Basic Introduction to Dose Determination from Radioactive Materials

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The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the Centers for Disease Control and Prevention/the Agency for Toxic Substances and Disease Registry.

Purpose:

The **Basic Introduction to Dose Determination from Radioactive Materials** is provided to health assessors to introduce and define the radiological terms used by ATSDR health physicists. Health physicists are individuals who have received specialized training in nuclear physics, radiation biology, radiation detection, radiation chemistry, and other related sciences. Their training helps them understand the ionizing radiation that radioactive materials emit. At ATSDR, the health physicists are tasked to evaluate radioactive substances in the environment, radiation measurements, and estimate the radiological doses resulting from environmental exposures. This introduction provides information on the differences between radiation exposure and radiation dose, an explanation of the various types of doses that can be calculated, and examples of issues associated with field detection of radiation, concepts of multiple dose estimations, and a brief discussion of risk assessment as it pertains to radiation.

The concepts in this document apply only to those radioactive emissions and materials commonly found in the environment. It does not pertain to medical radiation procedures (those that use x-rays or radioactive materials in nuclear medicine) or certain types of radiation associated with nuclear power plants and particle accelerators. These dosimetric concepts do not apply to ultraviolet light, visible light, infrared light, radio/microwaves, or cell phone radiation since these low-energy forms of radiation are non-ionizing.

Although similar to the methods ATSDR uses for chemical exposures, the evaluation of radiation exposure and doses from exposure to radioactive materials incorporates both physical and biological properties of the radioactive material. **Health assessors must not attempt these calculations and must discuss the data with an NCEH/ATSDR health physicist or health physicist in your state**. Any available site- or situation-specific information can be used in document discussions as long as justifications for modifying default values are given. Inclusion of modifications may reduce over-conservative estimates and reduce the uncertainty of the data discussed in the health assessments and consultations.

The appendices of this document contain a glossary that supplies additional descriptions of the terms used in this reference. The basic equations given are for reference only and should not be used to estimate the radiation doses where radioactive materials are a contaminant of concern at ATSDR or state lead sites.

Background:

Health physics is the science of the recognition, evaluation, and control of health hazards resulting from ionizing radiation (www.hps.org). In radiation science, exposure and dose are two separate and distinct quantities and are not used interchangeably. All radiation doses are the result of an "exposure" but not all exposures deliver a radiation dose. **Exposure**[1] only pertains to the energy deposited by certain types of radiations in air; whereas, **dose** is the amount of energy absorbed by matter regardless of the type of radiation. Therefore, an exposure delivers energy which, when absorbed, results in a dose. Not all the energy in an exposure is absorbed. It is the determination of the fraction of energy absorbed that forms the basis for radiation dosimetry. The fraction of energy absorbed ranges from 0 to over 100%, because of secondary interactions within any type matter including the body after the energy is absorbed.

In the United States, the conventional names for radiation units are still used by regulatory agencies. However, many other countries and professional organizations such as the Health Physics Society are using the International System of Units (SI). In this document, both the conventional units and the SI units are used. The conversion between the two systems is supplied later in this document.

Radioactivity and Radiation Decay

When an atom has too much energy in its nucleus, the atomic nucleus is unstable. To reach a stable state, this excess energy must be emitted by the nucleus. The process is called radioactivity and the emitted energy is called radiation. This transformation is called radioactive decay. The radiation is either in the form of an alpha particle or beta particle. An alpha particle is a helium nucleus, and can be released by very massive atoms. A beta particle is a type of electron released when a neutron changes into a proton or when a proton changes into a neutron. The type of particle and energy emitted in these decays will vary with the specific radioactive substance. In either case, the unstable nucleus then becomes the nucleus of a different element because the total number of protons has changed. After the emission of these particles, the nucleus is transformed (re-arranged). Most of these atoms are left with some excess energy, which they emit as a photon[2], called gamma radiation. The radioactivity of an element is a function of the number of atoms and its rate of decay (transformations per unit time; decay constant) and is related to its half-life:

A curie (Ci) defines radioactivity and represents 37 billion transformations per second. In the SI system, the unit is the Becquerel (Bq); 1 Bq ~ 27×10^{-12} Ci

$$A = \lambda N$$

1. Technically, exposure in this situation is the quantity of ionizations that gamma rays or x-rays produce in air, specifically 1 electrostatic unit per cubic centimeter of air at standard temperature and pressure (1 esu/cc at STP); exposure has the conventional unit the Roentgen (R), where 1 R = 1 esu/cc = 2.58×10^{-4} coulomb per kilogram of air.

2. The term photon is used to define electromagnetic radiation. Photons can be of any energy or wavelength. For example, visible light is composed of photons that are seen by humans; whereas, microwaves are photons that people cannot see.

where
A is the activity in transformations per second,
N is the number of atoms and
λ is the decay constant defined as the natural log of 2 divided by the half-life in seconds (ln (2)/T).

An atom that undergoes radioactive decay is called a radionuclide or radioisotope. Additional discussion of radioactivity, radiation, these types of decays and the energy released is beyond the scope of this document.

Many naturally occurring substances are radioactive. The origins of most begin with either uranium or thorium. These elements are considered primordial radioactive materials produced when the earth was formed, and they have very long half-lives. As uranium or thorium decay, new radioactive materials are formed. These materials are part of a system known as decay chains or decay series. An evaluation of the decay series can indicate if contamination is natural or enhanced by human intervention. Two other primordial radioactive materials that do not have decay chains are potassium 40 (K-40) and vanadium 50 (V-50). The other naturally-occurring radioactive materials are continuously being produced by the interactions of cosmic radiation with our atmosphere. A partial list of these includes tritium (H-3) [3], beryllium-7 (Be-7), and carbon-14 (C-14). Man-made radioactive materials also exist in the environment as a result of nuclear weapons testing or nuclear reactor normal operations or accidents. The list of man-made radioactive substances in the environment is quite extensive, and most have short half-lives. Some of the more common man-made contaminants with longer half-lives include cesium-137 (Cs-137), strontium-90 (Sr-90) and several plutonium (Pu) species.

Radiation dose

The generic term dose is used to express an estimate of the ionizing radiation energy absorbed by a mass such as an organ or tissue. However, using the term correctly requires an examination of the variables used to develop the "dose."

Exposure: pertains only to the deposition of electric charges in air. The unit of exposure is the Roentgen (R). The SI unit is the coulomb/kg; 1 coulomb/kg equals 3881 R.	≠	Dose: a generic term for the amount of energy absorbed per unit mass. The unit of dose is the rad. The SI unit is the Gray (gy); 1 Gy equals 100 rads.

