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Contractor Technical Report

Dose Coefficients for Discrete Radioactive Particles (DRP)

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Executive Summary

The dose coefficients contained herein support the U.S. Nuclear Regulatory Commission's (NRC) continued evaluation of its regulatory framework for discrete radioactive particles (DRPs) in the environment at decommissioning nuclear power plants. DRPs, also known as "hot particles," are very small fragments (less than 1 millimeter in any dimension) containing radioactive material with high specific activity that are insoluble in water. At nuclear power plants, DRPs are created during both normal operations and decommissioning activities. For dose assessment, hot particles are assumed to be of a spherical shape ranging in physical diameter from 10 to 1,000 microns (μm). The activity median aerodynamic diameter is of no significance to the dose coefficients developed in this report. It is a parameter used to assess the settling velocity of particles in the lung; DRPs are single particles and are assumed to be too large to get past the nasal vestibule and nasopharynx of the upper respiratory tract (URT). The exposure scenarios considered for dose coefficients include DRPs located on the skin surface, in the URT, and in the gastrointestinal (GI) tract. As a conservative approach, particles are assumed to be stuck in their respective locations, but those in the GI tract are also assumed to travel with the intestinal content.

Shallow dose equivalents (SDEs) for particles on the skin were calculated using the SkinDose module in VARSKIN+ v1.1 (Hamby et al. 2021). To be consistent with NRC regulations, the SDE was estimated to be an infinitely thin 10 square centimeter (cm^2) disk at a depth of 7 milligram/cm^2 (70 μm) in unit-density tissue. SDE is important for estimating the likelihood of ulceration of the skin exposed to a hot particle. A value of 1 cm^2 was originally chosen as the critical dose averaging area for skin, but it was then increased to 10 cm^2 to allow for particle movement on the clothing above the averaging area. Local dose equivalent (DE) for particles on the inner walls of the URT and the GI tract were also calculated using the SkinDose module. In this case, the DE was estimated as an infinitely thin 1 cm^2 disk to mimic the approximate maximum size of an ulcer consistent with a recommended dose threshold of 25 gray (Benke et al. 2022). The critical depths for dose estimation are 45 μm for extrathoracic surfaces in the URT, 140 μm for the small intestine, and 290 μm for the large intestine. Local DE to the URT and GI tissue is important for estimating the likelihood of ulceration in those organs due to a stationary DRP.

The Phantom with Moving Arms and Legs (PiMAL) code, coupled with Monte Carlo N-Particle® Version 6 (MCNP6), was used to estimate effective dose equivalent (EDE) resulting from electron and photon emissions from radionuclides at stationary locations on the skin surface, in the URT, and in the small and large intestines. These evaluations were conducted at various locations to determine and report the maximum EDE from a DRP in each of the three regions (i.e., skin surface, GI tract, and URT).

The committed effective dose equivalent (CEDE) following the ingestion of DRPs was estimated using the Integrated Modules for Bioassay Analysis (IMBA) code. The CEDE coefficients are independent of DRP size and are assumed to follow the International Commission on Radiological Protection (ICRP) GI tract model (ICRP 1979). All IMBA CEDE coefficients used the tissue weighting factors in ICRP Publication 26, "Recommendations of the ICRP," issued 1977 (ICRP 1977), and ICRP Publication 30 (Part 1), "Limits for Intakes of Radionuclides by Workers," issued 1979 (ICRP 1979).

The dose coefficients presented in this report could help form the technical basis for certain aspects of NRC's decommissioning oversight activities. Specifically, it may aid the US NRC in developing decommissioning policy and guidance and assist in staff reviews of license termination plans/decommissioning plans, final status survey reports, and license amendment requests when discrete

radioactive particles may be a concern. These dose coefficients can be used for both retrospective and prospective dosimetric studies. The dose estimates for a retrospective study are considered to be made with reasonable accuracy because exposure times are usually known with some degree of confidence. Exposure times for prospective studies, however, are uncertain, and dose estimates merely assess what could occur under assumed exposure conditions. Many times, prospective dose assessments are conducted with very conservative exposure assumptions to maximize the dose estimate or to compare a potential radiation dose with a regulatory limit.

Introduction

The dose coefficients (sometimes referred to as "dose conversion factors") in this report support the U.S. Nuclear Regulatory Commission (NRC) staff's evaluation of the regulatory framework for discrete radioactive particles (DRPs) in the environment at decommissioning nuclear power plants. DRPs, also known as "hot particles," are very small fragments (less than 1 millimeter (mm) in any dimension) containing radioactive material with high specific activity that are insoluble in water. At nuclear power plants, DRPs are created during both normal operations and decommissioning activities. This DRP analysis considers five different materials, including neutron activated Stellite, Inconel, concrete, irradiated fuel fragments, and thoriated welding rods.

DRPs could emit alphas, electrons, and photons as they transition through radioactive decay. In this report, the radiological exposure pathways of skin deposition, ingestion, and inhalation are analyzed for 23 radionuclides in the five DRP materials. For the most part, particles are assumed to be stationary in the various locations of the body. This report includes definitions of DRP material relevant to internal and external dosimetry, potential radioactive source characteristics, and possible exposure conditions. Dose coefficients for different DRP types are offered at the end of the document, with a short discussion on the use of those coefficients for dose assessment.

Materials Assessed

The five DRP materials, except fuel fragments, are assumed to be insoluble in stomach acid for reasonable residence periods. Fuel fragments have been shown to dissociate under environmental conditions (ICRP 2017, 2019); therefore, a fraction of that material could be taken up in the bloodstream following ingestion.

Stellite 6 (https://www.stellite.com/us/en/products/stellite-family/stellite-family-stellite.html) is an alloy of cobalt (67 percent by weight), chromium (2 percent), tungsten (5 percent), and carbon (1 percent). If Stellite is exposed to neutrons, naturally occurring cobalt (Co)-59 can be transformed into Co-60, a radioactive isotope of cobalt. Stellite has a bulk density of 8.4 grams (g) per cubic centimeter (cm^3) and an effective atomic number of 33; these parameter values are important for energy self-absorption calculations.

Similarly, Inconel 718 (DHS 2021) is a nickel alloy containing 15 elements, 3 of which are prominent: nickel (53 percent), chromium (19 percent), and iron (17 percent). Inconel has a bulk density of 8.2 g/cm^3 and an effective atomic number of 29. Upon exposure to neutrons, the alloy is activated, and two radioisotopes of nickel (Ni-59 and Ni-63) become important for dose assessment.

