Appendices

APPENDIX I

Glossary of Radiation Concepts, Terminology and Units

Absorbed dose (D) is the mean energy imparted by ionizing radiation per unit mass of material (e.g., biological tissue). The SI unit of absorbed dose is the joule per kilogram, also assigned the special name the **gray** (1 Gy = 1 joule/kg). The conventional unit of absorbed dose is the **rad** (1 rad = 100 ergs per gram = 0.01 Gy).

Activity refers to the average number of nuclear disintegrations of a radioisotope that occur per unit time. It is the product of the number of atoms and the radioactive decay constant, λ, of a given radioisotope, and can be defined as follows:

$$A = \lambda N$$

where A is the activity of the radioisotope in units of disintegrations per second (dps) or disintegrations per minute (dpm), N is the number of atoms present at a specified time, and λ is the decay constant in reciprocal units of time (i.e., sec^{-1} or min^{-1}), defined as:

$$\lambda = \frac{\ln(2)}{T_{1/2}} \approx \frac{0.693}{T_{1/2}}$$

where $T_{1/2}$ is the radioactive half-life of the radioisotope. Further, the activity of a radioisotope alone (i.e., unsupported by the decay of another radioisotope) can be calculated at any point in time t based on the activity present at some initial time t = 0 and on its decay constant, as follows:

$$A(t) = A_0 \, e^{-\lambda t}$$

where A(t) is the activity of the radioisotope at time t and A_0 is the initial activity of the isotope at t = 0. Quantities of radioactive isotopes are typically expressed in terms of activity at a given time t (see the definitions for Becquerel, Curie, counts per minute, and disintegrations per minute).

Atomic number is the number of protons in the nucleus of an atom. In its stable and neutral state, an atom has the same number of electrons as it has protons. The number of the protons determines the atom's chemical properties. For example, an atom with one proton is a hydrogen atom, and an atom with 92 protons is a uranium atom. The number of neutrons of an atom may vary in number without changing its chemical properties, only its atomic weight.

Atomic weight is the total number of neutrons and protons in the nucleus of an atom.

Becquerel (Bq) is the SI unit of activity defined as the quantity of a given radioisotope in which one atom is transformed per second (i.e., one decay per second or 1 dps). One Bq is equal to 2.7E-11 Ci.

Committed dose equivalent ($H_{T,50}$) is the integral of the dose equivalent in a particular tissue for 50 years after intake (corresponding to a working lifetime) of a given radionuclide.

Cosmogenic radionuclides are those radionuclides (e.g., H-3 and C-14) continually produced by natural cosmic processes in the atmosphere and not by the decay of naturally occurring series radionuclides.

Counting efficiency is the ratio of the number of counts registered by a given radiation-detection instrument each minute (i.e., cpm) over the number of nuclear disintegrations per minute of the radioactive source (dpm) being measured. For example, given a source decaying at a rate of 1,600 dpm and an instrument that detects 400 cpm, then the counting efficiency of this detection system would be 0.25 (400/1,600 = 1/4) or 25%.

Counts per minute (cpm) is the unit that describes the number of disintegrations detected by a radiation-detection instrument. Because radiation is emitted isotropically (i.e., equally in all directions) from a radioactive source, the probes of most radiation-detection instruments cannot detect all radiation emitted from a source. Therefore, cpm and dpm will not be equal. However, if the response characteristics of a detector are known for a given radiation source, the relation between cpm and dpm can be determined (see Counting efficiency).

Curie (Ci) is the conventional unit of activity defined as the quantity of a given radioisotope that undergoes nuclear transformation or decay at a rate of 3.7×10^{10} (37 billion) disintegrations each second. One Ci is equal to 3.7×10^{10} Bq and approximately equal to the decay rate of one gram of Ra-226. Because the curie is a very large amount of activity, subunits of the curie are often used:

1 millicurie (mCi) = 10^{-3} Ci
1 microcurie (μCi) = 10^{-6} Ci
1 nanocurie (nci) = 10^{-9} Ci
1 picocurie (pCi) = 10^{-12} Ci
1 femtocurie (fci) = 10^{-15} Ci

Disintegrations per minute (dpm) is the unit that describes the average number of radioactive atoms in a source disintegrating each minute. A 500 dpm source, for example, will have 500 atoms disintegrating every minute on the average. One picocurie (pCi) equals approximately 2.22 dpm.