Health physicists, including those at ATSDR, evaluate two major categories of radiation dose: internal dose and external dose. Internal dose is the dose received when radioactive material is inside the body: (a) radiation doses are calculated on the amount of energy absorbed per unit mass; (b) the dose rate changes over time as the radioactive materials inside the body undergo both biological elimination and physical decay, and; (c) all decay products that are radioactive

3. If you are using the chemical abbreviations for elements, be sure they are correct. For example, ATSDR health physicists have seen uranium abbreviated as Ur (incorrect). The correct form is U.

result in doses that must be factored into the overall dose estimate. Radioactive materials do not distribute uniformly throughout the body and not all parts of the body receive equal amounts of radiation, so the specific organ must be evaluated separately. It is for these reasons, ATSDR requires that health physicists are consulted and requested to perform the dose assessment for public health documents.

External dose is received from radioactive materials outside the body; that is, you can receive a radiation dose even if you do not come into direct contact with the radioactive material. The external dose delivered is modified by the length of exposure time, distance from the source, and any matter that provides shielding protection between the body and the radiation source. Portable radiation detection instruments are usually available to measure the external radiation at a location while laboratory instruments are used to measure the concentration of radioactive material in a sample collected at any location. The instruments, unless specially constructed and/or calibrated, do not report the exposure, the radiation dose, or the true radioactivity; they report the number of electrical signals generated by the radiation within the detectors. In most instances the instrument readout cannot be converted to units of exposure, dose, or activity. Thus, ATSDR recommends that health physicists be involved with the interpretation of the instrument readings.

Counts per Minute	$\neq$	Amount of Radioactivity Exposure Rate Dose Rate

Dose Terminology

Radiation Absorbed Dose (D_T)

The dose received from radiation depends on the amount of energy absorbed in a given mass[4]. Depending on the computational method used, the radiation dose can be expressed in different terms, all of which can be expressed as dose. Although it is a simple process to determine the mass, the determination of the energy deposited in that mass is an extremely complicated procedure involving multiple energy-related interactions. Many of the techniques used to measure this energy absorption in humans are based on physiological models called phantoms that simulate the body's size, sex, form, density, and organ placement. Modern phantoms are based on CT and MRI-derived data[5]. External dose is typically measured using radiation dosimeters (small devices clipped to the clothing). Internal dose is normally estimated by detecting radiation emitted from radioactive materials inside the body or less frequently from biopsy samples or human autopsy information. The energy deposited is a probability function of the particle or photon energy, the tissue density, atomic makeup of the tissue, shape of the tissue, and interactions within the tissue itself. These interactions include elastic and inelastic scattering, nuclear recoil, and ionization interactions. Discussion of these interactions is beyond the scope of

[4] Any mass, such as organ, body, wood, water, air.

5. A CT (computerized axial tomography; CAT) scan uses X-rays to produce cross-sectional views of the body. The MRI (magnetic resonance imaging) uses magnetic fields and radio waves to produce images of organs and tissues.

this document. Thus, the calculated radiation absorbed dose (rad) is based on the physical principles of mass and energy interactions. By definition, a rad (radiation absorbed dose) is the absorption of 100 ergs per gram of matter; 100 rads equals 1 joule per kilogram (J/kg) or 1 Gray (Gy). The equation for absorbed dose is:

$$D_T = E/m$$

where D_T is the absorbed dose in Grays, E is the energy deposited in the given mass (m). The determination of the Gray is the starting point for all additional radiation dose calculations such as those to specific organs and the whole body. The following discussion will define other commonly used dosimetric terms such as equivalent dose, effective dose, and committed dose.

Dose equivalent (conventional term) or Equivalent Dose (SI term) (H_T)

The equivalent dose (H_T) is a dose used to normalize radiation on a common scale for purposes of radiation safety. Typically the equivalent dose is used to describe the radiation dose to a specific tissue or organ in terms of its biological effect. To normalize the dose, the International Commission on Radiological Protection (ICRP 1991, 2007) established factors to equate levels of radiation damage produced by various particles and photon energies. These factors are called radiation weighting factors (W_R). Basically, for the same radiation absorbed dose, alpha particles produce 20 times more damage in the form of direct interactions and ionizations than either beta particles or photons. Therefore, the alpha particle W_R is set to 20; whereas, for beta particles and photon (gamma radiation), W_R is set to 1.0 (see footnote 6). Historically, this dose was called the radiation equivalent man (rem); the rem is the conventional unit and for the SI unit, the Sievert (Sv). Since the rem or Sievert is based on the Gy and a modifier (W_R), the equation for equivalent dose is:

$$H_T = D_T \times W_R$$

where D_T is the absorbed dose to the tissue and W_R is the radiation weighting factor. As with the Gy, the amount of energy absorbed is 1 J/kg so 1 Sv = 100 rem.

Every tissue or organ in the body has mass and density, and can absorb radiation, albeit, to different degrees. Because the tissue or organ masses and densities vary, the H_T for each tissue or organ is different. Using models one can estimate the equivalent dose to each of the organs[7]. The dose to the entire body is calculated by summing each of the tissue or organ equivalent doses:

$$H_T = \sum_R D_{T,R} W_R$$

where,

H_T is the equivalent dose absorbed by tissue T,

D_{TR} is the absorbed dose in tissue T by radiation type R, and

6. It is of interest to note that several studies suggest the W_R for radioactive hydrogen (H-3) may be as high as 3.0 with a value of 1.7 as an estimated mean.

7. Actual radiation doses to humans based on autopsy of radiation workers have been compared to models with close agreement between the actual dose and the modeled dose.

W_R is the radiation weighting factor.

For each type of radioactive material involved in the intake into the body, this must be repeated so the equation becomes

$$H_T = \sum_i D_{T,R} W_R$$

where the subscript i is the specific radioactive element. The equivalent dose for a particular radioactive substance is mostly used to determine the estimated radiation dose to a particular organ.

Radioactive material remains in the body for various amounts of time. The elimination of the material is based on the body's chemical processes (biological half-life of the element) and the radioactive decay (physical half-life of the radioactive material). The elimination is a function of each decay constant with the elimination constant called the effective half-life:

$$\lambda_e = \lambda_b + \lambda_p$$

where λ is ln (2) divided by the half-life. Some medical interventions and countermeasures are available for specific radioactive substances. These interventions decrease the biological half-life (e.g., through chemical blocking, chelation, emesis, or increasing urine or fecal excretion) but the physical half-life cannot be altered. **It is important to note that the body cannot recognize if an atom is radioactive. Chemistry determines its location, metabolism and biological elimination in the body.**

While in the body, the radioactive material continues to irradiate the tissues and organs, and any decay products also begin to irradiate tissues and organs, not necessarily the same ones as the initial material that was involved in the uptake. The irradiation from any intake will continue until all that radioactive material has decayed or been eliminated. The sum total of equivalent dose for all future time from any intake of radioactive material is called the committed equivalent dose. It is used to ease the administrative burden of assigning annual radiation doses from each intake for an individual's lifetime, and instead assigning that value to the year the intake occurred. Typically the committed equivalent dose is based on 50 years for workers or adults and 70 years for lifetime exposure. A peculiarity of the committed equivalent dose is that the dose is calculated over the integration period but that entire dose is considered to be delivered to the body in the year of intake. In equation form, the committed equivalent dose is:

$$H_T = \int_0^{50y \; or \; 70y} (D_{T,R} W_R) \, dT$$

The unit of the committed equivalent dose is the Sievert. As with the equivalent dose, the committed equivalent dose must be estimated for each radionuclide ingested or inhaled. Once inside the body, any other decay products are incorporated into the calculations. The ICRP has developed tables of dose coefficients based on these computations.