A compendium of material composition (DHS 2021) lists 26 different mixtures for "concrete." Because this work is being conducted for the NRC, this assessment uses the characteristics of "regulatory concrete." This material has a nominal density of 2.3 g/cm^3 and an effective atomic number of 10. Seven elements are included, with silicon and oxygen making up more than 87 percent by weight. The radioactivity in a given concrete sample will vary; this analysis considers radioactive isotopes of iron, cobalt, barium, and europium.

Fuel fragments can contain a number of long-lived radionuclides produced during nuclear fission. This analysis considers isotopes of strontium, cesium, europium, plutonium, americium, and curium. For this report, a fuel fragment is assumed to have an effective atomic number of 88 and a density of 11 g/cm^3.

Thoriated welding rods present another potential source of DRP (thorium (Th)-232) in remediated soils. These DRPs are made of tungsten with up to 4 percent by weight of added thorium. The effective atomic number is 74 and bulk density is 19 g/cm^3. Th-232 begins a long chain of radioactive decay products. This analysis includes four of those progeny (radium (Ra)-228, actinium (Ac)-228, Th-228, and Ra-224). The fifth progeny is a radioactive gas (radon (Rn)-220) and therefore assumed to dissipate.

Source Characteristics

The DRPs assessed are assumed to be of a spherical shape ranging in physical diameter from 10 to 1,000 microns (µm). The particles are characterized by elemental composition, effective atomic number, and bulk density. Half-lives of the radionuclides contained in the five different compositions are generally on the order of tens to thousands of years, with a few on the order of tens of years or less (table 1). Because the DRP radionuclides are aged for several years, radioactive progeny of strontium (Sr)-90 and cesium (Cs)-137 are considered to be in secular equilibrium with their parent. The first decay progeny of the plutonium, americium, and curium isotopes (table 1) are characterized by very long half-lives and therefore no equilibrium assumptions can be made. Thorium progeny with relatively short half-lives (Ac-228 and Ra-224) are included so that the analyst can take account of their contribution to dose if appropriate, given the exposure scenario.

Dose Averaging Area and Tissue Depths

Dose assessment for DRPs located on the skin surface (shallow dose equivalent (SDE)) is based on an exposed area of 10 square centimeters (cm^2) and a depth of 7 milligrams (mg)/cm^2. These values are specified in Federal law. An area of 10 cm^2 allows for the movement of a hot particle that may rest on clothing, and the depth of 7 mg/cm^2 accounts for a typical thickness of the dead layer of skin (10 CFR 20.1201 and 20.1003; 1991).

For internal DRPs, however, a dose averaging area of 1 cm^2 is assumed based on evidence of ulceration and sparing effects observed for small volumes of tissue (ICRP 2012). The averaging area of 1 cm^2 for DRP ulceration protection matches the area recommended by the National Council on Radiation Protection and Measurements (NCRP) and the International Commission on Radiological Protection (ICRP) for the same purpose. This assumption is consistent with (1) the extent to which surviving cells on the perimeter of an irradiation site will migrate—from diameters up to 15 mm according to ICRP (2012)—toward the central damaged site during tissue response and (2) observed sizes of DRP-induced ulcers that range from millimeters to a centimeter in diameter (NCRP 1989).

Anatomical differences among outer tissue of the skin and internal tissue of the respiratory and alimentary tracts justify selecting different depths for target cells in these regions. Target cell depths are reported to be 40–50 µm for extrathoracic surfaces in the upper respiratory tract (URT), 130–150 µm for the small intestine, and 280–300 µm for the large intestine (ICRP 1994, 2006). Representative depths are therefore selected for calculating dose to these target cells. The representative depths used here are 45 µm for extrathoracic surfaces in the URT, 140 µm for the small intestine, and 290 µm for the large intestine.

Table 1 DRP Material Characteristics and Radionuclides Considered

Nuclide	Half-Life (years)	Effective Atomic Number	Density (g/cm^3)
Stellite 6		**33**	**8.4**
Co-60	5.27		
Inconel 718		**29**	**8.2**
Ni-59	76,000		
Ni-63	101		
Regulatory Concrete		**10**	**2.3**
Fe-55	2.75		
Co-60	5.27		
Ba-133	10.5		
Eu-152	13.5		
Eu-154	8.6		
Fuel Fragment		**88**	**11**
Sr-90*	28.8		
Cs-137*	30.1		
Eu-154	8.6		
Eu-155	4.75		
Pu-238	87.7		
Pu-239	24,000		
Pu-240	6,600		
Pu-241	14.3		
Am-241	433		
Cm-244	18.1		
Welding Rod		**74**	**19**
Th-232	14 billion		
Ra-228	5.75		
Ac-228	6.1 **hrs**		
Th-228	1.91		
Ra-224	3.7 **days**		

*decay progeny assumed to be in secular equilibrium

Exposure Conditions

The exposure scenarios considered in this report include DRPs located on the skin surface, in the URT, and in the gastrointestinal (GI) tract (table 2). Note that every scenario, except the committed effective dose equivalent (CEDE) calculation, is assessed assuming the particle is stationary, either on the skin surface for a period of time or having become lodged in the inner walls of the respiratory or GI tracts. The ingestion CEDE dose coefficient is calculated assuming the particle travels through the GI tract with contents of the intestine.

Table 2 Exposure Scenarios Considered

Exposure	Mobility	Source Location	Reported Dose	Tabulated Dose Coefficients	Method of Calculation
External	Stationary	Skin Surface (nonspecific)	Shallow Dose Equivalent	Table 3	VARSKIN+ (SkinDose)
		Skin Surface (midtorso)	Effective Dose Equivalent	Table 7	PiMAL/MCNP
Internal		URT (nonspecific)	Local Dose Equivalent	Table 4	VARSKIN+ (SkinDose)
		URT (for max. EDE)	Effective Dose Equivalent	Table 7	PiMAL/MCNP
		Small Intestine (nonspecific)	Local Dose Equivalent	Table 5	VARSKIN+ (SkinDose)
		Large Intestine (nonspecific)	Local Dose Equivalent	Table 6	VARSKIN+ (SkinDose)
		GI (for max. EDE)	Effective Dose Equivalent	Table 7	PiMAL/MCNP
	Mobile	GI (ingested)	Committed Effective Dose Equivalent	Tables 9 & 10	IMBA

External Exposures

Stationary DRPs on the Skin Surface. SDE calculations for particles on the skin at no specific location were conducted using the SkinDose module in VARSKIN+ v1.1 (Hamby et al. 2021). To be consistent with NRC regulations (10 CFR 20.1201), the SDE was estimated to an infinitely thin 10 cm^2 disk at a depth of 7 mg/cm^2 (70 µm) in unit-density tissue. If the need arises for averaging to a smaller disk (e.g., 1 cm^2), a modified dose coefficient could be roughly approximated by a factor equal to the ratio of averaging areas (e.g., 10 cm^2/1 cm^2 = 10); the dose coefficient for 1 cm^2 averaging will be approximately 10 times that of the dose coefficient for 10 cm^2 averaging. A spherical source geometry was assumed, and backscatter factors were implemented to account for air above a source directly on the skin.

