Fuel Radiotoxicity and Screening Analysis

NWMO-TR-2021-16 Sept 2021

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NWMO

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ABSTRACT

Title: **Fuel Radiotoxicity and Screening Analysis**
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Abstract
The NWMO is responsible for the safe long-term containment and isolation of used nuclear fuel. This will be accomplished in part through placing the used fuel in a deep geologic repository. Used nuclear fuel contains hundreds of different radionuclides arising from fission, neutron activation and decay processes. The used fuel also contains many chemical elements, also as a result of these processes.

As part of the repository safety assessment, the risk due to these radionuclides and chemical elements is assessed. However, there is huge range in both the concentration and in the hazard of each of these various species (radionuclides or chemical elements). Many of these species are of no concern due to their low concentration and low intrinsic hazard. In this screening assessment, those species that are potentially important are identified for more detailed safety assessment.

This report describes the fuel radioactivity and radiotoxicity considering the full suite of species present in the fuel. This report also documents the data, methodology and results of the screening assessment used to identify key species for consideration in detailed safety assessments.

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1. INTRODUCTION

The NWMO is responsible for the safe long-term containment and isolation of used nuclear fuel. This will be accomplished in part through placing the used fuel in a deep geologic repository. Used nuclear fuel stored in the repository will contain hundreds of different isotopes arising from fission, neutron activation and decay processes. However, there is huge range in both the concentration and in the hazard of each of these various species (radionuclides or chemical elements).

The purpose of this report is three-fold.

1. Document supporting data for all isotopes present in the fuel (e.g., inventories, half-lives, dose-conversion factors, hazard criteria) and used for analysis in this report. Section 2 and Appendix A of this report detail this information.
2. Present, at a high level, the hazard to humans associated with the used fuel considering all species in the fuel. Section 3 of the report documents this hazard assessment.
3. Document a screening assessment used to identify key species for more detailed assessment in future safety analyses. Section 4 of this report documents the screening assessment.

2. SUPPORTING DATA

This section details the information (inventories, half-lives, dose conversion factors, and interim hazard criteria) for all species present in the fuel and used in the analyses presented in this report. This section will describe the source of the data and any assumptions made. Tabular data are presented in Appendix A.

2.1 Fuel Inventory

Inventories of species in used CANDU fuel bundles (fuel and Zircaloy) were calculated using the ORIGEN-S version SCALE 4.2 code (ORNL 2011) as reported in Heckman and Edward (2020). Heckman and Edward (2020) presents inventory data for a variety of CANDU bundle types, burnups and maximum power ratings for a number of times after discharge from a reactor. In total, inventory data for 586 isotopes (of which 328 are radionuclides) and 99 elements are listed.

Section 7.3 of Heckman and Edward (2020) describes the process by which a reference bundle is selected. In general, only small differences in isotope inventories (<5% change in inventory per kg U) were observed between the various CANDU bundle types. Due to projected abundance in the repository, the 37R bundle was selected as representative of the overall inventory of fuel in the repository.

Heckman and Edward (2020) notes that differences in isotope inventories were observed for bundles with different irradiation histories. Generally, isotope inventories changed linearly with bundle burnup, and non-linearly (less sensitive) with bundle power. However, no single trend for all radionuclides was observed with respect to the relation between bundle burnup, power and isotope inventory. Heckman and Edward (2020) concludes that a 37R bundle with a power of 720 kW (highest median bundle power in a decade of operation of the Canadian reactor fleet) and burnups of 220 MWh/kgU (highest median bundle burnup in any decade of operation) and 290 MWh/kgU (highest 95th percentile burnup observed in any decade of operation) are reasonable reference bundles.

For this report, four bundles are considered. The two reference bundles identified in Heckman and Edward (2020) and two bounding bundles with significantly higher and lower burnups and powers for which there is data in Heckman and Edward (2020). The bulk of the analysis in the report will consider only the reference bundles; however the bounding bundles will be used to show the range in fuel activity and radiotoxicity in Section 3. The four bundles are:

- Lower Bound - 37R bundle with burnup of 130 MWh/kgU and maximum power of 720 kW;
- Reference 1 - 37R bundle with burnup of 220 MWh/kgU and maximum power of 720 kW;
- Reference 2 - 37R bundle with burnup of 290 MWh/kgU and maximum power of 720 kW; and
- Upper Bound – 37R bundle with burnup of 710 MWh/kgU and maximum power of 900 kW.

Heckman and Edward (2020) determine the inventory of isotopes in the fuel and Zircaloy. However, another potential source of radionuclides in the fuel are surface deposits. These are corrosion products formed within the primary coolant circuit of a reactor which can deposit on the surfaces of the fuel bundles in the reactor core. Neutron activation of these corrosion products can generate radioactive isotopes. In addition, fission products and UO_2 fuel particulates released from defective fuel bundles can also deposit on the surfaces of fuel bundles.

Radionuclide inventories potentially increased by surface deposits include: Am-241, Am-242m, Am-243, C-14, Cm-243, Cm-244 Co-60, Cs-134, Cs-137, Fe-55, Ni-59, Ni-63, Sr-90, Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, U-234 and U-238. However, the inventory increases of these species due to surface deposits was estimated to be quite small (1.3% for Fe-55, 0.7% for Ni-59, 0.5% for C-14 and <<1% for other species) relative to the inventory in the fuel and zircaloy. Consequently, contributions to the inventory from surface deposits are ignored for the purposes of this report.

Section A.1 lists the inventories in the fuel and Zircaloy for the two reference bundles and a variety of times after discharge. The UO_2 fuel inventories are given in mol/(kg initial U) and the inventories in the Zircaloy are given in units of mol/(kg initial Zircaloy). The mass of U in a 37R fuel bundle (19.25 kg) and the mass of Zircaloy in a fuel bundle (2.2 kg) are required to calculate the total radionuclide inventories in a fuel bundle.

2.2 Decay Chains and Half-lives

The decay chains for radionuclides with half-lives greater than 1 day are provided in Table 19 in Section A.2. Progeny with half-lives less than 1 day are also shown in the table since they would contribute to the exposure dose of the parent. The half-life data in Table 19 are from Heckman and Edward (2020) which are from the libraries used with the SCALE 6.1.3 version of the ORIGEN-S code and are based on the ENDF/B-VII.1 decay data (Chadwick et al 2011). The branching ratios shown in the decay schemes are from ICRP (2008a) and IAEA (2021).

2.3 Dose Conversion Factors

Human dose conversion factor data are taken from ICRP publication 119 (ICRP 2012) for inhalation and ingestion and ICRP publication 144 (ICRP 2019) for water immersion, air immersion and groundshine. Human dose conversion factors data are shown in Section A.3, specifically Table 20. Dose conversion factors for humans are for an adult as defined in ICRP publication 23 (ICRP 1974).

Human dose conversion factor data presented in this report are for nuclear waste management applications. As such, short lived radionuclides initially present in the fuel (i.e., those with half-lives less than 1 day) are not typically of consequence. Doses from short-lived daughters of longer-lived parents are implicitly accounted for in the dose rate calculations. Specifically, short-lived daughters are assumed to be in secular equilibrium with their precursors and their contributions to the dose rate to humans are accounted for through their precursors dose conversion factor. For both internal and external exposure, the dose coefficients of the short-lived radionuclides are added to those of the parents to derive “effective dose coefficients” for the chain parent radionuclides. The decay chains shown in Table 19 identify the short-lived daughters. Table 21 shows the contribution to the parent dose conversion factor as a result of the short-lived daughters.

Non-human dose conversion factor data are taken from ICRP publication 136 (ICRP 2017). Section 2.3.6 describes the non-human dose coefficient data and assumptions. The resulting non-human dose conversion factors used in this assessment are shown in Table 22.

2.3.1 Inhalation Dose Conversion Factors

Inhalation dose conversion factor data is taken from ICRP publication 119 (ICRP 2012) and applicable to adult members of the public. Inhalation dose conversion factors depend on several factors including the chemical form of the radionuclide (e.g., particulate, gas, vapour), the solubility of particulate materials deposited in the respiratory tract and lung clearance types. For the purposes of this report the largest of the inhalation dose conversion factors considering all the factors discussed above are used. For most species this is the inhalation dose coefficient associated with inhalation of particulates.

ICRP 119 does not include inhalation dose conversion factors for noble gases (e.g., Ar, Kr, and Xe). However, ICRP 119 does provide combined dose coefficients for immersion in air and inhalation in (Sv/hr)/(Bq/m3). Consequently the inhalation dose coefficients for inert gases are assumed to be zero and the combined air immersion and inhalation is assessed via the air immersion dose coefficient (see Section 2.3.4).

Inhalation dose conversion factors for 733 radionuclides are included in ICRP 119. Of the 328 radionuclides identified in Heckman and Edward (2020), 49 do not have inhalation dose coefficients in ICRP 119. Of these 49 species, 29 are short-lived daughters and 4 are parents with short-lived daughters. These radionuclides are all assumed to have an inhalation dose coefficient equal to their chain member identified in Table 19 with the highest inhalation dose conversion factor for which there is a value in ICRP 119. For example, Rn-222 and several of its daughters do not have inhalation dose conversion factors in ICRP 119. Any Rn-222 chain members missing inhalation dose conversion factors are assigned values equal to Pb-214, the Rn-222 daughter with the highest inhalation dose conversion factor in ICRP 119.

The remaining 16 radionuclides missing inhalation dose coefficients are Ag-109m, Bi-208, Dy-154, Es-252, Gd-150, Ge-73m, Ho-163, Nb-91, Nb-91m, Nb-92, Po-208, Po-209, Re-183, Sc-45m, Tm-168, and Y-89m. Of these, Dy-154, Es-252, Po-208 and Po-209 are alpha emitters and are assumed to have an inhalation dose coefficient equal to that of Ac-227 (the species with the largest inhalation dose coefficient excluding species that undergo spontaneous fission). The remaining species do not decay via alpha emission and are assumed to have an inhalation dose conversion factor equal to Ra-228 (the species with the largest inhalation dose coefficient excluding species that decay via alpha emission or undergo spontaneous fission). These assumptions are adequate for the purposes of this screening assessment report. If it is found that the air inhalation dose rate from any of these radionuclides is relatively large then additional effort to calculate a more accurate value of the air inhalation dose coefficient could be warranted.

Short-lived daughters with half-lives less than one day are not explicitly accounted for in the analysis presented in this report. Instead, they are accounted for by adding their air inhalation dose coefficient (or a fraction thereof, depending on the decay scheme in Table 19) to that of the parent radionuclide to derive an effective air inhalation dose coefficient for the parent nuclide. This approach assumes that the short-lived daughters (present in air) are in secular equilibrium with their parents and that the daughters and parents are inhaled at the same time.

Proposed inhalation dose conversion factors are presented in Table 20. The contributions from short lived daughters are shown in Table 21. The species with the largest contribution from short-lived daughters was Rn-222 whose inhalation dose conversion factor was increased by a factor of 11 due to the contribution of its many short-lived daughters.

2.3.2 Ingestion Dose Conversion Factors

Ingestion dose conversion factor data is taken from ICRP publication 119 (ICRP 2012) and applicable to adult members of the public. Ingestion dose conversion factors depend on several factors including the chemical form of the radionuclide and the fractional adsorption of an ingested radionuclide from the gastrointestinal tract to blood. For most elements in ICRP 119, a single fraction adsorption factor is assumed for all chemical forms of a given radionuclide. For the purposes of this screening assessment report the largest of the ingestion dose conversion factors is used.

ICRP 119 does not include ingestion dose conversion factors for noble gases (e.g., Ar, Kr, and Xe). However, these dose coefficients can be assumed to be zero because noble gases are not typically ingested in appreciable quantities, are non-reactive and are not retained by the body (NCRP 1996).

As with the inhalation dose conversion factors, the same 49 species do not have ingestion dose conversion factors. A similar approach is adopted for the ingestion dose coefficients in which members of decay chains are assumed to have ingestion dose conversion factors equal to the chain member identified in Table 19 with the highest ingestion dose conversion factor for which there is a value in ICRP 119. The 4 alpha emitting radionuclides (Dy-154, Es-252, Po-208, Po-209,) are assumed to have an ingestion dose coefficient equal to that of Po-210 (the species having the largest ingestion dose coefficient excluding those that undergo spontaneous fission). The remaining non-alpha emitting radionuclides (Ag-109m, Bi-208, Gd-150, Ge-73m, Ho-163, Nb-91, Nb-91m, Nb-92, Re-183, Sc-45m, Tm-168, and Y-89m) are assumed to have an ingestion dose coefficient equal to Fe-60 (the species with the largest ingestion dose coefficient excluding species that decay via alpha emission or undergo spontaneous fission). These assumptions are adequate for the purposes of this report. If it is found that the ingestion dose rate from any of these radionuclides is relatively large, then additional effort to calculate a more accurate value of the ingestion dose coefficient could be warranted.

Short-lived daughters with half-lives less than one day are not explicitly accounted for in the analysis presented in this report. Instead, they are accounted for by adding their ingestion dose coefficient (or a fraction thereof, depending on the decay scheme in Table 19) to that of the parent radionuclide to derive an effective ingestion dose coefficient for the parent nuclide. This approach assumes that the short-lived daughters are in secular equilibrium with their parents and that the daughters and parents are ingested at the same time.

Ingestion dose conversion factors are presented in Table 20. The contribution from short lived daughters are shown in Table 21. The species with the largest contribution from short-lived daughters was Rn-222 whose ingestion dose conversion factor was increased by a factor of 11 due to the contribution of its many short-lived daughters.

2.3.3 Water Immersion Dose Conversion Factors

Water immersion dose conversion factors for adult members of the public are taken from ICRP publication 144 (ICRP 2019). ICRP 144 calculates water immersion dose conversion factors assuming an infinite source geometry with an individual completely immersed and place at the centre of a sphere of water with a radius of 2m.

ICRP 144 provides dose conversion factors for 1252 radionuclides, and of the 328 radionuclides included in Heckman and Edward (2020), 4 do not have water immersion dose conversion factors. These species are Bk-248, Es-252, Ge-73m, and Sc-45m. Bk-248 is a member of a decay chain and is assumed to have a water immersion dose coefficient equal to the dose coefficient of its short-lived daughter Am-244. The remaining three species are assumed to have water immersion dose coefficients equal to that of N-16 (the species having the largest water immersion dose coefficient excluding species that undergo spontaneous fission).

Water immersion dose conversion factors are presented in Table 20. The contribution from short lived daughters is shown in Table 21. There are several species in which the water immersion dose conversion factors are dominated by the contribution from the short-lived daughters. For example, the water immersion dose conversion factors for Ge-68, Ra-228, Rn-222, and Ru-106 are all over 1000 times higher when considering the contribution from short-lived daughters. The species with the largest contribution from short-lived daughters was Ru-106 whose water immersion dose conversion factor was increased by a factor of 7.6×10^{6} due to the contribution of Rh-106. Both Ru-106 and Rh-106 decay via beta emission however the decay of Rh-106 is roughly 90 times more energetic than that of Ru-106 (IAEA, 2021).

2.3.4 Air Immersion Dose Conversion Factors

Air immersion dose conversion factors for adult members of the public are taken from ICRP publication 144 (ICRP 2019). Air immersion dose conversion factors in ICRP 144 are calculated assuming the contaminated air is homogeneous in air activity concentration (i.e., well-mixed air) above a smooth air-ground interface.

The air immersion dose conversion factors for inert gases (e.g., Ar, Kr, Xe) are assumed to be equal to the combined air immersion and inhalation dose conversion factors recommended in ICRP 119. Air immersion dose conversion factors in ICRP 144 were compared with combined air immersion and inhalation dose conversion factors in ICRP 119. As one would expect, the ICRP 119 dose conversion factors were found to be higher in all cases. Increases in dose conversion factors ranged from 1 to 1.3 times the dose conversion factors from ICRP 144 except for Kr-81 which was roughly 6.5 times higher in ICRP 119.

As with the water immersion dose conversion factors, 4 radionuclides included in Heckman and Edward (2020) do not to have air immersion dose conversion factors in ICRP 144. These species are Bk-248, Es-252, Ge-73m, and Sc-45m. Bk-248 is a member of a decay chain and is assumed to have an air immersion dose coefficient equal to its short-lived daughter Am-244. The remaining three species are assumed to have an air immersion dose conversion factor equal to that of N-16 (the species having the largest air immersion dose coefficient excluding species that undergo spontaneous fission).

Air immersion dose conversion factors are presented in Table 20. The contribution from short lived daughters are shown in Table 21. Similar to the water immersion dose conversion factors, select air immersion dose conversion factors are dominated by the contribution from the short-lived daughters. For example, the water immersion dose conversion factors for Ge-68, Ra-228, Rn-222, and Ru-106 are all over 1000 times higher when considering the contribution from short-lived daughters. The species with the largest contribution from short-lived daughters was Ru-106 whose air immersion dose conversion factor was increased by a factor of 5.1×10^6 due to the contribution of Rh-106. As with the water immersion dose coefficient this is likely due to the more energetic decay of Rh-106 as compared to Ru-106.

2.3.5 Groundshine Dose Conversion Factors

Groundshine dose conversion factors for adult members of the public are taken from ICRP publication 144 (ICRP 2019). Groundshine dose conversion factors in ICRP 144 are calculated assuming planar surfaces at various depth. For this report, groundshine dose coefficients for a planar source at the soil surface are used.

As with the water immersion dose conversion factors, 4 radionuclides included in Heckman and Edward (2020) do not to have groundshine dose conversion factors in ICRP 144. These species are Bk-248, Es-252, Ge-73m, and Sc-45m. Bk-248 is a member of a decay chain and is assumed to have a groundshine dose coefficient of equal to its short-lived daughter Am-244. The remaining three species are assumed to have groundshine dose coefficients equal to that of Mn-50m (the species having the largest groundshine dose coefficient excluding species that undergo spontaneous fission).

Groundshine dose conversion factors are presented in Table 20. The contribution from short lived daughters are shown in Table 21. Similar to the water immersion dose conversion factors, select groundshine dose conversion factors are dominated by the contribution from the short-lived daughters. For example, the water immersion dose conversion factors for Ge-68, Ra-228, Rn-222, and Ru-106 are all over 1000 times higher when considering the contribution from short-lived daughters. The species with the largest contribution from short-lived daughters was Ru-106 whose groundshine dose conversion factor was increased by a factor of 3.5×10^6 due to the contribution of Rh-106. As with the water and air immersion dose coefficient this is likely due to the more energetic decay of Rh-106 as compared to Ru-106.

2.3.6 Non-Human Biota Dose Conversion Factors

Non-human dose conversion factors are taken from ICRP publication 136 (ICRP 2017). ICRP 136 contains dose coefficients for a variety of non-human biota (bee, wild grass, earthworm, frog, rat, duck, deer, pine tree, brown seaweed, crab, trout and flatfish) and for a variety of exposure pathways (internal, water immersion, soil immersion, on ground, above ground, and air immersion). ICRP publication 136 derives dose conversion factor data using the online BiotaDC software tool which uses the latest radiation emission dataset from ICRP publication 107 (ICRP 2008a). This tool represents an improvement over the dose conversion factors derived in ICRP publication 108 (ICRP 2008b) using the ERICA tool (Brown et al. 2008).

ICRP 136 internal dose conversion factors are derived assuming uniform distribution of radioactivity in a homogeneous “skeleton-less” body. Internal dose coefficients in ICRP 136 do not include inhalation as this would require organism specific biokinetic data and models. External immersion dose conversion factors are derived assuming immersion in an infinite water, soil or air source. The on soil and above soil dose conversion factors consider exposure to an infinite planer soil source. As compared to ICRP 108 the ICRP 136 methodology for assessment of external exposure dose conversion factors for terrestrial animals and plants has been systematically expanded and improved upon.

The ICRP 136 includes pre-derived dose conversion factors for each of the 12 biota and 6 exposure pathways listed above for a set of 75 radionuclides (the same 75 radionuclides included in ICRP 108). Internal dose conversion factors are presented in units of (µGy/hr)/(Bq/kg) and external dose conversion factors for water, soil and air are presented in units of (µGy/hr)/(Bq/L), (µGy/hr)/(Bq/kg), and (µGy/hr)/(Bq/m^3) respectively.