Effective Dose Equivalent (conventional term) or Effective Dose (SI term) (H_E)

The effective dose (H_E) is developed to normalize the equivalent dose to the radiation sensitivities of different tissues and organs. This normalization factor, called the tissue weighting factor (W_T) accounts for the relative carcinogenic susceptibility of the various tissues. The weighting factor values range from 1% to 20%. The greater the weighting factor, the more susceptible a tissue or organ is to radiation. **Table I** gives the major organ systems and their W_T. The tissue weighting factors are determined by the ICRP and have changed over time as radiation biology advances (ICRP 1991, 2007). As with equivalent dose, the unit of the effective dose is the Sievert so care must be taken to determine if the dose being estimated is H_T or H_E. The equation for the effective dose (when calculating it from the effective dose) is:

$$H_E = \sum_i H_T \times W_T$$

The term committed effective dose is used to estimate the dose committed to the body over time similarly to the equivalent dose. **Because the units of the equivalent dose, committed equivalent dose, effective dose, and committed effective dose are identical, the interpretation is best left to health physicists.**

In terms of risk, ATSDR uses the equivalent dose and the effective dose as general terms. In terms of probability, these doses can be used to estimate stochastic effects (occurring by chance) and are used mostly in radiation protection (future exposures). This approach is similar that used by the ICRP as discussed in their Publication 60 and Publication 103 (ICRP 1991, 2007).

Radiation dose coefficients

To ease the burden on radiation dosimetrists, the ICRP (1991, 2007) developed extensive methodologies and tabulations of dose coefficients to be used by properly trained individuals. These tabulations give dose coefficients in Sv/Bq (the dose per becquerel of radioactive material ingested or inhaled, or the concentration in which the individual is immersed). However, the usage is more than just reading the dose coefficient off a table and calculating a "dose." Each tabulation gives extensive information such as the percentage of uptake versus intake for ingestion. In the case of inhalation, not only is the form of the intake (gas, vapor, organic, inorganic, etc.) given but also the rate of solubility in lung fluids is given qualitatively (slow, medium, fast) as well as the particle size. The dosimetric values are computed and compiled for various parameters such as workers, members of the public, and age at time of intake. The tabulated data also show the organ having the highest committed equivalent dose coefficient. See the appendix for examples of dose coefficient tables (**see tables 2 and 3).**

Summary of Dose Determination

When ATSDR calculates the radiation dose, the recommended ATSDR body weights are not used nor are the recommended age groupings used. The basis for not using the ATSDR values is that the radiation dose coefficients or factors (DCFs) incorporate the relevant parameters of the organ or whole body and are age adjusted. Regardless, the equations are very similar, the issue being selecting the most appropriate dose coefficient:

$$Dose = DCF \times [Env.Conc.] \times ƒ$$

Where DCF is the appropriate dose coefficient, Env. Conc. is environmental concentration in Bq per unit mass or volume, and ƒ is intake frequency in concentration units per unit time.

The time coefficient will be either a single intake or daily intakes and the integration period to give either an equivalent or effective dose or a committed equivalent dose or committed effective dose. For every radioactive contaminant identified in the intake pathway, the equation is repeated. Recalling that the internal dose coefficients already consider the decay products produced while in the body, you do not have to calculate the dose from decay products a second time once they are in the body. See Appendix B for an example.

Determination of Health Effects

Radiation induced health effects are divided into two categories. These are stochastic and deterministic effects. **Stochastic effects** are probability-based effects and typically are the main long-term concerns following exposures to low levels of radiation. The most prominent believed stochastic effect is the induction of cancer many years following exposure, especially following chronic exposures. **Deterministic effects** are ruled by severity of exposure. An example of a deterministic effect is the severity of a burn, reddening of the skin to a blister.

The largest radiation-exposed populations include medical patients, radiologists and radiation technologists, atomic bomb survivors, atomic weapons complex workers, and nuclear power plant workers. Numerous studies of these populations can be found in the peer-reviewed literature. These studies have been summarized and published by the USEPA, the National Academy of Sciences, the Radiation Effects Research Foundation, and other scientific organizations and in government documents and peer-reviewed journals[8]. Using these publications form the basis for determining the harmful effects from radiation exposure. The studies have included individual radionuclides, external radiation sources, partial body exposures, whole body exposures, occupational and accidental exposures. The health assessor is referred to a radiation expert for assistance in using the calculated radiation doses to both the organ of interest and the entire body to determine possible harmful effects. Additional questions, answers, and fact sheets can be found at the CDC/NCEH/ATSDR web page (http://www.cdc.gov/nceh/radiation/default.htm), Health Physics Society Ask the Expert landing page (http://hps.org/publicinformation/ate/), the Radiation Information Network (www.radiationanswers.org).

The USEPA has published documents containing the estimated radiation induced cancer coefficients. The USEPA also has other tools and documents available on the internet at https://www.epa.gov/radiation/federal-guidance-radiation-protection; however, additional evaluations will be needed to ensure proper use of these tools. The tools include computer models to assess risk to humans from radioactively contaminated sites and from air emissions. The appropriate models calculate dose per unit intake of over 800 radionuclides and combine results with risk models to develop average lifetime risk estimates for a unit intake of radioactive material.

One method used to evaluate radiation doses is to compare the external dose received to the typical background radiation dose. In the United States the average background radiation dose

[8] Internet links to these sites are given in the References section of this document.

excluding both medical exposures and radon is on the order of 1 mSv. Including radon in the dose increases the average dose to approximately 3.1 mSv, and including medical radiation increases the average dose to approximately 6.2 mSv. However, depending on the geographical location (longitude, latitude, and altitude), the terrestrial component of background will vary. For example, every 200 foot gain in elevation increases the annual dose on the order of 0.01 mSv. Thus Denver has a higher background than most cities along the coastline. ATSDR has established a Minimal Risk Level (MRL) for chronic dose from ionizing radiation of 1 mSv per year (1 mSv/y). For the case of internal exposures, there are no particular ATSDR dose guidelines so the MRL is also applied to that value as well. The sum of the internal exposures and the external exposures are not to exceed the MRL of 1 mSv/y[9].

Health studies do exist for several radioactive materials deposited in the body. The most commonly studied radioactive elements in this case include some of the radioactive iodines, radium, radon, thorium, uranium, plutonium, and some of their respective decay products.

The risk from exposure and resulting dose from ionizing radiation has been estimated by several national and international organizations. The USEPA has released updated radiological risk and probability (uncertainty analyses) documents available online at https://www.epa.gov/radiation/tools-calculating-radiation-dose-and-risk (accessed on December 11, 2014). The nominal lifetime attributable sex averaged mortality risk from a radiation dose is 580 deaths per 10,000 person-Gy with females being slightly higher than males. The risk values contain both solid cancers[10] and leukemia risks.