Dose equivalent (H) considers the unequal biological effects produced from equal absorbed doses of different types of radiation and is defined as:

$$H = DQN$$

where D is the absorbed dose, Q is the quality factor that considers different biological effects, and N is the product of any modifying factors. Quality factors currently assigned by the International Commission on Radiological Protection (ICRP) include Q values of 20 for alpha particles, 10 for protons, and 1 for beta particles, gamma photons, and x-rays. Q values for neutrons depend on their energies and may range from 2 for thermal neutrons to 11 for 1 MeV neutrons. These factors may be interpreted as follows: On the average, an alpha particle will inflict approximately 20 times more damage to biological tissue than a beta particle or gamma ray, and twice as much damage as a neutron. The modifying factor is currently assigned a value of unity (N=1) for all types of radiation. The SI unit of the dose equivalent is the **sievert** (Sv), and the conventional unit is the **rem** (1 rem = 0.01 Sv). A commonly used subunit of the rem is the millirem (mrem).

Electron Volt (eV) is the unit used to describe the energy content of radiation, defined as the energy acquired by any charged particle carrying a unit (electronic) charge when it falls through a potential of 1 volt; it is equivalent to 1.6×10^{-12} ergs. Alpha particles range in energy from 1 to 10 **million electron volts (MeV)**, and beta particles are emitted over a wide energy range from a few **thousand electron volts (keV)** to a few MeV. Gamma photons also typically range from a few keV to one to two MeV.

Effective dose equivalent (H_E) and the **committed effective dose equivalent ($H_{E,50}$)**, defined as the weighted sums of the organ-specific dose equivalents, were developed by the ICRP to account for different cancer induction rates and to normalize radiation doses and effects on a whole body basis for regulation of occupational exposure. In general, the reader need not be concerned with these concepts for HRS scoring purposes. Still, the interested reader is referred to ICRP publications (ICRP 1977 and ICRP 1979) for additional information on these topics.

Exposure (sometimes called the **exposure dose**) refers to the number of ionizations occurring in a unit mass of air due to the transfer of energy from a gamma or x radiation field. The unit of exposure is the **roentgen (R)** expressed as coulombs of charge per kilogram of air (1 R = 2.58 x 10^{-4} C/kg). A common simplification is that 1 R of gamma or x-radiation is approximately equal to 1 rad of absorbed dose and to 1 rem of dose equivalent.

Exposure rate (or **exposure dose rate**) refers to the amount of gamma or x-ray radiation, in roentgen, transferred to air per unit time (e.g., R/hr or R/yr). Commonly used subunits of the roentgen are the milliroentgen (1 mR = 10^{-3} R) and the microroentgen (μR = 10^{-6} R), with corresponding subunits of mR/hr or μR/hr for exposure rates. The roentgen may be used to measure gamma or x radiation only.

External exposure refers to radiation exposure from radioactive sources located outside of the body.

Gray (Gy) is the SI unit of absorbed dose (1 Gy = 1 Joule kg^{-1} = 100 rad).

Internal exposure refers to radiation exposure from radionuclides distributed within the body.

ICRP is the International Commission on Radiological Protection.