Dose coefficients of effective dose equivalent (EDE) for DRPs resting on the mid-torso were calculated using Phantom with Moving Arms and Legs (PiMAL) coupled with Monte Carlo N-Particle® Version 6 (MCNP6). PiMAL uses a computational human phantom when coupled with MCNP for the assessment of radiation dose to various organs. MCNP6 is a general-purpose Monte Carlo radiation-transport code designed to track many particle types over broad ranges of energies. Many different combinations of particle placement were investigated to determine the maximum EDE coefficient reported for a DRP on the skin surface. The EDE was calculated using the tissue weighting factors in ICRP Publication 26, "Recommendations of the ICRP," issued 1977 (ICRP 1977), and ICRP Publication 30 (Part 1), "Limits for Intakes of Radionuclides by Workers," issued 1979 (ICRP 1979), as required by 10 CFR Part 20, "Standards for Protection Against Radiation."

Internal Exposures

Stationary DRPs in the URT. Calculations of local dose equivalent (DE) for particles stuck on the inner wall of the URT were also conducted using the SkinDose module in VARSKIN+ v1.1. The DE was estimated to an infinitely thin 1 cm^2 disk at a depth of 4.5 mg/cm^2 (45 µm) in tissue for spherical DRPs between 10 and

1,000 μm in diameter. Particles less than 10 μm are "respirable," meaning they can be breathed deep into the lung, and particles less than 100 μm are "inhalable" and can be captured in the inhalation airstream and lodged in the nasal vestibule or nasopharynx. Particles greater than about 100 μm are generally assumed to fall out of the air quickly and are too large to be inhaled (worksafe.qld.gov.au). The smaller dose averaging area was used to mimic the approximate maximum size of an ulcer consistent with a recommended dose threshold of 25 grays (Gy) (Benke et al. 2022). Dose coefficients were determined for a particle resting on a flat surface with air behind the source (i.e., VARSKIN+ backscatter correction implemented).

Dose coefficients for the EDE from internal stationary particles were determined using PiMAL and MCNP6. The EDE is calculated for a DRP in the URT by simulating energy deposition in various organs and assigning radiation weighting factors and summing organ doses using the ICRP 26/30 tissue weighting factors. Multiple locations were assessed, with the maximum EDE reported herein. This EDE is not a calculation of internal dosimetry (no biokinetics considered) but rather a calculation of weighted DE to various organs of the body from a single particle stuck in the URT (i.e., not different than the consideration of a particle stuck on the upper torso).

Stationary DRPs in the GI Tract. Similarly, calculations of local DE for particles stuck on the inner wall of the small and large intestines were conducted using the SkinDose module in VARSKIN+ v1.1. The DE was estimated to an infinitely thin 1 cm^2 disk at a tissue depth of 14 mg/cm^2 (140 μm) in the small intestine and a depth of 29 mg/cm^2 (290 μm) in the large intestine for spherical DRPs between 10 and 1,000 μm in diameter. Because of the physical separation between villi in the small intestine, DRPs greater than about 100 μm are not as likely to become lodged. As with the URT dose estimates, the dose averaging of 1 cm^2 was used to mimic the approximate maximum size of an ulcer consistent with a recommended dose threshold of 25 Gy (Benke et al. 2022). Dose coefficients were determined for a particle resting on a flat surface with intestinal contents (density of 1 g/cm^3) behind the source (i.e., VARSKIN+ backscatter correction ignored).

As with the URT, dose coefficients for the EDE for a DRP stationary in the GI tract were determined using PiMAL and MCNP6, with the same methodology noted above, again choosing placement that results in the maximum EDE.

Mobile DRPs in the GI Tract. Calculations of CEDE following the ingestion of DRPs were conducted using version 5.0.1 of the Integrated Modules for Bioassay Analysis (IMBA) code. The CEDE coefficients were independent of DRP size and were assumed to follow the ICRP GI tract model (ICRP 1979), with the use of ICRP 26/30 tissue weighting factors. The next section includes more details on the application of the ICRP 30 GI tract model and particle size dependence of the inhalation model.

A CEDE coefficient was not determined for the inhalation pathway because DRP particles are assumed to be too large to get past the URT. These particles would likely be expelled to the environment (e.g., by nose blowing) or swallowed, thereby following the ingestion pathway model.

Dose Coefficients

Stationary DRPs on the Skin Surface, in the URT, or in the GI Tract. The SkinDose module of VARSKIN+ v1.1 was used to estimate radiation dose to shallow layers of tissue resulting from exposure to DRPs. SkinDose carries out deterministic calculations of energy loss and absorption through a variety of source

materials, described by density and effective atomic number, at various depths in tissue. Dose is averaged over an infinitely thin disk with a cross-sectional area of 10 cm^2 for skin tissue and 1 cm^2 for localized dose calculated in the respiratory and GI tracts.

URT tissues are assumed to be overlain by air such that electron backscatter from the radioactive source is minimal. In the GI tract, however, the small and large intestines are assumed to be filled with typical intestinal content and therefore electron backscatter will contribute to localized tissue dose. Dose coefficients are provided per unit time (dose rate) so that radiation dose can be calculated for various exposure assumptions at a later time.

Tables 3 through 6 contain dose coefficients for stationary DRPs on the skin surface (table 3), in the URT (table 4), in the small intestine (table 5), and in the large intestine (table 6). Coefficients are provided for source particles with spherical diameters of 10, 20, 50, 100, 200, 500, and 1,000 µm. These tables include decay product emissions from Sr-90 and Cs-137; however, dose coefficients for the Th-232 decay series are listed separately due to various assumptions that are necessary regarding progeny ingrowth.