The appendix gives an example of how these concepts are applied.

[9] ATSDR, 1999.

[10] Cancers other than those that are blood-related

TABLE I. ICRP (2007) TISSUE WEIGHTING FACTORS* (PROPOSED)

Tissue	w_T	$\sum w_T$
Bone marrow (red), Colon, Lung, Stomach, Breast, Remainder Tissues	0.12	0.72
Bladder, Esophagus, Liver, Thyroid	0.04	0.16
Bone surface, Skin, Brain, Salivary Glands	0.01	0.04
Gonads (male or female)	0.08	0.08
Total		1.0

*The weighting factors have been updated in the international community. In the United States, they have not yet been accepted but the US Nuclear Regulatory Commission is in the process of adjusting their dosimetry. See ICRP 2007 for the international values.

TABLE II. INGESTION COEFFICIENTS (SIEVERTS PER BECQUEREL) FOR RADIUM-226

Age	Infant	1 y old	5 y old	10 y old	15 y old	Adult
f_1 (fraction absorbed)	6.00E-01	3.00E-01	3.00E-01	3.00E-01	3.00E-01	2.00E-01
Adrenals	5.31E-07	2.13E-07	1.32E-07	9.03E-08	8.11E-08	4.10E-08
Bone_Surface	1.61E-04	2.90E-05	2.27E-05	3.91E-05	9.46E-05	1.25E-05
Brain	5.27E-07	2.12E-07	1.32E-07	8.98E-08	8.08E-08	4.07E-08
Breast	5.25E-07	2.12E-07	1.31E-07	8.73E-08	7.26E-08	3.98E-08
Stomach Wall	5.39E-07	2.20E-07	1.35E-07	8.96E-08	7.44E-08	4.11E-08
Small Intestine Wall	5.42E-07	2.30E-07	1.40E-07	9.37E-08	7.82E-08	4.30E-08
Upper Large Intestine Wall	8.03E-07	4.11E-07	2.30E-07	1.47E-07	1.07E-07	6.67E-08
Lower Large Intestine Wall	1.67E-06	1.02E-06	5.36E-07	3.28E-07	2.13E-07	1.52E-07
Kidneys	7.05E-07	2.48E-07	1.64E-07	1.62E-07	2.46E-07	5.97E-08
Liver	3.81E-06	1.49E-06	7.82E-07	5.31E-07	3.97E-07	1.79E-07
Extra-Thoracic Region	5.25E-07	2.12E-07	1.31E-07	8.83E-08	7.64E-08	4.02E-08
Lung	5.27E-07	2.12E-07	1.31E-07	8.83E-08	7.58E-08	4.02E-08
Muscle	5.27E-07	2.12E-07	1.31E-07	8.87E-08	7.65E-08	4.03E-08
Ovaries	5.28E-07	2.14E-07	1.32E-07	8.92E-08	7.65E-08	4.07E-08
Pancreas	5.26E-07	2.12E-07	1.31E-07	8.83E-08	7.56E-08	4.03E-08
Red Marrow	1.95E-05	3.00E-06	1.78E-06	2.45E-06	4.04E-06	8.77E-07
Skin	5.26E-07	2.12E-07	1.31E-07	8.79E-08	7.45E-08	4.00E-08
Spleen	6.83E-07	2.45E-07	1.61E-07	1.46E-07	2.00E-07	5.40E-08
Testes	5.25E-07	2.12E-07	1.31E-07	8.73E-08	7.28E-08	3.98E-08
Thymus	5.25E-07	2.12E-07	1.31E-07	8.76E-08	7.40E-08	4.00E-08
Thyroid	5.25E-07	2.12E-07	1.31E-07	8.83E-08	7.64E-08	4.02E-08
Uterus	5.26E-07	2.13E-07	1.31E-07	8.80E-08	7.41E-08	4.02E-08
Urinary Bladder Wall	5.26E-07	2.12E-07	1.31E-07	8.77E-08	7.31E-08	4.00E-08
50 year committed effective dose	4.65E-06	9.55E-07	6.16E-07	8.02E-07	1.52E-06	2.80E-07

Values obtained from Federal Guidance Report 13 Supplement. Highlighted values are the organ and the highest delivered committed equivalent dose for a single intake. The 50 year committed effective dose is an integrated dose:

$$H_T = \int_0^{50y \text{ or } 70y} (D_{T,R} W_R)\, dT$$

TABLE III. INHALATION DOSE COEFFICIENTS FOR RA 226 COMPOUNDS BY SOLUBILITY TYPE (SIEVERTS PER BECQUEREL INHALED)