The set of radionuclides for which pre-derived dose conversion factors are available is relatively limited when compared to the 328 radionuclides included in Heckman and Edward (2020). The online BiotaDC tool contains additional radionuclide specific data and could be used to derive additional dose conversion factors however significant effort and expertise would be required to generate additional non-human biota dose conversion factors. For the purposes of this report only the pre-derived non-human dose conversion factors will be considered as many key radionuclides relevant to nuclear waste management application are included in the set of 75 radionuclides (e.g., I-129, C-14, Cs-135, Se-79 as well as the 4N, 4N+1, 4N+2 and 4N+3 actinide chains).

Generally, it was found that dose conversion factors across biota are of the same order of magnitude. For the purposes of this screening assessment the maximum dose conversion factor across all biota for each radionuclide will be used rather than asses each biota individually. Table 22 lists the non-human biota dose conversion factors used in this report. Note that the dose conversion factors in ICRP 136 account for the contribution from short lived daughters in the pre-derived dose conversion factors. For example, the Zr-95 dose conversion factors includes a contribution from Nb-95 and Nb-95m.

2.4 Chemical Hazard Criteria

Used CANDU fuel contains many chemical elements, due in part to the fission process. As with the radionuclides, a screening analysis is completed here to identify the important chemical elements for detailed hazard analysis.

The analysis considers all 99 elements up to and including Einsteinium. However, the following element are then excluded from the chemical hazard screening assessment for the reasons noted:

- Common or essential elements (C, H, N, O, Si) – These elements are essential to life or naturally abundant and therefore not considered to be chemically hazardous.
- Inert gases (Ar, He, Kr, Ne, Og, Rn, Xe) – Noble gases do not react chemically and are therefore not considered to be chemically hazardous.
- Actinide Elements (Ac, Am, Bk, Cf, Cm, Es, Fm, Lr, Md, No, Np, Pa, Pu, Th) – All isotopes of each of these elements are radioactive and it is assumed that toxicity is

sufficiently addressed through radiotoxicity. The notable exception is U which is a special actinide for which the chemical toxicity is significant.

- Transactinide elements (Bh, Cn, Db, Ds, Fl, Hs, Lv, Mt, Nh, Rf, Rg, Sg) – These elements are man-made and exist for less than a second.
- Radioactive Elements (At, Fr, Nh, Ra, Rn, Tc) – These elements only exist as radioactive isotopes occurring as a decay product of heavier elements. The hazard of these elements is sufficiently addressed through radiotoxicity.

The chemical hazard screening methodology used in the analysis is described in Section 4.3 and involves comparison against environmental criteria below which elements are not considered harmful to humans and non-human biota. Section A.4, specifically Table 23, provides the hazard criteria. Criteria for the remaining elements were developed following CNSC REGDOC-2.11.1 (Vol III) (CNSC 2021) guidance, using the suggested hierarchy of reference guidelines. Recommended guideline references of the CSA N288.6-12 (CSA 2012) are considered as well.

The references are divided into three tiers, as follows:

1. Primary References
   According to the CNSC REGDOC-2.11.1 (Vol III), the Canadian Council of Ministers of the Environment (CCME) guidelines should be the reference with the top priority. As such, CCME (2021a, 2021b, 2021c, and 2021d) are the primary references and constitute the suite of guidelines offered by the CCME (i.e., Water Quality Guidelines for the Protection of Aquatic Life, Water Quality Guidelines for the Protection of Agriculture, Soil Quality Guidelines for the Protection of Environmental and Human Health, and Sediment Quality Guidelines for the Protection of Aquatic Life.

2. Secondary References
   According to CNSC REGDOC-2.11.1 (Vol III), the federal and provincial guidelines and standards are of secondary priority. Health Canada (2020), GOC (2012a), Ontario (2003), OMECP (2020), MOE (2011), Ontario (2019), MOEE (1993), and MOEE (1994) were secondary references used in the compilation of criteria for this report. At the time of publication of this report, both potential repository sites in the site selection process are in Ontario. As such, the provincial references are from Ontario.

3. Tertiary References
   According to CNSC REGDOC-2.11.1 (Vol III), in the absence of CCME guidelines and provincial/territory guidelines, guidelines and standards from other jurisdictions or criteria derived using toxicity data may be used. Efroymson et al. (1997a, 1997b), EMI SIG (2018), GOA (2018), GOC (2012b), ODEQ (1998), Sample et al. (1996), Sneller et al. (2000), SNRL (2005), Suter and Tsoa (1996), TCEQ (2016), Thompson et al. (2005) and Fernandes (2019) were tertiary references used in development of environmental criteria for this report.

Despite efforts to identify environmental criteria from guidelines for all elements in all media, a number of elements do not have criteria for select media. For these species, criteria were derived from other media using methodology recommended in Fernandes (2019) (i.e., using surface water criteria as a basis for groundwater criteria), by assuming equivalency between soil and sediment criteria or by assuming criteria equal other chemically analogous elements with criteria. For example, several rare earth elements were assumed to have criteria equal to those available for Nd. Derived criteria or criteria from analogous elements are highlighted in Table 23.

3. FUEL ACTIVITY AND RADIOTOXICITY

In this section of the report the fuel activity and radiotoxicity are presented considering the full suite of radionuclides present in the fuel for Heckman and Edward (2020). Radionuclides in the fuel and Zircaloy have been categorized into actinides, fission products, activated light elements and Zircaloy.

The actinides are the collection of actinides and actinide daughters (e.g. U, Th, Pu). Fission products are species produced in the fuel as a result of fission. Activated elements are species present in the used fuel resulting from neutron activation of impurities in the fuel. Zircaloy is the collection of actinides, fission products and activated elements present in the fuel cladding.

3.1 FUEL ACTIVITY

Fuel activity is the fuel total radioactivity and is described using the SI unit becquerel (Bq). A becquerel is defined as the activity of a quantity of a radioactive material in which one atom is transformed per second. While total activity is not a direct indicator of hazard, it can be useful to understand how the overall hazard associated with used fuel will evolve with time. Figure 1 shows the total fuel activity in Bq/bundle for the two reference bundles (37R bundle with burnup of 220 or 290 MWh/kgU and maximum power of 720kW) and the two bounding bundles (37R bundle with a burnup of 130 or 710 MWh/kgU). The total activity for the four bundles are similar with the maximum difference between the bounding bundles being a factor of 4.7 and the maximum differences between the two reference bundles being a factor of 1.3. Differences in the bundle activities decrease with time and the activity for all four bundles is within 5% at 10^7 years. Activity data is taken from Heckman and Edward (2020).

Figure 2 shows the contribution of the actinides, fission products, activated light elements and zircaloy in the 220 MWh/kgU burnup bundle. For the first 100 years after discharge from the reactor the fuel activity is controlled by shorter lived fission products, specifically Cs-137. Following that time, the fuel activity is controlled by the actinides, specifically, Am-241 until about 500 years after discharge at which point Pu-240 and Pu-239 are dominant until about 100,000 years into the future. Beyond 100,000 years the fuel activity is controlled by the U-238 daughters Po-210, Bi-210, and Pb-210. The activated light elements and zircaloy were not found to significantly contribute to the fuel activity.

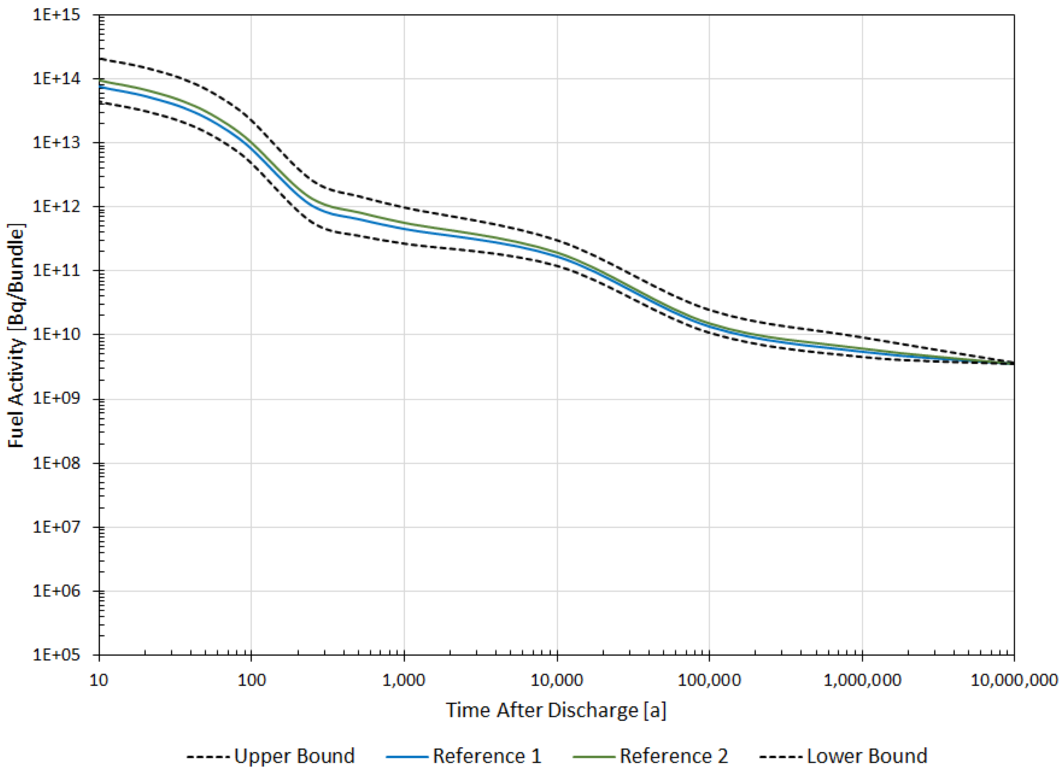

Figure 1: Range of Total Fuel Activity for a 37R Bundle

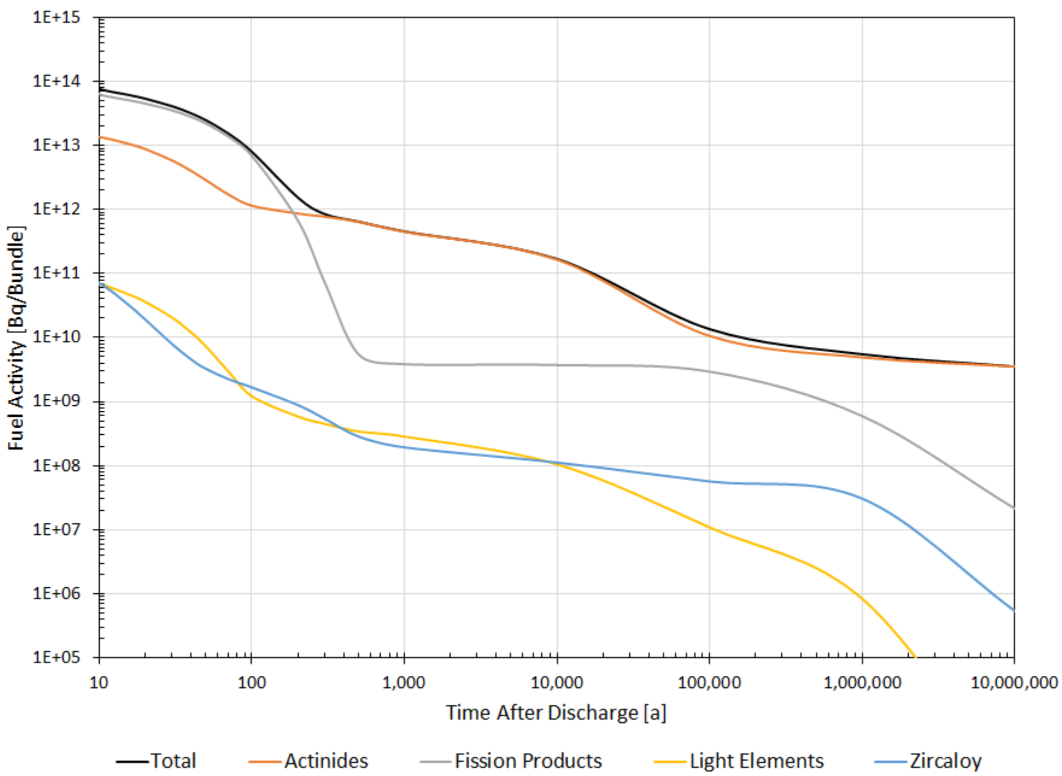

Figure 2: Breakdown of Total Activity for the 220 MWh/kgU 37R (Reference 1) Bundle

3.2 FUEL RADIOTOXICITY

Radiotoxicity is an indicator of potential hazard associated with exposure to the used fuel that takes into consideration the hazard characteristics of each radionuclide. These are dependent in part on the exposure pathway.

Table 1 identifies the key radionuclides contributing >10% of the total radiotoxicity to humans at various times for the Reference 1 bundle. Figure 3, Figure 5, Figure 7, Figure 9 and Figure 11 present the total radiotoxicity due to inhalation, ingestion, water immersion, air immersion and groundshine for the four bundles described in Section 2.1. Figure 4, Figure 6, Figure 8, Figure 10, and Figure 12 show the contribution to the total radiotoxicity due to the fuel actinides, fission products, activated light elements and zircaloy for the Reference 1 bundle. Note that all radiotoxicity plots are presented normalized to the Reference 1 (220 MWh/kgU burnup) bundle maximum radiotoxicity.

Table 1: Radionuclides Contributing >10% of Total Radiotoxicity

<table>
<tr><th>Time [a]</th><th>Inhalation</th><th>Ingestion</th><th>Water Immersion</th><th>Air Immersion</th><th>Groundshine</th></tr>
<tr><td>Discharge</td><td>Ag-109m</td><td>Ag-109m, Np-239</td><td>Nb-95, Np-239, Ru-103, Zr-95</td><td>Nb-95, Np-239, Ru-103, Zr-95</td><td>Nb-95, Np-239, Zr-95</td></tr>
<tr><td>5</td><td rowspan="4">Am-241, Pu-239, Pu-240, Pu-241</td><td rowspan="4">Cs-137, Sr-90</td><td>Cs-134, Cs-137</td><td>Cs-134, Cs-137</td><td>Cs-134, Cs-137, Ru-106</td></tr>
<tr><td>10</td><td rowspan="9">Cs-137</td><td rowspan="9">Cs-137</td><td rowspan="9">Cs-137, Y-90</td></tr>
<tr><td>15</td></tr>
<tr><td>20</td></tr>
<tr><td>30</td><td rowspan="9">Am-241, Pu-239, Pu-240</td><td rowspan="2">Am-241, Cs-137, Sr-90</td></tr>
<tr><td>40</td></tr>
<tr><td>50</td><td>Am-241, Cs-137, Sr-90, Pu-239</td></tr>
<tr><td>70</td><td rowspan="2">Am-241, Cs-137, Pu-239, Pu-240, Sr-90</td></tr>
<tr><td>100</td></tr>
<tr><td>200</td><td rowspan="4">Am-241, Pu-239, Pu-240</td></tr>
<tr><td>300</td><td>Am-241, Cs-137</td><td>Am-241, Cs-137</td><td>Am-241, Cs-137</td></tr>
<tr><td>500</td><td rowspan="2">Am-241</td><td rowspan="2">Am-241</td><td rowspan="2">Am-241</td></tr>
<tr><td>10^3</td></tr>
<tr><td>10^4</td><td>Pu-239, Pu-240</td><td>Pu-239, Pu-240</td><td>Np-239, Pa-233, Rn-222*, Sn-126</td><td>Np-239, Pa-233, Rn-222*, Sn-126</td><td>Np-239, Sn-126, Th-234</td></tr>
<tr><td>10^5</td><td>Pu-239</td><td>Pu-239</td><td>Rn-222*, Sn-126</td><td>Rn-222*, Sn-126</td><td>Rn-222*, Sn-126</td></tr>
<tr><td>10^6</td><td>Th-229, Th-230</td><td>Pb-210, Po-210</td><td rowspan="2">Rn-222*</td><td rowspan="2">Rn-222</td><td>Ac-225, Rn-222*</td></tr>
<tr><td>10^7</td><td>Th-230</td><td>Pb-210, Po-210, Ra-226</td><td>Rn-222*</td></tr>
</table>

Note: * It is unlikely that Rn-222 will be retained in water or soil and radiotoxicity will be influenced by next most radiotoxic species (i.e., Ac-225, Pa-233, Th-229 and Th-234).