Table 3 SDE Coefficients for a DRP of a Given Size Resting at a Random Location on the Skin Surface

SDE Coefficients (Sv/Bq h)							
Diameter (μm)	10	20	50	100	200	500	1000
Stellite 6	(Z = 33; ρ = 8.4 g/cm^3)						
Co-60	9.8E-08	8.8E-08	6.0E-08	3.7E-08	2.2E-08	1.2E-08	8.9E-09
Inconel 718	(Z = 29; ρ = 8.2 g/cm^3)						
Ni-59	1.5E-09	1.5E-09	1.6E-09	1.6E-09	1.7E-09	1.7E-09	1.6E-09
Ni-63	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Regulatory Concrete	(Z = 10; ρ = 2.3 g/cm^3)						
Fe-55	1.3E-09	1.3E-09	1.4E-09	1.4E-09	1.5E-09	1.5E-09	1.5E-09
Co-60	9.9E-08	9.7E-08	8.9E-08	7.6E-08	5.6E-08	3.0E-08	1.8E-08
Ba-133	1.1E-08	9.9E-09	9.5E-09	9.4E-09	9.3E-09	7.3E-09	5.0E-09
Eu-152	7.6E-08	7.5E-08	6.8E-08	5.9E-08	5.0E-08	3.8E-08	2.8E-08
Eu-154	1.8E-07	1.7E-07	1.5E-07	1.3E-07	1.1E-07	8.1E-08	5.7E-08
Fuel Fragment	(Z = 88; ρ = 11 g/cm^3)						
Sr-90*	1.4E-07	1.4E-07	1.2E-07	7.6E-08	4.2E-08	1.7E-08	8.5E-09
Cs-137*	1.5E-07	1.5E-07	1.2E-07	9.3E-08	5.8E-08	2.6E-08	1.4E-08
Eu-154	1.6E-07	1.4E-07	1.1E-07	8.1E-08	5.4E-08	2.7E-08	1.5E-08
Eu-155	2.3E-08	1.5E-08	7.2E-09	4.0E-09	2.3E-09	1.3E-09	9.0E-10
Pu-238	2.4E-10	2.4E-10	2.5E-10	2.6E-10	2.6E-10	2.5E-10	2.3E-10
Pu-239	1.1E-10	1.1E-10	1.2E-10	1.3E-10	1.3E-10	1.2E-10	1.1E-10
Pu-240	2.2E-10	2.3E-10	2.4E-10	2.5E-10	2.5E-10	2.3E-10	2.1E-10
Pu-241	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Am-241	1.0E-09	1.0E-09	1.0E-09	1.1E-09	1.1E-09	9.8E-10	9.1E-10
Cm-244	1.8E-10	1.8E-10	1.9E-10	2.0E-10	2.0E-10	1.9E-10	1.7E-10
Welding Rod	(Z = 74; ρ = 19 g/cm^3)						
Th-232	1.7E-10	1.8E-10	1.8E-10	1.9E-10	1.9E-10	1.8E-10	1.6E-10
Ra-228	3.3E-10	3.4E-10	3.6E-10	3.7E-10	3.7E-10	3.4E-10	3.2E-10
Ac-228#	1.7E-07	1.6E-07	1.4E-07	1.1E-07	6.9E-08	3.2E-08	1.7E-08
Th-228	1.1E-09	6.5E-10	4.0E-10	3.3E-10	2.8E-10	2.4E-10	2.2E-10
Ra-224	2.2E-09	1.8E-09	8.8E-10	4.8E-10	2.6E-10	1.3E-10	8.2E-11

* including progeny contributions assumed to be in secular equilibrium with the parent

instantaneous dose rate at time zero

Table 4 Local DE Coefficients for a DRP of a Given Size Stationary in a Random Location of the URT

Upper Respiratory Tract DE Coefficients (Sv/Bq h)							
Diameter (μm)	10	20	50	100	200	500	1000
Stellite 6	(Z = 33; ρ = 8.4 g/cm^3)						
Co-60	1.3E-06	1.2E-06	8.0E-07	4.7E-07	2.6E-07	1.3E-07	7.7E-08
Inconel 718	(Z = 29; ρ = 8.2 g/cm^3)						
Ni-59	2.0E-08	2.0E-08	2.0E-08	2.0E-08	2.0E-08	1.9E-08	1.7E-08
Ni-63	4.1E-10	2.1E-10	8.6E-11	4.4E-11	2.2E-11	9.0E-12	4.5E-12
Regulatory Concrete	(Z = 10; ρ = 2.3 g/cm^3)						
Fe-55	1.8E-08	1.9E-08	1.9E-08	1.9E-08	1.9E-08	1.8E-08	1.7E-08
Co-60	1.3E-06	1.3E-06	1.2E-06	1.0E-06	7.4E-07	3.8E-07	2.0E-07
Ba-133	2.3E-07	2.1E-07	1.5E-07	1.3E-07	1.2E-07	8.6E-08	5.4E-08
Eu-152	1.1E-06	1.1E-06	9.5E-07	7.8E-07	6.2E-07	4.2E-07	2.7E-07
Eu-154	2.5E-06	2.3E-06	2.1E-06	1.7E-06	1.4E-06	9.1E-07	5.7E-07
Fuel Fragment	(Z = 88; ρ = 11 g/cm^3)						
Sr-90*	1.7E-06	1.7E-06	1.4E-06	9.2E-07	5.0E-07	2.0E-07	8.9E-08
Cs-137*	1.7E-06	1.7E-06	1.5E-06	1.1E-06	6.6E-07	2.7E-07	1.3E-07
Eu-154	2.1E-06	1.8E-06	1.3E-06	9.6E-07	6.0E-07	2.7E-07	1.3E-07
Eu-155	4.6E-07	3.0E-07	1.4E-07	7.3E-08	4.0E-08	1.9E-08	1.2E-08
Pu-238	3.2E-09	3.2E-09	3.2E-09	3.0E-09	2.9E-09	2.6E-09	2.3E-09
Pu-239	1.8E-09	1.8E-09	1.7E-09	1.7E-09	1.6E-09	1.5E-09	1.4E-09
Pu-240	3.1E-09	3.0E-09	3.0E-09	2.9E-09	2.7E-09	2.4E-09	2.2E-09
Pu-241	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Am-241	1.7E-08	1.5E-08	1.3E-08	1.3E-08	1.2E-08	1.0E-08	9.2E-09
Cm-244	2.4E-09	2.4E-09	2.4E-09	2.3E-09	2.2E-09	2.0E-09	1.8E-09
Welding Rod	(Z = 74; ρ = 19 g/cm^3)						
Th-232	5.7E-09	4.0E-09	2.9E-09	2.5E-09	2.2E-09	1.9E-09	1.6E-09
Ra-228	4.5E-09	4.5E-09	4.5E-09	4.3E-09	4.1E-09	3.6E-09	3.2E-09
Ac-228#	2.0E-06	1.9E-06	1.6E-06	1.2E-06	7.3E-07	3.0E-07	1.4E-07
Th-228	2.6E-04	2.6E-04	2.6E-04	2.6E-04	2.6E-04	2.6E-04	2.6E-04
Ra-224	1.2E-03	1.2E-03	1.2E-03	1.2E-03	1.2E-03	1.2E-03	1.2E-03