Particle solubility	Type F (Fast)			Type M (Medium)			Type S (Slow)		
Age at intake	10 y old	15 y old	Adult	10 y old	15 y old	Adult	10 y old	15 y old	Adult
f_1 (Fraction absorbed)	3.00E-01	3.00E-01	2.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-02	1.00E-02	1.00E-02
Adrenals	8.19E-08	7.05E-08	5.34E-08	3.26E-08	3.01E-08	2.43E-08	4.02E-09	3.80E-09	3.42E-09
Bone Surface	3.55E-05	8.23E-05	1.63E-05	1.49E-05	3.44E-05	7.40E-06	2.26E-06	3.14E-06	9.53E-07
Brain	8.15E-08	7.03E-08	5.30E-08	3.24E-08	3.00E-08	2.42E-08	3.79E-09	3.60E-09	3.23E-09
Breast	7.92E-08	6.31E-08	5.19E-08	3.14E-08	2.70E-08	2.37E-08	3.82E-09	3.50E-09	3.34E-09
Stomach Wall	7.95E-08	6.35E-08	5.21E-08	3.20E-08	2.74E-08	2.40E-08	4.47E-09	3.90E-09	3.63E-09
Small Intestine Wall	8.07E-08	6.57E-08	5.28E-08	3.36E-08	2.88E-08	2.47E-08	6.19E-09	4.74E-09	4.31E-09
Upper Large Intestine Wall	9.88E-08	7.43E-08	6.06E-08	5.21E-08	3.80E-08	3.26E-08	2.42E-08	1.41E-08	1.23E-08
Lower Large Intestine Wall	1.60E-07	1.08E-07	8.82E-08	1.15E-07	7.21E-08	6.10E-08	8.66E-08	4.77E-08	4.11E-08
Kidneys	1.46E-07	2.14E-07	7.76E-08	5.90E-08	8.85E-08	3.53E-08	7.89E-09	8.90E-09	4.80E-09
Liver	4.82E-07	3.45E-07	2.33E-07	1.90E-07	1.46E-07	1.06E-07	2.07E-08	1.71E-08	1.45E-08
Extra Thoracic Region	5.27E-07	3.06E-07	2.89E-07	1.15E-05	6.38E-06	6.22E-06	5.97E-05	3.63E-05	3.63E-05
Lung	9.99E-08	8.39E-08	6.75E-08	3.82E-05	3.27E-05	2.75E-05	1.02E-04	8.61E-05	7.90E-05
Muscle	8.04E-08	6.65E-08	5.25E-08	3.19E-08	2.84E-08	2.39E-08	3.80E-09	3.55E-09	3.27E-09
Ovaries	8.05E-08	6.62E-08	5.27E-08	3.21E-08	2.84E-08	2.41E-08	3.93E-09	3.60E-09	3.32E-09
Pancreas	8.01E-08	6.58E-08	5.25E-08	3.18E-08	2.81E-08	2.39E-08	3.85E-09	3.58E-09	3.32E-09
Red Marrow	2.23E-06	3.52E-06	1.14E-06	9.18E-07	1.45E-06	5.21E-07	1.22E-07	1.38E-07	6.98E-08
Skin	7.97E-08	6.47E-08	5.21E-08	3.16E-08	2.76E-08	2.37E-08	3.69E-09	3.42E-09	3.20E-09
Spleen	1.33E-07	1.74E-07	7.03E-08	5.33E-08	7.20E-08	3.20E-08	6.95E-09	7.47E-09	4.42E-09
Testes	7.92E-08	6.33E-08	5.19E-08	3.14E-08	2.70E-08	2.36E-08	3.63E-09	3.34E-09	3.16E-09
Thymus	7.95E-08	6.43E-08	5.21E-08	3.16E-08	2.75E-08	2.38E-08	3.90E-09	3.60E-09	3.39E-09
Thyroid	8.01E-08	6.64E-08	5.24E-08	3.18E-08	2.84E-08	2.39E-08	3.77E-09	3.52E-09	3.25E-09
Uterus	7.97E-08	6.43E-08	5.23E-08	3.16E-08	2.75E-08	2.38E-08	3.74E-09	3.43E-09	3.22E-09
Urinary Bladder Wall	7.94E-08	6.35E-08	5.21E-08	3.15E-08	2.72E-08	2.38E-08	3.70E-09	3.39E-09	3.20E-09
50 year committed effective dose	7.20E-07	1.32E-06	3.59E-07	4.88E-06	4.47E-06	3.46E-06	1.23E-05	1.04E-05	9.51E-06

Values obtained from Federal Guidance Report 13 Supplement. Highlighted values are the organ and the highest delivered committed equivalent dose for a single intake. The 50 year committed effective dose is an integrated dose:

$$H_T = \int_0^{50y \text{ or } 70y} (D_{T,R} W_R)\, dT$$

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Appendix

Appendix A

Glossary

Definitions

See also the Toxicological Profile for Ionizing Radiation (ATSDR, 1999)

The concepts of radiation exposure and radiation dose are not interchangeable and are explicitly defined based on principles of physics. Basically, radiation is energy and exposure is defined by the amount of electrical charge produced by radiation in a kilogram of air (C/kg). Using physical principles beyond the scope of this document, this charge/mass can be converted to an air dose. The air dose can be converted to a tissue dose if the atomic composition of the tissue is known. Ultimately, the dose is the amount of charge (energy) deposited in matter. Not all exposures result in a dose. Depending on the type of radiation, the interaction with tissues, the distance within the body the radiation travels, only fractional amounts of the energy may be deposited in tissues giving rise to various doses within the body. Notice that these terms do not include a time reference. With the addition of time, the exposure becomes an exposure rate (exposure/time) or dose rate (dose/time). The units of exposure and dose are given in the definition portion of this guidance.

Activity (curie or Becquerel): The number of nuclear transformations occurring in radioactive material per unit time. A curie (Ci) is defined as 37 billion transformations in one second. (Said another way, a curie is the amount of material in which 37 billion atoms transform each second.) In the SI system, one transformation per second is one Becquerel (Bq). The activity is a function of the number of atoms, not the mass. The activity (A) = the number of atoms (N) x a decay constant (λ) which varies for each radioactive substance:

$$A = \lambda N$$

There is no direct conversion of an activity to an exposure or dose.

Dose (rads or Gray): A general term denoting the amount of energy from radiation that is absorbed per unit mass of absorber. Dose is a generic term and can mean absorbed dose, dose equivalent, deep dose equivalent, effective dose, effective dose equivalent, committed dose equivalent, committed effective dose equivalent, equivalent dose, or total effective dose equivalent. *For special purposes it must be appropriately qualified*. In the SI system, 1 Gray (Gy) equals an absorbed dose of 100 rads.

$$D = E/m$$

Where D is the absorbed dose, m is the mass in kilograms and E is the energy absorbed in joules. The derivation of E is beyond the scope of this document.

Equivalent dose (rem or Sievert; H_T): A quantity used in radiation protection. It expresses all radiations on a common scale for calculating the dose for purposes of radiation safety. H_T is the product of the absorbed dose in rad or gray to the organ or tissue and a quality factor, whose value depends on the

radiation. The equation for H_T is: ($H_T = W_R D_{T,R}$) where $D_{T,R}$ is the absorbed dose to the tissue from radiation type R and W_R is the radiation weighting factor. In the SI System, a Sievert (Sv) equals an equivalent dose 100 rem.

Effective dose (rem or Sievert; H_E): The sum of the products of the equivalent dose (H_T) and the tissue weighting factors (W_T) applicable to each of the body organs or tissues irradiated. The equation is: $H_E = \sum W_T H_T$. The effective dose equivalent recognizes the carcinogenic radiosensitivity of the several different tissues of the body. A Sievert equals 100 rem. *NOTE – the units of equivalent dose and effective dose are identical; therefore, additional information and methodology inspection is needed to determine the correct terminology to use in the assessment*.

Exposure: The general meaning of exposure refers either to radioactive material being ingested or inhaled, or to the radiation from that material depositing its energy in a substance, such as the human body.

The specific meaning is the quantity of ionization that gamma rays or x-rays produce in air, specifically 1 electrostatic unit per cubic centimeter of air at standard temperature and pressure (1 esu/cc at STP); exposure has the conventional unit the Roentgen (R), where 1 R = 1 esu/cc = 2.58×10^{-4} coulomb per kilogram of air. The ***roentgen (R)*** is the special unit only used for the quantity of ionization produced by gamma radiation in air. One R is approximately 0.88 rad in air. Since tissue is denser than air, a 1R exposure in air produces an absorbed dose of approximately 0.95 rad in tissue placed at that same location. This is the "rule of thumb" for 1 µR/h ~ 1 µrad/h. In the SI System, the unit of exposure is the coulomb per kilogram, and 1 coulomb per kilogram is equal to 3881 R.

Alpha particles and beta particles are not measured in terms of R. They are measured in terms of rad or Gy.