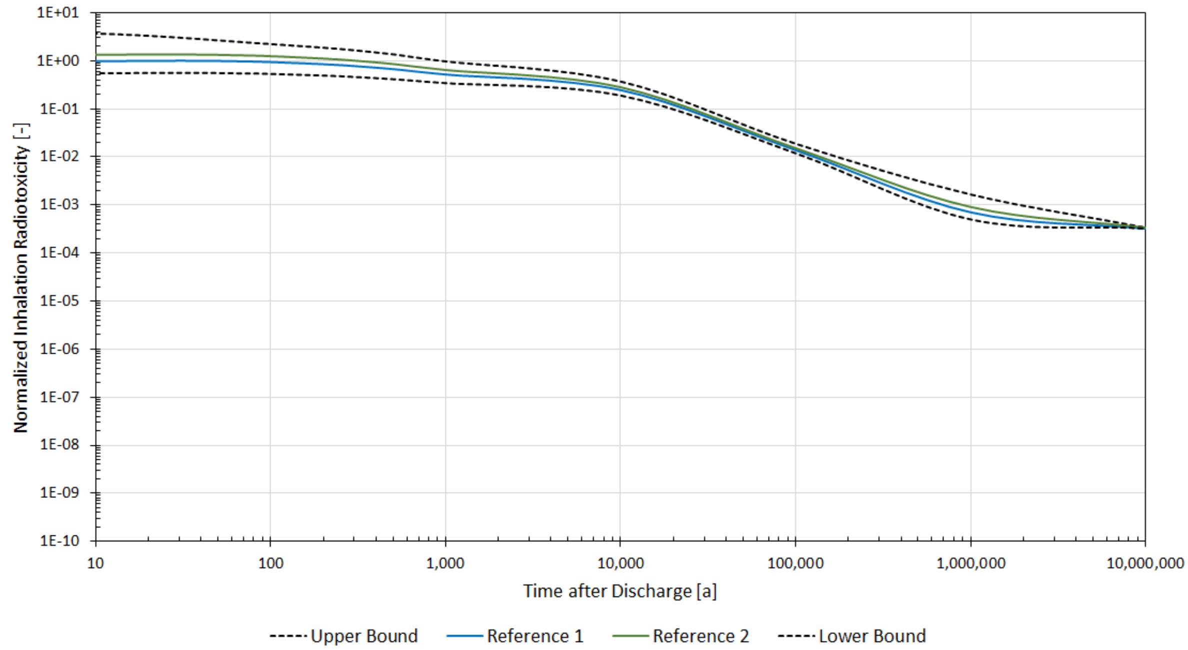

Figure 3: Range of Total Inhalation Radiotoxicity for a 37R Bundle

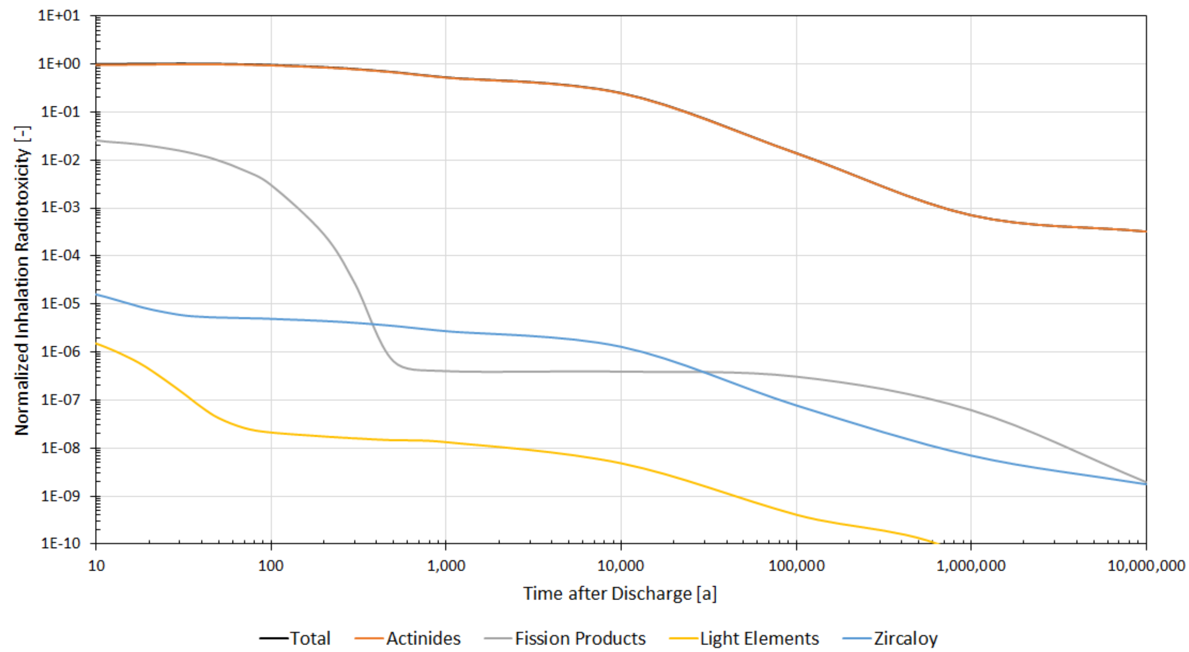

Figure 4: Breakdown of Reference 1 Bundle Inhalation Radiotoxicity

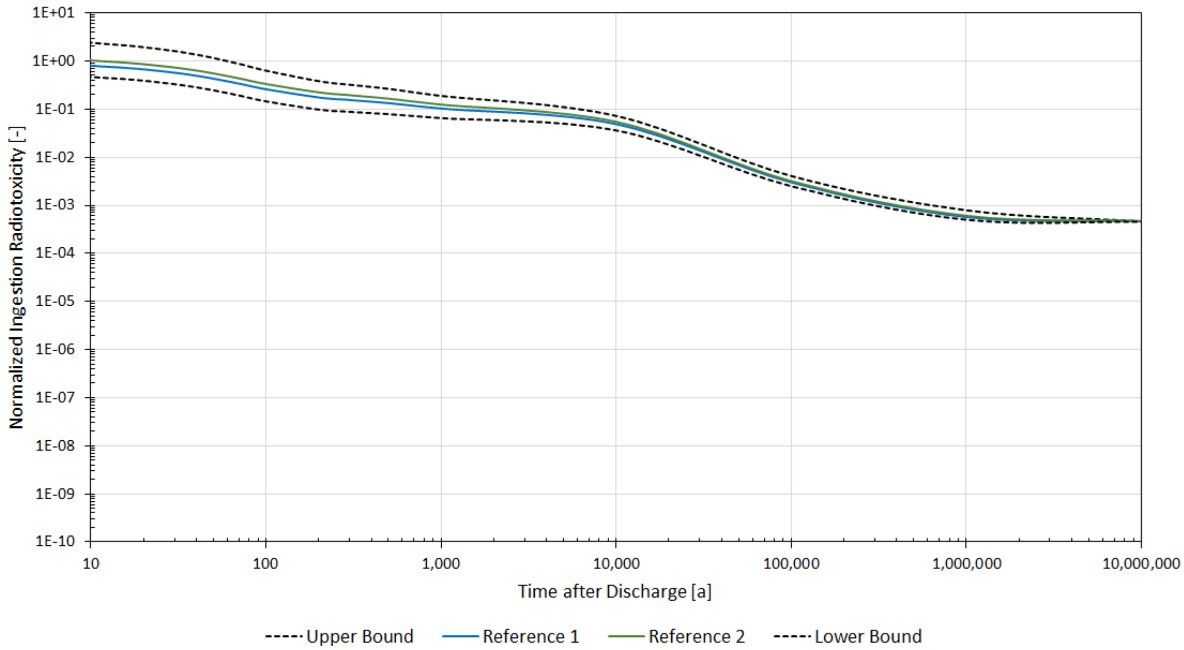

Figure 5: Range of Total Ingestion Radiotoxicity for a 37R Bundle

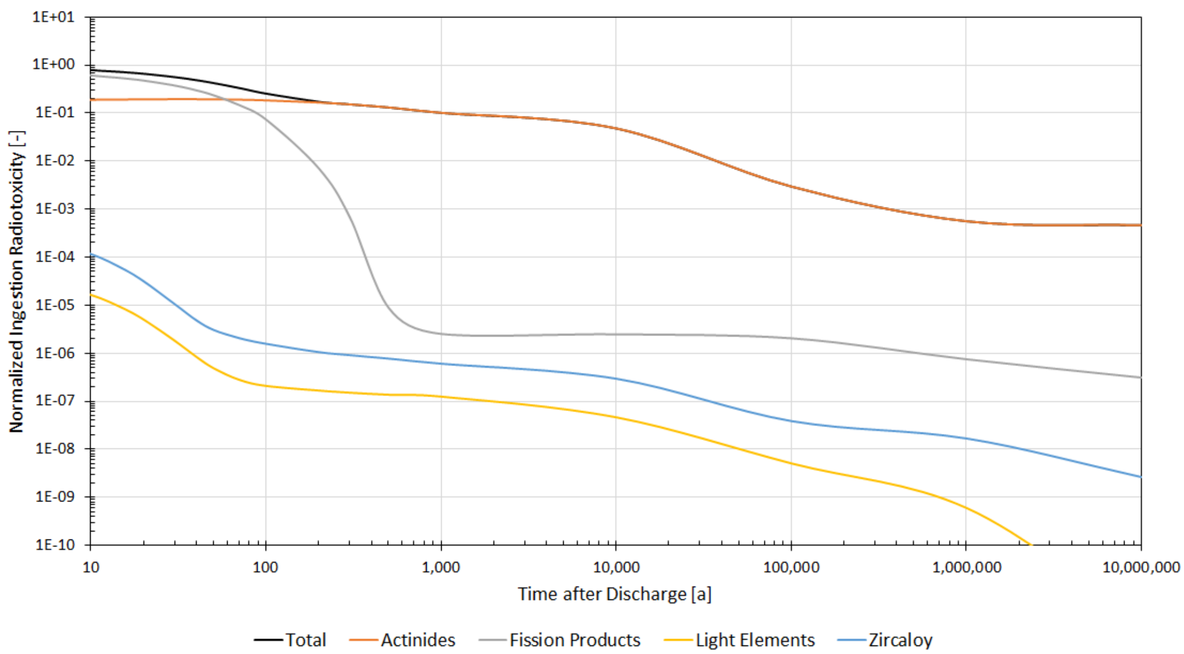

Figure 6: Breakdown of Reference 1 Bundle Ingestion Radiotoxicity

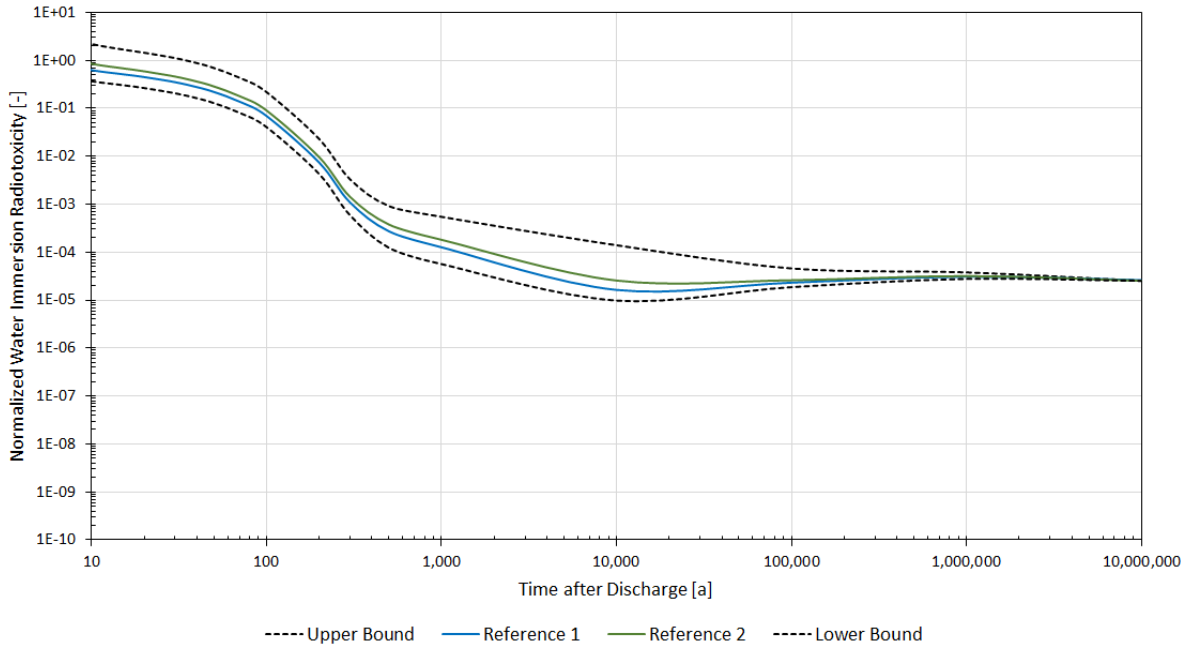

Figure 7: Range of Total Water Immersion Radiotoxicity for a 37R Bundle

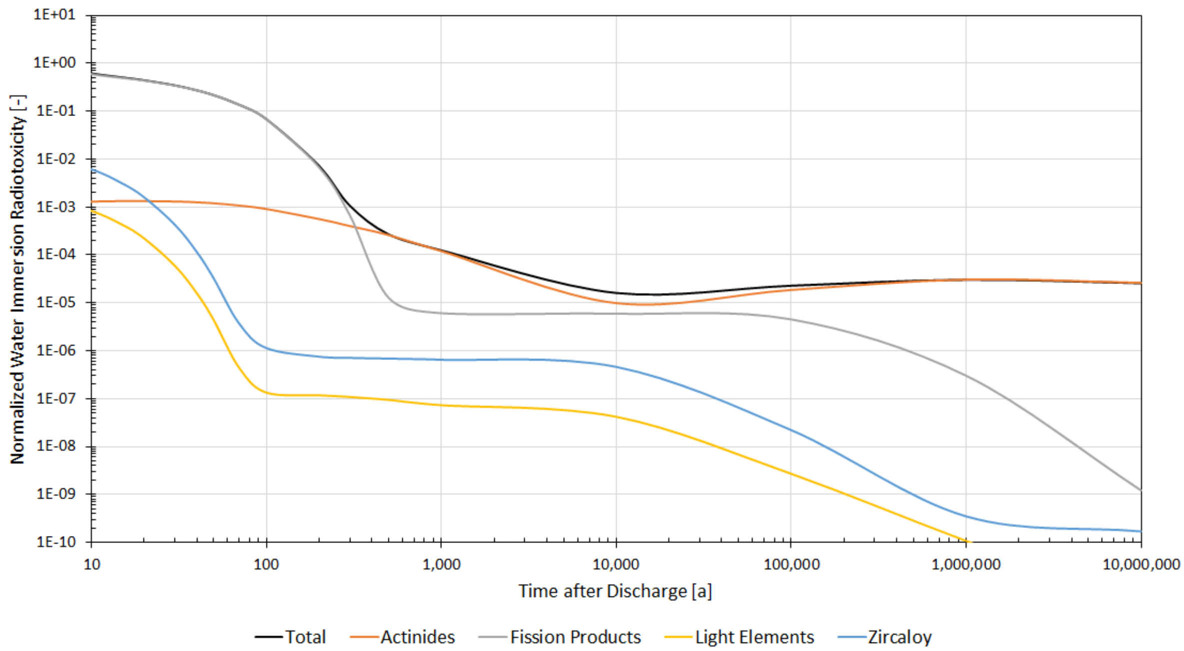

Figure 8: Breakdown of Reference 1 Bundle Water Immersion Radiotoxicity

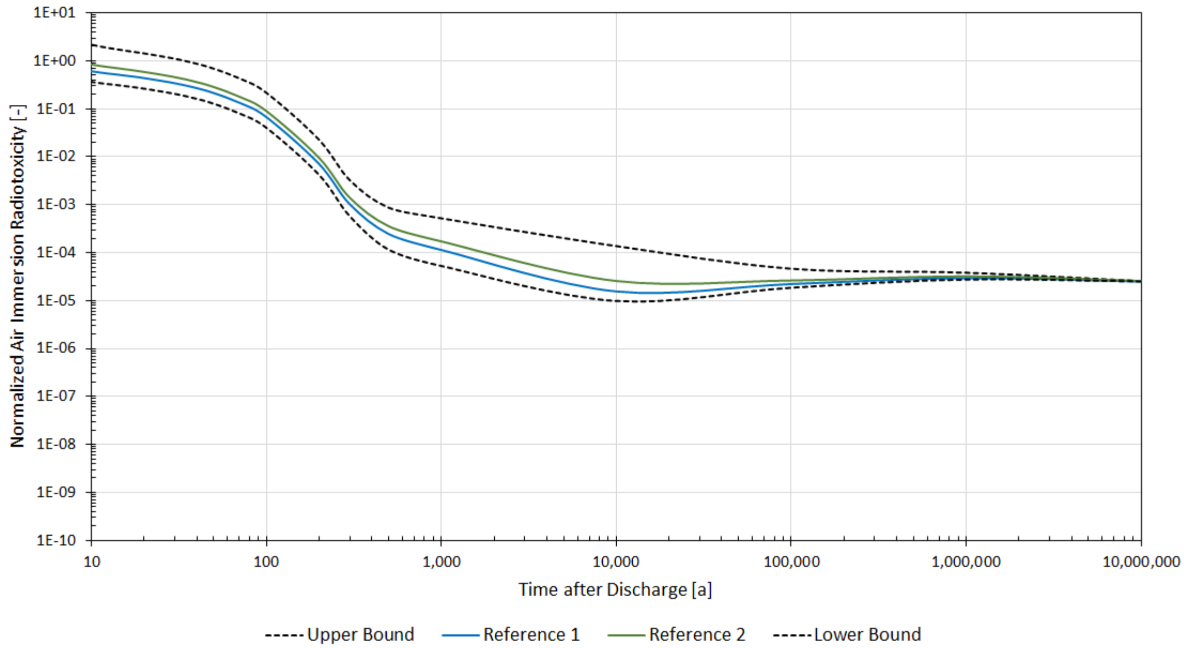

Figure 9: Range of Total Air Immersion Radiotoxicity for a 37R Bundle

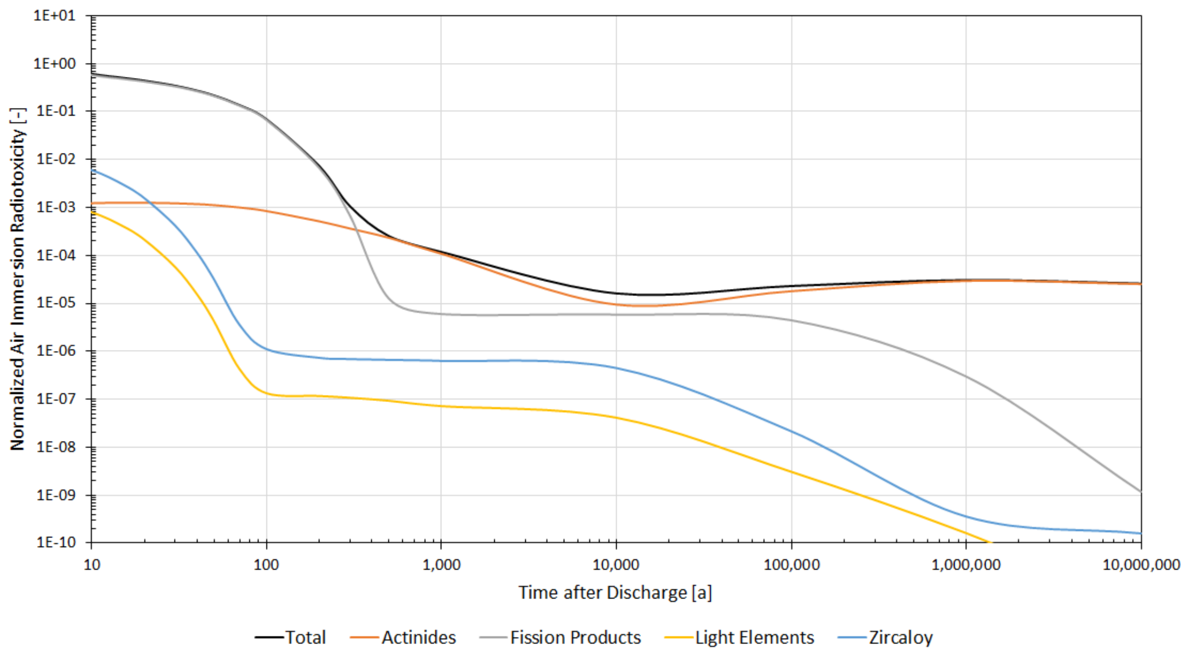

Figure 10: Breakdown of Reference 1 Bundle Air Immersion Radiotoxicity

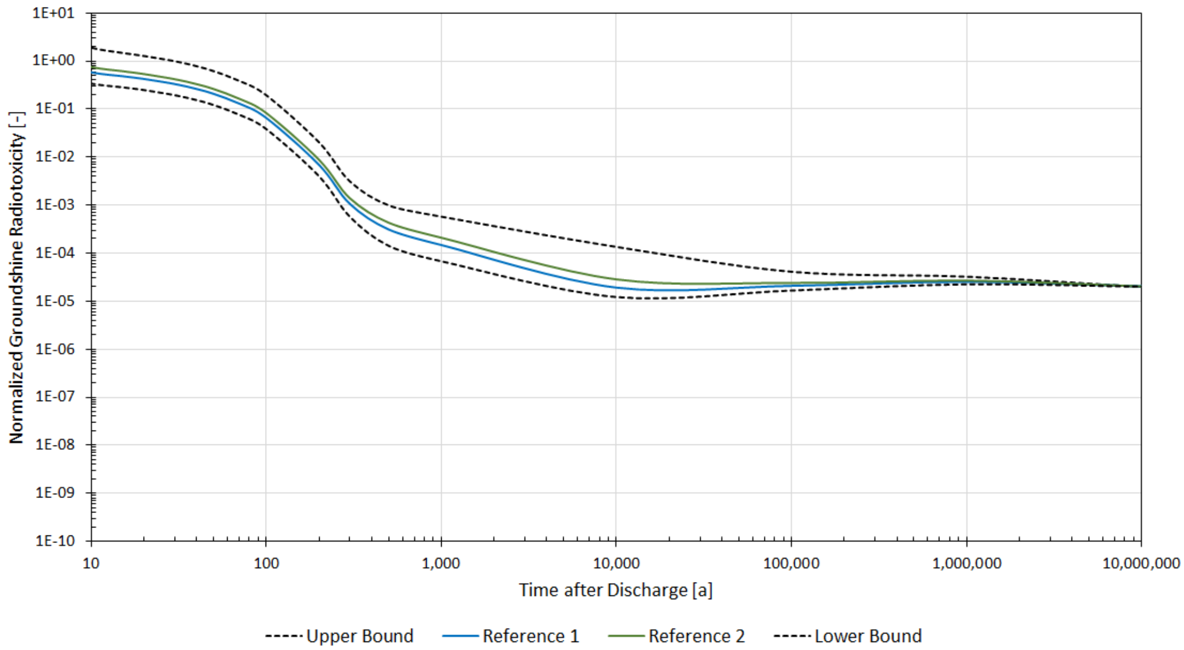

Figure 11: Range of Total Groundshine Radiotoxicity for a 37R Bundle

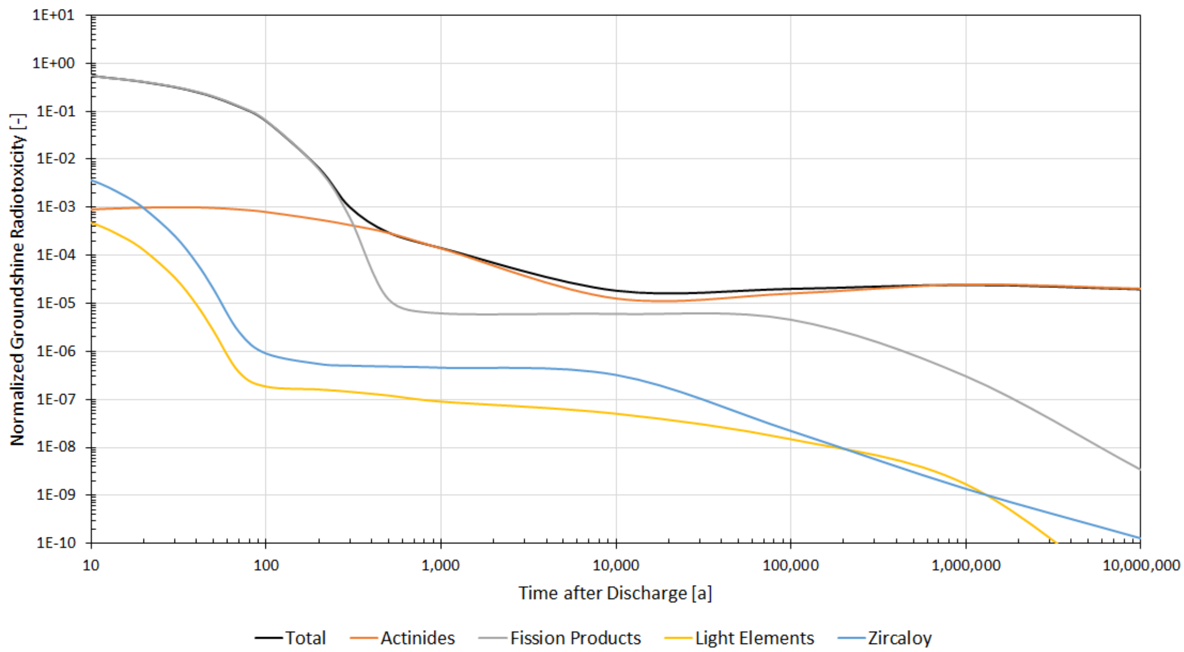

Figure 12: Breakdown of Reference 1 Bundle Groundshine Radiotoxicity

4. SCREENING ASSESSMENT

This section details the radionuclide and chemical hazard element screening assessment methodology, criteria and results. When determining which species must be considered in detailed assessments one must consider the different scenarios in which different species could be dominant contributors to the hazard. The three key safety assessment scenarios identified are:

- Preclosure;
- Postclosure; and
- Inadvertent Human Intrusion

The preclosure assessment considers the time period associated with operation of the repository. During this period fuel is received at the repository surface facilities from the generating stations and interim storage facilities and is placed in the repository. Exposure to the fuel from normal operating conditions and accident conditions are assessed.

