays to cause the hair to fall out (alopecia); it was later found that this treatment regimen led to a greater than expected incidence of thyroid tumors and brain cancers. Radium-224 (^{224}Ra) was used in the treatment of ankylosing spondylitis in Germany in the 1940s; these treatments later were associated with an increased incidence of bone cancers. In addition to x rays, radionuclides such as iodine-131 (^{131}I) and metastable technetium 99 (^{99m}Tc) are being used to successfully diagnose and/or treat a wide range of diseases. Laboratory research has benefitted from the use of radionuclides, typically in the form of radiolabeled tracers that enabled us to learn the details of the biochemistry of health and disease, and to develop new diagnostic techniques and new (non-radioactive) drugs for treatment of disease. Carbon 11 is a short half-life (20 minutes) radionuclide produced in cyclotrons in conjunction with several medical facilities and used in positron emission tomography (PET) studies that enable physicians to see inside the body and precisely locate sites of medical concern.

2.2.2 Basic Information on Ionizing Radiation

Ionizing radiation is any of several types of particles and rays given off by radioactive material, nuclear reactions, and radiation producing machines. Those that are primarily addressed in this profile because of their relevance to public health are alpha particles, beta particles, and gamma rays, which are also called alpha, beta, and gamma radiation. The term “ionizing” refers to the ions or charged atoms and molecules that radiation produces along its path by knocking electrons from atomic orbits. The term “radiation” refers to the way these particles and rays move away or radiate from their sites of production at speeds ranging from a few tenths of the speed of light to the speed of light. Our senses cannot detect radiation since it is odorless, tasteless, and invisible, and cannot be heard or felt. All life on earth is

exposed to low levels of ionizing radiation from terrestrial and cosmic sources every day. This profile will not address non-radiation, such as radiowaves, microwaves, infrared light, visible light, ultrasound, and ultraviolet light.

To explain exactly what radiation is, we begin at the atomic level with atoms, how they come to be radioactive, and how they give off radiation. The materials we call elements are composed of atoms, which in turn are made up of neutrons, protons, and electrons. Protons (positively charged particles) and neutrons (neutral particles with no charge) reside in and primarily comprise the nucleus of any atom, while electrons exist in a "cloud" of orbits around the nucleus. Nuclide is a general term referring to any atom. All atoms of an element have the same number of protons (the number of protons = the atomic number) but may have different numbers of neutrons (this is reflected in the atomic mass or atomic weight of the element). Atoms with the same atomic number but different atomic masses are referred to as isotopes of an element. An isotope is a specific nuclide that is characterized by the composition of its nucleus (by the number of protons and neutrons in the nucleus).

Radioactivity is the characteristic of any atom that is unstable due to the binding of the protons and neutrons within its nucleus. If the number of neutrons is too small or too large for the number of protons, the nucleus is unstable and the atom is said to be radioactive. Radioisotope refers to any radioactive isotopes of an element, and radionuclide is a generic term applying to any radioactive species of any element. Every radioactive nucleus will eventually change its neutron/proton ratio by one of four basic methods and simultaneously emit radiation to obtain a more stable energy configuration. These methods can involve the ejection of an alpha particle (a 2-proton 2-neutron packet) directly from the nucleus, the conversion within the nucleus of a neutron to a proton or a proton to a neutron with the emission of a beta particle and gamma rays, or the splitting or spontaneous fission of the nucleus. Each radionuclide has a unique configuration, so the radiation types, energies, and intensities are unique to it, and these are keys to its identification. The unstable radionuclide is transformed during this process into a new nuclide, which is typically stable. Radionuclides that are still radioactive after one transformation, continue through a series of one or more further transformations until a stable atom is formed. This series of transformations, called a "decay" chain, is typical of the very heavy natural elements like uranium and thorium. The first radionuclide in the chain is called the parent radionuclide, and the subsequent products of the transformation are called progeny, daughters, or transformation products. To summarize, radioactive decay results in a stable nuclide or a less unstable nuclide than the parent.

2. PRINCIPLES OF IONIZING RADIATION

Naturally-occurring radionuclides can be classified as either primordial (present from ancient times) or cosmogenic (produced by cosmic rays). Primordial radionuclides include ^{40}K, ^{238}U, ^{235}U, and ^{232}Th, which have existed since the earth was formed, and the series of radionuclides which each of the last three isotopes transform through before becoming stable isotopes of lead. ^{40}K and about half of the decay chain radionuclides emit beta and gamma radiation while ^{238}U, ^{235}U, ^{232}Th and the other half of their decay chain isotopes emit alpha particles. Cosmogenic radionuclides (^{3}H, ^{7}Be,^{14}C, etc.) are those which are constantly being formed in the atmosphere as cosmic rays and particles from space interact with and transform atmospheric gases. All of these transform by emitting beta and gamma radiation.

Natural background radiation is the combined radiation field produced by the primordial and cosmogenic radioactive materials that are around us plus cosmic radiation from space. Everyone is exposed to this background radiation throughout their lives, at levels that depend on the ambient concentration of those radioactive materials and the altitude at which we live. This background radiation is the major source of radiation exposure to humans and arises from several sources. Natural background dose rates are frequently used as a standard of comparison for doses from various man-made sources of radiation. Man-made radiation is that which is produced by machines, such as x ray machines, and from the decay of radioactive materials that we make. Man-made radioactive materials are those associated with nuclear reactor operation (fission products of uranium and plutonium, and neutron activated by-product material) and high-energy physics equipment (cyclotrons and particle accelerators that bombard targets with charged particles). A number of short-lived radionuclides are produced and used daily in the medical field to diagnose and treat illness. Currently-available equipment and methods can be used to produce radionuclides of any known element, and to even create new elements as scientists attempt to understand the atom more completely. Both naturally occurring and anthropogenic radionuclides have numerous applications in diagnostic and therapeutic medicine, industrial products, consumer products, and in scientific and industrial research. Trace amounts of some specific radionuclides remain in the environment, or have been redistributed in the environment, as a result of these applications and also from the production, testing, and use of nuclear weapons.

2.2.3 Principles of Radioactive Transformation

The stability of an atom is the result of the balance of the forces among the components of the nucleus. High-energy physicists exploring the nucleus have developed the field of quantum mechanics and semiempirical equations to express the binding energies or stability of nucleons in the nucleus. One general finding of those studies is that a nucleus with too many or too few neutrons for a given number of protons is unstable (radioactive) and will eventually undergo transformation to achieve a more stable energy state. Most radioactive atoms can achieve stability in one transformation, but most with atomic masses greater than lead require several successive transformations and are said to be in a decay chain. Any radionuclide can be uniquely characterized by its rate of transformation and the types, energies, and intensities of its radiations. Table 2-1 summarizes the basic characteristics of the more common types of radiation.

Table 2-1. Characteristics of Nuclear Radiations

Radiation	Rest mass[a]	Charge	Typical energy range	Path length		Comments
				Air	Solid	
Alpha (α)	4.0026 amu	+2	4–10 MeV	3–10 cm	25–80 μm	An electron-stripped He nucleus
Negatron (β^-)	5.48×10^{-4} amu; 0.51 MeV	–1	0–4 MeV	0–15 m	0–1 cm	Identical to electron
Positron (β^+)	5.48×10^{-4} amu; 0.51 MeV	+1	0-4 MeV	0–15 m	0–1 cm	Identical to electron except for sign of charge
Neutron	1.0086 amu; 939.55 MeV	0	0–15 MeV	b	0–100 cm	Free half-life: 10.4 min
x ray $_{(e.m.\ photon)}$	–	0	5 keV–100 keV	b	b	Photon from transition of an electron between atomic orbits
Gamma $(p)_{(e.m.\ photon)}$	–	0	10 keV–3 MeV	b	b	Photon from nuclear transformation

[a]The rest mass (in amu) has an energy equivalent in MeV that is obtained using the equation $E=mc^2$, where 1 amu = 9 32 MeV.
[b]Path lengths are not applicable to x- and gamma rays since their intensities decrease exponentially

amu = atomic mass unit; e.m. = electromagnetic; keV = KiloElectron Volts; MeV = MegaElectron Volts

The mode of transformation refers to the way the parent radionuclide undergoes its transformation. The modes that are most significant to public health are alpha and beta decay with the subsequent emission of gamma radiation, although others, such as electron capture and spontaneous fission, also occur in certain radionuclides. Alpha decay occurs among those radionuclides, such as the uranium isotopes, with sufficient excess nuclear energy to eject part of their mass, which is always a packet containing two protons and two neutrons, called an alpha particle. One of two types of beta decay occurs among the other radionuclides, and the type (negatron or positron) depends on the availability of neutrons to stabilize the nucleus. For neutron-rich nuclei, like those formed in nuclear reactors, a neutron converts to a proton and a negatively charged beta particle called a negatron, or simply a beta particle. For neutron-poor radionuclides, such as those produced using particle accelerators, a proton converts to a neutron and the nucleus emits a positively-charged beta particle called a positron. The two types of beta decay are often referred to generically as beta decay. One reason is that both positrons and negatrons are the same particle, an electron, but with different charges. Another mode of transformation for a neutron-poor nucleus is electron capture, in which the nucleus captures an orbital electron and uses it to convert a proton into a neutron. A transformation that is available to only a few radionuclides, such as ^{238}U, is spontaneous fission in which the nucleus splits into two fragments of unequal mass releasing a few neutrons and a large amount of energy. Spontaneous fission neutrons can be used to induce the chain reactions in nuclear reactors. Some radionuclides, such as ^{238}U, follow multiple modes with specific frequencies. The various decay modes often leave the nucleus with a small amount of excess energy that is released as a gamma ray. When alpha, beta, or gamma radiation interact with atoms along their paths, the electrons they knock from interior orbitals produce vacancies which the atom corrects by cascading electrons down from higher energy orbitals to fill the inner ones. In doing so, each electron drops to a lower energy state and the atom emits the energy difference in the form of a photon, called an x ray. X and gamma rays are different in their origin (electron shells or nucleus) but are indistinguishable in their characteristics. Both are massless bundles of electromagnetic energy with sufficient energy to ionize matter. During these transformations, the atom changes from one element into another, modifying the structure of the electron orbitals, and in some cases emitting x rays with energies characteristic of the new element. Characteristic x rays are useful in determining a material's elemental makeup.

The type of radiation may be categorized as charged particle (alpha, negatron, positron), uncharged particle (neutron), or electromagnetic radiation (gamma and x ray). The type of radiation can also be characterized as directly ionizing (alpha, negatron, positron, or proton) or indirectly ionizing (neutron,

gamma, or x ray). X- and gamma rays are categorized as indirectly ionizing radiation because they have no charge and it is the electrons that they liberate from atoms that produce most of the ionization.

Except for delayed neutrons emitted during the nuclear fission process, no radionuclides emit neutrons. For example, californium-252 (^{252}Cf), which undergoes spontaneous nuclear fission as well as alpha transformation, emits neutrons during the fission process. When neutrons are needed for neutron activation analysis or for radiography, they can be produced by a nuclear reactor, a sealed ^{252}Cf source, or a neutron generator (an alpha emitter surrounded by an appropriate target element). An example of such a neutron source is a mixture of a finely powdered alpha emitter, such as ^{210}Po and beryllium (Be). The alpha particle bombards the ^{9}Be isotope to produce ^{12}C and a neutron.

Each radionuclide has a characteristic rate of decay called the half-life, which is the time it takes for 50% of its atoms to decay. Each radionuclide transforms at a constant rate, which is independent of the temperature, pressure, or chemical form in which it exists. A high rate of transformation leads to a short half-life, while a long half-life means a slow rate of transformation. During one half-life, 50% of the radioactive atoms transform; during the next half-life, 50% of the remaining radionuclide transforms, and so on. For example, ^{32}P has a half-life of about 14 days. If one starts with 100 µCi of ^{32}P on day 1, on day 14 there will be exactly one-half, or 50 µCi of ^{32}P remaining. After another 14 days pass, exactly 25 µCi of ^{32}P will remain, and so on. This decrease in radioactivity is illustrated in Figure 2-1.

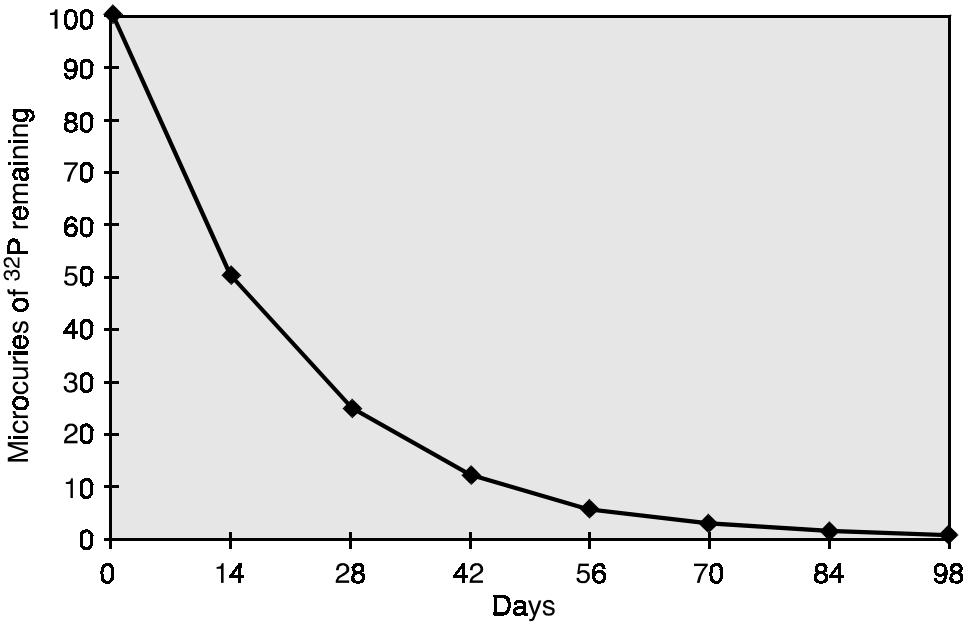

Figure 2-1. Transformation of 100 µCi of ^{32}P

Half lives of the various radionuclides range from fractions of a second to billions of years. The amount of radioactive material is expressed in terms of activity, which is defined as the number of disintegrations (or transformations) in the radioactive material during 1 second or 1 minute. The traditional unit for measurement of activity is the curie (Ci). The curie was originally defined as the activity of 1 gram of ^{226}Ra, which is about 3.69×10^{10} transformations or disintegrations per second (dps). Now it is defined as that quantity of radioactive material in which an average of 3.7×10^{10} atoms transform in 1 second. In the International System (SI), the unit of activity is the becquerel (Bq). One Bq is defined as the amount of radioactive material in which an average of 1 atom disintegrates in 1 second.