* including progeny contributions assumed to be in secular equilibrium with the parent

instantaneous dose rate at time zero

Table 5 Local DE Coefficients for a DRP of a Given Size Stationary at a Random Location in the Small Intestine

Small Intestine DE Coefficients (Sv/Bq h)							
Diameter (μm)	10	20	50	100	200	500	1000
Stellite 6	($Z = 33$; $\rho = 8.4$ g/cm^3)						
Co-60	4.6E-07	4.1E-07	2.7E-07	1.7E-07	1.0E-07	6.1E-08	4.5E-08
Inconel 718	($Z = 29$; $\rho = 8.2$ g/cm^3)						
Ni-59	1.1E-08	1.1E-08	1.1E-08	1.1E-08	1.1E-08	1.1E-08	1.0E-08
Ni-63	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Regulatory Concrete	($Z = 10$; $\rho = 2.3$ g/cm^3)						
Fe-55	8.8E-09	8.8E-09	8.8E-09	8.8E-09	8.8E-09	8.8E-09	8.6E-09
Co-60	5.0E-07	4.8E-07	4.8E-07	3.6E-07	2.6E-07	1.3E-07	8.2E-08
Ba-133	7.1E-08	7.1E-08	7.1E-08	7.1E-08	6.7E-08	4.7E-08	3.1E-08
Eu-152	4.5E-07	4.4E-07	4.4E-07	3.9E-07	3.6E-07	2.7E-07	1.9E-07
Eu-154	1.1E-06	1.1E-06	1.1E-06	9.1E-07	8.0E-07	5.8E-07	3.8E-07
Fuel Fragment	($Z = 88$; $\rho = 11$ g/cm^3)						
Sr-90*	1.1E-06	1.0E-06	8.1E-07	5.2E-07	2.8E-07	1.2E-07	5.7E-08
Cs-137*	1.2E-06	1.2E-06	9.4E-07	6.8E-07	4.2E-07	1.9E-07	9.4E-08
Eu-154	1.0E-06	9.2E-07	7.5E-07	5.6E-07	3.7E-07	1.8E-07	9.6E-08
Eu-155	4.6E-08	3.3E-08	1.8E-08	1.1E-08	7.5E-09	5.2E-09	4.2E-09
Pu-238	1.8E-09	1.7E-09	1.7E-09	1.7E-09	1.6E-09	1.4E-09	1.3E-09
Pu-239	7.6E-10	7.5E-10	7.5E-10	7.3E-10	7.0E-10	6.4E-10	5.6E-10
Pu-240	1.6E-09	1.6E-09	1.6E-09	1.6E-09	1.5E-09	1.4E-09	1.2E-09
Pu-241	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Am-241	7.0E-09	7.0E-09	6.9E-09	6.7E-09	6.4E-09	5.7E-09	5.0E-09
Cm-244	1.3E-09	1.3E-09	1.3E-09	1.3E-09	1.2E-09	1.1E-09	9.3E-10
Welding Rod	($Z = 74$; $\rho = 19$ g/cm^3)						
Th-232	1.3E-09	1.3E-09	1.3E-09	1.3E-09	1.2E-09	1.1E-09	9.6E-10
Ra-228	2.5E-09	2.5E-09	2.5E-09	2.4E-09	2.3E-09	2.1E-09	1.8E-09
Ac-228#	1.2E-06	1.2E-06	1.1E-06	8.1E-07	5.2E-07	2.3E-07	1.1E-07
Th-228	1.7E-09	1.7E-09	1.7E-09	1.6E-09	1.6E-09	1.4E-09	1.2E-09
Ra-224	1.3E-08	9.9E-09	4.9E-09	2.7E-09	1.5E-09	7.6E-10	4.8E-10

* including progeny contributions assumed to be in secular equilibrium with the parent
# instantaneous dose rate at time zero

Table 6 Local DE Coefficients for a DRP of a Given Size Stationary at a Random Location in the Large Intestine

Large Intestine DE Coefficients (Sv/Bq h)							
Diameter (μm)	10	20	50	100	200	500	1000
Stellite 6	($Z = 33$; $\rho = 8.4$ g/cm^3)						
Co-60	1.2E-07	1.1E-07	7.8E-08	5.9E-08	4.7E-08	3.7E-08	3.2E-08
Inconel 718	($Z = 29$; $\rho = 8.2$ g/cm^3)						
Ni-59	6.1E-09	6.1E-09	6.1E-09	6.1E-09	6.1E-09	6.1E-09	6.0E-09
Ni-63	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Regulatory Concrete	($Z = 10$; $\rho = 2.3$ g/cm^3)						
Fe-55	4.0E-09	4.0E-09	4.0E-09	4.0E-09	4.0E-09	4.0E-09	4.0E-09
Co-60	1.3E-07	1.2E-07	1.1E-07	9.6E-08	7.4E-08	5.0E-08	3.9E-08
Ba-133	4.7E-08	4.7E-08	4.6E-08	4.4E-08	3.9E-08	2.6E-08	1.8E-08
Eu-152	2.5E-07	2.5E-07	2.4E-07	2.3E-07	2.2E-07	1.8E-07	1.3E-07
Eu-154	5.3E-07	5.3E-07	5.1E-07	4.9E-07	4.5E-07	3.5E-07	2.5E-07
Fuel Fragment	($Z = 88$; $\rho = 11$ g/cm^3)						
Sr-90*	5.3E-07	5.2E-07	4.1E-07	2.7E-07	1.4E-07	5.9E-08	2.9E-08
Cs-137*	6.4E-07	6.2E-07	5.3E-07	4.0E-07	2.6E-07	1.2E-07	6.3E-08
Eu-154	5.1E-07	4.9E-07	4.4E-07	3.5E-07	2.4E-07	1.3E-07	7.0E-08
Eu-155	4.0E-09	3.5E-09	3.0E-09	2.8E-09	2.7E-09	2.5E-09	2.3E-09
Pu-238	1.3E-09	1.3E-09	1.2E-09	1.2E-09	1.2E-09	1.1E-09	9.6E-10
Pu-239	5.0E-10	5.0E-10	5.0E-10	4.9E-10	4.8E-10	4.4E-10	3.9E-10
Pu-240	1.2E-09	1.2E-09	1.2E-09	1.1E-09	1.1E-09	1.0E-09	9.0E-10
Pu-241	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Am-241	5.0E-09	5.0E-09	4.9E-09	4.8E-09	4.7E-09	4.3E-09	3.8E-09
Cm-244	9.1E-10	9.1E-10	9.0E-10	8.9E-10	8.6E-10	7.9E-10	6.9E-10
Welding Rod	($Z = 74$; $\rho = 19$ g/cm^3)						
Th-232	9.9E-10	9.8E-10	9.8E-10	9.6E-10	9.4E-10	8.7E-10	7.7E-10
Ra-228	1.8E-09	1.8E-09	1.8E-09	1.8E-09	1.7E-09	1.6E-09	1.4E-09
Ac-228#	7.7E-07	7.9E-07	7.3E-07	5.7E-07	3.7E-07	1.7E-07	8.8E-08
Th-228	1.3E-09	1.3E-09	1.3E-09	1.2E-09	1.2E-09	1.1E-09	9.8E-10
Ra-224	4.1E-09	2.9E-09	1.5E-09	8.8E-10	5.8E-10	3.7E-10	2.8E-10