The postclosure assessment considers the period of time after the repository has been decommissioned. In this screening safety assessment, it is assumed that used fuel containers are breached at some point in the future and radionuclides from the repository eventually end up in the surface environment. Exposure to people assumed to be living at or near the repository site are assessed.

The inadvertent human intrusion scenario assumes that institutional knowledge of the repository is lost at some point in the future. This is a disruptive scenario in which the repository's multiple barrier system is bypassed and fuel is brought to the surface via borehole drilling. Exposure to the drill crew operating the borehole and local residents near the borehole site are assessed.

4.1 RADIONUCLIDE SCREENING

The purpose of the radionuclide screening assessments is to identify radionuclides in the fuel and Zircaloy cladding which could contribute significantly to potential dose consequences to human in detailed safety assessments.

4.1.1 General Screening Methodology

This section details the general methodology used for the preclosure, inadvertent human intrusion and postclosure screening analyses. The screenings are performed by comparing the contribution of an individual radionuclide to the total radiotoxicity for a given scenario and exposure pathway. By normalizing the contribution of individual species to the total radiotoxicity the screening is largely independent of much of the pathway specific data (e.g, inhalation rates, exposure times, areas). A species is considered "screened in" for additional consideration in more detailed assessments if the condition shown in Equation 1 is met. This approach is broadly similar to that used by other waste management organizations (Haavisto 2014, Thorne 2006, Crawford 2018).

$$\frac{I_i(t) DCF_i^p f_i^p}{\sum_i I_i(t) DCF_i^p f_i^p} > Criteria \qquad [1]$$

Where,

$I_i(t)$	is the inventory of species i at fuel age t;
DCF_i^p	is the dose conversion factor for species i and pathway p;
f_i^p	is a generic term representing any radionuclide or exposure pathway dependent factor or factors used in the screening assessment (e.g., respirable fraction, deposition rates); and
$Criteria$	is the screening criteria described in Section 4.1.2.

The screening analyses considers the radionuclide inventories in the fuel and Zircaloy cladding for the two reference fuels described in Section 2.1 and dose conversion factor data described in Section 2.3.1 through Section 2.3.5. Any radionuclide or pathway specific data used in the preclosure, postclosure and inadvertent human intrusion screenings are described in Sections 4.1.3, 4.1.4 and 4.1.5 respectively. In generally, differences in the preclosure, postclosure and inadvertent human intrusion screenings arise from differences in the assumed age of the fuel as well as the exposure pathways considered in each screening assessment.

4.1.2 Screening Criteria

For the preclosure, postclosure, and inadvertent human intrusion screening assessments, any radionuclide found to contribute more than 0.1% of the total radiotoxicity of the fuel for a given exposure pathway at a given time will be screened in for additional analysis in more detailed assessments.

4.1.3 Preclosure Screening

The preclosure screening assessment considers fuel as received at the repository site. Fuels are generally expected to be at least 30 years old when received by the repository however this screening assessment considers both 10 and 30 year old fuel. The radionuclide screening considered both normal operations and accident scenarios.

For normal operations, the screening approach considers a hypothetical scenario in which the inventory in a used fuel bundle is released via a stack (for the airborne pathway) or into a small lake (for the waterborne pathway). It was assumed that both the airborne and waterborne emissions are filtered prior to release, removing 99% of particulates from the airborne or waterborne emissions. Most critical to the results of normal operations assessments is gaseous or volatile species as these are able to bypass the filtration prior to release. Under normal operations Ar, H-3, Kr, Rn, and Xe are assumed to be gases and C, Cl, I, Ru, and Se are assumed volatile.

The preclosure screening assessment for normal operations presented here first considers exposure due to inhalation and air immersion from gaseous or volatile species. The screening then considers exposure due to inhalation, air immersion, groundshine, and ingestion from particulates. The contribution from the water immersion pathway is not considered due to the limited time one is assumed to spend immersed in water.

For a hypothetical accident scenario, the screening approach considered an accident in which the inventory in a used fuel bundle is released via a stack. The screening is carried out assuming that the HEPA filter system in the stack release is operational, removing 99.97% of particulates, and repeated assuming that the HEPA filter system is not in use due to a failure. Most critical to the results of accident scenario assessments with filtration is gaseous or volatile species as these at able to bypass the filtration prior to release. Under accident conditions Ar, H-3, Kr, Rn, and Xe are assumed to be gases and C, Cd, Cl, Cs, I, Ru, Se, Sr and Te are assumed volatile. Additional species are assumed volatile under accident conditions due to the possibility of fires.

The preclosure screening assessment for accidents presented here first considers exposure due to inhalation and air immersion from gaseous or volatile species. The screening then considers exposure due to inhalation, air immersion, and groundshine from particulates. For all pathways, the factor f_i^p from Equation 1 differentiates between gaseous or volatile species and species assumed to be particulates in the normal and accident scenarios.

Table 2 identifies the resulting set of screened-in radionuclides for consideration in detailed assessment. In total, a set of 27 screened-in species have been identified. Table 2 also identifies the scenario for which a radionuclide was screened in, whether the radionuclide was volatile or a particulate, and the pathway(s) for which the radionuclide exceeded the screening criteria.

Table 2: Preclosure Screening Assessment Results for Normal Operations and Accidents

Radionuclide	Scenario	Type	Key Exposure Pathway
Am-241	Normal / Accident	Particulate	Inhalation, Air Immersion, Groundshine, Ingestion
Am-243	Normal / Accident	Particulate	Inhalation
C-14	Normal	Volatile	Inhalation
Ce-144	Normal / Accident	Particulate	Air Immersion, Groundshine
Cl-36	Normal	Volatile	Inhalation
Cm-244	Normal / Accident	Particulate	Inhalation, Ingestion
Co-60	Normal / Accident	Particulate	Air Immersion, Groundshine
Cs-134	Normal / Accident	Volatile / Particulate	Inhalation, Air Immersion, Groundshine, Ingestion
Cs-137	Normal / Accident	Particulate	Inhalation, Air Immersion, Groundshine, Ingestion
Eu-154	Normal / Accident	Particulate	Air Immersion, Groundshine
Eu-155	Normal / Accident	Particulate	Air Immersion, Groundshine
H-3	Normal	Gaseous	Inhalation
I-129	Normal	Volatile	Inhalation
Kr-85	Normal	Gaseous	Inhalation
Pm-147	Normal / Accident	Particulate	Groundshine, Ingestion
Pu-238	Normal / Accident	Particulate	Inhalation, Ingestion
Pu-239	Normal / Accident	Particulate	Inhalation, Ingestion
Pu-240	Normal / Accident	Particulate	Inhalation, Ingestion
Pu-241	Normal / Accident	Particulate	Inhalation, Ingestion
Ra-224	Normal / Accident	Particulate	Air Immersion, Groundshine, Ingestion
Ru-106	Normal / Accident	Volatile	Inhalation, Air Immersion
Sb-125	Normal / Accident	Particulate	Air Immersion, Groundshine
Se-79	Normal	Volatile	Inhalation
Sr-90	Normal / Accident	Volatile / Particulate	Inhalation, Air Immersion, Groundshine, Ingestion
Th-228	Normal / Accident	Particulate	Inhalation
U-232	Normal / Accident	Particulate	Inhalation, Ingestion
Y-90	Normal / Accident	Particulate	Air Immersion, Groundshine, Ingestion

4.1.4 Postclosure Screening

In this postclosure screening assessment, the assessment is conducted for fuel ages of 10^3, 10^4, 10^5, and 10^6 years. Earlier fuel ages are not considered because the time required to breach a used fuel container and for radionuclides to migrate from the repository to the surface environment is expected to be at least 1,000 years. Furthermore, important radionuclides at earlier times are also considered in the previous preclosure and inadvertent human intrusion scenarios.

A variety of hypothetical exposure pathways are plausible in the postclosure period given radionuclides enter the surface environment from the geosphere. Exposure pathways considered in NWMO (2017, 2018) include ingestion of contaminated water and food grown near the repository site, inhalation due to volatilized species in the water and soil, groundshine due to exposure to contaminated soil and immersion in air and water. These assessments have shown that the most consequential exposure pathway by far is ingestion followed by groundshine.

The contribution from other exposure pathways such as air immersion, water immersion and inhalation are typically many orders of magnitude less than those from ingestion. This is because radionuclides migrate to the biosphere via groundwater and the concentration of species in the air requires species in soils or surface waters to volatilize or be suspended in the air as particulates. Water immersion pathways are also not typically of consequence due to the limited time people spend immersed in water. Therefore, the postclosure screening assessment will consider only ingestion and groundshine pathways.

One of the most important factors in postclosure safety assessments is the mobility of a species in the engineered barrier system and the geosphere. In general, actinides are far less mobile in the environment compared to fission products and activated light elements. Actinides are typically more radiotoxic than fission products or activated light elements as shown in Section 3. In order to avoid transport calculations and site specific transport data such as sorption, the postclosure screening assessment considers actinides separately from fission products and activated light elements. For all pathways, the factor f_i^p from Equation 1 is used to differentiate between species categorized as actinides and those categorized as fission products or activated light elements.

In summary, for postclosure screening, the radionuclides categorized as actinides that contribute 0.1% or more of the total ingestion or groundshine radiotoxicity for actinides are screened in. Radionuclides identified as fission product or activated light elements that contribute 0.1% or more of the total ingestion or groundshine radiotoxicity for fission products and activated elements are also screening in.

The resulting set of screened-in radionuclides is shown in Table 3. In total, a set of 40 species have been identified for consideration in future postclosure assessments.

Table 3: Postclosure Screening Assessment Results

Radionuclide	Key Exposure Pathway
Ac-225	Ingestion, Groundshine
Ac-227	Ingestion
Ag-108m	Groundshine
Am-241	Ingestion, Groundshine
Am-243	Ingestion, Groundshine
Bi-210	Groundshine
C-14	Ingestion, Groundshine
Cl-36	Ingestion, Groundshine
Cs-135	Ingestion, Groundshine
I-129	Ingestion, Groundshine
Nb-93m	Ingestion, Groundshine
Nb-94	Ingestion, Groundshine
Np-237	Ingestion, Groundshine
Np-239	Groundshine
Pa-231	Ingestion, Groundshine
Pa-233	Groundshine
Pb-210	Ingestion
Pd-107	Ingestion
Po-210	Ingestion
Pu-239	Ingestion, Groundshine
Pu-240	Ingestion, Groundshine
Pu-242	Ingestion
Ra-223	Ingestion, Groundshine
Ra-225	Ingestion, Groundshine
Ra-226	Ingestion, Groundshine
Rn-222	Groundshine
Sb-126	Ingestion, Groundshine
Se-79	Ingestion
Sn-126	Ingestion, Groundshine
Tc-99	Ingestion, Groundshine
Th-227	Groundshine
Th-229	Ingestion, Groundshine
Th-230	Ingestion
Th-234	Ingestion, Groundshine
U-233	Ingestion
U-234	Ingestion
U-235	Groundshine
U-236	Ingestion
U-238	Ingestion
Zr-93	Ingestion

4.1.5 Inadvertent Human Intrusion Screening

The inadvertent human intrusion screening analysis assumes the fuel is at least 300 years old. This corresponds to the time at which institutional knowledge of the repository is assumed to be lost and inadvertent human intrusion possible (Medri 2015). It is also possible that inadvertent human intrusion could occur at any point in the future after institutional knowledge of the repository is lost. Therefore, fuel ages of 300, 10^3, 10^4, 10^5, and 10^6 years are considered in this screening assessment.

In the inadvertent human intrusion scenario, there are two key receptors the drill crew and a local resident. Medri (2015) describes the hypothetically exposure pathways to these receptors as groundshine, ingestion, and inhalation due to contamination of soils around the drill site. The same exposure pathways are considered in this screening assessment. For all pathways, the factor f_i^p from Equation 1 is assumed to be 1.

Table 4 identifies the resulting set of screened-in radionuclides. In total, a set of 38 screened in species have been identified for consideration in future inadvertent human intrusion scenario assessments.

Table 4: Inadvertent Human Intrusion Screening Results

Radionuclide	Key Exposure Pathway
Ac-225	Groundshine, Inhalation, Ingestion
Ac-227	Inhalation, Ingestion
Am-241	Groundshine, Inhalation, Ingestion
Am-243	Groundshine, Inhalation, Ingestion
Bi-210	Groundshine
Cl-36	Groundshine
Cs-137	Groundshine, Ingestion
I-129	Ingestion
Nb-94	Groundshine
Np-237	Groundshine, Inhalation, Ingestion
Np-239	Groundshine
Pa-231	Groundshine, Inhalation, Ingestion
Pa-233	Groundshine
Pb-210	Groundshine, Inhalation, Ingestion
Po-210	Inhalation, Ingestion
Pu-238	Inhalation, Ingestion
Pu-239	Groundshine, Inhalation, Ingestion
Pu-240	Groundshine, Inhalation, Ingestion
Pu-242	Inhalation, Ingestion
Ra-223	Groundshine, Inhalation, Ingestion
Ra-224	Groundshine
Ra-225	Groundshine, Inhalation, Ingestion
Ra-226	Groundshine, Inhalation, Ingestion
Rn-222	Groundshine
Sb-126	Groundshine
Sn-126	Groundshine
Sr-90	Groundshine, Ingestion
Tc-99	Groundshine
Th-227	Groundshine, Inhalation
Th-229	Groundshine, Inhalation, Ingestion
Th-230	Inhalation, Ingestion
Th-234	Groundshine, Ingestion
U-233	Inhalation, Ingestion
U-234	Inhalation, Ingestion
U-235	Groundshine, Inhalation
U-236	Inhalation, Ingestion
U-238	Inhalation, Ingestion
Y-90	Groundshine

4.1.6 Summary of Radionuclide Screening Results

Table 5 identifies the set of radionuclides identified here for consideration in future detailed assessments. In total 59 unique radionuclides were screened in across the preclosure, postclosure and inadvertent human intrusion screening assessments. The notes in Table 5 identifies the type of radionuclide (actinide, fission product, activated light element), if the radionuclide is a member of a decay chain, and if the radionuclide has a significant contribution to the inventory in the bundle from the zircaloy cladding (>5% of the total bundle inventory).

The results of the inadvertent human intrusion screening and the postclosure screening are similar. Notable differences include additional fission products or activated light elements (e.g., C14, Se79) being screened in for the postclosure assessment and some shorter-lived fission products (e.g., Cs137, Sr90) being screened in for the inadvertent human intrusion assessment. This is expected given the emphasis on fission products and activated light elements in the postclosure screening and the earlier fuel ages considered in the inadvertent human intrusion screening.

The preclosure screening results are markedly different from the other two screenings and identifies a number of short-lived species with high radiotoxicity at early times not identified in the other two screenings. A number of gaseous or volatile species (e.g., H-3, Kr-85) were also screened in.

Section 4.1.7 compares the results of this screening analysis with other assessments conducted by the NWMO and other waste management organizations.

Table 5: Summary of Radionuclide Screening Results

Isotope	Preclosure	Postclosure	Human Intrusion	Notes
Ac-225		✓	✓	Actinide, Member of 4n+1 Chain
Ac-227		✓	✓	Actinide, Member of 4n+3 Chain
Ag-108m		✓		Fission Product / Light Element, Significant Zircaloy Inventory
Am-241	✓	✓	✓	Actinide, Member of 4n+1 Chain
Am-243	✓	✓	✓	Actinide, Member of 4n+3 Chain
Bi-210		✓	✓	Actinide, Member of 4n+2 Chain
C-14	✓	✓		Light Element, Significant Zircaloy Inventory
Ce-144	✓			Fission Product, Member of Chain
Cl-36	✓	✓	✓	Light Element, Significant Zircaloy Inventory
Cm-244	✓			Actinide, Member of 4n Chain
Co-60	✓			Light Element, Significant Zircaloy Inventory
Cs-134	✓			Fission Product
Cs-135		✓		Fission Product
Cs-137	✓		✓	Fission Product
Eu-154	✓			Fission Product
Eu-155	✓			Fission Product
H-3	✓			Light Element, Significant Zircaloy Inventory
I-129	✓	✓	✓	Fission Product
Kr-85	✓			Fission Product
Nb-93m		✓		Fission Product, Light Element, Significant Zircaloy Inventory
Nb-94		✓	✓	Light Element, Significant Zircaloy Inventory
Np-237		✓	✓	Actinide, Member of 4n+1 Chain
Np-239		✓	✓	Actinide, Member of 4n+3 Chain
Pa-231		✓	✓	Actinide, Member of 4n+3 Chain
Pa-233		✓	✓	Actinide, Member of 4n+1 Chain
Pb-210		✓	✓	Actinide, Member of 4n+2 Chain
Pd-107		✓		Fission Product
Pm-147	✓			Fission Product, Member of a Chain
Po-210		✓	✓	Actinide, Member of 4n+2 Chain
Pu-238	✓		✓	Actinide, Member of 4n+2 Chain
Pu-239	✓	✓	✓	Actinide, Member of 4n+3 Chain
Pu-240	✓	✓	✓	Actinide, Member of 4n Chain
Pu-241	✓			Actinide, Member of 4n+1 Chain
Pu-242		✓	✓	Actinide, Member of 4n+2 Chain
Ra-223		✓	✓	Actinide, Member of 4n+3 Chain
Ra-224	✓		✓	Actinide, Member of 4n Chain
Ra-225		✓	✓	Actinide, Member of 4n+1 Chain
Ra-226		✓	✓	Actinide, Member of 4n+2 Chain
Rn-222		✓	✓	Actinide, Member of 4n+2 Chain

Isotope	Preclosure	Postclosure	Human Intrusion	Notes
Ru-106	✓			Fission Product
Sb-125	✓			Fission Product, Member of a Chain
Sb-126		✓	✓	Fission Product, Member of a Chain
Se-79	✓	✓		Fission Product
Sn-126		✓	✓	Fission Product, Member of a Chain
Sr-90	✓		✓	Fission Product, Member of a Chain
Tc-99		✓	✓	Fission Product
Th-227		✓	✓	Actinide, Member of 4n+3 Chain
Th-228	✓			Actinide, Member of 4n Chain
Th-229		✓	✓	Actinide, Member of 4n+1 Chain
Th-230		✓	✓	Actinide, Member of 4n+2 Chain
Th-234		✓	✓	Actinide, Member of 4n+2 Chain
U-232	✓			Actinide, Member of 4n Chain
U-233		✓	✓	Actinide, Member of 4n+1 Chain
U-234		✓	✓	Actinide, Member of 4n+2 Chain
U-235		✓	✓	Actinide, Member of 4n+3 Chain
U-236		✓	✓	Actinide, Member of 4n Chain
U-238		✓	✓	Actinide, Member of 4n+2 Chain
Y-90	✓		✓	Fission Product, Member of a Chain
Zr-93		✓		Fission Product / Light Element, Significant Zircaloy Inventory

4.1.7 Comparison with Other Assessments

This section compares the screening results in Table 5 with those from previous NWMO assessments and as well as assessments conducted by other waste management organizations. Table 6 compares radionuclides identified in this assessment with those included in Villagran (1993), Posiva (2013), NWMO (2016), NWMO (2017), Posiva (2012), SKB (2006), Nagra (2002) and Medri (2015). Radionuclides identified in this assessment are highlighted in blue.