The activity of a radionuclide at time t may be calculated by the equation:

$$A = A_o e^{-0.693t/T(phys)}$$

where A is the activity in appropriate units, such as Ci, Bq, or dps; A_o is the activity at time zero; t is the time that has elapsed; and T_{phys} is the physical radioactive half-life of the radionuclide. T_{phys} and t must be in the same time units.

2.2.4 Interaction of Radiation with Matter

Radiation will interact with matter: it will lose kinetic energy to any solid, liquid, or gas through which it passes; this occurs by several mechanisms and at different rates. The partial or complete transfer of energy to a medium by either electromagnetic (gamma) or particulate (alpha or beta) radiation may be sufficient to excite electrons or to "knock out" electrons from the absorber atoms or molecules. For those electrons that are knocked out of the atom, the process is called ionization and is the source of the name "ionizing radiation." Compared to other types of radiation that may be absorbed (e.g., ultraviolet radiation), ionizing radiation deposits a relatively large amount of energy into a small volume of matter, possibly resulting in harmful biological effects.

Radiation may interact with a biological medium to cause damage either directly or indirectly. A direct effect occurs when an ionizing event disrupts a critical molecule (such as an enzyme, DNA, or RNA) by knocking out an intramolecular bonding electron. Indirect effects occur when ionized or disrupted molecules, mainly water (since the body is about 80% water), recombine to form chemically toxic compounds, such as hydrogen peroxide (H_2O_2) (Casarett and Doull 1996). Indirect effects also involve

free radicals. Indirect effects occur when these radiolysis products diffuse and damage a nearby biological molecule along their path. Further discussion of the direct and indirect effects of radiation is presented in Chapter 5.

Each type of radiation is also classified as to its directness (directly or indirectly ionizing) and its ionizing density (linear energy transfer). Radiations that produce significant ionization themselves (alpha, beta) are called directly ionizing radiation, while those that produce minimal primary ionization (gamma, x ray, neutron) are called indirectly ionizing radiation. The amount of energy that the radiation transfers per unit of path length is called its linear energy transfer (LET) and is measured in units of MeV/μm. This feature reflects a radiation's ability to produce biological damage. Radiation is classified as either high linear energy transfer (high LET) or low linear energy transfer (low LET), based on the amount of energy it transfers per unit path length it travels. Alpha radiation is high LET; beta and gamma radiation are low LET. Alpha particles are classified as high LET radiation because their large +2 charge and relatively large mass (about 7,200 times that of an electron) cause them to move relatively slowly and interact strongly with any material they pass through, producing dense ionization along its path. Beta particles, which are energetic electrons, are classified as low LET radiation. Even though they interact with matter in a manner similar to alpha particles, their smaller +1 or -1 charge and smaller mass result in a greater distance between ionizing collisions and, thus, a lower rate of energy transfer. Gamma rays are indirectly ionizing radiation. Depending on its energy and the atomic number of the absorbing material, a gamma ray photon interacts with an absorber atom by one of three primary mechanisms (photoelectric interaction, Compton scattering, and pair production), which results in the production of highly energetic electrons, which dissipate their energy by interacting with other atoms in their path in exactly the same manner as beta particles (which are electrons) and excite and ionize these atoms. Since the ionizations resulting from gamma radiation are due to electrons, gamma radiation is a low LET radiation.

Both high and low LET interactions can cause significant damage to the DNA and can result in a wide array of biological effects. Radiation can also react with molecules other than DNA (lipids, proteins, water, etc.) to produce free radicals, which can then go on to adversely react with the DNA molecule. Regardless of the method of energy transfer, DNA is the primary molecule of concern for effects from low level radiation because DNA damage from radiation and from other sources is cumulative and can (but does not always) result in carcinogenesis or other adverse cellular events months or years after exposure.

2.2.5 Characteristics of Emitted Radiation

2.2.5.1 Alpha Radiation

Alpha radiation has little penetrating power compared with other types of radiation. The alpha particle is hazardous only if there is internal exposure (i.e., from a radionuclide that has been ingested, inhaled, or otherwise absorbed internally) (see Table 2-2).

An alpha particle is composed of two protons and two neutrons, and thus is a helium nucleus. When a parent radionuclide emits an alpha particle, its atomic mass number (number of protons plus neutrons) decreases by four and its atomic number (number of protons) decreases by two, resulting in the formation of a different element. In nature, alpha particles come from the radioactive transformation of heavy elements (e.g., uranium, radium, thorium, and radon) where long transformation chains produce several successive alpha and beta particles until the resulting nuclide has a stable configuration. A specific alpha emitting radionuclide emits monoenergetic alpha particles of discrete energies and relative intensities, making it possible to identify each alpha emitting radionuclide by its alpha energy spectrum.

The alpha particle's electrical charge of +2 and mass number of 4, both of which are larger than most other types of radiation, cause it to interact strongly with matter. This relatively slow-moving, highly charged, high LET particle spends a relatively long time in the vicinity of each atom it passes; this enables it to pull electrons easily off those atoms. With a mass about 7,200 times that of each electron, each interaction has only a small effect on its velocity, but the strong interaction with each atom it encounters causes it to lose energy very quickly. As a result of these characteristics, the alpha particle has less penetrating power than other types of radiation. Typically, an alpha particle cannot penetrate an ordinary sheet of paper. Its range in air (the distance the charged particle travels from the point of origin to its resting point) is approximately 3–10 cm; in biological tissue, the range decreases dramatically to 25–80 μm (see Table 2-1). Thus, alpha particles deposit all of their energy in a small volume. Once its energy is expended, the alpha particle will combine with two electrons to become a helium atom, which does not chemically react with biological material.

Table 2-2. Effective Half-Lives of Selected Radionuclides in Major Adult Body Organs

Radionuclide	Critical organ	Half-life		
		Physical	Biological	Effective
Tritium (^{3}H) [a]	Whole body	12.3 yr	12 d	12d
Iodine-131 (^{131}I)	Thyroid	8 d	138 d	7.6 d
Strontium-90 (^{90}Sr)	Bone	28 yr	50 yr	18 yr
Plutonium-239 (^{239}Pu)	Bone	24,400 yr	200 yr	198 yr
	Lung	24,400 yr	500 yr	500
Cobalt-60 (^{60}Co)	Whole body	5.3 yr	9.5 d	9.5 d
Iron-55 (^{55}Fe)	Spleen	2.7 yr	600 d	388 d
Iron-59 (^{59}Fe)	Spleen	45.l d	600 d	41.9 d
Manganese-54 (^{54}Mn)	Liver	303 d	25 d	23 d
Cesium-137 (^{137}Cs)	Whole body	30 yr	70 d	. 70 d

[a] Mixed in body water as tritiated water
d = days; yr = years

2.2.5.2 Beta Radiation

A beta particle is a high-velocity electron ejected from a transforming nucleus. This occurs when a nuclide has a nucleus that is very unstable because it has too many or too few neutrons to stabilize the number of protons. The particle may be either a negatively charged electron, called a negatron (β^-), or a positively charged electron, called a positron (β^+).

Beta minus or negatron (β^-) transformation is a process by which a radionuclide with too many neutrons achieves stability. It does not stabilize by emitting an extra neutron; instead, a neutron changes into a proton and the nucleus emits a negatron (β^-) and an antineutrino (see glossary). This nuclear transformation results in the formation of a different element with one more proton, one fewer neutron, and the same mass number as the original nucleus. The energy spectrum of a beta particle ranges from zero to a specific maximum, which is a characteristic of that particular radionuclide, with the mean energy of the beta spectrum being about one-third of the maximum. Overexposure to negatron-emitting radionuclides outside the body can cause more injury to the skin and superficial body tissues than alpha particles or gamma radiation. They are even more harmful as an internal radiation hazard when excessive amounts are taken into the body.

Beta positive (β^+), or positron, transformation occurs when there are not enough neutrons (or too many protons) in the nucleus. In this case, a proton changes into a neutron and the nucleus emits a positron (β^+)

and a neutrino (see glossary). This nuclear transformation results in the formation of a different element with one more neutron, one less proton, and the same atomic mass number as the original nucleus. The positron is a very reactive species; when sufficiently slowed through successive ionizing collisions, it will combine with an electron. At this point, the electron-positron pair is annihilated (their combined mass is converted into energy in the form of two gamma ray photons of 0.51 MeV each). The gamma radiation resulting from the annihilation (see glossary) of the positron makes all positron-emitting isotopes more of an external radiation hazard than pure negatron (β^-) emitters of equal energy. The neutrino in β^+ transformation and the antineutrino in β^- transformation are not known to produce any biological damage.

2.2.5.3 Gamma Radiation

Gamma radiation is the main source of external radiation hazard because it is highly penetrating. Radioactive transformation by alpha or beta emission often leaves the nucleus in an excited energy state with some residual energy. The nucleus cannot remain in this elevated energy state indefinitely, and will eventually release this energy and achieve ground state, or the lowest possible stable energy level. The energy is released in the form of gamma radiation (high-energy photons) and is equal to the change in the energy state of the nucleus. Gamma rays are low LET because the average distance between ionizations is large and they liberate energetic electrons when absorbed in matter. The liberated electrons are also low LET.

Gamma radiation and x rays are types of electromagnetic radiations that behave identically but differ in their origin; gamma emissions originate in the nucleus while x rays originate in the orbital electron structure, or from the slowing down or stopping of highly energetic beta particles or electrons. The x rays that originate in the orbital structure are called *characteristic* x rays, and are useful in chemical analysis while those due to stopping high speed electrons are called *bremsstrahlung*.

2.2.6 Estimation of Energy Deposition in Human Tissues

Humans can be exposed externally from radiation sources outside the body, or internally from radioactive material deposited inside the body. Internally deposited radioactive material is more hazardous than external (superficial or skin) deposition. Internal exposures occur when radionuclides that have entered the body through the inhalation, ingestion, or dermal pathways undergo radioactive transformation

resulting in the deposition of energy to internal cells and organs. This radioactive material may be eliminated quickly (hours to days) or may result in a long-term retention pattern of the radionuclide (weeks to years).

When radioactive material is inside a living organism, either naturally or as the result of an accidental intake, the radioactive material is eliminated by both radioactive transformation and biological removal. A rate constant called the biological half-time (T_{biol}) is the time required for the sum of all of the available biological processes to eliminate one-half of the retained radioactivity. This time is the same for both stable and radioactive isotopes of any given element since they behave identically in the body. The time required for a radioactive element to be halved as a result of the combined action of radioactive transformation and biological elimination is the effective half-time (T_{eff}), and is described in the equation:

$$T_{eff} = (T_{biol} \times T_{phys})/(T_{biol} + T_{phys}).$$

This basic equation is typically more complicated in reality because the biological half-time can differ from one organ to another within the body. In addition, radioactive material distributes throughout the body and its radiations may penetrate to and expose tissues other than those in which it was deposited. Current internal dosimetry methods account for these multiple clearance rates and the distribution of radioactive material in the body. (See Table 2-2 for representative effective half-times of some radionuclides.)

External exposures occur when the body is irradiated directly from sources located outside the body, such as radiation from radionuclides on ground surfaces, dissolved in water, or dispersed in the air. In general, external exposures are from gamma-emitting radionuclides, from which the radiation readily penetrates the skin and internal organs. Beta and alpha radiation from external sources are far less penetrating and deposit their energy primarily on the skin's outer layer. High levels of beta contamination of the skin may lead to skin burns. However, while the skin dose from beta radiation may be very high, the beta contribution to the total body dose from external radiation, compared to that contributed by gamma rays, may be small.

Characterizing the radiation dose to persons or laboratory animals from external radiation is relatively simple, but determining the dose from internal radiation is a complex issue. However, through the use of physiologically-based mathematical models, the dose from internal exposure can be estimated with a sufficient degree of accuracy to establish reliable radiation safety standards.

2.3 FUNDAMENTALS OF IONIZING RADIATION DOSIMETRY

2.3.1 Dose Units

In radiation biology, the term “dose” refers to the amount of energy that radiation deposits in an organ or tissue as it passes through rather than to the energy of that radiation or the quantity of radioactive material that is present.

Absorbed dose is the energy absorbed per unit mass of the absorber. The traditional unit of absorbed dose is the rad, with 1 rad = 100 ergs of energy deposited in 1 gram = 0.01 joule of energy/kg in any irradiated medium. The SI unit of absorbed dose is the gray (Gy), which is equivalent to 100 rad or 1 J/kg. External radiation dose is obtained by multiplying the radiation dose rate (measured using instruments) by the exposure time. Internal radiation dose at different sites within the body can be obtained from a knowledge of the quantity of radioactive material present; the uptake fraction and the distribution and retention kinetics of the chemical species involved; the type, energy, and intensity of its radiations; and the energy transfer parameters for those radiations to the tissues involved; and the radioactive half-life. An exposure is classified as "acute" or "chronic" depending on how long an individual or organ was exposed to the radiation. For internally deposited radionuclides, it is the effective half-life (which accounts for clearance by radioactive decay and chemical elimination) which determines whether the radiation dose is of acute, intermediate, or chronic duration. For an acute-duration intake of a radioactive material, a very short effective half-life results in an acute-duration radiation dose, but a very long effective half-life results in an intermediate- or chronic-duration radiation dose.