* including progeny contributions assumed to be in secular equilibrium with the parent
# instantaneous dose rate at time zero

Table 7 contains coefficients of EDE for stationary DRPs on the skin surface at mid-torso, in the URT, and in the GI tract. Dose coefficients are calculated by assuming a point source, as doses to the whole body are negligibly affected by self-attenuation in particles as small as assumed DRPs. Multiple simulations using PiMAL/MCNP6 coupling were conducted to find the source location resulting in the maximum EDE.

Table 7 EDE Coefficients for a DRP of a Given Size Stationary on the Skin at Mid-torso (External Chest) and Stationary in the Upper Respiratory and GI Tracts, with Specific Locations on Skin and Organ Surfaces that Result in the Maximum EDE

EDE Coefficients (Sv/Bq h)			
Nuclide	External Chest Surface	Upper Respiratory Tract	Gastrointestinal Tract
Stellite 6			
Co-60	5.8E-10	8.8E-08	2.7E-09
Inconel 718			
Ni-59	4.6E-13	2.8E-09	3.5E-10
Ni-62	0.0E+00	0.0E+00	0.0E+00
Regulatory Concrete			
Fe-55	4.1E-14	2.6E-09	2.4E-10
Co-60	5.8E-10	8.8E-08	2.7E-09
Ba-133	5.5E-09	2.3E-08	1.4E-08
Eu-152	1.3E-08	4.1E-08	2.9E-08
Eu-154	1.4E-08	4.3E-08	3.0E-08
Fuel Fragment			
Sr-90*	1.9E-09	1.3E-06	4.9E-08
Cs-137*	1.4E-10	1.8E-08	7.0E-10
Eu-154	3.1E-10	4.3E-08	1.5E-09
Eu-155	8.4E-10	3.3E-09	2.5E-09
Pu-238	2.7E-11	1.3E-09	2.3E-10
Pu-239	1.0E-11	5.4E-10	9.4E-11
Pu-240	2.5E-11	1.2E-09	2.1E-10
Pu-241	0.0E+00	0.0E+00	0.0E+00
Am-241	3.5E-10	5.9E-09	1.3E-09
Cm-244	2.7E-11	8.5E-10	1.8E-10
Welding Rod			
Th-232	1.4E-11	8.9E-10	1.5E-10
Ra-228	1.2E-13	8.6E-10	1.5E-13
Ac-228#	9.2E-09	3.4E-08	2.0E-08
Th-228	6.6E-13	1.2E-09	3.4E-12
Ra-224	2.5E-12	4.4E-10	1.4E-11

* including progeny contributions assumed to be in secular equilibrium with the parent
# instantaneous dose rate at time zero

Mobile DRP Committed Internally

CEDE from DRP Ingestion. The ICRP 30 GI tract model (ICRP 1979) is based on the mathematical compartmentalization of the human body. Loss of radionuclides from any compartment is governed by

first order kinetics, allowing for retention of radioactive atoms in any organ or compartment to be described by either a single exponential or the sum of a number of exponential terms. The ICRP 30 ingestion model consists of the stomach, small intestine, upper large intestine, and the lower large intestine. Translocation to the body fluids, and subsequently to organs other than the GI tract, only occurs in the small intestine compartment. Clearance to the body fluids is also governed by first order kinetics and is driven by f_1, the fraction of a stable element reaching the body fluids following ingestion.

The rate of linear translocation of radionuclides between GI tract compartments following ingestion is independent of the ingested material (i.e., the radioactive material is assumed to follow the movement of the intestinal contents). Thus, the biological rate constants shown in table 8 are valid for all radionuclides, regardless of physical or chemical compositions. Outside of the translocation of radionuclides to the body fluids, the ICRP 30 GI tract model simply describes the translocation of the GI contents. In other words, first order kinetics are used to model the movement of GI contents regardless of the presence of radioactive material. The ingested radioactive material is simply assumed to be uniformly distributed within the contents of the GI tract and, therefore, its translocation follows the same kinetics.

Table 8 Mean Residence Time and Biological Rate Constants for ICRP 30 GI Tract Model Sections

Section of GI tract	Mean residence time (day)	Biological rate constant (day $^{-1}$)
Stomach	1/24	24
Small Intestine	4/24	6
Upper Large Intestine	13/24	1.8
Lower Large Intestine	24/24	1

According to table 8, the GI content (and subsequent radionuclides uniformly distributed therein) remains in the stomach for an average of 1 hour before translocating to the small intestine, where it remains for an average of 4 hours. The resulting number of nuclear transformations that occur in each of these compartments is provided in table A.2 of ICRP 30. These transformation numbers are based on the radionuclide decay constant, the biological rate constants (table 8), and the body fluids rate constant. As stated previously, the biological rate constants are independent of the radionuclides ingested and their physical or chemical form. They are based on the kinetics of the GI content and are applied to the radionuclides under the assumption of uniform distribution within the GI content.

The assumption of uniform distribution of radionuclides within the GI content and subsequent application of the ICRP 30 GI tract model needs careful consideration and justification when addressing the ingestion of DRPs. A single DRP traveling with intestinal content will exist in each GI tract compartment for a period of time before translocating to the next compartment. The location of the single DRP within the GI content of a given compartment is assumed to be completely random. In other words, rather than be uniformly distributed within the GI content, the DRP is assumed to be randomly located with the GI content of a compartment. Therefore, for the purposes of estimating the number of disintegrations in a given compartment, it is assumed that the translocation of the DRP between compartments will follow the same ICRP 30 kinetics as the GI content. This assumes that the DRP does not become immobilized within the GI tract (i.e., does not become lodged in the intestinal lining).