Sections 4.1.7.1 through 4.1.7.2 details the differences between this assessment and the radionuclides considered in other assessments. In general, the set of radionuclides identified in this screening assessment is similar to those considered in other assessments and by other waste management organizations. It was also found that key radionuclides driving dose results in other detailed assessments were identified in this screening assessment.

One consideration to note is that not all waste management organization distinguish between radionuclides identified for preclosure or operational safety, postclosure safety and inadvertent human intrusion. In particular, inadvertent human intrusion is often considered a disruptive scenario in the postclosure assessment and is not subject to additional screening.

Table 6: Comparison of Radionuclides Considered in Other Assessments

Preclosure			Postclosure						Human Intrusion	
This Analysis	Villagran (1993)	Posiva (2013)	This Analysis	NWMO (2016)	NWMO (2017)	Posiva (2012)	SKB (2006)	Nagra (2002)	This Analysis	Medri (2015)
			Ac-225	Ac-225	Ac-225				Ac-225	Ac-225
			Ac-227	Ac-227	Ac-227			Ac-227	Ac-227	Ac-227
			Ag-108m			Ag-108m	Ag-108m	Ag-108m		Ag-108m
Am-241	Am-241		Am-241	Am-241	Am-241	Am-241	Am-241	Am-241	Am-241	Am-241
	Am-242m						Am-242m	Am-242m		Am-242m
Am-243			Am-243			Am-243	Am-243	Am-243	Am-243	Am-243
						Be-10		Be-10		
			Bi-210	Bi-210	Bi-210				Bi-210	Bi-210
C-14	C-14	C-14	C-14	C-14	C-14	C-14	C-14	C-14		C-14
				Ca-41	Ca41		Ca-41	Ca-41		
							Cd-113m			Cd-113m
Ce-144	Ce-144									
Cl-36			Cl-36	Cl-36	Cl-36	Cl-36	Cl-36	Cl-36	Cl-36	Cl-36
							Cm-242			Cm-242
							Cm-243			Cm-243
Cm-244	Cm-244						Cm-244	Cm-244		Cm-244
						Cm-245	Cm-245	Cm-245		Cm-245
						Cm-246	Cm-246	Cm-246		
Co-60	Co-60						Co-60			Co-60
Cs-134	Cs-134									Cs-134
		Cs-135	Cs-135	Cs-135	Cs-135	Cs-135	Cs-135	Cs-135		Cs-135
Cs-137	Cs-137	Cs-137				Cs-137	Cs-137	Cs-137	Cs-137	Cs-137
Eu-154	Eu-154						Eu-154			Eu-154
Eu-155	Eu-155									Eu-155
	Fe-55									
H-3	H-3	H-3						H-3		H-3
							Ho-166m	Ho-166m		Ho-166m

Preclosure			Postclosure						Human Intrusion	
This Analysis	**Villagran (1993)**	**Posiva (2013)**	**This Analysis**	**NWMO (2016)**	**NWMO (2017)**	**Posiva (2012)**	**SKB (2006)**	**Nagra (2002)**	**This Analysis**	**Medri (2015)**
I-129	I-129	I-129	I-129	I1-29	I-129	I-129	I-129	I-129	I-129	I-129
Kr-85	Kr-85	Kr-85					Kr-85			Kr-85
						Mo-93		Mo-93		
						Nb-91				
						Nb-92				
			Nb-93m			Nb-93m		Nb-93m		Nb-93m
	Nb-94		Nb-94			Nb-94	Nb-94	Nb-94	Nb-94	Nb-94
	Ni-59					Ni-59	Ni59	Ni59		
	Ni-63					Ni-63	Ni63	Ni63		Ni-63
			Np-237	Np-237	Np-237	Np-237	Np-237	Np-237	Np-237	Np-237
			Np-239						Np-239	Np-239
			Pa-231	Pa-231	Pa-231	Pa-231	Pa-231	Pa-231	Pa-231	Pa-231
			Pa-233	Pa-233	Pa-233				Pa-233	Pa-233
			Pb-210	Pb-210	Pb-210			Pb-210	Pb-210	Pb-210
		Pd-107	Pd-107	Pd-107	Pd-107	Pd-107	Pd-107	Pd-107		Pd-107
Pm-147	Pm-147									Pm-147
			Po-210	Po-210	Po-210			Po-210	Po-210	Po-210
Pu-238	Pu-238					Pu-238	Pu-238	Pu-238	Pu-238	Pu-238
Pu-239	Pu-239		Pu-239	Pu-239	Pu-239	Pu-239	Pu-239	Pu-239	Pu-239	Pu-239
Pu-240	Pu-240		Pu-240	Pu-240	Pu-240	Pu-240	Pu-240	Pu-240	Pu-240	Pu-240
Pu-241	Pu-241					Pu-241		Pu-241		Pu-241
			Pu-242	Pu-242	Pu-242	Pu-242	Pu-242	Pu-242	Pu-242	Pu-242
			Ra-223	Ra-223	Ra-223				Ra-223	Ra-223
Ra-224					Ra-224				Ra-224	Ra-224
			Ra-225	Ra-225	Ra-225				Ra-225	Ra-225
			Ra-226	Ra-226	Ra-226	Ra-226	Ra-226	Ra-226	Ra-226	Ra-226
				Ra-228	Ra-228			Ra-228		Ra-228
			Rn-222	Rn-222	Rn-222				Rn-222	Rn-222

Preclosure			Postclosure						Human Intrusion	
This Analysis	**Villagran (1993)**	**Posiva (2013)**	**This Analysis**	**NWMO (2016)**	**NWMO (2017)**	**Posiva (2012)**	**SKB (2006)**	**Nagra (2002)**	**This Analysis**	**Medri (2015)**
Ru-106	Ru-106									Ru-106
Sb-125	Sb-125									Sb-125
			Sb-126	Sb-126					Sb-126	Sb-126
Se-79		Se-79	Se-79	Se-79	Se-79	Se-79	Se-79	Se-79		
					Sm-147					
					Sm-148					
						Sm-151	Sm-151	Sm-151		Sm-151
		Sn-126	Sn-126	Sn-126		Sn-126	Sn-126	Sn-126	Sn-126	Sn-126
Sr-90	Sr-90	Sr-90		Sr-90		Sr-90	Sr-90	Sr-90	Sr-90	Sr-90
		Tc-99	Tc-99	Tc-99	Tc-99	Tc-99	Tc-99	Tc-99	Tc-99	Tc-99
	Te-125m									Te-125m
			Th-227	Th-227	Th-227				Th-227	Th-227
Th-228					Th-228			Th-228		Th-228
			Th-229	Th-229	Th-229	Th-229	Th-229	Th-229	Th-229	Th-229
			Th-230	Th-230	Th-230	Th-230	Th-230	Th-230	Th-230	Th-230
				Th-231	Th-231					Th-231
				Th-232	Th-232	Th-232	Th-232	Th-232		Th-232
			Th-234	Th-234	Th-234				Th-234	Th-234
U-232								U-232		U-232
			U-233	U-233	U-233	U-233	U-233	U-233	U-233	U-233
	U-234		U-234	U-234	U-234	U-234	U-234	U-234	U-234	U-234
			U-235	U-235	U-235	U-235	U-235	U-235	U-235	U-235
			U-236	U-236	U-236	U-236	U-236	U-236	U-236	U-236
	U-238		U-238	U-238	U-238	U-238	U-238	U-238	U-238	U-238
Y-90									Y-90	Y-90
			Zr-93			Zr-93	Zr-93	Zr-93		Zr-93

4.1.7.1 Comparison of Preclosure Screening Results

The preclosure screening analysis identified 27 radionuclides for consideration in detailed assessment. Results are compared with a previous screening analysis Villigran (1993) and an operational safety report by Posiva (Posiva 2013).

Villagran (1993) identifies 28 species for consideration in preclosure assessments and in general the species identified were similar to those identified in this assessment. Differences include Fe55, Ni59 and Ni63 which were included in Villagran (1993) on the basis that they could have significant inventories in surface deposits. An estimate of the surface deposit inventory in this analysis found the surface deposits contributed <2% of the total inventory of these species and the resulting radiotoxicity of these species was found to be less than the screening criteria and therefore they are screened out here. Te-125m was also included in Villagran (1993) on the basis that under reactor operating conditions Te-125m could behave in a similar fashion to I-129. A similar assumption was made in this screening analysis with Te being assumed to be volatile. However, Te-125m was not found to significantly contribute to the fuel radiotoxicity for volatile species and was screened out. There were also some differences in the actinides identified in Villagran (1993) but the most radiotoxic (e.g., Pu) were identified in this assessment and Villagran (1993).

Posiva (2013) is a preclosure safety assessment conducted by Posiva. This assessment considers several species for which the Finish Radiation and Nuclear Safety Authority, STUK, has issued constraints on activity releases to the environment. The list of species is relatively short and identifies several fission products and activation products. Several of these species (C-14, Cs-137, H-3, I-129, Kr-85, Se-79, Sr-90) were also identified in this preclosure screening assessment. The remaining species (Cs-135, Pd-107, Sn-126 and Tc-99) did not exceed the preclosure screening assessment criteria but were identified more broadly in this postclosure screening assessment.

It is also worth noting that while not specifically preclosure assessments, Posiva (2012), SKB (2006) and Nagra (2002) consider the hazard associated with the fuel for all times after discharge and consider a number of species relevant to the preclosure period (e.g., Cs-137, Sr-90) identified in this assessment.

Overall results of the preclosure screening compare well with radionuclides considered in other assessments. Additional confidence in the results can be gained by looking at the detailed operational safety assessment results to ensure key radionuclides driving dose results were identified in this assessment. For example, detailed assessment results included in Posiva (2013) show dose results are dominated by Kr-85 (external dose), Sr-90 and Cs-137 (inhalation), with H-3, I-129, and C-14 also contributing to doses or select dose pathways (e.g., thyroid dose). Key radionuclides dominating doses in Grondin et al. (1994) were Sr-90, Cs-134, Cs-137, H-3, Am-241, Pu-241, and Pu-239. All key radionuclides have also been identified in this screening assessment.

4.1.7.2 Comparison of Postclosure Screening Results

The postclosure screening analysis identified 40 radionuclides for consideration in more detailed studies. These species were compared with species considered in the postclosure assessments NWMO (2016), NWMO (2017), Posiva (2012), SKB (2006) and Nagra (2002). In general, the core set of radionuclides considered in all these assessments are similar with some minor differences in fission products and activated light elements being considered. Differences between this study and the other references are described below.

NWMO (2016) is a generic postclosure safety assessment of a repository at a hypothetical Canadian crystalline rock site. The radionuclides considered in NWMO (2016) are similar to those identified in this assessment. Notable differences include are Ag-108m, Ca-41, Nb-93m, Nb-94, Ra-228, Th-231, Th-232 and Zr-93. NWMO (2016) did not identify Zr-93, Nb-94 and Nb-93m because of differences in the screening methodology, specifically the screening was based on a transport model that assumed a sorption coefficient for these species. Ag-108m was identified in this assessment due to a higher (~20 times) ingestion dose conversion factor as compared to that used in NWMO (2016) screening. Ca-41 is perhaps the most notable species found to be screened out in this assessment. This is due to the decreased inventory (-50%) and ingestion dose conversion factors (-25%) in this assessment as compared to those used in NWMO (2016). Ra-228, Th-231 and Th-232 were all below the screening threshold in this assessment but will need to be included in detailed assessments to correctly account for decay and ingrowth within the actinide chains.

NWMO (2017) is a generic postclosure safety assessment of a repository at a hypothetical Canadian sedimentary rock site. The radionuclides considered in NWMO (2017) are similar to those identified in this assessment. Notable differences include Ag-108m, Ca-41, Ra-228, Nb-93m, Nb-94, Th-231, Th-232 and Zr-93 for the same reason as described above. Other differences include Sb-126, Sn-126, Sm-147 and Sm-148. Similarly, Sb-126 and Sn-126 were not identified in NWMO (2017) due to sorption coefficients assumed for these species in the NWMO (2017) screening assessment. Sm-148 was not identified in this screening assessment due to differences in the dose conversion factors (zero in ICRP 144 and ICRP 119). Sm-147 has the same dose conversion factors and a similar inventory to that used in NWMO (2017). However, changes in other data resulted in Sm-147 being just below the screening threshold in this assessment. Neither Sm-147 nor Sm-148 were found to be of consequence to the detailed assessment results in NWMO (2017).

Posiva (2012) describes the assessment of the radionuclide release scenarios for the safety case for the disposal of spent nuclear fuel at Olkiluoto. In general, the list of radionuclides considered are similar to those identified in this assessment. Differences between this assessment and Posiva (2012) are primarily due to differences in the screening methodology and the fuel composition. Posiva (2012) considers the hazard associated with the fuel at all times after discharge and consequently identified several shorter-lived actinides, fission products, and activated light elements (e.g., Cm-245, Cm-246, Cs-137, Sm-151, Sr-90) not identified in this assessment. Another significant difference between Posiva (2012) and this assessment is the fuel considered. Posiva (2012) assesses BWR, PWR and VVER-440 fuel assemblies and these assemblies have significant inventories of Mo-93, Nb-92, Ni-59 and Ni-63 in the fuel cladding and “other metal parts”. CANDU fuels do not have the same components or materials and the activation products differ as a result. Finally, it should be noted that short lived daughters of the actinide chains (e.g., Pb-210 and Po-210) are not explicitly considered in Posiva (2012) and are assumed to be in secular equilibrium with the longer-lived parents.

SKB (2006) is a data report for the SR-CAN postclosure assessment and Section 1.9 of this report describes the selection of radionuclides for analysis. The methodology used by SKB is the same as this report with screening being based on radiotoxicity and the amount of each radionuclide present in the fuel. The screening also considered fission products and activated light elements separately from actinides and the screening criteria was also 0.1% of the total health hazard. As in Posiva (2012), SKB (2006) considers all fuel ages after discharge and the used fuel considered is PWR and BWR assemblies. Consequently, many of the same species considered in Posiva (2012) were also considered in SKB (2006). Short lived actinide daughters (e.g., Pb-210 and Po-210) are also not explicitly considered in SKB (2006). There were some differences unique to SKB (2006) such as inclusion of Ca-41 and Ho-166m. However, inclusion of these species is likely due to slight differences in inventories and other supporting data.

Nagra (2002) is a postclosure assessment assessing the long-term safety of disposal of spent fuel, vitrified high level waste, and long-lived intermediate level waste. Despite the variety of wasteforms considered the set of radionuclides considered is quite similar to those identified in this assessment. As in Posiva (2012) and SKB (2006) all times after discharge are considered and several shorter-lived actinides, fission products and activation products are considered as a result. The spent fuel considered is PWR and BWR fuel as well as some MOX fuel assemblies resulting in some activation products such as Mo-93, Ni-59 and Ni-63 being considered. One notable difference unique to Nagra (2002) is it considers organic and inorganic C-14 due to the inventory of long-lived intermediate level wastes.

Overall results of the postclosure screening compare well with radionuclides considered in other assessments. Additional confidence in the results can be gained by looking at the detailed postclosure safety assessment results to ensure key radionuclides driving dose results were identified in this assessment. Postclosure safety assessments performed by the NWMO and other waste management organizations consider a broad range of scenarios which can alter which species drive dose results. Despite this, several commonalities were found and results can be grouped into two categories which are dose results driven primarily by fission and activation products notably I-129, C-14, Cl-36, Se-79 and results driven primarily by actinide daughters notably Ra-226, Pb-210 and Po-210. Most scenarios in NWMO (2016), NWMO (2017), Posiva (2012) and Nagra (2002) are driven by fission and activation products but select sensitivities can have contributions from actinide daughters. SKB results (SKB 2011) on the other hand are generally dominated by Ra-226 with contributions from I-129, Se-79, Ni-59 and Nb-94. With the exception of Ni-59 which less relevant for CANDU fuel, all of these key radionuclides have been identified in this screening assessment.

4.1.7.3 Comparison of Inadvertent Human Intrusion Screening Results

The inadvertent human intrusion screening analysis identified 38 radionuclides for consideration in more detailed studies. In general results of this screening are very similar to the results of the postclosure screening assessment with some key differences in fission products and activated light elements identified (e.g., C-14, Cs-137, Sr-90, and Y-90). The differences are due to the younger fuel age (300 years) considered in the inadvertent human intrusion screening and the emphasis placed on mobile, longer lived fission products in the postclosure assessment. As noted in Section 4.1.7, other waste management organizations do not distinguish between species relevant to inadvertent human intrusion and those for postclosure assessments. Generally, the results of this assessment are consistent with those from Posiva (2012), SKB (2006) and Nagra (2002). Notable differences are discussed further in Section 4.1.7.2.

Medri (2015) assesses the consequences of inadvertent human intrusion to a hypothetical Canadian repository. Medri (2015) considered a total of 79 radionuclides (some not shown in Table 6) with the most consequential (Am-241, Pu-239, Pu-240, and Rn-222) also being identified in this assessment. Medri (2015) considered many species due to very conservative screening criteria and included any species that contributed >0.0001% of the total radiotoxicity for a variety of fuel ages. As such many of the species identified in Medri (2015) were not of consequence in the assessment. One notable difference between this assessment and Medri

(2015) is that C-14 was not identified in this assessment. C-14 was found to contribute approximately 0.7% of the local resident dose at 300 years in Medri (2015). In this assessment C-14 was below the screening threshold. The radiotoxicity of C-14 was found to be similar to Medri (2015) however its relative contribution to the total radiotoxicity was reduced due to changes in radionuclide inventories and dose conversion factors for other species.

Overall results of the inadvertent human intrusion screening results compare well with radionuclides considered in other assessments. Additional confidence in the results can be gained by looking at the detailed inadvertent human intrusion assessment results to ensure key radionuclides driving dose results were identified in this assessment. For example, results of the detailed inadvertent human intrusion scenario assessed in Medri (2015) and Posiva (2012) identify several actinide species (notably Am-241, Pu-239 and Pu-240) dominating dose results in all scenarios. Cs-137 also contributes to the dose in some scenarios in Medri (2015). All of these key radionuclides have been identified in this screening assessment.

4.2 NON-HUMAN BIOTA RADIONUCLIDE SCREENING

Section 4.1 describes the radionuclides screening in which radionuclides of relevance to humans are identified for consideration in more detailed safety assessments. One must also consider the potential radiological effects of the repository on non-human biota.

In general one would expect similar radionuclides to those of consequence to humans to also be of relevance to non-human biota either due to the abundance of a particular radionuclide in the fuel or due to the amount of energy decay of a given radionuclide can impart on a receptor. However, due to biological differences between humans and non-human biota it is plausible that unique radionuclides relevant only to non-human biota could be identified.

This section details the non-human biota radionuclide screening analysis in which radionuclides relevant to non-human biota are identified for consideration in more detailed safety assessments.