The roentgen (R) is the unit of x ray or gamma radiation exposure related to the intensity of an x ray or gamma radiation field, and is measured by the amount of ionization caused in air by x ray or gamma radiation. One roentgen produces 2.58×10^{-4} coulomb per kg of air. In the case of gamma radiation, over the commonly encountered range of photon energy, the energy deposition in tissue for an exposure of 1 R is 0.0096 J/kg of tissue (0.96 rad) which for most purposes is about equal to 1 rad. Thus, although the roentgen is a unit of x ray exposure (not dose), it continues to be used for radiation safety measurements because an exposure of 1 R leads to a dose of approximately 1 rad. An exposure of 1 R is considered a dose equivalent of 1 rem (0.01 sievert). The dose equivalent units, the rem and the sievert, are discussed

below in Section 2.3.3. Health physics survey meters that are used to measure external x ray or gamma radiation are usually calibrated in units or subunits of R (roentgens) per hour.

External doses are measured directly with radiation dosimeters or calculated from hand-held survey meter readings as the product of the exposure time and the dose rate in rad/unit time. Internal doses, however, are not measured directly; they are calculated with data obtained from measurements of radiation emissions from the body or from the radioactivity in excreta samples in counts/unit time. The radioactive material(s) are identified and their radiation characteristics are used to calculate the activity inside the body in curies or becquerels. Physiologically based biokinetic models are then used to calculate the dose from the radioactive materials take into the body. For radiation safety purposes and for regulatory requirements, the dose is multiplied by the quality factor Q rem/rad, for that specific radiation to convert rad to rem. Special units are used to describe the concentration and exposure to radon and its progeny.

Certain types of radiation with short-lived progeny are measured in units called working levels (WL). The potential inhalation hazard from atmospheric radioisotopes ^{222}Rn and ^{220}Rn (thoron) is due to their short-lived progeny. The concentration of these short-lived progeny (^{218}Po through ^{214} Po from ^{222}Rn and ^{216}Po through ^{212}Po from ^{220}Rn) is measured by the working level (WL). One WL is defined as any combination of short-lived radon daughters per L of air that will result in the emission of 1.3×10^5 MeV of alpha energy. An activity concentration of 100 picocuries (pCi) of ^{222}Rn per L of air, in equilibrium with its daughters, corresponds to 1 WL. The WL unit for thoron (^{220}Rn) daughters at 50% equilibrium is 14.8 pCi/L. Thoron daughters in radioactive equilibrium with thoron at a concentration of 7.43 pCi/L represents 1 WL. The total radiation dose to radon progeny is commonly expressed in working level months (WLM) units. One WLM corresponds to exposure to a concentration of 1 WL for the reference period of 170 working hours per month, or to a concentration of 0.5 WL for 340 hours, etc.

2.3.2 Dosimetry Models

Physiologically based biokinetic dosimetry models are used to estimate the dose from radioactive material taken into the body. The models for internal dosimetry consider the quantity of radionuclides entering the body, the factors affecting their movement or transport through the body, the distribution and retention of radionuclides in the body, and the energy deposited in organs and tissues from the radiation that is emitted during spontaneous transformation processes. The dose pattern for radioactive materials in the

body may be strongly influenced by the route of entry of the material. The most frequent exposure routes for industrial workers have been inhalation of radioactive particles with pulmonary deposition and puncture wounds with subcutaneous deposition.

Ingestion. Ingestion of radioactive materials is most likely to occur from contaminated food and water, or by eventually swallowing inhaled compounds initially deposited in the lung but transported to the throat by the mucociliary clearance pathway. Ingestion of an excessive amount of radioactive material may result in toxic effects as a result of either absorption of the radionuclide from the intestine, irradiation of the gastrointestinal tract during passage through the tract, or a combination of both. The fraction of radioactive material absorbed from the gastrointestinal tract is variable, depending on the specific element, its chemical and physical form, the diet, and the individual's own metabolic and physiological factors. The absorption of some elements is influenced by age, usually with higher absorption rates in very young animals. These factors are quantitatively considered in the model that describes the gastrointestinal tract in terms of four compartments—stomach, small intestine, upper large intestine, and lower large intestine—and a fifth compartment that includes all the body fluids (NCRP 1988).

Inhalation. The inhalation route is a major route of exposure for radioactive materials. The deposition site of particles within the lung is largely dependent upon the size of the particles being inhaled. After the particle is deposited, the retention will depend upon the physical and chemical properties of the dust, the physiological status of the lung, and the site of deposition. There are at least three distinct mechanisms that operate simultaneously to remove or clear radioactive material from the lung. Ciliary clearance acts only in the upper respiratory tract (i.e., trachea and the major and minor conducting airways of the lung). Cilia, short hairlike filaments growing out of the lining cells of the upper respiratory tract, are covered by the layer of mucous in the upper respiratory tract. The cilia move in a synchronized beating motion that pushes the mucous blanket, on which the large sized inhaled particles are deposited, upwards into the throat. There the particles can be coughed up or swallowed. The second and third mechanisms, phagocytosis and systemic absorption following dissolution of a particle, act mainly in the deep respiratory tract. Phagocytosis is the engulfing of foreign bodies by alveolar macrophages and their subsequent removal either up the ciliary "escalator" or by entrance into the lymphatic system. These factors are considered by the biokinetic model of the respiratory tract. This model includes four major compartments— extra-thoracic region (nasal airways and throat), tracheo-bronchial region (windpipe and bronchi), pulmonary region (alveolar area from which oxygen and carbon dioxide diffuse into and out of

the blood), and pulmonary lymph node region. Dosimetric lung models are reviewed by NCRP (1994), James (1987, 1994) and James and Roy (1987).

Internal emitters. When a radionuclide is ingested or inhaled, it becomes an internal emitter. The absorbed dose from an internally deposited radionuclide is determined by the concentration of absorbed energy in the tissue. Thus, the dose to an organ or tissue depends on its mass, the quantity of radioactive material introduced into the organ, the length of time that the radioactivity remains in the organ (represented by the effective half-life), and the energy and type of radiation. Since alpha and beta particles travel only short distances, all alpha particle energy and all or most beta particle energy is absorbed in the tissue that contains the radioactive material. Many common radionuclides also emit gamma rays that are so penetrating that a significant number escape from that tissue and interact with remote portions of the body, or pass out of the body entirely without interacting. For this reason, the gamma radiation dose to an organ considers both the dose from radioactive material in that organ plus the exposure from the gamma emitter deposited in other organs in the body. For a radionuclide distributed uniformly throughout an infinitely large medium, the concentration of absorbed energy must be equal to the concentration of energy emitted by the isotope. An infinitely large medium may be approximated by a tissue mass whose dimensions exceed the range of the particulate radiation. All of the alpha radiation (due to its very short traveling distance in biological tissue) and most of the beta radiation will be absorbed in the organ (or tissue of reference).

2.3.3 Terms Used in Radiation Safety Practice and Regulation

The terms defined below are also included in the glossary in Chapter 9.

Absorbed dose. The energy imparted by radiation per unit mass of irradiated material is called the absorbed dose. The units of absorbed dose are the rad, in traditional units, and the gray (Gy), in SI units. (See “Units of radiation dose” for more information on absorbed dose).

ALARA. This acronym for “As Low As is Reasonably Achievable” refers to the practice of making every effort to keep exposure to radiation as far below the dose limit as possible while still achieving the purpose for which the radiation is intended to be used. It takes into account the state of technology, the economics of improvements in relation to state of technology, the economics of improvements in relation

to benefits to the public health and safety, and other societal and socioeconomic considerations. In addition, ALARA is applied to the utilization of nuclear energy and licensed materials in the public interest.

ALI. This acronym for "Annual Limit on Intake" is the derived limit for the amount of radioactive material taken into the body of an adult worker by inhalation or ingestion in a year. For a given radionuclide, ALI is defined as the smaller of the intakes that would result in a committed effective dose equivalent of 5 rem (0.05 Sv) or a committed dose equivalent of 50 rem (0.5 Sv) to any individual organ or tissue. Committed dose equivalent is the total dose equivalent that radioactive material internalized in a particular year will deliver to the body in that and all subsequent years out to 50 years after the intake. For radionuclides with effective half-lives of a month or less, essentially all the radiation dose will be delivered in the same year as the radioactive material intake, and the committed dose equivalent equals the dose equivalent received that year. However, radionuclides with longer half-lives remain in and expose the body for more than 1 year, and the committed dose equivalent accounts for this by summing the estimated dose equivalents produced by the radioactive material during the current year and every year out to 50 years.

Dose equivalent (H). The dose equivalent is used in radiation safety dosimetry to account for differences in biological effectiveness among the various radiations. The same energy imparted (absorbed dose) may result in different levels of biological effects for α, β, and γ rays. To account for the differences in biological effectiveness, a normalizing factor is used. The normalizing factor (Q) is used as a multiplier of the radiation absorbed dose (D) to give the *dose equivalent*. The dose equivalent, symbolized by H, is expressed in units of rem in the traditional system of units and in sievert (Sv) units in the SI (international) measuring system (100 rem = 1 sievert). This relationship is expressed as

$$H = D \times Q$$

Effective dose equivalent (H_E). The effective dose equivalent is used for radiation safety purposes and for regulatory purposes to account for the relative susceptibility of the various organs and tissues to radiation-induced non-deterministic or stochastic effects (principally cancer) in cases of non-uniform irradiation. The basis for the effective dose equivalent concept is that the probability of a non-deterministic effect from non-uniform irradiation should be equal to that due to uniform whole body irradiation. The effective dose equivalent is found by multiplying the dose equivalent (H_T) to each irradiated tissue or organ by a tissue weighting factor, W_T, and then summing these products for all the irradiated tissues, as shown in the equation

$$H_E = G(W_T \times H_T)$$

W_T represents the fraction of the probability of a non-deterministic effect resulting from irradiation of that tissue to the total probability of a non-deterministic effect when the whole body is uniformly irradiated. The values for W_T used by the USNRC and ICRP are listed below in Table 2-3.

For occupational exposure, the USNRC specifies an upper limit of 5 rem (0.05 Sv) in 1 year for the effective dose equivalent. The regulations also specify an upper annual limit of 50 rem (0.5 Sv) for all organs and tissues except the lens of the eye, for which an annual maximum of 15 rem (0.15 Sv) is prescribed.

Table 2-3. Tissue Weighting Factors Used by the USNRC and ICRP to Calculate Effective Dose

Tissue	USNRC Weighting factor for Effective Dose Equivalent (ICRP 1977; USNRC 1997a)	ICRP Weighting factor for Effective Dose (ICRP 1991)
Whole body	1.00 [a]	–
Gonads	0.25	0.20
Breast	0.15	0.05
Red bone marrow	0.12	0.12
Lung	0.12	0.12
Thyroid	0.03	0.05
Bone surface	0.03	0.01
Colon	–	0.12
Stomach	–	0.12
Bladder	–	0.05
Liver	–	0.05
Esophagus	–	0.05
Skin	–	0.01
Remainder	0.30 [b]	0.05

[a]The whole body weighting factor was introduced by the USNRC and is not addressed by either the ICRP or the NCRP.
[b]0.30 results from 0.06 being assigned to each of the five remaining organs (excluding the skin and lens of the eye) that receive the highest doses.

External dose. Radiation dose from a radiation source originating from outside of the body.

Health physics. Health physics is the science concerned with recognition, evaluation, and control of health hazards from ionizing and non-ionizing radiation. Health physics covers environmental, occupational, and medical areas, and includes radiobiology and the study of mechanisms of health effects.

The scientific and engineering aspects of health physics deal with the measurement of radiation and radioactivity, the establishment of dose-response relationships for radiation exposure, movement of radioactivity through the body and the environment, the design of radiologically safe processes and equipment, and the maintenance of a radiologically safe environment. The health physicist is the professional who deals with radiation safety.

Internal dose. Radiation dose from radioactive material inside the body.

Quality factor (Q). For health physics purposes, a normalizing factor, called the *quality factor* (Q), is applied to the radiation absorbed dose to account for the relative biological effectiveness (RBE) of the different radiations. The numerical values for the quality factors are determined by a committee of experts, and are based on a conservative upper limit of the RBE for the biological effect believed to be of the greatest interest to humans. Values for Q that are used in the USNRC safety standards in the Code of Federal Regulations (CFR) 10, Part 20, are listed below in Table 2-4.

Table 2-4. Quality Factors Used in USNRC Radiation Safety Regulations

Type of radiation	Quality factor (Q)
Alpha particles, multiple charged particles, fission fragments, and heavy charged particles	20
x rays, gamma rays, electrons, negatrons, or positrons	1
Thermal neutrons	2
Fast neutrons, neutrons of unknown energy, or high-energy protons	10

Source: USNRC 1997a

Relative biological effectiveness (RBE). The toxicity of a given absorbed radiation dose depends on the LET of the radiation: the higher the LET, the more toxic is the radiation and the smaller is the dose needed to produce a specific biological end point. To account for this LET effect, radiobiologists use the term *relative biological effectiveness* (RBE). The RBE for any radiation is typically defined as the ratio of the dose from 200 keV x rays required for a given biological effect to the dose that would produce the same effect with that radiation. RBEs can also be defined for specific scenarios that compare the effects of different radiation types or energies on producing the same end point. The term RBE is restricted in application to radiobiology.

Units of radioactive material. The following two units of radioactivity are commonly used when describing the quantity of radioactivity:

Becquerel (Bq). The SI unit of measure for radioactive material; one becquerel equals that quantity of radioactive material in which one atom disintegrates in one second.

Curie (Ci). The conventional unit used to measure the quantity of radioactive material. The curie is equal to that quantity of radioactive material in which 37 billion atoms transform per second. This is approximately the activity of 1 g of radium.

Units of radiation dose. The International Commission on Radiation Units and Measurements (ICRU 1980), International Commission on Radiological Protection (ICRP 1984), and National Council on Radiation Protection and Measurements (NCRP 1985) now recommend that the traditional units: rad, roentgen, curie, and rem be replaced by the SI units: gray (Gy), coulomb per kilogram (C/kg), becquerel (Bq), and sievert (Sv), respectively. However, the regulations used in the United States are written with the traditional units or with both traditional and SI units. The following four dosimetric units are commonly used:

Gray (Gy). The SI unit of absorbed dose. One gray = 1 J/kg = 100 rad.
Rad. The unit of absorbed dose. One rad = 100 erg/g = 0.01 Gy.
Sievert (Sv). The SI unit of dose equivalent, equal to absorbed dose in gray multiplied by the quality factor. One Sv = 100 rem.
Rem. The conventional unit of dose equivalent. One rem = 0.01 Sv.