Radiation Weighting Factor (W_R): An indication of the amount of the relative biological effectiveness of radiation to cause damage. The values are 1.0 for electrons, beta radiation, and gamma radiation. The value for alpha particle radiation is 20. Neutron radiation is not considered here as it is not an issue with environmental radiation. The radiation weighting factors are determined by the International Commission on Radiological Protection (ICRP).

Tissue Weighting Factor (W_T): A dosimetric value used in the practice of health physics (radiation safety) to account for the relative carcinogenic susceptibility of the various tissues. The values range from 5% to 12%. See TABLE I for the major organ systems and their W_T. The tissue weighting factors are determined by the ICRP (2007).

Dose Coefficient: A factor (Sv/Bq or rem/Ci) that is multiplied by the intake quantity of a radionuclide (Bq or Ci) to estimate the dose equivalent from radiation (Sv or rem). The dose conversion factor depends on the route of entry (inhalation, ingestion, or immersion), the lung clearance class (S,

	M, or F) for inhalation, the fractional uptake from the small intestine to blood (f_1) for ingestion, and the organ of interest. EPA provides separate dose conversion factor tables for inhalation, ingestion, and immersion, and each provides factors for the gonads, bladder, breast, esophagus, liver, lung, stomach, colon, red marrow, bone surface, skin, thyroid, remainder, and effective whole body.

Appendix B

Assessing Health Effects

All radioactive elements are classified as human carcinogens. Natural uranium is not considered a carcinogen (https://cfpub.epa.gov/ncea/iris2/chemicalLanding.cfm?substance_nmbr=259). Until recently, no non-cancer health effects were associated with radiation exposure. Studies from the Radiation Effects Research Foundation (www.rerf.jp) have shown statistically significant cardiovascular diseases in atomic bomb survivors.

The majority of radiation exposures are considered chronic exposures. Acute exposures only occur as a result of medical procedures using x-rays or radioactive material, detonation of above ground nuclear weapons (Japan), radiation accidents such as those arising from nuclear accidents, industrial exposures, weapons production or related activities. The health effects of acute exposures are well defined with the first observable effect being depression of blood elements (doses greater than 75 rads (0.75 Gray Gy; Gy) or ulceration and necrosis of the skin and deeper tissues (doses of several Gy, e.g. from fluoroscopy). Typical environmental exposures are less than 0.3 rads (0.003 Gy).

To evaluate noncarcinogenic effects from radiation exposure, ATSDR derived a chronic-duration external exposure minimal risk level (MRL) of 1 milliSievert (mSv) per year above background. ("Chronic-duration" exposures are defined as exposures exceeding 365 days.) This MRL is an estimate of the human exposure that is likely to be without appreciable risk of adverse *noncancer* health effects. For a more in depth discussion of the derivation of the ATSDR MRL for ionizing radiation, see ATSDR, 1999.

When evaluating carcinogenic effects from radiation exposure, ATSDR health physicists use the dose of 5,000 millirem (mrem) over 70 years as the radiation-induced cancer comparison value. This value is a committed effective dose (CED) calculated from the intake of radionuclides, with the assumption that the entire dose (a 70-year dose) is received in the year of intake. Doses below this CED, are not expected to result in adverse health effects. ATSDR derived the value after examining peer-reviewed literature and other documents that evaluate the health effects of exposure to ionizing radiation.

If the estimated radiation doses at a site are above comparison values, ATSDR proceeds with a more in-depth health effects evaluation to determine if the doses are sufficient to trigger public health action to limit, eliminate, or further study any potential harmful exposures. ATSDR scientists conduct a health effects evaluation by carefully examining site-specific exposure conditions about actual or likely exposures; conducting a critical review of available radiological, medical, and epidemiologic information to ascertain the levels of significant human exposure; and comparing an estimate of the radiation doses that people might frequently encounter at a site to situations that have been associated with disease and injury. This health effects evaluation involves a balanced review and integration of site-related environmental data, site-specific exposure factors, and toxicologic, radiologic, epidemiologic, medical, and health outcome data to help determine whether exposure to contaminant levels might result in harmful effects. The goal of the health effects evaluation is to decide whether or not harmful effects might be possible in the exposed population by weighing the scientific evidence and keeping site-specific doses in perspective.

Examples

ATSDR has a limited number of toxicological profiles for radioactive materials. Excluding the chemical hazards associated with uranium, all radioactive substances have the same MRL of 1 mSv/y. Moreover, this MRL only applies to chronic external radiation. There is no MRL established for internalization of radioactive materials. Therefore, to properly assess the possible health effects associated with radioactive materials, one must know the specifics of the external radiation field, radioactive contaminants, including the specific chemistry and biochemistry, lung solubilities, intestinal uptake, its organ of interest, its half-life (physical and biological), environmental behavior, and its decay products and their environmental parameters (fate and transport). The following examples illustrate some of the techniques that must be used to adequately estimate a radiological dose and evaluate its health implications.

1. **External Dose**

Using an exposure meter properly calibrated with a cesium-137 standard, an indoor exposure reading of 30 µR/h is measured. The background reading is 10 µR/h and the contaminant of concern is radium-226. You are asked if there is a public health hazard for 24 h/d, 365 d/y occupancy.

The "rule of thumb" is that 1 µR/h is about 95 micrograys (9.5 millirads) per year. Taking into account the background reading of 10 µR/h, the estimated dose above background is 20 µR/h x 95 microGy/ µR = 1.9 milliGy per year. Because we are only measuring photon radiation with a W_R=1, the effective dose is 1.9 mSv/y which is greater the ATSDR MRL for ionizing radiation of 1mSv/y. Because the site-specific radiation dose exceeds ATSDR's radiation MRL, this dose requires additional evaluation to determine whether harmful effects are likely to occur. Furthermore, as radium-226 is the concern, the health assessor must also consider indoor radon (radon 222) as a potential contaminant as radon is a decay product of the radium-226. CONFOUNDER: the radiation signature of cesium-137 and radium-226 are sufficiently different so an instrument calibrated with cesium-137 used to measure radium-226 will be over-reporting the true exposure value. Hence the need for further evaluation of the instrumentation used, calibration, measurement techniques, and additional radiation readings to determine if indeed the readings are elevated.

2. **External Dose**

Using an exposure meter properly calibrated with a cesium-137 standard, an outdoor exposure reading of 30 µR/h is measured. The background reading is 10 µR/h and the contaminant of concern is thorium-232. You are asked if there is a public health hazard associated with the thorium-232 for 24 h/d, 365 d/y from the thorium contamination.

This is a trick question! In this case, there is a hidden issue if the assessor is unfamiliar with radiation instrumentation and radiation detection. Unless specifically constructed, calibrated and properly used, many instruments are incapable of field detection of thorium-232. Therefore, the radiation being detected is not specifically from the thorium-232. Most likely, there is another radiation source in the area. The recommended course of action is to seek appropriate help.

3. Internal Dose (ingestion and inhalation evaluated similarly)

A residential yard is thought to have elevated levels of radium-226 in the soil. The local average background Ra-226 concentration is 1 pCi/g (0.037 Bq/g). The level of radium-226 as determined by laboratory analysis is 5 pCi/g with an uncertainty of 30%[11]. What is the internal dose to a 5-year old child who eats 0.2 grams of soil per day? Does this concentration represent a health concern?