4.2.1 Non-Human Biota Radionuclide Screening Methodology

The overall methodology for the non-human biota radionuclide screening assessment is very similar to that of the radionuclide screening assessment described in Section 4.1.1. The screening is performed by comparing the contribution of an individual radionuclide to the total radiotoxicity for a given scenario and exposure pathway. A species is considered “screened in” for additional consideration in more detailed assessments if the criteria defined in Section 4.2.2 is met.

The non-human biota radionuclide screening analyses considers the radionuclide inventories in the fuel and Zircaloy cladding for the two reference fuels described in Section 2.1 and dose conversion factor data described in Section 2.3.6.

The non-human biota radionuclides screening assessment considers a variety of fuel ages ranging from 30 years to 1 million years out of reactor and considers exposure via the internal, water immersion, soil immersion, on ground, above ground and air immersion pathways identified in ICRP 136. Similar to the postclosure screening assessment (Section 4.1.4) actinides are considered separately from fission products and activated light elements for the purposes of this screening assessment.

4.2.2 Non-Human Biota Radionuclide Screening Criteria

For the non-human biota radionuclide screening assessment, any radionuclide found to contribute more than 0.1% of the total radiotoxicity of the radionuclide type (e.g., actinides) for a given exposure pathway at a given time will be screened in for additional analysis in more detailed assessments.

4.2.3 Non-Human Biota Radionuclide Screening Results

This section presents the results of the non-human biota radionuclide screening assessment. The non-human biota radionuclide screening assessment methodology is described in Section 4.2.1. The final set of elements for consideration in future detailed assessments are shown in Table 7.

In total 33 radionuclides are identified for further study in more detailed safety assessments. In general, the radionuclides identified in the non-human biota screening assessment are similar to those identified in Table 5. Notable differences are K-40 and Ni-59 which were not identified in the radionuclide screening for humans. K-40 and Ni-59 were screened in but are not anticipated to have a large impact on detail dose assessments to non-human biota. Based on the screening these radionuclides could have a contribution on the order of approximately 0.1-1%.

Assessments completed by other waste management organizations have not typically performed screening assessments in which radionuclides specifically of consequence to non-human biota are identified. The set (or subset) of radionuclides considered by other waste management organizations usually relies on results assessing the radiological impact of a repository to humans. For example, SKB (2013) considers a set of radionuclides very similar to those considered in SKB (2011) whereas Posiva (2010) and Enviros (2008) consider a subset of radionuclides considered in Posiva (2007) and Nirex (2003) respectively.

Results of SKB (2013), Posiva (2007) and Enviros (2008) show a similar trend to radiological impacts to humans with doses to non-human biota being dominated by contributions from similar key radionuclides. Key radionuclides in SKB (2013) were Pu-242, Np-237, Ra-226, Po-210, Nb-94, and Ni-59; key radionuclides in Posiva (2007) were Ra-226, Po-210, Cl-36 and C-14 and key radionuclides in Enviros (2008) were Np-237, Th-229, Th-230, Ra-226 and Po-210. While the non-human biota assessment results depend heavily on assessment methodology, data used, and biota considered all the key radionuclides considered in assessments by other waste management organization were identified in this screening assessment.

Table 7: Non-Human Biota Radionuclide Screening Assessment Results

Radio nuclide	Key Exposure Pathway
Am-241	Internal, Water Immersion, Soil Immersion, On Ground, Above Ground and Air Immersion
C-14	Internal and Water Immersion
Cl-36	Internal, Water Immersion, Soil Immersion, On Ground, Above Ground and Air Immersion
Cm-244	Internal
Co-60	Soil Immersion, On Ground, Above Ground and Air Immersion
Cs-135	Internal and Water Immersion
Cs-137	Internal, Water Immersion, Soil Immersion, On Ground, Above Ground and Air Immersion
Eu-154	Internal, Water Immersion, Soil Immersion, On Ground, Above Ground and Air Immersion
I-129	Internal, Water Immersion, Soil Immersion, On Ground, Above Ground and Air Immersion
K-40	Water Immersion, Soil Immersion, On Ground, Above Ground and Air Immersion
Nb-94	Internal, Water Immersion, Soil Immersion, On Ground, Above Ground and Air Immersion
Ni-59	Soil Immersion, On Ground and Air Immersion
Np-237	Internal, Water Immersion, Soil Immersion, On Ground, Above Ground and Air Immersion
Pa-231	Internal, Water Immersion, Soil Immersion, On Ground, Above Ground and Air Immersion
Pb-210	Internal and Water Immersion
Po-210	Internal, on Ground and Air Immersion
Pu-238	Internal
Pu-239	Internal, Water Immersion, Soil Immersion, On Ground, Above Ground and Air Immersion
Pu-240	Internal, Water Immersion, Soil Immersion, On Ground, Above Ground and Air Immersion
Pu-241	Internal
Ra-226	Internal, Water Immersion, Soil Immersion, On Ground, Above Ground and Air Immersion
Se-79	Internal and Water Immersion
Sr-90	Internal and Water Immersion
Tc-99	Internal, Water Immersion, Soil Immersion, On Ground, Above Ground and Air Immersion
Th-227	Internal, Water Immersion, Soil Immersion, On Ground, Above Ground and Air Immersion
Th-228	Internal, Water Immersion, Soil Immersion, On Ground and Air Immersion
Th-229	Internal, Water Immersion, Soil Immersion, On Ground, Above Ground and Air Immersion
Th-230	Internal
Th-234	Internal, Water Immersion, Soil Immersion, On Ground, Above Ground and Air Immersion
U-233	Internal
U-234	On Ground and Air Immersion
U-235	Internal, Water Immersion, Soil Immersion, On Ground, Above Ground and Air Immersion
U-238	Internal

4.3 CHEMICAL HAZARD SCREENING

The purpose of the chemical hazard screening assessment is to identify elements in the fuel and Zircaloy cladding which could contribute significantly to chemical hazard consequences in detailed safety assessments.

4.3.1 Chemical Hazard Screening Methodology

Section 6.2.5 of CSA (2012) provides guidance on screening of chemically hazardous species and recommends that the maximum measured or modelled amounts of contaminants at receptor locations should be compared to criteria. Such an analysis requires a number of assumptions which can be difficult to justify in this general screening context. For example, the area or volume in which a contaminant is diluted can greatly impact which elements are identified for further study.

This screening assessment avoids use of arbitrary assumptions such as water, soil or air volumes by determining the volume of an environmental media (surface water, groundwater, soil, sediment or air) required for an individual element to meet the acceptance criteria described in Section 2.4. The species requiring the largest dilution volumes are considered the most hazardous and are screened in for consideration in future detailed assessments. This approach is similar to that described in Jones et al. (2010).

Given the simple nature of this screening assessment, results will be applicable to both preclosure and postclosure assessments. Results are also applicable to both humans and non-human biota as the selected chemical hazard acceptance criteria ensure both groups are protected.

4.3.2 Screening Criteria

This assessment will include the species requiring 0.1% of the largest dilution volume to meet the criteria defined in Section 2.4 for further study in detailed assessments.

4.3.3 Chemical Hazard Screening Results

This section presents the results of the chemical hazard screening assessment. The chemical hazard screening assessment methodology is described in Section 4.3.1. The final set of elements for consideration in future detailed assessments are shown in Table 8.

In total 18 elements are identified for further study in more detailed preclosure and postclosure studies. Section 4.3.4 compares the results of this screening with other similar assessments.

Table 8: Chemical Hazard Screening Results

Surface Water	Groundwater	Soil	Sediment	Air	Combined
Ag	Ag		Ag		Ag
			Ba		Ba
Cd			Cd		Cd
Cr		Cr		Cr	Cr
Pb		Cs	Cs		Cs
Hg			Pd		Hg
La	La				La
		Mo	Mo		Mo
Nd					Nd
			Pb		Pb
Pd	Pd	Pd			Pd
		Rb	Rb		Rb
		Rh			Rh
		Ru			Ru
		Sn			Sn
		Te			Te
U	U	U	U	U	U
Zr	Zr	Zr	Zr		Zr

4.3.4 Comparison with Other Assessments

This section compares the screening results in Table 8 with those from previous NWMO assessments (NWMO 2011, NWMO 2016, NWMO 2017) as well as other non-radiological assessments (CNL 2021, Jones et al. 2010, Neall et al. 2007) conducted by other waste management organizations. Table 9 compares elements identified in this assessment with those included in other assessments. Elements common between this assessment and other assessments are highlighted in blue.

It should be noted that some of the other assessments (NWMO 2011, CNL 2021) include a more comprehensive list of non-radiological hazards and include several hazardous chemical compounds (e.g., dioxins, furians, PCBs) and other irritants (e.g., odours). This assessment focuses purely on the hazard posed by elements in the fuel. Therefore, only potentially hazardous elements are compared between references.

Table 9: Comparison of Chemical Elements Considered in Other Assessments

This Assessment	NWMO (2011)	NWMO (2016)	NWMO (2017)	CNL (2021)	Jones et al. (2010)	Neall et al. (2007)
Ag		Ag	Ag	Ag	Ag	
				Al	Al	
	As			As		
				B		
Ba	Ba			Ba	Ba	
	Be			Be		
		Bi				Bi
		Br		Br		
						Ca
Cd	Cd	Cd		Cd	Cd	
					Ce	
	Co			Co	Co	Co
Cr	Cr			Cr	Cr	Cr
Cs						Cs
	Cu			Cu	Cu	
				Fe	Fe	Fe
				Gd		
Hg	Hg	Hg	Hg	Hg		
		I		I		I
La					La	
				Li		
	Mn			Mn	Mn	Mn
Mo		Mo	Mo	Mo	Mo	Mo
				Nb		Nb
Nd			Nd		Nd	
	Ni			Ni	Ni	Ni
Pb	Pb			Pb	Pb	Pb
Pd			Pd			Pd
					Pr	
Rb						Rb
Rh			Rh			
Ru			Ru			
	Sb	Sb		Sb	Sb	
				Sc		
	Se	Se		Se		
					Sm	
Sn				Sn	Sn	Sn
	Sr			Sr		Sr
		Tc				Tc
Te		Te		Te		Te

This Assessment	NWMO (2011)	NWMO (2016)	NWMO (2017)	CNL (2021)	Jones et al. (2010)	Neall et al. (2007)
				Tl		
						Th
						Ti
U	U	U		U	U	U
				V	V	
		W		W		
					Y	
	Zn			Zn		
Zr	Zr			Zr		

In general, the list of elements identified for more detailed study in this assessment are similar to those from other assessments with several key elements (e.g., Ag, Cd, Cr, Hg, Mo, Ni, Pb, and U) being common across several of the studies despite significant differences in methodologies, criteria and wasteforms considered.

Some of the studies considered (NWMO 2011, CNL 2021) are for broader nuclear waste management application such as the disposal of low and intermediate level waste and can have more substantial inventories of several species not found in the fuel in significant quantities (e.g., Zn).

Jones et al. 2010 and Neall et al. 2007 identify potentially hazardous elements within the KBS disposal concept used by SKB and Posiva. Both these assessments consider the hazard associated with the fuel as well as the canister, which leads to Cu and Fe being considered. The present assessment considers only elements in the fuel; Fe and Cu will likely be considered in a more holistic assessment of the potential hazard associated with Canadian disposal concept.

Species identified in this assessment but not widely considered in the other assessments include Cs, La, Pd, Rb, Rh, Ru and Zr. Many of these species have significant inventories in CANDU fuel. The absence of these species from other studies could be explained by a lack of hazard criteria for these elements, as well as differences in the assessment methodologies and wasteforms.

5. SUMMARY AND CONCLUSIONS

The NWMO is responsible for the safe long-term containment and isolation of used nuclear fuel. This will be accomplished in part through placing the used fuel in a deep geologic repository. Used nuclear fuel contains hundreds of different isotopes arising from fission, neutron activation and decay processes.

As part of the repository safety assessment, the risk due to these various radionuclides and chemical elements is assessed. However, there is huge range in both the concentration and in the hazard of each of these various species (radionuclides and chemical elements). Many of these species are of no concern due to their low concentration and low intrinsic hazard. In this screening assessment, those species that are potentially important are identified for consideration in more detailed safety assessments.

Section 2 and Appendix A of this report provide the isotope inventory data (Section 2.1), decay and half-life data (Section 2.2), dose conversion factor data (Section 2.3) and chemical hazard criteria data (Section 2.4) required to assess the hazard associated with the fuel.

Using the data from Section 2 and Appendix A, Section 3 provides some indication of the radiological hazard associated with the fuel considering all radionuclides in the fuel. Section 3.1 and Section 3.2 present the fuel activity and fuel radiotoxicity for a range of expected fuel burnups and maximum powers respectively. In general, the fuel activity and radiotoxicity were found to initially be controlled by shorter lived fission products. However, after about 1000 years after discharge the actinides were found to control the fuel activity and radiotoxicity.

Section 4 of this report details a simple assessment used to identify those isotopes in the fuel which should be considered in more detailed assessments. The screened-out isotopes are present only in small concentrations and/or low have low intrinsic hazard.

Section 4.1 and Table 5 detail the three radionuclides screening assessments which identified:

- 27 radionuclides for consideration in detailed preclosure assessments;
- 40 radionuclides for consideration in detailed postclosure assessments; and
- 38 radionuclides for consideration in detailed inadvertent human intrusion assessments.

In total 59 unique radionuclides were screened-in for consideration in more detailed assessments. Results of the radionuclide screenings were compared against radionuclides considered in previous NWMO assessments and assessments conducted by other waste management organizations. In general, the set of radionuclides identified in this assessment were found to be similar to those considered in other assessments.

Section 4.2 and Table 7 detail the non-human biota radionuclide screening assessment which identified 33 radionuclides for consideration in detailed safety assessments. The radionuclides identified in this screening were found to be similar to those in the radionuclides screening in Section 4.1 with all but two of the radionuclides being the same. Key radionuclides from other non-human biota assessments were also compared to the set of screened in radionuclides and all key radionuclides were identified in this assessment.

Section 4.3 and Table 8 detail the chemical hazard screening assessment which identified 22 chemically hazardous elements for consideration in detailed assessments. Results of the chemical hazard screening analysis were compared against species considered in previous NWMO assessments and assessments conducted by other waste management organizations. In general, many of the elements identified in this assessment were also considered in other assessments.

The complete set of radionuclides and chemically hazardous elements identified in this assessment as summarized in Table 10.

Finally, it is recognized that this report considers only CANDU fuel for which data is available and that different fuel types such experimental fuels or fuels from small modular reactors could change the results of the hazard and screening assessments. These fuels will need to be assessed in the future once data become available.

Table 10: Summary of All Screening Results

Radionuclide / Element	Preclosure	Postclosure	Human Intrusion	Non-Human Biota	Chemical Hazard
Ac-225		✓	✓		
Ac-227		✓	✓		
Ag					✓
Ag-108m		✓			
Am-241	✓	✓	✓	✓	
Am-243	✓	✓	✓		
Ba					✓
Bi-210		✓	✓		
C-14	✓	✓		✓	
Cd					✓
Ce-144	✓				
Cl-36	✓	✓	✓	✓	
Cm-244	✓			✓	
Co-60	✓			✓	
Cr					✓
Cs					✓
Cs-134	✓				
Cs-135		✓		✓	
Cs-137	✓		✓	✓	
Eu-154	✓			✓	
Eu-155	✓				
H3	✓				
Hg					✓
I-129	✓	✓	✓	✓	
K-40				✓	
Kr-85	✓				
La					✓
Mo					✓
Nb-93m		✓			
Nb-94		✓	✓	✓	
Nd					✓
Ni-59				✓	
Np-237		✓	✓	✓	
Np-239		✓	✓		
Pa-231		✓	✓	✓	
Pa-233		✓	✓		
Pb					✓
Pb-210		✓	✓	✓	
Pd					✓

Radionuclide / Element	Preclosure	Postclosure	Human Intrusion	Non-Human Biota	Chemical Hazard
Pd-107		✓			
Pm-147	✓				
Po-210		✓	✓	✓	
Pu-238	✓		✓	✓	
Pu-239	✓	✓	✓	✓	
Pu-240	✓	✓	✓	✓	
Pu-241	✓			✓	
Pu-242		✓	✓		
Ra-223		✓	✓		
Ra-224	✓		✓		
Ra-225		✓	✓		
Ra-226		✓	✓	✓	
Rb					✓
Rh					✓
Rn-222		✓	✓		
Ru					✓
Ru-106	✓				
Sb-125	✓				
Sb-126		✓	✓		
Se-79	✓	✓		✓	
Sn					✓
Sn-126		✓	✓		
Sr-90	✓		✓	✓	
Tc-99		✓	✓	✓	
Te					✓
Th-227		✓	✓	✓	
Th-228	✓			✓	
Th-229		✓	✓	✓	
Th-230		✓	✓	✓	
Th-234		✓	✓	✓	
U					✓
U-232	✓				
U-233		✓	✓	✓	
U-234		✓	✓	✓	
U-235		✓	✓	✓	
U-236		✓	✓		
U-238		✓	✓	✓	
Y-90	✓		✓		
Zr					✓
Zr-93		✓			

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APPENDIX A: SUPPORTING DATA

A.1 Inventory Data

The inventory of the various isotopes and element in the used fuel is shown in the tables below. Table 11 through Table 14 show the fuel and Zircaloy inventories for radionuclides and chemical elements identified in Section 4 for 220 MWh/kgU burnup 37R fuel for a variety of times after discharge from the reactor. Table 15 through Table 18 show the fuel and Zircaloy inventories for radionuclides and chemically elements identified in Section 4 for 290 MWh/kgU burnup 37R fuel for a variety of times after discharge from the reactor. Fuel inventories are listed in mol/kgU and Zircaloy inventories are listed in mol/kgZr. Inventories data for all isotopes and elements are provided in the data files associated with Heckman and Edward (2020).