The relationship between the traditional units and the international system of units (SI) for radiological quantities is shown in Table 2-5.

Table 2-5. Common and SI Units for Radiation Quantities

Quantity	Traditional units	SI units	Relationship
Activity (A)	curie (Ci)	becquerel (Bq)	1 Ci = 3.7×10^{10} Bq 1 Bq = 1 dps, 1 S^{-1}
Absorbed dose (D)	rad	gray (Gy)	1 rad = 0.01 Gy 1 Gy = 1 Jkg^{-1}
Dose equivalent (H)	rem	sievert (Sv)	1 rem = 0.01 Sv 1 Sv = 1 Jkg^{-1}

dps = transformations per second; Jkg^{-1} = Joules per kilogram; S^{-1} = per second

Source: Shleien 1992

Weighting factor (W_T). This factor is used for radiation safety purposes to account for the different sensitivities of the various organs and tissues to the induction of non-deterministic radiation effects.

Other terms used in discussions of radiation protection and regulation include: bioassay, collective dose, embryo/fetus, eye dose equivalent, public dose, shallow dose equivalent, total effective dose equivalent, whole body, and working level. These terms and their definitions may be found in Chapter 9.

2.4 BIOLOGICAL EFFECTS OF RADIATION

Radiation interactions within the body produce microscopic subcellular-level effects that may result in cellular responses and, in the aggregate, may ultimately produce macroscopically observable effects on specific organs or tissues, such as the skin, eye lenses, and thyroid.

Irradiation of biological tissue sets into motion a series of intracellular biochemical events that start with ionization of a molecule, and which may ultimately lead to cellular injury. Injury to a large number of cells may, in turn, lead to further injury to the organ and to the organism. Many factors may modify the response of a living organism to a given dose of radiation. Factors related to the dose include the dose rate, the energy and type of radiation, and the temporal pattern of the exposure. Biological factors include species, age, sex, the portion of the body tissues exposed, and repair mechanisms. A generally applicable rule of thumb is the Law of Bergonie3 and Tribondeau, based on their research in 1906, which states that cells are sensitive to radiation damage if they have a high mitotic rate, a long mitotic cycle, and are not specialized (undifferentiated) (Casarett and Alison 1968). In addition, the concurrent exposure to

radiation and other substances may result in antagonistic, additive, or synergistic effects, such as the synergism between ionizing and ultraviolet radiation to produce skin cancer.

The DNA is considered to be the primary target molecule for radiation toxicity. Molecular damage, which includes damage to the DNA, can occur in one of two ways from an exposure to radiation. First, radiation can interact directly with the DNA, resulting in single or double-strand DNA breaks or unbonding base pairs. Second, radiations can interact directly with other surrounding molecules within or outside of the cell, such as water, to produce free radicals and active oxygen species. These reactive molecules, in turn, interact with the DNA and/or other molecules within the cell (cell membranes, mitochondria, lipids, proteins, etc.) to produce a wide range of damage at the cellular and tissue levels of the organism. High LET radiation is an efficient producer of free radicals and H_2O_2, both of which can act directly on macromolecules. About 66% of the damage from low LET radiation and about 50% of the damage from high LET radiation comes from aqueous radiolytic products.

Regardless of how the DNA is damaged, the mammalian body has remarkable abilities to repair its damaged DNA. Mammalian DNA repair schemes, classified as either direct or indirect repair mechanisms, include many mechanisms such as nucleotide excision (via endonuclease), base excision (via DNA glycosylase), and mismatch repair. The success or failures of these inherent DNA repair systems depend on many factors, such as the dose and dose rate of radiation received and the tissue that received the radiation. Depending on the dose and the tissue exposed, inherent DNA repair mechanisms may be highly successful, resulting in total repair of the DNA. These mechanisms may fail completely if the repair mechanism is overwhelmed with very high doses of radiation, or may fail to repair all of the DNA damage caused by lower doses of radiation. This failure can result in necrosis due to cell death, apoptosis (programmed cell death), altered cell function, or the development of neoplastic cells several years after the damage occurred. DNA repair systems may be able to adequately repair the radiation damage to the DNA itself, but may do nothing to protect the irradiated cell from damage to other cellular structures (membranes, mitochondria, etc.) by the radiation (Zajtchuk 1989). Other repair mechanisms must be employed to protect the cell against these injuries.

Several protective strategies are used to minimize the damage from free radicals and reactive oxygen species that occur in cells exposed to high acute doses of radiation. Some of these methods include hypoxia (protective at high dose; can be observed for cell killing at doses >1 Gy), which decreases the

amount of oxygen available to form such reactive species; hypothermia; the use of free radical scavenging agents (aminothiols, vitamins A, E, and C); and eicosanoids. These methods have been used in special cases, such as in radiation therapy of tumors, to protect the surrounding healthy tissue. Genetic methods (repair by hydrogen transfer, regeneration) are also being investigated (Zajtchuk 1989).

The study of the mechanisms by which radiation exerts its toxicological effects is an important and constantly evolving field of toxicology. More information on the mechanisms of action of radiation can be found in Chapter 5 of this toxicological profile. Several excellent reviews of the biological effects of radiation have been published, and the reader is referred to these for a more in-depth discussion (BEIR V 1990; ICRP 1984; Kondo 1993; Rubin and Casarett 1968). A general overview of the health effects of alpha, beta, and gamma types of radiation in some types of biological tissue is presented below; more in-depth information on the health effects of radiation is presented in Chapters 3 and 5 of this toxicological profile (UNSCEAR 1993).

2.4.1 Radiation Effects at the Cellular Level

According to Mettler and Moseley (1985), at acute doses up to 10 rad (0.1 Gy), single-strand breaks in DNA may be produced. These single-strand breaks may be repaired rapidly. With doses in the range of 50 to 500 rad (0.5–5 Gy), irreparable double-strand DNA breaks are likely, resulting in cellular reproductive death after one or more divisions of the irradiated cell. At large doses of radiation, usually greater than 500 rad (5 Gy), direct cell death before division (interphase death) may occur from the direct interaction of free radicals with essential cellular macromolecules. Morphological changes at the cellular level, the severity of which is dose-dependent, may also be observed at this dose level. Specific clinical symptoms and other health effects associated with different doses of radiation are discussed in Chapter 3 of this profile.

The sensitivity of various cell types within an organism may vary widely, depending on specific cell and tissue characteristics. According to the Law of Bergonie and Tribondeau, the sensitivity of cell lines is directly proportional to their mitotic rate and inversely proportional to the degree of differentiation (Mettler and Moseley 1985; Rubin and Casarett 1968). This means that cells that undergo frequent mitosis under normal physiologic circumstances or are not well-differentiated in histologic cell-type characteristics will tend to be more susceptible to the effects of radiation than those cells in which the converse is true. Rubin and Casarett (1968) devised a classification system that categorized cells

according to type, function, and mitotic activity. The five categories range from the most sensitive type, "vegetative intermitotic cells," found in the stem cells of the bone marrow and the gastrointestinal tract, to the least sensitive cell type, "fixed postmitotic cells," found in striated muscles or long-lived neural tissues. This classification system is shown in Table 2-6.

Cellular changes in susceptible cell types may result in cell death; extensive cell death may produce irreversible damage to an organ or tissue, or may result in the death of the individual. If the cells recover, altered metabolism and function may be the ultimate sequelae, and the damage imposed may be repaired to a normal state, produce some characteristic manifestation of clinical symptoms, or result in apoptosis (programmed cell death). If the cells are adequately repaired and relatively normal function is restored, the more subtle DNA alterations may also be expressed at a later time as mutations and/or tumors. More information on the genetic effects of radiation is presented in Chapter 5 of this profile.

Table 2-6. Relative Radiosensitivity of Mammalian Cells

Class	Category	Characteristics	Cell types
I	Vegetative intermitotic cells	Rapidly dividing, short-lived; daughter cells will either differentiate or form more cells like the parent cell	Hemocytoblast, lymphoblast, erythroblast, myelobalst, primitive intestinal crypt cell, type A spermatogonia, primitive oogonia, lymphocytes
II	Differentiated intermitotic cells	Somewhat less radiosensitive than Class I cells; rapid proliferation rates, but daughter cells become more radioresistant than the parent cell	Type B spermatogonia, oogonia, cells of the intermediate stages of erythropoiesis and myelopoiesis
III	Multipotential connective tissue cells	Cells divide regularly in response to injury and irritation	Endothelium, fibroblast, mesenchymal cells.
IV	Reverting postmitotic cells	Normally do not undergo cell division	Epithelial cells of salivary glands, liver, kidney, pancreas, lung; parenchymal cells of sweat glands and endocrine glands. Interstitial cells of testis and ovary
V	Fixed postmitotic cells	Cells that will not divide; highly radioresistant	Mature nerve cells, muscle cells, sperm, erythrocytes.

Source: Sanders and Kathren 1983

2.4.2 Radiation Effects at the Organ Level

In most organs and tissues, the injury and the underlying mechanism for that injury are complex and involve a combination of events. The extent and severity of this tissue injury depend on the dose and the radiosensitivity of the various cell types in that organ system. Rubin and Casarett (1968) describe and schematically display the events following radiation in several organ system types. These include: a rapid renewal system, such as the gastrointestinal mucous; a slow renewal system, such as the pulmonary epithelium; and a nonrenewable system, such as neural or muscle tissue. In the rapid renewal system, organ injury results from the direct destruction of highly radiosensitive cells, such as the stem cells in the bone marrow. Injury may also result from constriction of the microcirculation and from edema and inflammation of the basement membrane, which is called the histohematic barrier (HHB); the injury may progress to fibrosis. In slow renewal and nonrenewable systems, the radiation may have little effect on the parenchymal cells, but ultimate parenchymal atrophy and death over several months may result from HHB fibrosis and occlusion of the microcirculation.

2.4.3 Acute and Delayed Somatic Effects

2.4.3.1 Acute Effects

The result of acute overexposure to radiation is commonly referred to as Acute Radiation Syndrome (ARS). This effect is seen only after whole-body exposures to relatively high doses (>100 rad, >1.0 Gy) such as might occur in a serious nuclear accident, close to a nuclear weapon detonation, or after a period of exposure to the high radiation field of irradiator sources, such as occurred to Chernobyl on-site responders and individuals in Goiania, Brazil (see Chapter 4). The four stages of ARS are prodrome (or initial), latent stage, manifest illness stage, and recovery or death. The probability of the prodromal phase is characterized by nausea, vomiting, malaise and fatigue, increased temperature, and blood changes. The latent stage is similar to an incubation period. Subjective symptoms may subside, but changes may be taking place within the blood-forming organs and elsewhere that will subsequently give rise to the next stage. The manifest illness stage gives rise to signs and symptoms specifically associated with the radiation injury: hair loss, fever, infection, hemorrhage, severe diarrhea, prostration, disorientation, and cardiovascular collapse. Convulsions are possible at extremely high doses. The severity and time of onset of the signs and symptoms depend upon the radiation dose received (see Chapter 3), with the time of onset decreasing with increasing dose.

2.4.3.2 Delayed Effects

The level of exposure to radiation and radioactive materials that may be encountered in the environment, even large exposures spread over a long enough period of time, is expected to be too low to result in the acute effects described above. Occupational and medical radiation may produce long-term effects that manifest themselves years after the original exposure and may be due to a single elevated exposure or a continuous low-level exposure.

Exposure to radiation has resulted in a number of adverse health effects. The rapidly dividing cells in the developing fetus put it at a higher risk of the adverse biological effects of radiation than a post-partum child, who in turn is more radiosensitive than an adult. External alpha (because it is non-penetrating) and beta radiation are of little concern due to the protection afforded by the mother's body tissues and the placental sac; however, gamma radiation can provide a more uniform exposure to the fetus. Analysis of the human data from the children exposed *in utero* by the bombing of Hiroshima and Nagasaki suggests that the cells of the developing central nervous system are the cells most sensitive to the effects of radiation in the developing human fetus. The major clinical effect on these susceptible cells is impaired intelligence and mental retardation that is observed during childhood development, mainly for those fetuses exposed to doses of radiation during weeks 8–15 after conception. A "no observable effect" threshold exists for doses in the range of 20–40 rad (0.2–0.4 Gy); at a dose of 100 rad (1 Gy), the frequency of observed mental retardation was 43% (BEIR V 1990).

The lens of the eye is also susceptible to the effects of radiation. Sufficient exposure of the lens to radiation results in cataract formation, ranging from mild visual impairment to blindness. The lens fibers are normally transparent and function in focusing light entering from the pupil onto the retina; however, after exposure to large doses of radiation, these cells fail to divide to produce lens fibers of the appropriate length or transparency. This results in increased opacity of the crystalline lens of the eye (cataracts). Cataracts have been induced by as little as 200 rad (2 Gy) of acute gamma or x ray exposure of the eye (Adams and Wilson 1993), but 500 rad (5 Gy) is required when fractionated over 5 weeks. Chronic occupational exposures to 70–100 rad (0.7–1.0 Gy) of gamma and x ray radiation have not caused cataracts, and the higher doses at which they have been observed require the dose to be delivered at a threshold dose rate of greater than 15 rad/yr (0.15 Gy/yr) (UNSCEAR 1993; NRC 1990). Data from victims exposed to large doses of radiation after the bombings of Hiroshima and Nagasaki give a cataract threshold of 60–150 rad (0.6–1.5 Gy); however, typical human exposure over a long period of time is thought to have a threshold greater than 800 rad (8 Gy) (BEIR V 1990). This is an established example of a radiation effects threshold that does not follow the standard linear, no-threshold theory that is applied

only to non-deterministic effects (cancer). This observation may mean that the effect on the lenses is actually below an effects threshold, or it could mean that the latency period for developing the effect is longer than the current human life span.