Ionization of an atom is the removal of one of its orbital electrons. When an electron is removed, two charged particles, or ions, result: the free electron, which is electrically negative, and the rest of the atom, which bears a net positive charge. These are called an **ion pair**. Radiation is one mechanism that produces ionization. Alpha and beta radiation cause ionization primarily through collisions, that is, moving alpha and beta particles physically "collide" with orbital electrons, transferring some or all their energy to these electrons. Multiple collisions with electrons eventually reduce the energy of the alpha or beta particle to zero. These particles are then either absorbed or stopped. De-energized beta particles become free electrons that often are absorbed by positive ions. A doubly-positive alpha particle frequently captures two free electrons to become a helium atom. Gamma radiation causes ionization by three processes: the photoelectric effect, the Compton effect, and pair production. The photoelectric effect occurs when the total energy of the gamma photon is absorbed by an electron and the incident gamma photon is annihilated. The Compton effect occurs when part of the energy of the gamma photon is transferred to an orbital electron and the initial incident gamma photon is deflected with reduced energy. In pair production, the incident gamma photon interacts with the atomic nucleus forming two electrons and the photon is annihilated. Because of their ability to remove orbital electrons from neutral atoms, alpha, beta, and gamma radiation are referred to as **ionizing radiation.**

Isotopes are atoms of the same chemical element that have the same number of protons but different numbers of neutrons. All isotopes of a given element have the same atomic number but different atomic weights.

Naturally occurring radionuclides are those radionuclides of primordial origin and terrestrial nature which possess sufficiently long half-lives to have survived in detectable quantities since the formation of the earth (about 3 billion years ago), with their radioactive decay products.

Rad is the conventional unit of absorbed dose (1 rad = 100 ergs/g of tissue = 0.01 Gy).

Radiation (specifically, Ionizing Radiation) refers to the energy released in the form of particles (i.e., alpha, beta, or neutrons), electromagnetic waves (i.e., gamma photons and x rays), or both, during the radioactive decay of an unstable atom.

Radioactivity is the property of an unstable atom of a radioactive element whereby the atom transforms (decays) spontaneously by emission of radiation into an atom of a different element. Radioactive properties of unstable atoms are determined by nuclear considerations only and are independent of their physical or chemical states.

Radioactive contamination is commonly used to describe radioactive atoms that are unconfined or in undesirable locations.

Radioactive decay is the process whereby an unstable nucleus of a radioactive atom ejects one or more particles (i.e., alpha, beta, or neutrons) from its nucleus to establish a more stable state. These particles are sometimes accompanied by a release of electromagnetic energy (i.e., gamma or x ray radiation). Together, ejected particles and released energy are called **radiation**. Radioactive decay results in the formation of an atom of a different element called a **decay product** (**progeny** or **daughter**) which also may be radioactive. There are three principal modes of radioactive decay: alpha, beta, and neutron.

- **Alpha decay** occurs when the neutron to proton ratio is too low and, because of this instability, the unstable nucleus ejects an **alpha particle** (alpha radiation). An alpha particle has two protons and two neutrons. Emission of an alpha particle from an atom decreases its atomic weight by four and its atomic number by two. Thus, the new atom of another element has two fewer protons and two fewer neutrons and its chemical properties are different from those of its parent element. It too may be radioactive. For example, when an atom of radium-226 (with 88 protons and 138 neutrons) emits an alpha particle, it becomes an atom of radon-222 (with 86 protons and 136 neutrons), a gas. Since radon-222 is also radioactive, it too decays and forms an atom of still another element. Alpha particles are somewhat massive and carry a double positive charge. They can be completely attenuated by a sheet of paper.

- **Beta decay** occurs when an electrically neutral neutron splits into two parts, a proton and an electron. The electron is emitted as a **beta particle** (beta radiation) and the proton remains in the nucleus. The atomic number of the resulting decay product is increased by one, and the chemical properties of the progeny differ from those of its parent. Still, the atomic weight of the decay product remains the same since the total number of neutrons and protons stays the same, that is, a neutron has become a proton, but the total number of neutrons and protons combined remains the same. Beta particles will penetrate farther than alpha particles because they have less mass and only carry a single negative charge. Beta radiation can be attenuated by a sheet of aluminum.