Table 11: 220 MWh/kgU Burnup Fuel Radionuclide Inventory

Fuel Radionuclide Inventory [mol/kgU]										
Isotope \ Time	0 [a]	10 [a]	30 [a]	100 [a]	300 [a]	10^3 [a]	10^4 [a]	10^5 [a]	10^6 [a]	10^7 [a]
Ac-225	4.07E-14	9.34E-15	2.12E-14	6.24E-14	1.79E-13	5.69E-13	3.98E-12	1.01E-11	1.31E-11	6.68E-13
Ac-227	1.49E-11	4.68E-10	1.04E-09	1.60E-09	1.67E-09	1.65E-09	1.41E-09	6.44E-10	5.73E-10	5.68E-10
Ag-108m	1.57E-09	1.54E-09	1.49E-09	1.34E-09	9.74E-10	3.22E-10	2.10E-16	0.00E+00	0.00E+00	0.00E+00
Am-241	9.48E-06	4.52E-04	8.73E-04	1.02E-03	7.48E-04	2.44E-04	6.87E-10	3.79E-13	0.00E+00	0.00E+00
Am-243	2.35E-05	2.36E-05	2.35E-05	2.34E-05	2.29E-05	2.15E-05	9.21E-06	1.94E-09	2.88E-15	1.93E-15
Bi-210	1.47E-11	6.00E-16	3.27E-16	1.52E-16	1.84E-15	1.93E-14	7.72E-13	6.91E-12	1.29E-11	1.27E-11
C-14	6.69E-06	6.68E-06	6.66E-06	6.61E-06	6.45E-06	5.92E-06	1.98E-06	3.50E-11	0.00E+00	0.00E+00
Ce-144	1.38E-03	1.91E-07	3.64E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cl-36	9.77E-06	9.77E-06	9.77E-06	9.77E-06	9.77E-06	9.75E-06	9.55E-06	7.76E-06	9.77E-07	9.73E-16
Cm-244	2.12E-06	1.44E-06	6.72E-07	4.61E-08	2.18E-11	5.03E-23	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Co-60	4.04E-07	1.08E-07	7.81E-09	7.85E-13	2.15E-16	2.15E-16	2.14E-16	2.05E-16	1.35E-16	2.11E-18
Cs-134	1.08E-04	3.77E-06	4.58E-09	2.86E-19	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cs-135	1.77E-04	1.82E-04	1.82E-04	1.82E-04	1.82E-04	1.82E-04	1.81E-04	1.76E-04	1.34E-04	8.92E-06
Cs-137	2.51E-03	1.99E-03	1.26E-03	2.50E-04	2.49E-06	2.46E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Eu-154	2.07E-05	9.26E-06	1.85E-06	6.55E-09	6.54E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Eu-155	1.24E-05	2.89E-06	1.56E-07	5.75E-12	1.23E-24	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
H-3	9.79E-06	5.58E-06	1.81E-06	3.53E-08	4.57E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
I-129	3.33E-04	3.41E-04	3.41E-04	3.41E-04	3.41E-04	3.41E-04	3.41E-04	3.40E-04	3.27E-04	2.19E-04
K-40	2.46E-06	2.46E-06	2.46E-06	2.46E-06	2.46E-06	2.46E-06	2.46E-06	2.46E-06	2.45E-06	2.44E-06
Kr-85	8.33E-05	4.38E-05	1.21E-05	1.32E-07	3.34E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nb-93m	7.17E-10	7.74E-09	1.53E-08	2.06E-08	2.08E-08	2.08E-08	2.07E-08	1.99E-08	1.32E-08	2.24E-10
Nb-94	5.39E-08	5.39E-08	5.39E-08	5.37E-08	5.34E-08	5.21E-08	3.83E-08	1.77E-09	7.97E-23	0.00E+00
Ni-59	2.17E-06	2.17E-06	2.17E-06	2.17E-06	2.16E-06	2.15E-06	1.98E-06	8.72E-07	2.37E-10	0.00E+00
Np-237	1.46E-04	1.60E-04	1.83E-04	2.96E-04	5.78E-04	1.08E-03	1.32E-03	1.28E-03	9.60E-04	5.23E-05
Np-239	5.26E-04	2.06E-11	2.06E-11	2.05E-11	2.01E-11	1.88E-11	8.06E-12	1.70E-15	2.52E-21	1.69E-21

Fuel Radionuclide Inventory [mol/kgU]										
Isotope \ Time	0 [a]	10 [a]	30 [a]	100 [a]	300 [a]	10^3 [a]	10^4 [a]	10^5 [a]	10^6 [a]	10^7 [a]
Pa-231	2.52E-06	2.52E-06	2.52E-06	2.52E-06	2.51E-06	2.47E-06	2.12E-06	9.69E-07	8.63E-07	8.55E-07
Pa-233	9.15E-06	5.53E-12	6.30E-12	1.02E-11	1.99E-11	3.73E-11	4.56E-11	4.43E-11	3.31E-11	1.80E-12
Pb-210	1.07E-12	9.71E-13	5.28E-13	2.46E-13	2.97E-12	3.12E-11	1.25E-09	1.12E-08	2.09E-08	2.05E-08
Pd-107	6.79E-04	6.79E-04	6.79E-04	6.79E-04	6.79E-04	6.79E-04	6.78E-04	6.72E-04	6.10E-04	2.34E-04
Pm-147	5.48E-04	4.26E-05	2.16E-07	2.00E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Po-210	2.69E-10	1.66E-14	9.02E-15	4.20E-15	5.07E-14	5.32E-13	2.13E-11	1.91E-10	3.56E-10	3.50E-10
Pu-238	2.07E-05	2.26E-05	1.93E-05	1.11E-05	2.30E-06	9.32E-09	4.39E-29	0.00E+00	0.00E+00	0.00E+00
Pu-239	1.08E-02	1.13E-02	1.13E-02	1.13E-02	1.12E-02	1.10E-02	8.48E-03	6.39E-04	1.31E-14	6.32E-15
Pu-240	5.25E-03	5.25E-03	5.24E-03	5.20E-03	5.09E-03	4.73E-03	1.83E-03	1.36E-07	6.61E-13	6.12E-13
Pu-241	1.16E-03	7.15E-04	2.71E-04	9.08E-06	5.95E-10	3.81E-11	1.83E-11	1.19E-14	0.00E+00	0.00E+00
Pu-242	4.13E-04	4.13E-04	4.13E-04	4.13E-04	4.13E-04	4.12E-04	4.05E-04	3.43E-04	6.45E-05	3.59E-12
Ra-223	1.86E-14	6.72E-13	1.49E-12	2.30E-12	2.40E-12	2.37E-12	2.02E-12	9.26E-13	8.24E-13	8.17E-13
Ra-224	3.02E-11	2.46E-10	2.06E-10	1.02E-10	1.36E-11	1.34E-14	1.48E-15	1.49E-15	1.66E-15	3.06E-15
Ra-225	7.66E-14	1.39E-14	3.15E-14	9.30E-14	2.66E-13	8.48E-13	5.94E-12	1.51E-11	1.95E-11	9.95E-13
Ra-226	1.53E-14	3.24E-13	2.33E-12	2.42E-11	2.14E-10	2.25E-09	9.00E-08	8.06E-07	1.50E-06	1.48E-06
Rn-222	9.38E-20	2.12E-18	1.53E-17	1.58E-16	1.40E-15	1.47E-14	5.89E-13	5.27E-12	9.85E-12	9.67E-12
Ru-106	7.89E-04	8.70E-07	1.06E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sb-125	2.64E-05	2.22E-06	1.46E-08	3.34E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sb-126	4.80E-08	1.02E-12	1.02E-12	1.02E-12	1.02E-12	1.01E-12	9.86E-13	7.52E-13	4.99E-14	8.27E-26
Se-79	1.63E-05	1.63E-05	1.63E-05	1.63E-05	1.63E-05	1.62E-05	1.59E-05	1.29E-05	1.55E-06	1.01E-15
Sn-126	4.94E-05	4.94E-05	4.94E-05	4.94E-05	4.93E-05	4.92E-05	4.79E-05	3.65E-05	2.42E-06	4.02E-18
Sr-90	1.56E-03	1.23E-03	7.59E-04	1.41E-04	1.14E-06	5.46E-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Tc-99	2.39E-03	2.43E-03	2.43E-03	2.43E-03	2.42E-03	2.42E-03	2.35E-03	1.75E-03	9.10E-05	1.33E-17
Th-227	3.06E-14	1.08E-12	2.40E-12	3.72E-12	3.86E-12	3.81E-12	3.26E-12	1.49E-12	1.33E-12	1.32E-12
Th-228	5.94E-09	4.69E-08	3.94E-08	1.95E-08	2.60E-09	2.56E-12	2.82E-13	2.85E-13	3.16E-13	5.84E-13
Th-229	9.20E-10	2.50E-09	5.68E-09	1.67E-08	4.79E-08	1.53E-07	1.07E-06	2.71E-06	3.51E-06	1.79E-07
Th-230	8.42E-10	5.88E-09	1.61E-08	5.31E-08	1.64E-07	5.60E-07	5.45E-06	3.80E-05	7.09E-05	6.96E-05

Fuel Radionuclide Inventory [mol/kgU]										
Isotope \ Time	**0 [a]**	**10 [a]**	**30 [a]**	**100 [a]**	**300 [a]**	**10^3 [a]**	**10^4 [a]**	**10^5 [a]**	**10^6 [a]**	**10^7 [a]**
Th-234	2.69E-09	6.10E-11	6.10E-11	6.10E-11	6.10E-11	6.10E-11	6.10E-11	6.10E-11	6.10E-11	6.09E-11
U-232	1.85E-06	1.69E-06	1.38E-06	6.82E-07	9.12E-08	7.97E-11	1.25E-15	8.31E-16	1.41E-17	2.75E-35
U-233	2.74E-05	3.65E-05	3.65E-05	3.65E-05	3.65E-05	3.66E-05	3.89E-05	5.76E-05	7.61E-05	3.88E-06
U-234	1.77E-04	1.79E-04	1.83E-04	1.91E-04	2.00E-04	2.02E-04	2.03E-04	2.08E-04	2.26E-04	2.27E-04
U-235	7.23E-03	7.24E-03	7.24E-03	7.27E-03	7.33E-03	7.55E-03	1.01E-02	1.79E-02	1.85E-02	1.84E-02
U-236	3.42E-03	3.43E-03	3.44E-03	3.48E-03	3.59E-03	3.95E-03	6.85E-03	8.65E-03	8.43E-03	6.45E-03
U-238	4.13E+00	4.13E+00	4.13E+00	4.13E+00	4.13E+00	4.13E+00	4.13E+00	4.13E+00	4.13E+00	4.13E+00
Y-90	4.40E-07	3.12E-07	1.93E-07	3.57E-08	2.89E-10	1.38E-17	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Zr-93	2.02E-03	2.03E-03	2.03E-03	2.03E-03	2.03E-03	2.03E-03	2.02E-03	1.94E-03	1.29E-03	2.18E-05

Table 12: 220 MWh/kgU Burnup Zircaloy Radionuclide Inventory

Zircaloy Radionuclide Inventory [mol/kgZr]										
Time / Isotope	0 [a]	10 [a]	30 [a]	100 [a]	300 [a]	10^3 [a]	10^4 [a]	10^5 [a]	10^6 [a]	10^7 [a]
Ac-225	1.87E-18	4.30E-19	9.74E-19	2.87E-18	8.22E-18	2.62E-17	1.83E-16	4.65E-16	6.02E-16	3.07E-17
Ac-227	6.86E-16	2.15E-14	4.77E-14	7.38E-14	7.67E-14	7.57E-14	6.48E-14	2.96E-14	2.64E-14	2.61E-14
Ag-108m	1.59E-08	1.56E-08	1.52E-08	1.36E-08	9.88E-09	3.26E-09	2.13E-15	0.00E+00	0.00E+00	0.00E+00
Am-241	4.36E-10	2.08E-08	4.02E-08	4.70E-08	3.44E-08	1.12E-08	3.16E-14	1.74E-17	0.00E+00	0.00E+00
Am-243	1.08E-09	1.08E-09	1.08E-09	1.07E-09	1.05E-09	9.88E-10	4.24E-10	8.93E-14	1.32E-19	8.88E-20
Bi-210	4.36E-12	3.60E-19	1.93E-19	2.70E-20	8.45E-20	8.86E-19	3.55E-17	3.18E-16	5.94E-16	5.83E-16
C-14	2.38E-05	2.38E-05	2.37E-05	2.35E-05	2.30E-05	2.11E-05	7.06E-06	1.25E-10	0.00E+00	0.00E+00
Ce-144	6.34E-08	8.77E-12	1.67E-19	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cl-36	4.33E-05	4.33E-05	4.33E-05	4.33E-05	4.33E-05	4.32E-05	4.23E-05	3.44E-05	4.33E-06	4.31E-15
Cm-244	9.73E-11	6.64E-11	3.09E-11	2.12E-12	1.00E-15	2.32E-27	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Co-60	2.58E-05	6.92E-06	4.99E-07	5.01E-11	6.95E-15	6.95E-15	6.92E-15	6.64E-15	4.38E-15	6.84E-17
Cs-134	1.38E-07	4.82E-09	5.86E-12	3.66E-22	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cs-135	3.16E-08	3.18E-08	3.18E-08	3.18E-08	3.18E-08	3.18E-08	3.18E-08	3.09E-08	2.35E-08	1.57E-09
Cs-137	1.15E-07	9.17E-08	5.78E-08	1.15E-08	1.15E-10	1.13E-17	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Eu-154	7.91E-09	3.54E-09	7.06E-10	2.50E-12	2.50E-19	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Eu-155	3.78E-09	8.77E-10	4.74E-11	1.74E-15	3.75E-28	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
H-3	4.93E-06	2.80E-06	9.10E-07	1.77E-08	2.30E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
I-129	3.18E-08	3.23E-08	3.23E-08	3.23E-08	3.23E-08	3.23E-08	3.23E-08	3.22E-08	3.09E-08	2.08E-08
K-40	1.43E-06	1.43E-06	1.43E-06	1.43E-06	1.43E-06	1.43E-06	1.43E-06	1.44E-06	1.43E-06	1.42E-06
Kr-85	3.95E-09	2.08E-09	5.72E-10	6.28E-12	1.59E-17	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nb-93m	3.87E-08	2.96E-08	1.99E-08	1.31E-08	1.28E-08	1.28E-08	1.27E-08	1.21E-08	8.07E-09	1.37E-10
Nb-94	5.03E-06	5.03E-06	5.02E-06	5.01E-06	4.98E-06	4.86E-06	3.57E-06	1.65E-07	7.43E-21	0.00E+00
Ni-59	4.94E-05	4.94E-05	4.94E-05	4.93E-05	4.92E-05	4.89E-05	4.51E-05	1.98E-05	5.40E-09	0.00E+00
Np-237	6.74E-09	7.38E-09	8.41E-09	1.36E-08	2.66E-08	4.98E-08	6.08E-08	5.91E-08	4.42E-08	2.41E-09
Np-239	2.42E-08	9.49E-16	9.47E-16	9.41E-16	9.23E-16	8.65E-16	3.71E-16	7.81E-20	1.16E-25	7.77E-26

Zircaloy Radionuclide Inventory [mol/kgZr]										
Time / Isotope	0 [a]	10 [a]	30 [a]	100 [a]	300 [a]	10^3 [a]	10^4 [a]	10^5 [a]	10^6 [a]	10^7 [a]
Pa-231	1.16E-10	1.16E-10	1.16E-10	1.16E-10	1.15E-10	1.14E-10	9.74E-11	4.46E-11	3.97E-11	3.93E-11
Pa-233	4.21E-10	2.54E-16	2.90E-16	4.69E-16	9.17E-16	1.72E-15	2.10E-15	2.04E-15	1.52E-15	8.29E-17
Pb-210	7.83E-16	5.81E-16	3.12E-16	4.36E-17	1.37E-16	1.43E-15	5.75E-14	5.15E-13	9.61E-13	9.44E-13
Pd-107	6.42E-08	6.42E-08	6.42E-08	6.42E-08	6.42E-08	6.42E-08	6.41E-08	6.35E-08	5.77E-08	2.21E-08
Pm-147	2.53E-08	1.97E-09	9.98E-12	9.25E-20	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Po-210	8.00E-11	1.09E-17	5.32E-18	7.45E-19	2.33E-18	2.45E-17	9.80E-16	8.78E-15	1.64E-14	1.61E-14
Pu-238	9.51E-10	1.04E-09	8.90E-10	5.12E-10	1.06E-10	4.29E-13	2.02E-33	0.00E+00	0.00E+00	0.00E+00
Pu-239	4.95E-07	5.19E-07	5.19E-07	5.18E-07	5.15E-07	5.05E-07	3.90E-07	2.94E-08	6.03E-19	2.91E-19
Pu-240	2.42E-07	2.41E-07	2.41E-07	2.39E-07	2.34E-07	2.17E-07	8.40E-08	6.23E-12	3.04E-17	2.82E-17
Pu-241	5.34E-08	3.29E-08	1.25E-08	4.17E-10	2.74E-14	1.75E-15	8.42E-16	5.47E-19	0.00E+00	0.00E+00
Pu-242	1.90E-08	1.90E-08	1.90E-08	1.90E-08	1.90E-08	1.90E-08	1.86E-08	1.58E-08	2.97E-09	1.65E-16
Ra-223	8.54E-19	3.09E-17	6.85E-17	1.06E-16	1.10E-16	1.09E-16	9.31E-17	4.26E-17	3.79E-17	3.76E-17
Ra-224	1.39E-15	1.13E-14	9.49E-15	4.70E-15	6.28E-16	6.16E-19	6.80E-20	6.87E-20	7.62E-20	1.41E-19
Ra-225	3.52E-18	6.40E-19	1.45E-18	4.28E-18	1.22E-17	3.90E-17	2.73E-16	6.92E-16	8.97E-16	4.58E-17
Ra-226	7.05E-19	1.49E-17	1.07E-16	1.11E-15	9.84E-15	1.03E-13	4.14E-12	3.71E-11	6.92E-11	6.80E-11
Rn-222	4.32E-24	9.74E-23	7.02E-22	7.27E-21	6.44E-20	6.76E-19	2.71E-17	2.43E-16	4.53E-16	4.45E-16
Ru-106	3.63E-08	4.00E-11	4.86E-17	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sb-125	1.08E-05	8.78E-07	5.77E-09	1.32E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sb-126	4.36E-09	4.77E-17	4.77E-17	4.77E-17	4.76E-17	4.75E-17	4.63E-17	3.53E-17	2.34E-18	3.88E-30
Se-79	5.30E-09	5.30E-09	5.31E-09	5.31E-09	5.30E-09	5.30E-09	5.18E-09	4.20E-09	5.07E-10	3.31E-19
Sn-126	2.32E-09	2.32E-09	2.32E-09	2.32E-09	2.31E-09	2.31E-09	2.25E-09	1.71E-09	1.14E-10	1.88E-22
Sr-90	7.22E-08	5.68E-08	3.51E-08	6.50E-09	5.27E-11	2.52E-18	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Tc-99	2.69E-07	2.74E-07	2.74E-07	2.74E-07	2.74E-07	2.73E-07	2.65E-07	1.98E-07	1.03E-08	1.50E-21
Th-227	1.41E-18	4.98E-17	1.10E-16	1.71E-16	1.78E-16	1.75E-16	1.50E-16	6.86E-17	6.11E-17	6.06E-17
Th-228	2.73E-13	2.16E-12	1.81E-12	8.96E-13	1.20E-13	1.18E-16	1.30E-17	1.31E-17	1.45E-17	2.69E-17
Th-229	4.23E-14	1.15E-13	2.61E-13	7.70E-13	2.20E-12	7.02E-12	4.91E-11	1.25E-10	1.61E-10	8.24E-12
Th-230	3.87E-14	2.71E-13	7.41E-13	2.44E-12	7.54E-12	2.58E-11	2.51E-10	1.75E-09	3.26E-09	3.20E-09

Zircaloy Radionuclide Inventory [mol/kgZr]										
Isotope / Time	0 [a]	10 [a]	30 [a]	100 [a]	300 [a]	10^3 [a]	10^4 [a]	10^5 [a]	10^6 [a]	10^7 [a]
Th-234	1.24E-13	2.81E-15	2.81E-15	2.81E-15	2.81E-15	2.81E-15	2.81E-15	2.81E-15	2.81E-15	2.80E-15
U-232	8.52E-11	7.76E-11	6.35E-11	3.14E-11	4.20E-12	3.67E-15	5.74E-20	3.82E-20	6.47E-22	1.26E-39
U-233	1.26E-09	1.68E-09	1.68E-09	1.68E-09	1.68E-09	1.68E-09	1.79E-09	2.65E-09	3.50E-09	1.79E-10
U-234	8.16E-09	8.25E-09	8.40E-09	8.78E-09	9.19E-09	9.30E-09	9.32E-09	9.58E-09	1.04E-08	1.04E-08
U-235	3.33E-07	3.33E-07	3.33E-07	3.34E-07	3.37E-07	3.47E-07	4.63E-07	8.24E-07	8.52E-07	8.45E-07
U-236	1.57E-07	1.58E-07	1.58E-07	1.60E-07	1.65E-07	1.82E-07	3.15E-07	3.98E-07	3.88E-07	2.97E-07
U-238	1.90E-04	1.90E-04	1.90E-04	1.90E-04	1.90E-04	1.90E-04	1.90E-04	1.90E-04	1.90E-04	1.90E-04
Y-90	3.10E-08	1.44E-11	8.90E-12	1.65E-12	1.34E-14	6.40E-22	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Zr-93	1.24E-03	1.24E-03	1.24E-03	1.24E-03	1.24E-03	1.23E-03	1.23E-03	1.18E-03	7.85E-04	1.33E-05