Sufficient evidence exists from high dose studies of both human populations and laboratory animals to establish that radiation can be carcinogenic and that the incidence of cancer increases with the dose of radiation. Human data are extensive and include epidemiological studies of atomic bomb survivors, many types of radiation-treated patients, underground miners, and radium dial painters. Reports on the survivors of the atomic bomb explosions at Hiroshima and Nagasaki, Japan (with whole-body external radiation doses up to 200 rad [2 Gy]), indicate that cancer mortality has increased in that exposed population compared to control (non-exposed) individuals (BEIR V 1990; Kato and Schull 1982; NCRP 1990b,1993; NRC 1990; UNSCEAR 1993). The use of x rays (at doses of approximately 100 rad [1 Gy]) in the medical treatment for ankylosing spondylitis and other non-cancerous conditions, and for diagnostic purposes has resulted in excess cancers in the irradiated organs (BEIR 1980, 1990; UNSCEAR 1977, 1988). Leukemia has been observed in children exposed *in utero* to doses of 0.2 to 20 rad (0.02–0.2 Gy) (BEIR 1980, 1990; UNSCEAR 1977, 1988). The medical use of Thorotrast (colloidal thorium dioxide) resulted in increases in the incidence of cancers of the liver, bone, and lung (ATSDR 1990b; BEIR 1980, 1990). Occupational exposure to radiation provides further evidence of the ability of radiation to cause cancer. Numerous studies of underground miners exposed to radon and radon daughters (which are α emitters), in combination with silica dust, diesel fumes, and other potential toxicants in uranium and other hard rock mines, have demonstrated increases in lung cancer in exposed workers, especially smokers (Harley 1990b, 1996c). Workers who ingested ^{226}Ra while painting watch dials had an increased incidence of osteogenic sarcoma (ATSDR 1990d). Animal studies indicate that, depending on the radiation dose and the exposure schedule, radiation can induce cancer in nearly any tissue or organ in the body. However, radiation has not been shown to cause cancer of the prostate, uterus, testis, and mesentery in humans (Sanders and Kathren 1983). Radiation-induced cancers in humans are found to occur in the hemopoietic system, lung, thyroid, hepatic, bone, skin, and many other tissues.

The effects of sex, age, smoking, and other susceptibility factors have also been reviewed (BEIR V 1990). Generally, cancer rates after exposure to radiation are age-dependent and increase with age. The effect of smoking on lung cancer incidences in those individuals who also have prolonged exposure to inhaled alpha emitters indicates a multiplicative risk (or near multiplicative risk); however, this may not be the case for acute exposures to x rays or gamma rays. In contrast, the data on lung cancer and smoking in the Japanese atomic bomb survivors indicate an additive risk (no interaction between radiation and smoking).

It is not presently clear how a person's sex influences cancer rates. Males appear to be more susceptible to lung and non-sex-specific cancers than are females; however, this may be related to the male's increased exposure to carcinogens and promoting agents in occupational situations, as well as a number of lifestyle factors, and not necessarily due to increased radiation dose.

Laboratory animal data show that high doses of radiation are carcinogenic and mutagenic, and can result in cell lethality. These effects are not seen at low doses. This raises a question about the relationship between high and low doses. There is uncertainty regarding the shape of the dose response curve with regard to extrapolating from high-dose effects to effects of low doses or doses received over protracted periods of time, where no effects have been seen. If the dose-response relationship is assumed to be linear all the way down to zero dose, then a proportional decrease in the incidence of the effect being measured (cancer, reciprocal chromosome translocations, locus mutations, life-span shortening, etc.) would be expected as the dose or dose rate of radiation decreases. However, in laboratory studies with high doses, a dose rate effect was found. That is, an acute-duration exposure delivered over several days required a higher dose to produce a given effect than if delivered within hours. To account for this, a compensation factor or Dose Rate Effectiveness Factor (DREF) can be incorporated into the dose response models to extrapolate cancer risk from high to low doses or low dose rates. For low LET radiation, DREF factors from 2 to 10 have been suggested, with a DREF of 2.5 for human leukemia. Assumptions about DREF are largely based on laboratory animal data. A comprehensive discussion of radiation-induced cancer is found in BEIR IV (1988), BEIR V (1990), and UNSCEAR (1988) and in Chapters 3 and 5 of this toxicological profile.

Lifetime radioactive material feeding studies using Beagle dogs indicate that radiation effects may be viewed from a perspective of life-span shortening which is linear with dose rate rather than with dose. Time-to-death plots as a function of dose rate show three separate sections, representing mortality from acute radiation syndrome, cancer, and old age, each with separate linear slopes that intersect at points of equal competing causes of death. At extreme dose rates, death is caused exclusively by acute radiation syndrome, with time-to-death increasing with a steep linear slope as the dose rate decreases. At a low enough dose rate, cancer replaces ARS as the primary cause of death, and the time to death curve assumes a shallower slope. At a low enough dose rate, cancer deaths are replaced by the limit of the normal life span (Raabi 1993, 1996).

2.4.4 Genetic Effects

All genes have a natural and spontaneous mutation rate, but radiation can induce additional genetic damage, such as gene mutations and a variety of chromosomal aberrations, by causing changes in the structure, number, or genetic content of chromosomes in the cell nucleus. Radiation increases the mutation rate. No new types of mutations are known to be produced by radiation. The evidence for the mutagenicity of radiation is derived from studies in laboratory animals, primarily mice (BEIR 1980, 1988, 1990; UNSCEAR 1982, 1986, 1988, 1993). Evidence for genetic effects in humans is derived from tissue cultures of human lymphocytes from persons exposed to ingested or inhaled radionuclides (ATSDR 1990d, 1990e). Evidence for mutagenesis in human germ cells (cells of the ovaries or testis) is not conclusive (BEIR 1980, 1988, 1990; UNSCEAR 1977, 1986, 1988,1993). Chromosome aberrations following radiation exposure have been demonstrated in humans and in experimental animals (BEIR 1980, 1988, 1990; UNSCEAR 1982, 1986, 1988,1993). This finding is not thought to be in conflict with results of animal studies that indicate induction of mutations by radiation; instead, the finding may result from the difficulty of demonstrating a slight increase of effects of this type in a human population (UNSCEAR 1993). However, no genetic effects have been observed in any human population exposed to any radiation at any dose level. An important source of data on genetic effects in humans are Japanese survivors of the atomic bombs and their offspring. More information on the genetic effects of radiation can be found in Chapters 3 and 5 of this toxicological profile.

2.4.5 Teratogenic Effects

There is sufficient evidence from x ray and gamma ray studies to suggest that some forms of radiation produce teratogenic effects in animals. Rapidly multiplying cells tend to be more sensitive to the adverse effects of radiation than slowly multiplying cells. Leukemia and other childhood cancers are the principle effects of *in utero* exposure at low doses (<100 rad [<1 Gy]). It appears that the developing fetus is more sensitive to radiation than the mother and is most sensitive to radiation-induced damage during the early stages of organ development (first trimester) due to the rapid cellular proliferations occurring at that time. The type of malformation depends on the stage of development and the cells that are undergoing the most rapid differentiation at the time. Studies of mental retardation, intelligence reduction, microcephaly, and growth retardation in children exposed *in utero* to high doses of radiation from the atomic bombs at Hiroshima and Nagasaki provide evidence that radiation can produce teratogenic effects in human fetuses if delivered in large enough doses during weeks 8 through 25 after conception (Otake and Schull 1984; Zajtchuk 1989). The damage to the child was found to be related to the dose that the fetus received *in utero*. In addition, numerous studies have been conducted on the carcinogenicity of *in utero* irradiation,

and some appear to indicate that *in utero* exposure may produce a larger cancer risk per unit dose than postnatal irradiation (NCRP 1995). Chapters 3 and 8 contain more information on the teratogenic effects of radiation.

2.4.6 Internal Exposure to Ionizing Radiation

For the purposes of this profile, internal exposure is defined as the energy deposited in the body by the transformation of radioactive material that is inside the body. The pathways by which radioactive materials enter the body include inhalation, ingestion, dermal absorption, and injection. The material's solubility and chemical nature, and not its radioactive properties, determine the degree to which the material will stay in one place or redistribute throughout the body. Thus, the internal radiation dose is determined from the types and energies of emitted radiation, the rates of radioactive transformation and biological elimination, and the distribution of the material throughout the body. The dose to one part of the body is the sum of the doses to that part from radiation emitted from all other organs and tissues that contain the radionuclide.

2.4.6.1 Inhalation

Inhalation is an important route by which internal exposure to radionuclides can occur. Many of the inhalation studies discussed in Chapter 3 are further indexed by no-observed-adverse-effect level (NOAEL) and lowest-observed-adverse-effect level (LOAEL) in Chapter 8 of this toxicological profile. The total absorbed radiation dose to a specific site, such as the lungs and any surrounding structures, is dependent on the physicochemical characteristics of the radioactive element, the molecule in which it is present, or the particle to which the radioactive element is bound or incorporated when deposited in the respiratory tract. In many of the studies reported in Chapters 3 and 8 of this profile, laboratory animals were exposed to a radionuclide that was bound to a particle of some type. The radionuclide "piggy-backing" on that particle was inhaled, the initial lung burden was determined, and the health effects on the animal observed over a period of days or over its lifespan. Particle kinetics are a major determinant in the size of the total absorbed radiation dose that lung tissue and other tissues and organs receive from inhaled radioactive material. Several excellent reviews are available that discuss the deposition and clearance of inhaled particles in humans and in laboratory animals (Gore and Patrick 1978; Lippmann and Esch 1988; Lippman and Schlesinger 1984; Schlesinger 1989; Snipes 1989; Stahlhofen et al. 1980, 1981). A brief review is presented below. Internal radionuclide exposures may occur from direct medical administration for diagnosis or treatment of disease, or from passive inhalation of radionuclides that are present in normal breathing air.

Particle deposition and clearance mechanisms in the respiratory tract are complex. The patterns of deposition and clearance differ among animal species, but some generalities have been reported (Snipes 1989). As a rule of thumb, the larger the particle inhaled, the more likely that particle will be deposited in the upper airways (nasal tract and upper conducting airways); the smaller the particle, the more likely that alveolar and deep penetration of the particle into the lung will occur, regardless of the particle's solubility. Particles that are soluble in the lung fluid milieu generally have shorter residence times or biological half-lives than those that are insoluble in lung fluid. These concepts are important when considering inhaled radioactive particles. For example, particles that are 3 μm in diameter and that are also insoluble (such as fused aluminosilicate particles [FAP]) containing a radionuclide such as ^{144}Ce are likely to be largely deposited deep in the lung (bronchioles and alveoli). Retention of particles deep within the lung may be due to a number of factors, including the lack of cilia and less mucous in the smaller airways than in larger airways (trachea and bronchi) (Snipes et al. 1996). These insoluble particles are also likely to be cleared slowly from the respiratory tract over a period of several months or years, thereby subjecting the tissues around that particle to long-term exposure to radiation. On the other hand, particles that are very large (10–12 μm and above) may not reach the deep lung and will either lodge in the nasal cavity or be cleared by mucociliary clearance from the conducting airways, resulting in a low radiation dose to the respiratory tract (but may increase the dose to the gastrointestinal tract or nasal passages). Soluble particles will dissolve, releasing the material into the surrounding tissue, where it will behave toxico-kinetically like its nonradioactive counterpart. Leaching of radionuclides from insoluble particles has also been reported to occur.

Factors that influence particle clearance include: (1) particle characteristics, such as geometric size, shape, density, hygroscopicity, and electrical charge; (2) respiratory tract characteristics, such as the individual airway caliber, branching patterns of the conducting (tracheobronchial) airway tree, and the path length to the terminal airways, all of which contribute further to the disposition of particles in the respiratory tract; (3) mode of breathing (oral, nasal, oronasal), respiratory rate, tidal volume, interlobular distribution of ventilated air, length of respiratory pauses, etc; and (4) other factors (lung disease, age of the animal, irritant exposure, etc.) which also play significant roles in how long a particle remains lodged in the respiratory tract. Several natural body mechanisms function to clear the respiratory tract of these foreign bodies. Such mechanisms include sneezing, coughing, mucociliary transport, dissolution (for highly as well as slightly soluble particles), and removal by macrophages; these decrease the particle residence time in the respiratory tract, thereby decreasing the total radiation dose to the tissues (Schlesinger 1989). Deposition and clearance mechanisms are important factors influencing radiation dose from a radionuclide to lung tissue and in relating that dose to a corresponding health-related effect.

2.4.6.2 Ingestion

Oral exposure to radionuclides may occur with the ingestion of contaminated food or water. There is little literature available that describes the toxicity of ingested radioactivity in humans. The main source of information on oral toxicity of a radionuclide is the experience of the radium dial painters who "tipped" their paint brushes with their lips and/or tongues, subsequently ingesting radioactive radium. The radium in the paint contained both the long-lived ^{226}Ra and the shorter-lived ^{228}Ra isotopes. Some of these exposed individuals later developed bone sarcomas and head carcinomas that appeared from 5 to 50 years after their first exposure to these isotopes (Mays 1988; Spiess and Mays 1970). On the other hand, millions of people have been given individual administrations of 200–500 MBq (5–14 mCi) of radioiodine orally to aid in the diagnosis of thyroid disorders, with no apparent harmful effects. Although a number of radionuclides are in widespread use, the use of ^{131}I to treat thyroid conditions predominates worldwide, and radiopharmaceuticals administered by various routes currently produce an estimated population dose of 930,000 man-rem/yr (9,300 man-Sv/yr) (UNSCEAR 1993).

For most radionuclides present at chemical waste sites containing low-levels of radioactive isotopes, oral exposure is not a major route of exposure; however, the oral exposure route cannot be disregarded because of the potential for groundwater contamination, consumption of animals that have ingested radioactive compounds in their diet, and uptake by plants following erosion of ground cover from a contaminated site.

2.4.6.3 Dermal

Dermal exposure to radionuclides is a minor route of exposure at low-level radioactive waste sites. Swimming or bathing in water containing soluble radioactive compounds in the water itself or water-insoluble radioactive compounds in sediment or sludge are potential sources of dermal exposure in highly contaminated areas. Contact with tritiated water is another situation in which skin absorption of a radionuclide can be significant. Depending on the specific physical properties of the radionuclide that may reside on the skin, the percutaneous absorption of radionuclides from particles is usually negligible (especially if the skin is thoroughly washed immediately following exposure), with long-term biological effects being demonstrated locally at the level of the dermis (and its vasculature) and epidermis; however, these effects depend greatly on the size of the dose and length of exposure. More soluble forms of the radionuclides may result in a small percentage of the nuclide being absorbed if it was not removed from the skin's surface. This absorption may, in turn, affect tissues other than the skin.