- **Neutron decay** occurs during nuclear fission reactions, resulting in the emission of a **neutron**, two smaller nuclei, called fission fragments, and beta and gamma radiation. In general, neutron-emitting radionuclides are unlikely to be encountered or of much concern at most Superfund sites.

- **Gamma radiation** may accompany alpha, beta, or neutron decay. It is electromagnetic energy emitted from the atomic nucleus and belongs to the same wave family as light, radio waves, and x rays. X rays, which are extra-nuclear in origin, are identical in form to gamma rays, but have slightly lower energies. Gamma radiation can be attenuated by heavy material such as concrete or lead.

Radioactive Decay Series or Chains are radionuclides which decay in series. In a decay series, an unstable atom of one radioisotope (the parent isotope) decays and forms a new atom of another element. This new atom may, in turn, decay to form a new atom of another element. The series continues until a stable or very long-lived atom is formed. At that point, the decay chain ends or is stopped. The number of radionuclides in a series varies, depending upon the number of transformations required before a stable atom is achieved. This process can be illustrated as follows:

$$\mathbf{N_1 \rightarrow N_2 \rightarrow N_3 \twoheadrightarrow N_n \text{ (stable)}}$$

where N_1 is the number of atoms of the parent radioisotope decaying to form atoms of the first decay product, N_2, which in turn decays to form atoms of the second decay product, N_3, which continues to decay until a stable atom, N_n, is formed. Examples of important naturally occurring decay series include the uranium series, the thorium series, and actinium series. There are three major reasons why it is important to identify decay series and to characterize the properties of each decay product in those series:

- First, the total activity content (and the potential hazard) of a radioactive source may be substantially underestimated if the activity contributions from each of the decay products are not included. If it is assumed incorrectly that only one radionuclide of potential concern is present in a source when, in fact, one or more decay products also may be present, then the total activity of and threat posed by that source may not be considered completely;

- Second, decay products may be more toxic, either alone or in combination, than the parent nuclide. Because each radioactive isotope possesses its own unique chemical, physical, and radioactive properties, the hazard presented by decay products may be substantially greater than that posed by the parent nuclide alone.

- And third, the environmental fate, transport, and bioaccumulation characteristics of the decay products may be different from those of the parent nuclide. All relevant migration pathways for both the parent nuclide and decay products must be considered to account for site threats.

Radioactive equilibrium refers to the activity relationship between decay series members. Three types of radioactive equilibrium can be established: secular, transient, and no equilibrium. **Secular equilibrium** refers to the state of equilibrium that exists when series radioisotopes have equal and constant activity levels. This equilibrium condition is established when the half-life of the parent isotope is much greater than that of its decay product(s) (i.e., $T_{1/2}$ of the parent >>> $T_{1/2}$ of the decay product, or when expressed in decay constants, $\lambda_2 >>> \lambda_1$). **Transient equilibrium** is the state of equilibrium existing when the half-life of the parent isotope is slightly greater than that of its decay product(s) (i.e., $T_{1/2}$ of the parent > $T_{1/2}$ of the decay product, or $\lambda_2 > \lambda_1$) and the daughter activity surpasses that of the parent. **No equilibrium** is the state that exists when the half-life of the parent isotope is smaller than that of the decay product(s) (i.e., $\lambda_2 < \lambda_1$). In this latter case, the parent activity will decay quickly, leaving only the activity of the decay product(s).

Radioactive half-life ($T_{1/2}$) (sometimes referred to as the **physical half-life**) is the time required for any given radioisotope to decrease to one-half its original activity. It is a measure of the speed with which a radioisotope undergoes nuclear transformation. Each radioactive isotope has its own unique rate of decay that cannot be altered by physical or chemical operations. For example, if one starts with 1,000 atoms of iodine-131 (I-131) that has a half-life of 8 days, the number of atoms of I-131 remaining after 8 days (one half-life), 16 days (two half-lives), and 24 days (three half-lives) will be 500, 250, and 125, respectively. In fact, the fraction of the initial activity of any radioisotope remaining after n half-lives can be represented by the following relationship:

$$\frac{A}{A_0} = \frac{1}{2^n}$$

where A_0 is the initial activity and A is the activity left after n half-lives. After one half-life (n=1), 0.5 (or 50%) of the initial activity remains; after three half-lives (n=3), 13% remains; and after five half-lives (n=5), 3% remains. Further, the activity of any radioisotope is reduced to less than 1% after 7 half-lives. For radioisotopes with half-lives greater than six days, the change in activity in 24 hours will be less than 10%. Over 1,600 different radioisotopes have been identified to date, with half-lives ranging from fractions of a second to billions of years.

Radioactive isotopes (**radioisotopes** or **radionuclides**) are radioactive atomic variations of an element. Two radioactive isotopes of the same element have the same number of protons but different numbers of neutrons. They share common chemical properties, but exhibit different and unique radioactive, and possibly physical, properties because of the differences in their respective nuclear stabilities and decay modes.

Radionuclide slope factor is the lifetime excess cancer incidence rate per unit intake of (or per unit exposure to) a given radionuclide.

Rem is the acronym for roentgen equivalent man and is the unit of dose equivalent (1 rem = 0.01 Sv).

Roentgen (R) is a unit of external exposure which refers to the number of ionizations occurring in a unit mass of air due to the transfer of energy from a gamma or x radiation field emitted by a radioactive source. The unit is expressed as coulombs of charge per kilogram of air (1 R = 2.58 x 10^{-4} C/kg). Commonly used subunits of the roentgen are the milliroentgen (mR = 10^{-3} R) and the microroentgen (μR = 10^{-6} R), with corresponding subunits of mR/hr or μR/hr for exposure rates. The roentgen may be used to measure gamma or x radiation only. [See Exposure and Exposure Rate.]

System International (SI) is the international system of radiation measurements and units.

Sievert (Sv) is the SI unit for dose equivalent (1 Sv = 100 rem).

Specific activity (SpA) relates the number of curies per gram of a given radioisotope, as follows:

$$SpA\ (Ci/g) = \frac{1.3x10^{8}}{(half\text{-}life,\ days)\ (atomic\ weight)}$$

For example, the SpA for the long-lived, naturally occurring uranium isotope U-238 (half-life, 4.51 x 10^9 years) is 3.3 x 10^{-7} Ci/g, whereas the SpA for the short-lived phosphorous isotope P-32 (half-life, 14.3 days) is 2.9 x 10^5 Ci/g. Expressed in another way, one Ci of U-238 weighs 3 megagrams (3 x 10^6 grams), whereas one Ci of P-32 weighs 3.4 micrograms (3.4 x 10^{-6} gram). From this example it is clear that the shorter the half-life (i.e, the faster the disintegration rate) of a radioisotope, the smaller the amount of material required to equal a curie quantity; conversely, the longer the half-life of a radioisotope, the larger the amount of material required to obtain a curie amount. The specific activity of a radioisotope is one major factor determining its relative hazard.

Specific ionization is the number of ion pairs produced by ionizing radiation per unit path length. The number of ion pairs produced depends on the mass and charge of the incident radiation. Because of their somewhat massive size and charge, alpha particles create more ion pairs than do beta particles, which, in turn, create more ion pairs than do gamma photons. Since it may take more than one ionizing collision to absorb a radiation particle or photon, particulate or electromagnetic radiation may produce several ion pairs.

Total ionization is the total number of ion pairs produced by ionizing radiation in a given media (e.g., air or biological material).

Ubiquitous manmade radionuclides are those radionuclides, naturally occurring or synthetic, generated by man's activities and widely distributed in the environment.

Working level (WL) is a special unit used to describe exposure to the short-lived radioactive decay products of radon (Rn-222) and is defined as any combination of radon decay products in one liter of air that will result in the ultimate emission of 1.3 x 10^5 MeV of alpha energy.

Working level month (WLM) is the exposure to 1 WL for 170 hours (1 working month).