With the exception of fuel fragments, all DRPs are assumed to have zero translocation to the body fluids (f_1 = 0). The CEDE coefficients calculated here assume that the radioactivity moves with intestinal content, and nothing is transferred to body fluids (table 9). The CEDE coefficients published in Federal Guidance Report (FGR) No. 11, "Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion," issued 1988 (Eckerman et al. 1988), are based on the ICRP 30 GI tract model. These coefficients were developed assuming that there is nonzero translocation of radionuclides to the body fluids (f_1 greater than zero). There is some evidence that irradiated fuel fragments are partially soluble in the fluids of the stomach and small intestine (ICRP 2017, 2019) and will therefore follow the biokinetics that allow for translocation to the body fluids.

Ingestion CEDE coefficients with zero body fluid translocation were developed herein using IMBA version 5.0.1 (IMBA 2005). The IMBA code is a suite of software modules for internal dosimetry that implements respiratory tract, GI tract, tissue dosimetry, and biokinetic and bioassay models as recommended by the ICRP. IMBA implements the ICRP 30 GI tract model and gives the user the option to set f_1 to any value between zero and one (1).

Table 9 CEDE Coefficients for Ingested DRPs

CEDE Coefficient (Sv/Bq)	
Stellite (Z = 33; ρ = 8.4 g/cm^3)	
Co-60	1.8E-09
Inconel (Z = 29; ρ = 8.2 g/cm^3)	
Ni-59	2.9E-11
Ni-63	7.1E-11
NRC Concrete (Z = 10; ρ = 2.3 g/cm^3)	
Fe-55	2.4E-11
Co-60	1.8E-09
Ba-133	5.2E-10
Eu-152	1.2E-09
Eu-154	1.9E-09
Thoriated Welding Rod (Z = 74; ρ = 19 g/cm^3)	
Th-232	3.3E-09
Ra-228	2.2E-09
Ac-228	3.9E-10
Th-228	9.7E-09
Ra-224	1.8E-08

Fuel fragment CEDE coefficients (table 10, first column) were taken as the FGR 11 coefficient reported for the maximum (most limiting) f_1 value. While ICRP Publication 137, "Occupational Intakes of Radionuclides: Part 3," issued 2017 (ICRP 2017), and ICRP Publication 141, "Occupational Intakes of Radionuclides: Part 4," issued 2019 (ICRP 2019), provide CEDE coefficients for fuel fragments containing the radionuclides, they are based on the human alimentary tract model in ICRP Publication 100, "Human Alimentary Tract Model for Radiological Protection," issued 2006 (ICRP 2006), not the ICRP 30 GI tract model. Translocation of radionuclides into the body fluids in ICRP 100 is specified by the alimentary tract

transfer factor, f_A, instead of the f_1 value as given for the GI tract model described in ICRP 30. All IMBA CEDE coefficients were calculated using ICRP 26/30 tissue weighting factors.

The use of a nonzero f_1 value assumes that the ingested radionuclide is available for translocation to the body fluids at the specified rate. Given that this assumption may not be valid for a single DRP that has not completely disintegrated in the stomach and small intestine contents, CEDE coefficients were computed in IMBA for fuel fragments using 10 percent and 1 percent of the maximum f_1 value in FGR 11, denoted with $FGR_{0.1}$ and $FGR_{0.01}$, respectively. Coefficients were also calculated assuming zero translocation to the body fluids for fuel fragment radionuclides to provide a lower bound.

Table 10 CEDE Coefficients for Ingested Fuel Fragment DRPs

CEDE Coefficient (Sv/Bq)				
Fuel Fragment (Z = 88; ρ = 11 g/cm^3)				
	Varying f_1 values			
	FGR 11[a]	FGR $11_{0.1}$[b]	FGR $11_{0.01}$[c]	$f_1 = 0$[d]
Sr-90	3.9E-08	5.3E-09	2.2E-09	2.0E-09
Cs-137	1.4E-08	2.6E-09	1.4E-09	1.3E-09
Eu-154	2.6E-09	1.9E-09	1.9E-09	1.9E-09
Eu-155	4.1E-10	3.0E-10	3.0E-10	3.0E-10
Pu-238	8.7E-07	7.7E-08	1.2E-08	4.6E-09
Pu-239	9.6E-07	8.5E-08	1.3E-08	4.3E-09
Pu-240	9.6E-07	8.5E-08	1.3E-08	4.3E-09
Pu-241	1.9E-08	1.7E-09	1.8E-10	2.2E-11
Am-241	9.8E-07	7.7E-08	1.3E-08	4.8E-09
Cm-244	5.5E-07	4.8E-08	9.2E-09	4.8E-09

a. FGR 11 CEDE coefficient for highest listed f_1 value
b. IMBA CEDE coefficient using f_1 value equal to 10% of FGR 11 maximum f_1 value
c. IMBA CEDE coefficient using f_1 value equal to 1% of FGR 11 maximum f_1 value
d. IMBA CEDE coefficient using f_1 value equal to zero

CEDE from DRP Inhalation. The ICRP 30 respiratory tract model biokinetics are highly dependent on the inhaled aerosol activity median aerodynamic diameter (AMAD). The AMAD is based on the distribution of aerodynamic diameters of particles present in an aerosol. A DRP with a single physical diameter and corresponding aerodynamic diameter would not permit the determination of an AMAD, given that a distribution of sizes cannot be assumed for a single particle. This makes the application of the ICRP 30 respiratory tract model inappropriate if trying to determine a CEDE coefficient resulting from inhalation of a single DRP.

Upon inhalation of a DRP, it can be assumed that the particle is either swallowed and enters the GI tract (i.e., reaches the pharynx) or it resides in the anterior part of the nasal region until removed extrinsically. If it is assumed that the DRP is swallowed, the CEDE coefficients for ingestion (tables 9 and 10) should be used. If the DRP is assumed to stay in the anterior part of the nasal region until removed extrinsically, the EDE coefficients (table 7) should be used. CEDE coefficients are not provided for DRP inhalation because the size of a DRP (10 to 1,000 μm) is too large to move deeper into the respiratory tract.

Utility of the DRP Dose Coefficients

The dose coefficients provided herein can be used for both retrospective and prospective dosimetric studies. A retrospective study is one in which a particular person has come into contact with a DRP of known activity (i.e., an estimate of a past or current event). The study can be quite specific because such personal attributes as DRP characteristics, intake routes, and exposure conditions are known or can be estimated with confidence. The dose estimates for a retrospective study are considered to be made with reasonable accuracy.