2.4.7 External Exposure to Ionizing Radiation

External radiation is also a major source of exposure to radiation. External radiation is defined here as radiation exposure from a radioactive source that is outside of the body. Common natural sources are terrestrial radiation (originating from the soil, water, building materials, and air) and cosmic radiation from outer space. Common sources of man-made external radiation include medical and dental x rays, consumer products, licensed radioactive sources, and being near someone undergoing a medical radionuclide treatment. Technologically enhanced sources consist of concentration of naturally radioactive elements, such as uranium mine and mill tailings or the uranium-containing slag from phosphate rock processing.

In situations involving external exposure to radiation, radionuclides that are gamma emitters are of greatest importance. Alpha particles travel only a few inches in the air and are not capable of penetrating a piece of paper or the stratum corneum (the dead outer layer of the skin); beta particles are less energetic and have only limited penetrating ability. In contrast, gamma radiation is highly penetrating, and thus more capable of irradiating the whole body from distant sources.

2.5 MEASURING INTERNAL AND EXTERNAL SOURCES OF IONIZING RADIATION

The radiation from some internally deposited radionuclides cannot be measured directly. The radioactivity of such radionuclides within the body is determined by bioassay methods, and the data obtained are applied to physiologically-based biokinetic models to calculate the dose.

Dose rates for external radiation can be directly measured with appropriate instruments; the total dose is determined by multiplying the dose rate by the exposure time. Total dose from external sources can be easily measured. This is usually done with a personal monitoring device, such as an electronic dosimeter, a pocket dosimeter and film badge, or a thermoluminescent dosimeter (TLD). Table 2-7 lists some of the methods and instruments used by the health physicist to determine a person's radiation dose. The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) manual provides information on how various types of field and laboratory equipment are used to measure radiation dose rates and quantities of radioactive material (MARSSIM 1997).

2.5.1 Internal Radiation Measurements

The amounts of radioactive material in the body are measured by *in vivo* or *in vitro* methods or a combination of *in vivo* and *in vitro* techniques. These types of measurements, called bioassays, are used to determine the type, quantity, location, and retention of radionuclides in the body. *In vivo* techniques measure the quantities of internally deposited radionuclides directly, while *in vitro* analyses are performed on the materials excreted or removed from the body. A synopsis of the analytical methods used to measure the quantity of radioactivity both inside and outside of the body is presented in Table 2-7.

Table 2-7. Common Analytical Methods for Measuring Radioactive Material Inside and Radiation Outside the Body

Sample matrix	Preparation method	Device used	Reference
Whole body, portion of body, or organ (x or γ radiation)	Position individual in front of detector with area of interest shielded from extraneous radiation	Multichannel analyzer with NaI detector for up to a few γ-emitters, a germanium detector for any number of γ-emitters, or a planar germanium detector for α-emitters that also emit x rays.	NCRP 1978
Urine, blood or feces	Put any solids into solution; do chemical separation if multiple radioactive elements are present; deposit thin layer on a planchet or mix with liquid scintillation cocktail.	Liquid scintillation for α- or β-emitters; alpha spectroscopy for α-emitters; GM counter for high-energy β- or γ-emitters; multichannel analyzer for γ-emitters.	Jia et al. 1994
Personal monitoring: external radiation dose (β- and γ-radiation)	Heat dosimeter to produce thermoluminescence	TLD	Lynch et al. 1994
	Develop film	Film badge	Shapiro 1990c
	None	Electronic dosimeter	
Contamination monitoring: surfaces, skin, clothing, shoes (β- and γ-radiation)	None	GM counter	NCRP 1978
Contamination monitoring: surfaces, skin, clothing (α-radiation)	None	Proportional counter	NCRP 1978

α = alpha; β = beta; γ = gamma; GM = Geiger-Mueller; TLD = thermoluminescent dosimeters

One *in vivo* or direct method of measuring radionuclides in the body is performed with a radiation detection system and its associated electronics, called a whole-body counter (see Figure 2-2). Equipment for whole-body counting varies from facility to facility and is selected based on the needs of each facility. Equipment changes also continue as the state of the art advances. Commonly, the subject is seated in front of a single large detector; however, the subject can remain standing during the count, as shown in Figure 2-2. This system measures the emission of gamma rays or x rays from internally deposited radionuclides. The use of whole-body counters is limited to assessment of radionuclides that emit x ray or gamma radiation as these counters are insensitive to the alpha and beta particles emitted from radionuclides. Whole-body counting systems can vary from single, unshielded detectors that can be used in the field to shielded multi-detector scanning systems (NCRP 1987).

Figure 2-2. Whole Body Counter. The linear geometry NaI based WBC pictured here is designed to maximize sensitivity and accuracy for internally deposited fission/activation products such as isotopes of Cs and Co. (Photograph courtesy of Canberra Nuclear/Packard BioScience Co.)

The complexity of whole-body counting systems depends on their intended uses and the radionuclides to be measured, as well as the accuracy and precision required of the measurement. Multiple, fixed position detectors may also be used for simultaneously assessing multiple areas of the body (e.g., lung and thyroid detectors). The detector is placed a short distance from the body, such as over the chest when a lung count is desired. Examples of types of detectors used include solid, inorganic scintillators (e.g., sodium iodide), and semiconductors (e.g., germanium detectors).

Examples of radionuclides that may be readily identified and quantified using whole-body counting techniques are ^{134}Cs, ^{137}Cs, ^{58}Co, ^{60}Co, ^{131}I, ^{99m}Tc, and ^{133}Xe. If a particular portion of the body requires monitoring after exposure to alpha particle emitters that also emit x rays or gamma rays, such as uranium, plutonium, and americium, a low-energy germanium lung counter can be used to maximize detection sensitivity for x rays or gamma rays that are emitted from such internally deposited radionuclides (see Figure 2-3). Typical count time for the instrument shown in Figure 2-3 is 15–30 minutes. Another detector variation consists of moving one or several detectors along the length of the subject, or moving the subject in relation to a fixed detector, and determining radioactivity in the body as a function of the position of the detector (NCRP 1987). Photons from the radionuclides in the body enter the detector and interact with the detection medium. In the case of a sodium iodide detector, this interaction produces flashes of light (scintillations). The intensity of each scintillation is proportional to the interaction energy of the photon producing it. Photomultiplier tubes convert the light energy to an electrical pulse with an output voltage proportional to the intensity of the scintillation. The output pulses are then amplified and sorted by energy level. If a germanium semiconductor detector is used, the photon interaction directly produces an electrical impulse whose magnitude is proportional to the photon's energy. With either detector, qualitative and quantitative analyses of the energy profiles are then performed to identify the radionuclides present and their activities.

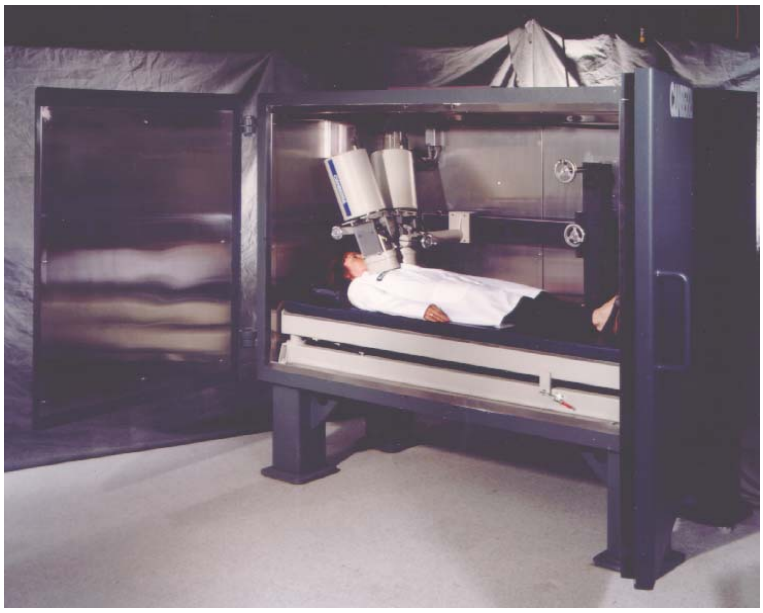

Figure 2-3. Low Energy Germanium (LEGe) Based Lung Counter. This instrument is designed to maximize sensitivity for internally deposited U, Pu and Am isotopes. Germanium is used to provide the system with the ability to resolve the differences between photons which are close in energy to each other. (Photograph courtesy of Canberra Nuclear/Packard BioScience Co.)

In vivo counting systems are calibrated using tissue-equivalent phantoms. These phantoms have shapes similar to the human torso and are made of polystyrene or other tissue equivalent material. Standard radioactive sources of known activities are inserted into the phantom at locations or geometries approximating internal depositions of particular radionuclides in the human body. Relationships are thus determined between the radiations detected and the known activity in the phantom (DOE 1988; HPS 1996).

The Health Physics Society developed the American National Standard on Performance Criteria for Radiobioassay (HPS 1996) to establish performance criteria for accuracy, bias, and precision for

bioassays. The sensitivity of a whole-body counting system is specified by the acceptable Minimum Detectable Amount (MDA) which is the smallest activity or mass of an analyte in a sample or the body that will be detected, given assigned type I and type II error limits. The criterion imposed on a participating laboratory is the Minimum Testing Level (MTL) or the amount of radioactive material that the service laboratory should be able to measure. When the analysis facility can measure an acceptable MTL with acceptable bias and precision, the performance requirements of the ANSI standard are considered to have been met. Some examples of MTLs are 9 kBq (0.24 μCi) of ^{239}Pu or 3 kBq (81 nCi) of ^{60}Co in the lung by direct test methods, or 0.01 Bq (0.27 pCi) of ^{239}Pu or 2 Bq (54 pCi) of ^{60}Co per liter of biological material by indirect methods (HPS 1996).

For radionuclides that transform by alpha or beta particle emission and do not emit readily measurable gamma rays, *in vitro* or indirect analyses can be performed. *In vitro* analyses may also be performed in support of an *in vivo* monitoring program, or in cases where the size of an operation does not justify the cost of a whole-body counting facility. These analyses usually involve measurement of radionuclides in urine, but other body materials such as feces, blood, or tissue samples may also be measured. Urine sample analysis is a rapid way to determining whether an intake of radioactive material has occurred. Urine samples are easily obtained and easy to analyze; however, fecal, blood or tissue samples are difficult to obtain, and thus these analyses are not routinely performed. ^{3}H, ^{14}C, various isotopes of uranium and plutonium, and many other β- or α-emitting radionuclides are often assessed by *in vitro* techniques.

Gamma ray measurements of excreta may not require chemical processing and separation prior to counting due to the penetrating characteristic of gamma radiation. For alpha and beta radiation measurements, the energy spectra of the various radionuclides overlap. In such cases, chemical separation of samples prior to quantification of the radioactivity may be required. If only the total activity, not the identity of the radionuclide, is needed, gross alpha and gross beta quantification can be performed with minimal sample preparation. There are no standard chemical separation or preparation procedures for *in vitro* analysis that are recommended by any recognized authority; however, many acceptable procedures are available and in use at a large variety of laboratories and facilities, and DOE and EPA laboratories have some standard procedures that they routinely follow. Regardless of the procedures used by each laboratory, the methods should be capable of meeting the acceptable MTLs identified by HPS (1996).

Detectors commonly used to quantify alpha, beta, and gamma radiation in *in vitro* samples include scintillation (Figures 2-4) and liquid scintillation detectors (Figure 2-5), Geiger-Mueller (GM) detectors, gas-filled proportional counters, and semiconductor detectors. In scintillation counters, photons from the

radionuclides exit the sample (i.e., urine, feces, tissue) and interact with the scintillator (e.g., zinc sulfide for α-emitters, toluene for α- and β-emitters; NaI crystals for γ-emitters) to produce flashes of light (scintillations). Photomultiplier tubes convert the light energy into an electrical pulse with an output voltage proportional to the energy of the radiation interaction. The output pulses are then amplified and sorted by energy level. Gamma rays interact, producing a broad energy spectrum from Compton interactions superimposed by peaks from photoelectric events. The peak centroids and areas are used to identify the isotopes and their activities.

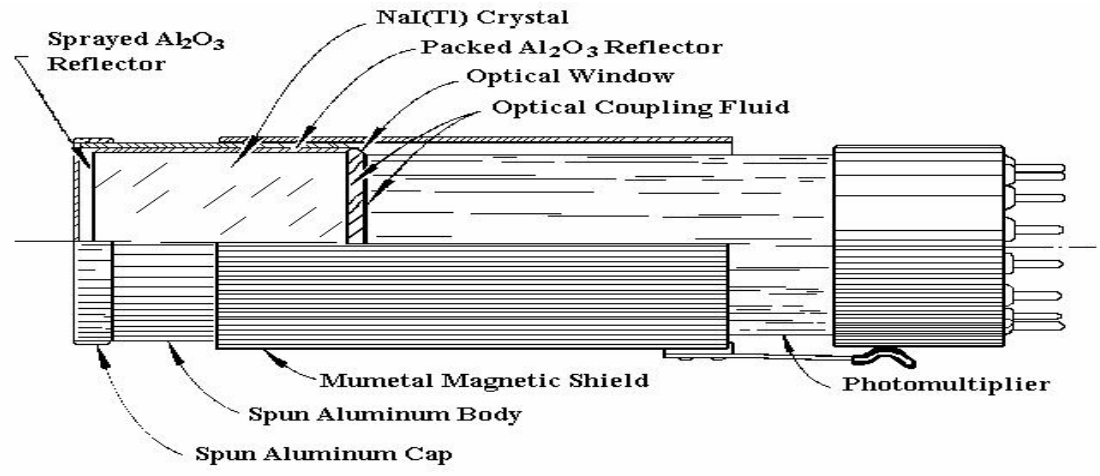

Figure 2-4. Components of a Scintillation Detector (adapted from http://tweedledee.wonderland.caltech.edu/-derose/labs/exp12.html)

Liquid scintillation counters (Figure 2-5) are used to isotopically identify and measure the activity of alpha or beta radionuclides in a range of sample matrices. This method is useful in avoiding some of the difficulties that arise when analyzing alpha or low-energy beta emitters, such as ^{3}H and ^{14}C, where self-absorption within the sample matrix can be significant. The sample is dissolved directly into a liquid scintillator and placed inside a light-tight system. The radiation from the sample activates the scintillator, causing flashes of light (scintillations) whose intensities are proportional to

Figure 2-5. Liquid Scintillation Counting (LSC) System. Shows system (left) and closeup view of sample vials to be loaded (right). (from Canberra/Packard Bioscience Co.)

the radiation energy. These scintillations are measured by an integral photomultiplier tube. The counting efficiency of current generation photomultiplier tubes is about 90%. Most liquid scintillation fluids (cocktails) are organic-based solvents, such as toluene. The signal from the dissolved sample is reduced or quenched through partial absorption of the light by the dissolved sample, so an optical comparison of pure and sample laden scintillation cocktail is made to correct for this phenomenon (Knoll 1989).