There are several issues associated with this scenario: 1) is the radium concentration elevated; 2) if so, is it greater than an appropriate regulation; 3) what is the equivalent dose and the effective dose; and 4) are these doses considered to be hazardous to ones' health based on scientific data reviews?

In the Code of Federal Regulations, 40 CFR 192 pertains to the standards for health and environmental protection associated with uranium and thorium mill tailings. In this regulation, the allowable radium-226 concentration in the top 5 cm of soil is 5 pCi/g above background. This regulation is not necessarily a public health-derived limit but it has been used as an USEPA Applicable or Relevant and Appropriate Requirements (ARAR; OSWER Directive 9200.4-25). Thus the argument can be made that this soil is within the legal limits.

To calculate the dose following a single ingestion, first determine the intake less background:

(5-1) pCi/g x 0.2 g/day = 0.8 pCi (0.0296 Bq) intake/day

and adjust for significant figures[12] so the intake is 0.03 Bq/day. Since this a one-time intake, the total intake is 0.03 Bq.

Radium chemically behaves similarly to calcium so the most significant dose will be to the bone surfaces (an equivalent dose since it is an organ). Thus the equivalent dose is:

(2.27E-05 Sv/Bq) x 0.03 Bq = 6.82E-07 Sv (after rounding)

Because of the ICRP methodology, the bone surface dose also is considered the critical tissue for determining the lifetime dose to the child following a single intake. The lifetime dose is considered to be delivered in the first year following the intake. If the intake is continuous over a year, you can approximate the total annual dose by multiplying by 365 days yielding an estimated 1-year bone dose of 1.24E-4 Sv (0.124 mSv).

To estimate the whole body doses, the appropriate dose coefficients and equations to use are:

6.16E-07 x 0.03 Bq = 18.5E-09 Sv (lifetime) from a single intake

6.16E-07 x 0.03 Bq/d x 365 d/y = 6.74E-06 Sv/y (lifetime estimated first year dose)

The ATSDR MRL for ionizing radiation is 1 mSv/y (1E-03 Sv/y) and the resulting first year dose is below the ATSDR MRL.

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11. Typically, laboratory results for radiological analyses include a total uncertainty of the measurement. The uncertainty includes sampling errors, laboratory errors, and radiological detection issues. Unless otherwise noted, the uncertainty is expressed as a 1 sigma (σ) where 1 σ indicates a data spread from the 39th to the 68th percentiles of a normal distribution.

12. The importance of significant figures refers to accuracy. Most, if not all the calculated coefficients are expressed in scientific notation and as two significant figures to the right of the decimal point.

The question then becomes, if the whole body dose is below the MRL, why should you perform additional dose evaluations? Answer: Radium is known to cause bone related cancers including bone sarcomas and blood-related cancers. The dose to the entire body is about 37 times lower than the dose to the bone tissues. How does this intake compare to the peer-reviewed literature? You would then review the Toxicological Profile for Radium for a discussion of the health implications.

Radium carcinogenesis (bone cancers) has been observed in radium dial painters. However, an intake of over 100 microcuries (100 million pCi; 37 million Bq) was required before the first instances were observed in the painters (similar to a Lowest Observed Adverse Effect Level (LOAEL). In our example, the uptake for the year was about 1E-07 lower than the LOAEL.

Note on Example 3

If the radioactive material being evaluated has a sufficiently long effective half-life, the procedure in this example works well. Radium-226 has a physical half-life of 1602 years and a biological half-life of approximately 43 years yielding an effective half-life of approximately 41 years. After a year, the amount of radium-226 remaining in the body is over 98% of the initial amount. If the effective half-life is less than a year, the dose estimate will be incorrect unless a steady state intake occurs. For example, the effective half-life of H-3 is 12 days and the effective half-life of Iodine-131 is 7.6 days.

Appendix C

Radiological Environmental Assessment

Fate and Transport

The movement of materials through the environment, including its uptake into bioavailable materials is dependent on the chemical properties. Chemical properties are dependent on the electronic shells (orbital electrons). Similarly, the movement of radioactive materials through the environment is also based on the chemical properties of the radioactive element. The only difference between a radioactive element and its non-radioactive counterpart (if a non-radioactive form exists) is at the level of the atom's nucleus, not the orbital electrons. Every naturally occurring element has one or more radioactive forms that are naturally occurring or made by man. The following table gives a few examples of non-radioactive and radioactive elements.

Table C-1. Examples of non-radioactive and radioactive elements

Element (number of stable isotopes)	Examples of Stable Isotopes*	Examples of Radioactive Isotopes†	Number of electrons (also number of protons)
Hydrogen (2)	H-1; H-2	H-3	1
Strontium (4)	Sr-84, Sr-86, Sr-87, Sr-88	Sr-89, Sr-90	38
Tin (11)	Sn-118, Sn-120	Sn-121, Sn-123	50
Lead (4)	Pb-204, Pb-206, Pb-207, Pb-208	Pb-210	82
Bismuth (1)	Bi-209	Bi-210	83
Uranium‡ (0)	No stable isotopes	U-234; U-235, U-238	92

*All elements with less than 84 protons (polonium) have one or more stable isotopes.

†All elements have some form of radioactive isotopes, either naturally occurring or man-made.

‡All forms of uranium decay to some stable isotope of lead.

Consider the following example. You are evaluating the environmental fate and transport of lead. Lead in the environment will consist of the four stable isotopes. When you evaluate the fate and transport of lead through the environment, do you evaluate each stable isotope separately? Probably not. If that environmental lead concentration has a bit of radioactive lead-210 mixed in, will lead-210 behave any differently than non-radioactive lead? No, chemically the lead-210

behaves exactly like its non-radioactive counterparts. When the lead-210 decays, it is no longer lead (it decays into bismuth-210 which decays into polonium-210 that decays into stable lead-208).

If you have a generic model that evaluates metals, that model can be used to evaluate both radioactive and non-radioactive metals. What the model cannot evaluate is the radioactive decay issues associated with the radioactive form. Conversely, if you have a model of the movement of radioactive lead through the environment, the model can be used to evaluate the radiation dose at each point in the environment, and since non-radioactive lead behaves identically to radioactive lead, its concentrations can be estimated from the calculated radiation dose from the radioactive concentration.