A prospective study, however, is one in which no information is known about the exposed person or any exposure conditions (i.e., it is a prediction of a possible future event). In this case, the dose estimate is uncertain and merely an assessment of what could occur. Many times, prospective dose assessments are conducted with very conservative exposure assumptions to maximize a dose estimate or to compare a potential radiation dose with a regulatory limit.

The dose coefficients herein provide a means for approximating dose to an individual exposed to a radiation source of estimated activity for an estimated exposure time. If multiple nuclides are present in a given DRP, the dose from each nuclide must be summed to obtain a total dose. For the most part, the DRP dose coefficients are given in units of dose rate per unit activity intake (sievert (Sv)/becquerel (Bq)-hour (h)). The CEDE dose coefficients, however, are provided in units of dose per unit intake (Sv/Bq) because their exposure or residence time is determined by the kinetic model describing the movement of intestinal content.

To assess, for example, the potential skin dose from a DRP contamination event, the assumptions of exposure conditions might be that a 50 kilo (k)Bq Co-60 DRP source, with a spherical diameter of 200 µm, remains on the skin surface for 24 hours. In this case, the dose coefficient of 2.2×10^{-8} Sv Bq^{-1} h^{-1} is obtained from Table 3 and a dose to the shallow layer of skin (SDE) is determined from

$$SDE = A \cdot t \cdot DC$$

where A = activity [Bq];
t = exposure time [h]; and
DC = SDE dose coefficient [Sv Bq^{-1} h^{-1}].

The SDE in this example is, therefore,

$$SDE = 5x10^{4}\ [Bq] \cdot 24\ [h] \cdot 2.2x10^{-8}[Sv\ Bq^{-1}\ h^{-1}] = 0.026\ [Sv].$$

The total skin dose in this case is directly proportional to source activity and to exposure time (i.e., doubling exposure time results in twice the dose). Dose to other localized tissues can be determined with similar methods.

Alternative uses of the dose coefficients would allow the analyst to estimate an activity threshold, given a particular exposure time, resulting in a target dose. For example, if it is assumed that a 500 µm diameter DRP of concrete with barium (Ba)-133 remains lodged in the large intestine for 2 weeks (336 hours), the activity necessary for a dosimetric threshold of an assumed 25 Gy (or 25 Sv) to be exceeded can be

estimated. Table 6 provides a dose coefficient of $2.6x10^{-8}$ Sv Bq^{-1} h^{-1}; therefore, the threshold activity (A) is calculated from

$$A = \frac{D_T}{DC \cdot t}$$

where D_T = recommended ulceration threshold dose [Sv];
t = exposure time [h]; and
DC = dose coefficient for a stationary particle in the large intestine [Sv Bq^{-1} h^{-1}].

The ulceration threshold activity for a 336-hour exposure in the large intestine is, therefore,

$$A = \frac{25\ [Sv]}{2.6x10^{-8}\ [Sv\ Bq^{-1}\ h^{-1}] \cdot 336\ [h]} = 2.9\ MBq.$$

And, with this same scenario, if the activity were 100 megabecquerels (MBq), the exposure time necessary to exceed the same threshold can be estimated. That calculation is executed by rearranging the above equation and solving for time (t), whereby,

$$t = \frac{D_T}{DC \cdot A}$$

and

$$t = \frac{25\ [Sv]}{2.6x10^{-8}\ [Sv\ Bq^{-1}\ h^{-1}] \cdot 1x10^{8}\ [Bq]} = 10\ h.$$

The specific activity of potential DRPs will dictate the maximum activity present in a given sized particle. For example, if iron (Fe)-55 in a concrete DRP (ρ = 2.3 g cm^{-3}) of 500 µm (0.05 cm) diameter (0.025 cm radius) has an expected specific activity of 4.7 µCi g^{-1} ($1.7x10^5$ Bq g^{-1}), the total activity (A) in the DRP would be

$$A = SA \cdot \rho \cdot \frac{4}{3}\pi \cdot r^3$$

where SA = specific activity [Bq g^{-1}];
ρ = DRP density [g cm^{-3}]; and
R = DRP physical radius [cm].

The total activity in the DRP is, therefore,

$$A = 1.7x10^5\ [Bq\ g^{-1}] \cdot 2.3[g\ cm^{-3}] \cdot \frac{4}{3}\pi(0.025\ [cm])^3 = 26\ Bq.$$

Calculations similar to the examples above can be instrumental in determining the likelihood of dose thresholds being exceeded if an individual were exposed to a DRP.

Summary

The dose coefficients presented support the NRC's continued evaluation of its regulatory framework for DRPs in the environment at decommissioning nuclear power plants. The exposure scenarios considered for DRP dose coefficients include particles stationary on the skin surface, in the URT, and in the GI tract. As a conservative approach, DRPs are assumed to be stuck in their respective locations, but an ingested particle may also travel with the intestinal content (for the calculation of CEDE).

SDEs for particles on the skin were calculated using the SkinDose module in VARSKIN+ v1.1 (Hamby et al. 2021). To be consistent with NRC regulations, the SDE was estimated to an infinitely thin 10 cm^2 disk at a depth of 7 mg/cm^2 (70 µm) in unit-density tissue. Calculations of local DE for particles on the inner walls of the URT and the GI tract were also conducted using the SkinDose module. The DE was estimated to an infinitely thin 1 cm^2 disk to mimic the approximate maximum size of an ulcer consistent with a recommended dose threshold of 25 Gy (Benke et al. 2022). The depths for dose calculations are 45 µm for extrathoracic surfaces in the URT, 140 µm for the small intestine, and 290 µm for the large intestine.

MCNP6, coupled with PiMAL, was used to estimate beta (electrons) and gamma (photons) EDE resulting from electron and photon emissions from radionuclides at stationary locations on the skin surface, in the URT, and in the small and large intestines. These evaluations were conducted at various locations to determine the maximum EDE from a DRP in each of the three regions (i.e., skin surface, GI tract, and URT).

CEDEs following the ingestion of DRPs were calculated using the IMBA code. The CEDE coefficients were independent of DRP size and were assumed to follow the ICRP GI tract model (ICRP, 1979). All IMBA CEDE coefficients used ICRP 26/30 tissue weighting factors.

The dose coefficients provided herein can be used for both retrospective and prospective dosimetric studies. The dose estimates for a retrospective study are considered to be made with reasonable accuracy in that exposure times are usually known within some confidence level. Exposure times for prospective studies, however, are uncertain, and dose estimates merely assess what could occur for assumed exposure conditions. Many times, prospective dose assessments are conducted with very conservative exposure assumptions to maximize a dose estimate or to compare a potential radiation dose with a regulatory limit.

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