GM counting systems consist of a gas-filled detector tube, associated electronics, and counting circuit and display. The tube end can have a thin covering (window) that allows low-energy beta particles to enter the tube. When an incident particle from a radionuclide enters the tube window and interacts with at least one gas molecule, it initiates a series of ionizations that result in generation of a voltage pulse of about 1 volt. These radiation-induced electrical pulses trigger a circuit which counts the pulses. The GM counter is not capable of discriminating among various types of radiation (alpha, beta, gamma); the instrument simply records the number of pulses. However, the use of different window thicknesses allows the user to discriminate among the different radiations. An aluminum window 0.1 mm thick will stop all beta particles emitted from ^{14}C; to measure alpha particles, an aluminum window thickness of less than 0.02 mm is required. Gamma radiation does not require a special window because gamma rays will penetrate the tube from all directions (Shapiro 1990).

Gas-filled proportional counters are used to measure alpha and beta particles; they are particularly well-suited for low-level alpha measurements due to their large counting areas and low background. Like the GM counters, the voltage pulse output signal produced in proportional counters is a result of an electrical charge resulting from the ionization of the gas by the incident particle. Electrons released by the ionization are drawn toward the positively charged central wire. As they travel toward the wire, the electrons collide with other gas molecules, producing more ionizations and an amplification effect. At certain counter operating voltages, the amplified charge produced is proportional to the energy absorbed in the detector and facilitates energy discrimination techniques. Alpha particles, due to their larger size, large charge, and lower speed, interact with more gas molecules over a given path-length than beta particles. Thus, the alpha-to-beta particle pulse height ratio is substantial (Shapiro 1990). Proportional detectors use this difference to distinguish between alpha and beta particles, based on pulse-height discrimination.

Semiconductor detectors are characterized by their use of crystalline silicon or germanium as the ionization medium. A sensitive volume is produced in the crystal by electrochemical means. The interaction of radiation with the crystalline lattice within the sensitive volume generates electrons by ionization, and the collection of these electrons leads to an electrical output pulse whose size is proportional to the energy of the radiation. A semiconductor detector requires only about one-tenth as much energy to produce an ionization as other types of detectors. This leads to a great increase in the detector's resolving power (i.e., in the ability

of the detector to separate pulses from particles whose energy differences are very small). For this reason, semiconductor detectors find their main use in nuclear spectroscopy, where they can simultaneously separate, accurately identify, and quantify various radionuclides. Several types of semiconductor systems are available, including *in-situ* spectrometers and both portable and stationary systems equipped with multichannel analyzers (Cember 1996; Shapiro 1990).

2.5.2 External Radiation Measurements

People who could be occupationally exposed to radiation are routinely monitored for external radiation dose by several different devices called dosimeters. The most commonly used personal monitoring dosimeters are thermoluminescent dosimeters (TLDs) and nuclear emulsion monitors (film dosimeters), which can be used to measure exposure to β, x ray, and γ radiation doses. The TLDs and the film dosimeters are integrating devices that measure the total dose over the period that the TLD or film badge is used or worn.

The most widely used thermoluminescent material for measuring beta and gamma radiation is a lithium fluoride crystal. The energy absorbed from the radiation raises the electrons in the lattice structure of the crystal to a higher energy level, where a portion are trapped by added impurities. The electrons remain in these excited states until the TLD is heated to temperature high enough to return the material to its normal energy level (Lynch et al. 1994). Light is emitted which can be measured; the amount of light is proportional to the radiation dose to which the TLD was exposed. Automated systems called TLD readers for measuring the light output from the heated TLDs are commercially available. TLDs are normally worn from 1 day to 1 quarter before results are processed; TLDs posted around occupied areas to assess doses to unmonitored individuals are normally posted for 1 month to 1 year; the TLD can be used again (Shapiro 1990).

When individuals are exposed to mixed radiation fields (e.g., mixtures of beta/gamma radiation), measurements for each radiation type must be performed. Either film badges or TLDs can be made to distinguish among various radiations, and are commonly used to monitor personal exposures to β, x, and γ radiation, but not α radiation. Due to the limited range of beta particles in tissue, the exposure of concern is primarily to the skin, although beta particles whose energy exceeds 0.8 MeV can penetrate to the lens of the eye. Penetrating x ray and gamma radiation can expose the whole body, including the lens of the eye. These types of radiation are assessed simultaneously using multiple TLDs individually covered with absorbers of various materials, or a strip of film with sections covered with absorbers that separate the radiations according to their penetrability. The skin dose, called the shallow dose equivalent (SDE), is measured with the dosimeter behind a very thin absorber that is 7 mg/cm^2 thick and represents the dead skin layer above live tissue. The dose to the lens of the eye, called the eye dose equivalent (EDE), is measured behind 300 mg/cm^2 of material

equal to the thickness of the cornea plus liquid that covers the lens. The whole-body dose, called the deep dose equivalent (DDE), is measured behind an absorber whose thickness of 1,000 mg/cm^2 which is equal to about 1 cm of tissue or the depth inside the body where the dose from high energy gamma rays tends to be the highest. For example, most TLDs and film badges have a small beta window shielded only by a thin sheet of mylar, and a gamma ray detection area consisting of one or more sections shielded with thin sheets of plastic, metal (like copper, aluminum, steel, tin, or lead), or combinations of these. The radiation exposure of the film is determined by the degree of darkening of the photographic film. A densitometer is used to read the film darkening, which is proportional to the absorbed dose in the tissue (Shapiro 1990).

In addition to wearing TLDs and film badges, many radiation workers also carry self-reading pocket dosimeters to provide the wearer an indication of the radiation dose received during the day. Because the pocket dosimeters may be read by the individual locally, it gives the worker the necessary information to prevent an overexposure and the worker can leave an area before a particular radiation dose is exceeded. The dosimeters are usually worn beside the primary dosimeter and typically measure x ray or γ radiation. They respond to betas but are not meant to measure betas. By lining the interior of the chamber with boron, the devices may also be made to monitor thermal neutron exposure. In this instrument, a quartz fiber is electrostatically displaced by charging the dosimeter to a potential of about 200 volts. As with other dosimeters, ionizations caused by radiation discharge the dosimeter which returns the fiber to its usual position as it loses its charge. The relative position of the fiber is calibrated to an exposure scale, usually in the range of 0 to 200 mR. The position of the fiber against the scale may be viewed through the end of the instrument.

There are two type of pocket dosimeters. The second type, called a condenser-type dosimeter, is an indirect reading dosimeter. An additional device, referred to as a charger-reader, is needed to charge and read the dosimeter. The dosimeter is basically a capacitor with an exterior wall made of an electrically conducting plastic or metal and an interior central wire which is insulated from the outer wall. Using the charter-reader, a positive charge is placed on the central wire. When exposed to x or gamma radiation, the ionizations discharge the unit. The amount of charge remaining in the dosimeter at any point is inversely proportional to the ionization produced in the cavity. The degree of discharge, and therefore the exposure, is measured by attaching the dosimeter to the charger-reader. Pocket dosimeters gradually discharge over time due to cosmic radiation and charge leakage across the insulating material. Because of the natural discharging and the potential for malfunction due to dropping the device, they are typically worn in duplicate with a film badge or TLD and are read and recharged daily (Cember 1996)

Electronic dosimeters are now widely used. These dosimeters feature solid-state detectors and a microprocessor to monitor x and gamma ray dose, dose rate, and dose history. Also, these small, programmable, lightweight dosimeters feature audible and vibrating alarms and visible digital readouts that keep the wearer informed of their radiation dose status at all times. Units with telemetric capabilities can be monitored at stations outside the work area where the dosimetry of a number of individuals can be simultaneously viewed and assessed to facilitate a higher degree of radiological control, such as for activities involving high intensity radiation sources. These dosimeter can be retained indefinitely by the individual and the person's dose history can be accumulated remotely, stored digitally in database fashion, and used to produce computer generated dosimetry reports on demand.

Figure 2-6. Geiger-Mueller Counter with an Energy-compensated Gamma Probe. (Photo courtesy of Ludlum Measurements, Inc.)

2.5.3 Field Radiation and Contamination Surveys

Environmental radiation arises from four basic sources: (1) natural radioactivity from uranium, thorium, and other primordial radionuclides; (2) cosmic rays and radionuclides produced by cosmic-ray interactions in the atmosphere; (3) contaminants from nuclear-weapons fallout; and (4) effluent from nuclear and medical facilities (NCRP 1985). Two methods are routinely used for measuring environmental radiation: (1) field surveys using portable survey instruments, and (2) analysis of samples procured in the field that are returned to the laboratory for quantification.

Figure 2-7. Geiger-Mueller Counter with a Beta/gamma Pancake-type Detection Probe. (Photo courtesy of Ludlum Measurements, Inc.)

2.5.3.1 Field Measurements of Ionizing Radiation

External radioactivity and radiation measurements can be made with portable, hand-held survey instruments. The primary purpose of some types of survey instruments is to measure the radiation levels to which people

are exposed, while others detect any contamination that may be present on an individual's skin, clothing, shoes or in the environment.

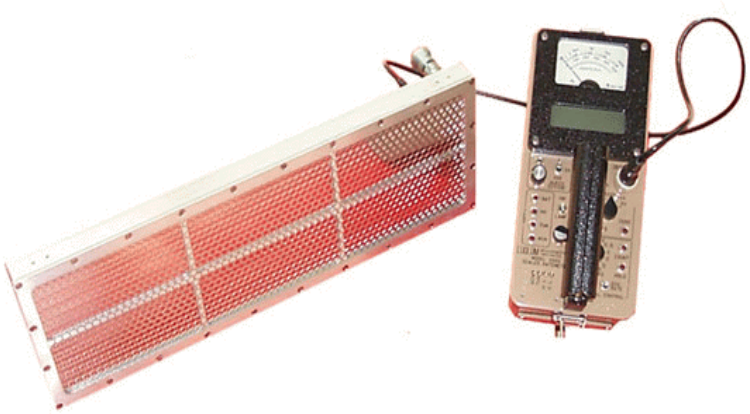

Figure 2-8. Large Area Alpha Radiation Detector with Digital/Analog Survey Meter (photo courtesy of Ludlum Measurements, Inc.)

Various types of radiation detectors (e.g., Geiger-Mueller or scintillation) are coupled with a count rate meter designed to detect alpha, beta, and gamma radiation. The count rate meter has a scale with a needle indicator or digital display that provides an immediate readout of levels of radiation or contamination that may be present in units of milliroentgens per hour (mR/hr) (1 mR ≈ 1 mrem = 0.01 mSv) or counts per minute (cpm). Two frequently used GM survey meters are the energy compensated GM detector (Figure 2-6) and the GM thin window "pancake" type detector (Figure 2-7). The energy compensated type of GM detector surrounds the detector chamber with a material of density and thickness that somewhat normalizes the dose response over a range of energies, which sacrifices some sensitivity for accuracy. The pancake detector typically has a very thin window and a relatively large detection area. The typical survey meter for identifying alpha contamination uses a zinc sulfide scintillator material that can reliably detect 200–500 dpm per 100 cm^2 (DOE 1988). Disintegrations per minute per 100 cm^2 of contaminated area is the criterion that has been chosen by regulatory agencies for control purposes. The alpha reading may be inaccurately low if the surface is irregular, porous, or damp since these conditions can attenuate the alpha particles. Recent developments in large area gas and gas-flow proportional counter technology, which have enabled these detectors to achieve higher sensitivities than alpha scintillator detectors, have made them acceptable for use in decommissioning operations. Figure 2-8 is an example of a current generation large area detector with digital survey meter. Figure 2-9 is a floor monitor system with multi-detector array that covers a wide path. The detector is slowly moved over a building or roadway surface to locate radioactive contamination and then held in place to quantify the level. Floor monitors with drive, data recording, and positioning systems are used to develop digitized reports and plots of alpha and beta contamination levels; these units can quantify contamination levels while continuously moving.

Figure 2-9. Floor Monitor System with Multi-detector Array. (Photo courtesy of Ludlum Measurements, Inc.)

Field surveys can be either qualitative (to provide a go/no-go indication for excess radiation levels) or quantitative (to provide a numerical value for the level and possible identification of the radionuclides present). Most field surveys involve the use of calibrated, portable, hand-held survey meters equipped with count-rate meters or digital displays that provide an immediate reading of the radiation field strength or the surface contamination level.

The radiation detector used in a survey must be appropriate to the type of radiation being measured. Typical alpha radiation detectors use the alpha scintillator material ZnS, as well as gas-flow surface contamination monitors. Typical beta radiation detectors are pancake type GM detectors and gas-flow surface contamination monitors. Gamma radiation detectors include a wide range of equipment types, including the GM and sodium iodide scintillation counters. Counter-type survey instruments are highly sensitive and are used mainly to search for and detect radiation. Ion chambers are used for measuring the radiation dose rate, with pressurized ion chambers being used for very low radiation levels.

Specialty instruments are available for more detailed field work, but their use generally requires special skills and training. The *in-situ* germanium spectrometer is a multichannel analyzer with a germanium detector that can identify a range of γ-emitting isotopes and quantify their concentration in surface soil. The Laser Ablation Inductively Coupled Plasma mass spectrometer (LA-ICP-MS) can measure 0.3 pCi/g of ^{238}U in soil. The Long Range Alpha Detector (LRAD) can measure alpha soil contamination down to 10 pCi/g. The Field Instrument for Detection of Low Energy Radiation (FIDLER) is used to measure plutonium and americium surface contamination. The field x ray fluorescence spectrometer can measure the relative concentration of metal atoms in soil or water down to the parts per million (ppm) range.