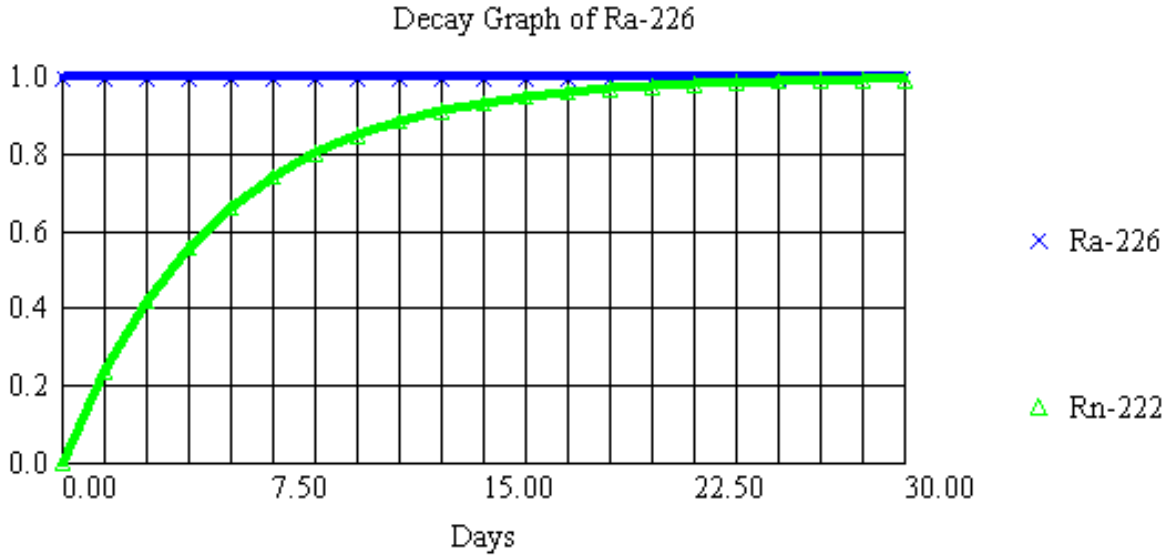
The variation with radiological material fate and transport is that the element, being radioactive will undergo transformations into a new element and thus different chemical properties. For example, all forms of radium are radioactive and will behave similarly to calcium. Although the chemical properties of the various forms of radium are identical, their presence in the environment will change with the holding times of the sample holding times. Table C-2 gives some of more common forms of radium and its decay products. The following graphs illustrate the isotopic differences of a sealed sample (regardless of environmental media) held for 30 days.

Table C-2. Decay products of radium.

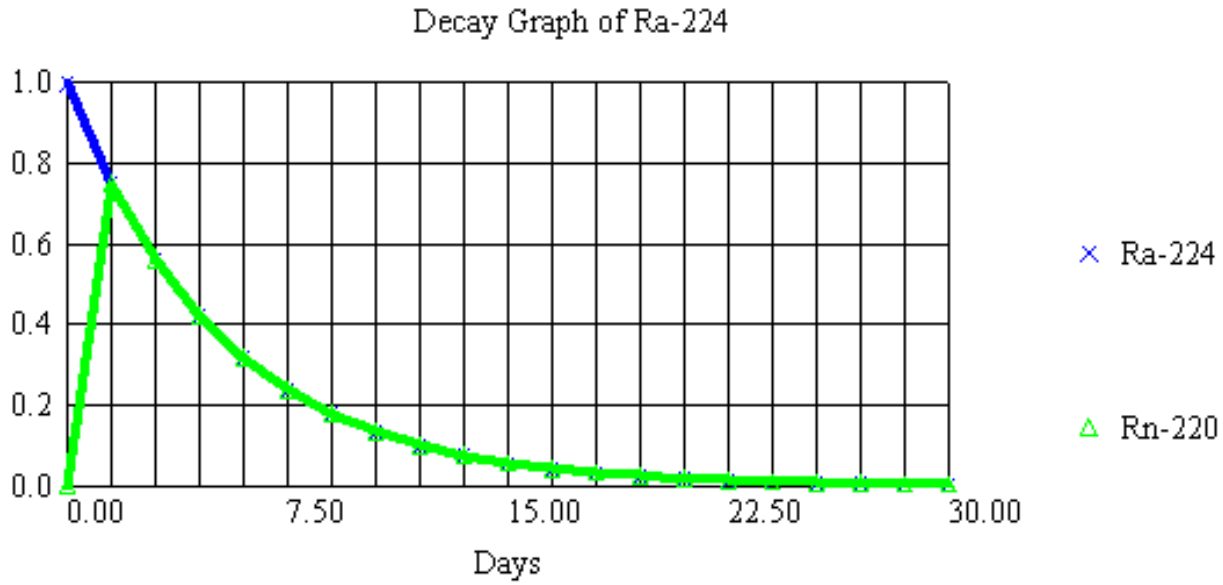
Radium Isotope (half-life)	Formed by decay of*	Radium decay product (half-life)	Stable isotope produced
Radium-226 (1600 years)	Uranium-238 (4.5 billion years)	Radon-222 (3.82 days)	Lead-206
Radium-224 (3.66 days)	Thorium-232 (14 billion years)	Radon-220 (55.6 seconds)	Lead-208
Radium-228 (5.76 years)		Actinium-228 (6.15 hours)	Lead-208
Radium-223 (11.44 days)	Uranium-235 (704 million years)	Radon-219 (3.96 seconds)	Lead-207
*Each isotope listed in this column is the initial radioactive element of a multi-step decay chain. Uranium-234 is not listed because it is produced during the decay of Uranium-238.			

In the top figure, the concentration of radium 226 does not change significantly over the 30 days but the amount of radon-222 continuously increases until its activity equals that of the radium-226. In the lower figure, the activity of the radium-224 decreases at a constant rate, a function of

its half-life. The radon-220 after about 1.5 days equals the activity of the radium-224 and both are almost undetectable after 30 days.



This decay graph of Ra-226 compares Ra-226 and Rn-222 activity on the y-axis over 0 to 30 days on the x-axis. Ra-226 stays at 1.0, while Rn-222 increases from 0 at 0 days to 1.0 at 30 days.



This decay graph of Ra-224 compares Ra-224 and Rn-220 activity on the y-axis over 0 to 30 days on the x-axis. Ra-224 decreases from a 1.0 at 0 days to nearly 0 at 30 days. Rn-220 increases from 0 at 0 days until it meets the Ra-224 curve at a y-value of approximately 0.75, and then follows the same decreasing curve as Ra-224.

The bottom line is that if you hold your soil sample for more than 1 month, you will never find radium-224 as it will have decayed away but radium-226 still will be detectable. There is a caveat, however, in that if your sample also contains thorium-232, then there will be radium-224 in the sample regardless of the holding time.

In water, however, you have to consider the chemical forms. For example, thorium sulfate is water soluble; whereas, radium sulfate is water insoluble. Depending on the water oxidation-reduction potential as well as the geochemical formations, the concentrations of thorium and radium may vary greatly.

In summary, the movement of radioactive and non-radioactive elements through the environment is a function of the chemical properties. When a radioactive element decays, then it will behave differently because a new element is formed and that element's fate and transport will be different.

The application of models used to estimate movement of elements through the environment can be used to estimate either non-radioactive or radioactive species of the same element. The application of models designed to estimate the radiation dose can be used to estimate the concentration of non-radioactive atoms at that same instant in time.