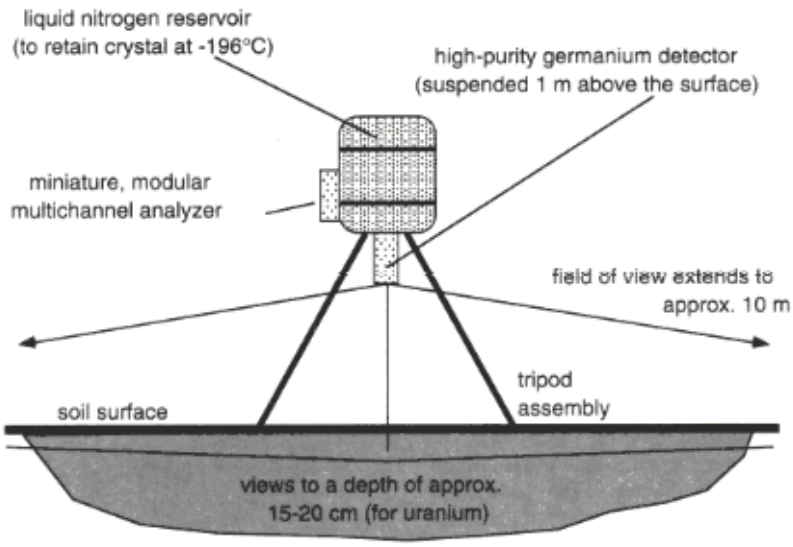

Figure 2-10. *In-Situ* Gamma Ray Spectrometer
(adapted from http://www.em.doe.gov/rainplum/fig16.html)

Field survey instruments provide timely information on the presence and levels of radiation fields or radioactive materials.

Measurements of radiation fields or loose radioactive material can be made in the field with portable instrumentation (Figure 2-10). Similar surveys can also be performed on people when contamination is suspected since both environmental surveys and personnel surveys use many of the same types of portable instrumentation.

Semi-permanent instruments or instruments placed in the field for extended periods of time are sometimes used to measure ambient environmental radiation levels or to detect changes in ambient environmental radiation levels (for example, around nuclear facilities). Pressurized ionization chambers (PICs) are used as a standard for measuring gamma radiation levels. Readings are recorded on a real-time strip chart recorder or on a magnetic card, and can be arranged to transmit these data to a central site for computer processing. Several types of portable survey instruments using ionization chamber detectors are also available. Ionization chamber detectors can only be used for ambient environmental radiation monitoring, if the detection sensitivity is several μrad/hour (Kathren 1984). Ion chamber survey meters typically exhibit long response times, particularly at low radiation levels, requiring up to several minutes to record a detectable measurement above background levels at low radiation levels.

GM counters and both plastic and NaI scintillators have also been used for field measurements of ambient radiation. These instruments have detection capability down to several μrad/hour (nGy/hr). They are rugged and have a shorter time constant than a pressurized ion chamber (PIC), making them more suitable than PICs when numerous environmental measurements are to be made. Counter-type survey meters, such as GM and scintillation counters, are very energy dependent when used to measure dose. They can be used to reliably measure dose or dose rate only for radiation whose energy is the same as the energy of the calibration source. Energy flattening filters are sometimes used in GM survey meters to compensate for the energy dependence (Kathren 1984; NCRP 1976, 1985). The energy response problem can largely be overcome by taking paired PIC and GM or NaI readings at several points to develop factors for converting GM or NaI readings to true exposure levels in mR/hr (EPA 1994).

Scintillation detectors and semiconductor detectors, when used in conjunction with a multichannel analyzer and computing capabilities, make it possible to determine whether the radiation fields originate from terrestrial radiation, cosmic radiation, or anthropogenic radiation, or from a combination of these sources. These instruments are useful for environmental monitoring around reactor sites and sites undergoing remediation for unrestricted use by the public.

The very short range of the alpha particle makes it necessary for the distance between the α-emitting source and the alpha detector to be very small. It also requires that the detector window be very thin to enable passage of the alpha particle into the detector. A scintillation detector that is frequently used is silver-activated ZnS. The ZnS scintillation detector is relatively insensitive to beta or gamma radiation and exhibits a low background count, thus permitting measurement of alphas in the presence of high beta or gamma radiation fields. Gas-filled proportional counters are particularly well-suited for low-level alpha measurements due to their large counting areas and low background. Proportional detectors can distinguish between alpha and beta particles based on differences in the size of the output voltage pulses from alphas and betas (NCRP 1978; Shapiro 1990).

Awareness of the need for detection of plutonium in the environment has increased due to several accidents that have occurred in the past (see Section 3.5). Plutonium transforms by α emission with a small percentage of accompanying x rays with energies in the region of 17 keV from the excited ^{237}Np daughter. Due to the difficulties associated with measurement of alpha particles, an instrument called a FIDLER (Field Instrument for Detection of Low Energy Radiation) was developed. This instrument measures the 17 keV photons associated with the transformation of ^{239}Pu using a 5-inch diameter crystal of NaI, 1/16th of an inch thick. FIDLER measurements are also made of the 60 keV photons from americium-241 (^{241}Am), which is often associated with plutonium as an impurity (Kathren 1984).

Large-scale environmental monitoring for contamination is sometimes carried out on roads and railroad tracks using scintillation detectors mounted on vehicles. The detectors are shielded on the sides and tops and are suspended above the ground surface. In addition, aerial surveys for radioactivity are useful for mineral exploration, special studies of uranium fields, nuclear facilities monitoring, fallout measurements, etc. The detector of choice for most of these measurements is the scintillator, usually a large single crystal (Kathren 1984) or multiple smaller detectors with summed responses. The correlation of airborne measurements with ground-level data indicates agreement to within about ± 20% in a strip of land 400 meters wide under the flight lines (NCRP 1976).

In addition to the use of survey instruments, environmental radiation is also measured with passive integrating detectors such as film badges or TLDs. TLDs are superior to film badges in energy dependence, angular dependence of radiation incident upon the dosimeter, permissible time in the field, resistance to environmental conditions, and lower limit of detection (10 mrad for film compared with 1 mrad for TLD)

(Kathren 1984; NCRP 1976). Several different thermoluminescent phosphors are available for environmental measurements, including LiF, CaF_2, $CaSO_4$ (Kathren 1984; NCRP 1976) and Al_2O_3. In the field, TLDs do not require a great deal of protection; however, some phosphors may exhibit sensitivity to light and humidity. Consequently, it is useful to package the TLD in some sort of light and water-tight material.

A good source of information on the performance of field radiation surveys, the collection and processing of samples and the applicability, operation, specificity, sensitivity, cost, and cost of operation of field and laboratory equipment is the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) prepared by EPA, NRC, DOD, and DOE as a consensus guide for conducting the final status survey in releasing a radiation site for unrestricted public use (MARSSIM 1997).

2.5.3.2 Laboratory Analysis of Environmental Samples

There are standardized analytical methods for the quantification of radioactive material in air, water, sediment, food, vegetation, and other biota (DOE 1997a); however, current philosophy supports performance-based rather than prescriptive methods. In many cases, particularly in occupational settings, the radionuclide(s) are known so the analysis can be confined to that particular radionuclide(s). If the radioactivity in a sample is from an unknown radionuclide(s), the sample should be examined for α and β/γ-emitting nuclides. Environmental samples usually involve measurement of low levels of specific radionuclides in the presence of naturally occurring radionuclides. Consequently, the analyzing analytical instrumentation is sensitive and the effect of natural background radiation levels on the detectors should be minimized. Background reductions are usually achieved mechanically by the use of shields around the detectors and electronically by pulse size discrimination (NCRP 1978).

Preparation of various environmental media for analysis of radioactive content may require concentrating the radioactive material from a large sample into a small volume to increase the sensitivity of the analysis or to reduce the sample to a form more suitable for counting. For example, solvent extraction may be used for samples with high salt content whereas ion exchange chromatography may be used for samples with low salt content. However, some standardized methods for environmental sample preparation have been developed in laboratories for analysis of radionuclides in various matrices (EPA 1984) and in drinking water (EPA 1980). Chemical separation techniques and nuclear instrumentation for assessment

of several radionuclides in various matrices can be found in the ATSDR profiles for plutonium, radium, and uranium (ATSDR 1990c, 1990d, 1999b).

There are several methods in use for quantification of alpha particles. If the identity of the α-emitting radionuclide is not needed or is already known, alpha activity of samples can be quantified by gross or "total" alpha counting (NCRP 1985). However, the short range of alpha particles in liquid and solid samples usually requires physical and/or chemical separation of the radionuclide from the matrix as described by EPA procedures (EPA 1980, 1984). Since the energies of the radiations from radionuclides are specific for those radionuclides, alpha spectroscopy, using a high-resolution silicon diode surface barrier detector with a resoulution of 10–20 keV, is used when it is necessary to determine both the identity and the quantity of the α-emitting radionuclide(s) in a sample (Knoll 1989; NCRP 1985); procedures manuals of the DOE's Environmental Measurements Laboratory and the Los Alamos National Laboratory contain example procedures for such analyses (DOE 1997a).

For environmental samples containing radionuclides that emit gamma rays, scintillation detectors (sodium iodide) and semiconductor detectors (germanium) are commonly used. These detectors, along with the appropriate electronics, computers and software, can be used to simultaneously identify and quantify a number of γ-emitting radionuclides (Kathren 1984; Knoll 1989; NCRP 1985). Germaniuim detectors have superior resolution and are more suitable if more than a few radionuclides are present in the sample.

A number of radionuclides, including ^{3}H, ^{14}C, ^{32}P, ^{35}S, ^{45}Ca, ^{89}Sr, ^{90}Sr, and ^{90}Y, emit only beta radiation (NCRP 1985). Liquid scintillation counting systems are widely used for the assay of low levels of β-emitting radionuclides and can be used to quantify all of the radionuclides listed above. GM detectors are also used for quantification of beta particles; however, GM detectors are not used to quantify ^{3}H because of its very low beta energy. Another instrument used for assessment of beta particles in environmental samples is the gas-flow proportional counter. Gas-flow proportional counters can readily quantify the β-emitting radionuclides identified above, as well as ^{3}H and ^{14}C, either when the detector window is very thin (in the case of ^{14}C) or when the detector is windowless (in the case of ^{3}H). In general, liquid scintillation, gas-flow proportional and GM counters provide data on total beta activity, although some liquid scintillation counters have some ability to resolve energy spectra. Also, solid organic scintillators, which are usually made from plastic or crystals of anthracene and trans-stilbene, may be used to quantify and identify beta particles (Knoll 1989).

2.6 CONCLUSIONS

The study of the effects of radiation is a highly specialized area of toxicology that requires knowledge and understanding of radiation physics and radioactivity, radiation dose, and biology. Radiation interacts in unique ways with matter to yield carcinogenic and non-carcinogenic effects after acute and chronic exposures.

Low levels of radiation have always been present in the environment. Only in the past 100 years have humans discovered its ubiquitous presence. During the 20th century, scientists and governments have developed uses for radionuclides both for peaceful purposes, such as medical diagnosis and treatment and electrical power generation, and for military purposes, such as weapons technology. Much research has been performed to define the different types of radiation, to explain how radiation interacts with matter, and to determine how to measure both the radioactivity and the radiation dose from a given exposure. This and other information has been used to correlate absorbed dose (from short-term high doses to long-term low doses) with toxicological diseases ranging from almost immediate death after an initial exposure to the induction of carcinogenesis years after a non-lethal exposure. This chapter summarized some of the information about radiation and methods for measuring radiation and radiation exposure. The remainder of this toxicological profile discusses in more depth the biological and toxicological effects and mechanisms of action of radiation (Chapters 3 and 5), sources of population exposure (Chapter 6), and regulatory situation specific to ionizing radiation (Chapter 7). Observed Health Effects from Radiation and Radioactive Material tables for ionizing radiation are presented in Chapter 8.

2.7 OTHER SOURCES OF INFORMATION

The Internet sites listed in Table 2-8 provide information on the general principles and health effects of the different forms and doses of radiation. Information obtained from internet sources should not be considered to have been peer reviewed unless separately authenticated.

Table 2-8. Some Internet Sites Related to Ionizing Radiation

HyperText Transfer Protocol (HTTP) address	Web page contents
http://www.uic.com.au/ral.htm	A beginner's reference for radiation.
http://www.dne.bnl.gov/CoN/index.html	Radionuclide information on half-life, transformation energies, etc.
http://www.nih.gov/health/chip/od/radiation	Summary information on radiation and its health effects
http://www.umich.edu/~radinfo/introduction	Introduction to radiation; professional, research and educational resources
http://radefx.bcm.tmc.edu/	Baylor College of Medicine Radiation Effects Homepage. Health effects documents, downloadable software, Chernobyl information, links to other radiation-related sites.
http://www.em.doe.gov/cgi-bin/tc/tindex.html	DOE Environmental Management. Public information access and links to DOE research laboratories
http://www.rerf.or.jp/	Radiation Effects Research Foundation. Human health impact of the atomic bomb release on Hiroshima and Nagasaki, Japan.
http://www.ohre.doe.gov/	DOE "cold war" radiation research using human subjects.
http://www.hps.org	Health Physics Society. Involved in the development, dissemination, and application of radiation protection. Concerned with understanding, evaluating, and controlling the risks from radiation exposure relative to the benefits derived.
http://www.epa.gov/narel/index.html http://www.epa.gov/narel/erd-online.html	Reports nationwide radionuclide concentrations in air, drinking water, surface water, precipitation, and milk.
http://www.aapm.org	American Association of Physicists in Medicine. Concerned with the safe use of radiation and radioactive materials in medicine.
http://law.house.gov/4.htm	U.S. House of Representatives internet law library of the Code of Federal Regulations. Provides CFR text.
http://www.nrc.gov/	USNRC. Nuclear waste, nuclear reactors in operation, and rule-making procedures.