Table 13: 220 MWh/kgU Burnup Fuel Element Inventory

Fuel Element Inventory [mol/kgU]										
Time / Element	0 [a]	10 [a]	30 [a]	100 [a]	300 [a]	10^3 [a]	10^4 [a]	10^5 [a]	10^6 [a]	10^7 [a]
Ag	2.74E-04	2.74E-04	2.74E-04	2.74E-04	2.74E-04	2.74E-04	2.74E-04	2.74E-04	2.74E-04	2.74E-04
Ba	2.78E-03	2.78E-03	2.78E-03	2.78E-03	2.78E-03	2.78E-03	2.78E-03	2.78E-03	2.78E-03	2.78E-03
Cd	1.80E-04	1.80E-04	1.80E-04	1.80E-04	1.80E-04	1.80E-04	1.80E-04	1.80E-04	1.80E-04	1.80E-04
Cr	2.80E-04	2.80E-04	2.80E-04	2.80E-04	2.80E-04	2.80E-04	2.80E-04	2.80E-04	2.80E-04	2.80E-04
Cs	5.27E-03	5.27E-03	5.27E-03	5.27E-03	5.27E-03	5.27E-03	5.27E-03	5.27E-03	5.27E-03	5.27E-03
Hg	2.47E-06	2.47E-06	2.47E-06	2.47E-06	2.47E-06	2.47E-06	2.47E-06	2.47E-06	2.47E-06	2.47E-06
La	2.41E-03	2.41E-03	2.41E-03	2.41E-03	2.41E-03	2.41E-03	2.41E-03	2.41E-03	2.41E-03	2.41E-03
Mo	8.36E-03	8.36E-03	8.36E-03	8.36E-03	8.36E-03	8.36E-03	8.36E-03	8.36E-03	8.36E-03	8.36E-03
Nd	6.01E-03	6.01E-03	6.01E-03	6.01E-03	6.01E-03	6.01E-03	6.01E-03	6.01E-03	6.01E-03	6.01E-03
Pb	4.18E-06	4.18E-06	4.18E-06	4.18E-06	4.18E-06	4.18E-06	4.18E-06	4.18E-06	4.18E-06	4.18E-06
Pd	2.95E-03	2.95E-03	2.95E-03	2.95E-03	2.95E-03	2.95E-03	2.95E-03	2.95E-03	2.95E-03	2.95E-03
Rb	1.02E-03	1.02E-03	1.02E-03	1.02E-03	1.02E-03	1.02E-03	1.02E-03	1.02E-03	1.02E-03	1.02E-03
Rh	1.25E-03	1.25E-03	1.25E-03	1.25E-03	1.25E-03	1.25E-03	1.25E-03	1.25E-03	1.25E-03	1.25E-03
Ru	7.33E-03	7.33E-03	7.33E-03	7.33E-03	7.33E-03	7.33E-03	7.33E-03	7.33E-03	7.33E-03	7.33E-03
Sn	1.47E-04	1.47E-04	1.47E-04	1.47E-04	1.47E-04	1.47E-04	1.47E-04	1.47E-04	1.47E-04	1.47E-04
Te	1.13E-03	1.13E-03	1.13E-03	1.13E-03	1.13E-03	1.13E-03	1.13E-03	1.13E-03	1.13E-03	1.13E-03
U	4.14E+00	4.14E+00	4.14E+00	4.14E+00	4.14E+00	4.14E+00	4.14E+00	4.14E+00	4.14E+00	4.14E+00
Zr	1.02E-02	1.02E-02	1.02E-02	1.02E-02	1.02E-02	1.02E-02	1.02E-02	1.02E-02	1.02E-02	1.02E-02

Table 14: 220 MWh/kgU Burnup Zircaloy Element Inventory

Zircaloy Element Inventory [mol/kgZr]										
Time / Element	0 [a]	10 [a]	30 [a]	100 [a]	300 [a]	10^3 [a]	10^4 [a]	10^5 [a]	10^6 [a]	10^7 [a]
Ag	3.09E-05	3.09E-05	3.09E-05	3.09E-05	3.09E-05	3.09E-05	3.09E-05	3.09E-05	3.09E-05	3.09E-05
Ba	4.36E-06	4.36E-06	4.36E-06	4.36E-06	4.36E-06	4.36E-06	4.36E-06	4.36E-06	4.36E-06	4.36E-06
Cd	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05
Cr	2.50E-02	2.50E-02	2.50E-02	2.50E-02	2.50E-02	2.50E-02	2.50E-02	2.50E-02	2.50E-02	2.50E-02
Cs	2.04E-06	2.04E-06	2.04E-06	2.04E-06	2.04E-06	2.04E-06	2.04E-06	2.04E-06	2.04E-06	2.04E-06
Hg	1.40E-06	1.40E-06	1.40E-06	1.40E-06	1.40E-06	1.40E-06	1.40E-06	1.40E-06	1.40E-06	1.40E-06
La	6.78E-07	6.78E-07	6.78E-07	6.78E-07	6.78E-07	6.78E-07	6.78E-07	6.78E-07	6.78E-07	6.78E-07
Mo	8.68E-04	8.68E-04	8.68E-04	8.68E-04	8.68E-04	8.68E-04	8.68E-04	8.68E-04	8.68E-04	8.68E-04
Nd	5.37E-07	5.37E-07	5.37E-07	5.37E-07	5.37E-07	5.37E-07	5.37E-07	5.37E-07	5.37E-07	5.37E-07
Pb	5.31E-04	5.31E-04	5.31E-04	5.31E-04	5.31E-04	5.31E-04	5.31E-04	5.31E-04	5.31E-04	5.31E-04
Pd	5.12E-05	5.12E-05	5.12E-05	5.12E-05	5.12E-05	5.12E-05	5.12E-05	5.12E-05	5.12E-05	5.12E-05
Rb	2.14E-06	2.14E-06	2.14E-06	2.14E-06	2.14E-06	2.14E-06	2.14E-06	2.14E-06	2.14E-06	2.14E-06
Rh	1.69E-07	1.69E-07	1.69E-07	1.69E-07	1.69E-07	1.69E-07	1.69E-07	1.69E-07	1.69E-07	1.69E-07
Ru	7.70E-07	7.70E-07	7.70E-07	7.70E-07	7.70E-07	7.70E-07	7.70E-07	7.70E-07	7.70E-07	7.70E-07
Sn	1.43E-01	1.43E-01	1.43E-01	1.43E-01	1.43E-01	1.43E-01	1.43E-01	1.43E-01	1.43E-01	1.43E-01
Te	8.00E-05	8.00E-05	8.00E-05	8.00E-05	8.00E-05	8.00E-05	8.00E-05	8.00E-05	8.00E-05	8.00E-05
U	1.91E-04	1.91E-04	1.91E-04	1.91E-04	1.91E-04	1.91E-04	1.91E-04	1.91E-04	1.91E-04	1.91E-04
Zr	1.07E+01	1.07E+01	1.07E+01	1.07E+01	1.07E+01	1.07E+01	1.07E+01	1.07E+01	1.07E+01	1.07E+01

Table 15: 290 MWh/kgU Burnup Fuel Radionuclide Inventory

Fuel Radionuclide Inventory [mol/kgU]										
Time / Isotope	0 [a]	10 [a]	30 [a]	100 [a]	300 [a]	10^3 [a]	10^4 [a]	10^5 [a]	10^6 [a]	10^7 [a]
Ac-225	6.67E-14	1.34E-14	2.68E-14	7.37E-14	2.06E-13	6.50E-13	4.59E-12	1.29E-11	1.81E-11	9.23E-13
Ac-227	1.27E-11	3.79E-10	8.39E-10	1.30E-09	1.35E-09	1.33E-09	1.13E-09	5.43E-10	5.05E-10	5.00E-10
Ag-108m	2.05E-09	2.02E-09	1.95E-09	1.75E-09	1.27E-09	4.21E-10	2.74E-16	0.00E+00	0.00E+00	0.00E+00
Am-241	1.62E-05	6.27E-04	1.21E-03	1.41E-03	1.03E-03	3.37E-04	2.65E-09	1.68E-12	0.00E+00	0.00E+00
Am-243	6.23E-05	6.24E-05	6.23E-05	6.19E-05	6.08E-05	5.69E-05	2.44E-05	5.14E-09	2.46E-14	1.65E-14
Bi-210	1.52E-11	7.52E-16	4.08E-16	1.57E-16	1.80E-15	1.97E-14	7.95E-13	7.09E-12	1.29E-11	1.26E-11
C-14	8.95E-06	8.94E-06	8.91E-06	8.84E-06	8.63E-06	7.92E-06	2.65E-06	4.68E-11	0.00E+00	0.00E+00
Ce-144	1.61E-03	2.23E-07	4.25E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cl-36	1.28E-05	1.28E-05	1.28E-05	1.28E-05	1.28E-05	1.28E-05	1.25E-05	1.02E-05	1.28E-06	1.27E-15
Cm-244	7.87E-06	5.37E-06	2.50E-06	1.71E-07	8.11E-11	1.87E-22	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Co-60	5.25E-07	1.41E-07	1.01E-08	1.02E-12	3.17E-16	3.17E-16	3.16E-16	3.03E-16	2.00E-16	3.12E-18
Cs-134	1.82E-04	6.34E-06	7.71E-09	4.81E-19	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cs-135	2.44E-04	2.48E-04	2.48E-04	2.48E-04	2.48E-04	2.48E-04	2.47E-04	2.41E-04	1.84E-04	1.22E-05
Cs-137	3.30E-03	2.62E-03	1.65E-03	3.29E-04	3.28E-06	3.24E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Eu-154	3.32E-05	1.49E-05	2.96E-06	1.05E-08	1.05E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Eu-155	1.82E-05	4.23E-06	2.29E-07	8.42E-12	1.81E-24	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
H-3	1.18E-05	6.73E-06	2.18E-06	4.25E-08	5.51E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
I-129	4.57E-04	4.66E-04	4.66E-04	4.66E-04	4.66E-04	4.66E-04	4.66E-04	4.64E-04	4.46E-04	2.99E-04
K-40	3.22E-06	3.22E-06	3.22E-06	3.22E-06	3.22E-06	3.22E-06	3.22E-06	3.22E-06	3.22E-06	3.20E-06
Kr-85	1.02E-04	5.35E-05	1.47E-05	1.62E-07	4.09E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nb-93m	1.07E-09	9.87E-09	1.93E-08	2.59E-08	2.63E-08	2.62E-08	2.61E-08	2.51E-08	1.67E-08	2.83E-10
Nb-94	7.24E-08	7.24E-08	7.24E-08	7.22E-08	7.17E-08	7.00E-08	5.15E-08	2.38E-09	1.07E-22	0.00E+00
Ni-59	2.79E-06	2.79E-06	2.79E-06	2.78E-06	2.78E-06	2.76E-06	2.54E-06	1.12E-06	3.04E-10	0.00E+00
Np-237	2.03E-04	2.19E-04	2.50E-04	4.07E-04	7.98E-04	1.50E-03	1.83E-03	1.77E-03	1.33E-03	7.23E-05
Np-239	5.42E-04	5.47E-11	5.46E-11	5.42E-11	5.32E-11	4.98E-11	2.14E-11	4.50E-15	2.16E-20	1.44E-20
Pa-231	2.04E-06	2.04E-06	2.04E-06	2.04E-06	2.03E-06	2.00E-06	1.71E-06	8.16E-07	7.60E-07	7.53E-07

Fuel Radionuclide Inventory [mol/kgU]										
Time / Isotope	0 [a]	10 [a]	30 [a]	100 [a]	300 [a]	10^3 [a]	10^4 [a]	10^5 [a]	10^6 [a]	10^7 [a]
Pa-233	9.43E-06	7.55E-12	8.62E-12	1.40E-11	2.75E-11	5.15E-11	6.29E-11	6.11E-11	4.57E-11	2.49E-12
Pb-210	1.44E-12	1.22E-12	6.59E-13	2.54E-13	2.92E-12	3.18E-11	1.29E-09	1.15E-08	2.09E-08	2.04E-08
Pd-107	1.02E-03	1.02E-03	1.02E-03	1.02E-03	1.02E-03	1.02E-03	1.02E-03	1.01E-03	9.16E-04	3.51E-04
Pm-147	6.51E-04	5.00E-05	2.53E-07	2.35E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Po-210	3.16E-10	2.08E-14	1.13E-14	4.34E-15	4.98E-14	5.43E-13	2.20E-11	1.96E-10	3.56E-10	3.49E-10
Pu-238	3.66E-05	4.13E-05	3.53E-05	2.03E-05	4.20E-06	1.70E-08	7.74E-29	0.00E+00	0.00E+00	0.00E+00
Pu-239	1.12E-02	1.17E-02	1.17E-02	1.17E-02	1.16E-02	1.14E-02	8.84E-03	6.67E-04	8.44E-14	5.40E-14
Pu-240	6.91E-03	6.90E-03	6.89E-03	6.84E-03	6.70E-03	6.22E-03	2.40E-03	1.78E-07	1.91E-12	1.77E-12
Pu-241	1.60E-03	9.87E-04	3.74E-04	1.25E-05	9.46E-10	1.69E-10	8.13E-11	5.28E-14	0.00E+00	0.00E+00
Pu-242	8.14E-04	8.14E-04	8.14E-04	8.13E-04	8.13E-04	8.12E-04	7.99E-04	6.76E-04	1.27E-04	7.08E-12
Ra-223	1.88E-14	5.45E-13	1.21E-12	1.87E-12	1.94E-12	1.91E-12	1.63E-12	7.80E-13	7.26E-13	7.19E-13
Ra-224	4.40E-11	2.75E-10	2.31E-10	1.14E-10	1.53E-11	1.48E-14	1.46E-15	1.48E-15	1.68E-15	3.42E-15
Ra-225	1.22E-13	2.00E-14	4.00E-14	1.10E-13	3.07E-13	9.68E-13	6.84E-12	1.92E-11	2.69E-11	1.38E-12
Ra-226	3.40E-14	3.60E-13	2.31E-12	2.33E-11	2.10E-10	2.29E-09	9.27E-08	8.27E-07	1.50E-06	1.47E-06
Rn-222	2.12E-19	2.35E-18	1.51E-17	1.53E-16	1.38E-15	1.50E-14	6.07E-13	5.41E-12	9.84E-12	9.64E-12
Ru-106	1.11E-03	1.22E-06	1.48E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sb-125	3.62E-05	3.01E-06	1.98E-08	4.53E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sb-126	5.29E-08	1.42E-12	1.42E-12	1.42E-12	1.42E-12	1.42E-12	1.38E-12	1.05E-12	6.99E-14	1.16E-25
Se-79	2.06E-05	2.06E-05	2.06E-05	2.06E-05	2.06E-05	2.06E-05	2.01E-05	1.63E-05	1.97E-06	1.29E-15
Sn-126	6.92E-05	6.92E-05	6.92E-05	6.91E-05	6.91E-05	6.90E-05	6.71E-05	5.12E-05	3.40E-06	5.63E-18
Sr-90	1.90E-03	1.50E-03	9.24E-04	1.71E-04	1.39E-06	6.64E-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Tc-99	3.09E-03	3.14E-03	3.14E-03	3.14E-03	3.13E-03	3.13E-03	3.03E-03	2.26E-03	1.18E-04	1.72E-17
Th-227	3.08E-14	8.78E-13	1.94E-12	3.01E-12	3.13E-12	3.09E-12	2.63E-12	1.26E-12	1.17E-12	1.16E-12
Th-228	8.58E-09	5.25E-08	4.41E-08	2.18E-08	2.91E-09	2.82E-12	2.79E-13	2.83E-13	3.21E-13	6.52E-13
Th-229	1.79E-09	3.59E-09	7.19E-09	1.98E-08	5.52E-08	1.74E-07	1.23E-06	3.46E-06	4.84E-06	2.47E-07
Th-230	1.22E-09	5.89E-09	1.55E-08	5.13E-08	1.63E-07	5.71E-07	5.62E-06	3.90E-05	7.09E-05	6.94E-05
Th-234	2.85E-09	6.08E-11	6.08E-11	6.08E-11	6.08E-11	6.08E-11	6.08E-11	6.08E-11	6.08E-11	6.08E-11

Fuel Radionuclide Inventory [mol/kgU]										
Isotope \ Time	0 [a]	10 [a]	30 [a]	100 [a]	300 [a]	10^3 [a]	10^4 [a]	10^5 [a]	10^6 [a]	10^7 [a]
U-232	2.08E-06	1.89E-06	1.54E-06	7.64E-07	1.02E-07	8.92E-11	1.92E-15	1.27E-15	2.16E-17	4.22E-35
U-233	3.21E-05	4.15E-05	4.15E-05	4.15E-05	4.15E-05	4.17E-05	4.52E-05	7.38E-05	1.05E-04	5.37E-06
U-234	1.64E-04	1.67E-04	1.73E-04	1.88E-04	2.04E-04	2.08E-04	2.09E-04	2.13E-04	2.25E-04	2.26E-04
U-235	4.53E-03	4.53E-03	4.54E-03	4.56E-03	4.63E-03	4.86E-03	7.47E-03	1.57E-02	1.63E-02	1.62E-02
U-236	3.79E-03	3.79E-03	3.81E-03	3.86E-03	4.00E-03	4.48E-03	8.29E-03	1.07E-02	1.04E-02	7.96E-03
U-238	4.12E+00	4.12E+00	4.12E+00	4.12E+00	4.12E+00	4.12E+00	4.12E+00	4.12E+00	4.12E+00	4.11E+00
Y-90	5.44E-07	3.79E-07	2.34E-07	4.34E-08	3.52E-10	1.69E-17	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Zr-93	2.55E-03	2.55E-03	2.55E-03	2.55E-03	2.55E-03	2.55E-03	2.54E-03	2.44E-03	1.62E-03	2.75E-05

Table 16: 290 MWh/kgU Burnup Zircaloy Radionuclide Inventory

Zircaloy Radionuclide Inventory [mol/kgZr]										
Time / Isotope	0 [a]	10 [a]	30 [a]	100 [a]	300 [a]	10^3 [a]	10^4 [a]	10^5 [a]	10^6 [a]	10^7 [a]
Ac-225	3.07E-18	6.16E-19	1.23E-18	3.39E-18	9.47E-18	2.99E-17	2.11E-16	5.94E-16	8.31E-16	4.25E-17
Ac-227	5.83E-16	1.74E-14	3.86E-14	5.98E-14	6.21E-14	6.13E-14	5.22E-14	2.50E-14	2.32E-14	2.30E-14
Ag-108m	2.00E-08	1.97E-08	1.91E-08	1.71E-08	1.25E-08	4.12E-09	2.68E-15	0.00E+00	0.00E+00	0.00E+00
Am-241	7.43E-10	2.88E-08	5.56E-08	6.50E-08	4.76E-08	1.55E-08	1.22E-13	7.75E-17	0.00E+00	0.00E+00
Am-243	2.86E-09	2.87E-09	2.87E-09	2.85E-09	2.80E-09	2.62E-09	1.12E-09	2.36E-13	1.13E-18	7.59E-19
Bi-210	4.53E-12	4.90E-19	2.63E-19	3.46E-20	8.31E-20	9.04E-19	3.66E-17	3.26E-16	5.93E-16	5.81E-16
C-14	3.18E-05	3.18E-05	3.17E-05	3.14E-05	3.07E-05	2.82E-05	9.43E-06	1.66E-10	0.00E+00	0.00E+00
Ce-144	7.41E-08	1.02E-11	1.96E-19	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cl-36	5.67E-05	5.67E-05	5.67E-05	5.66E-05	5.66E-05	5.65E-05	5.54E-05	4.50E-05	5.66E-06	5.63E-15
Cm-244	3.62E-10	2.47E-10	1.15E-10	7.88E-12	3.73E-15	8.61E-27	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Co-60	3.35E-05	8.99E-06	6.48E-07	6.51E-11	1.03E-14	1.03E-14	1.02E-14	9.80E-15	6.47E-15	1.01E-16
Cs-134	1.70E-07	5.93E-09	7.18E-12	4.49E-22	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cs-135	5.03E-08	5.05E-08	5.05E-08	5.05E-08	5.06E-08	5.05E-08	5.04E-08	4.90E-08	3.73E-08	2.49E-09
Cs-137	1.52E-07	1.21E-07	7.61E-08	1.52E-08	1.51E-10	1.49E-17	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Eu-154	7.70E-09	3.44E-09	6.86E-10	2.43E-12	2.43E-19	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Eu-155	3.72E-09	8.65E-10	4.68E-11	1.72E-15	3.70E-28	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
H-3	5.48E-06	3.11E-06	1.01E-06	1.97E-08	2.56E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
I-129	4.29E-08	4.35E-08	4.35E-08	4.35E-08	4.35E-08	4.35E-08	4.35E-08	4.33E-08	4.16E-08	2.80E-08
K-40	1.88E-06	1.88E-06	1.88E-06	1.88E-06	1.88E-06	1.88E-06	1.88E-06	1.88E-06	1.88E-06	1.87E-06
Kr-85	4.85E-09	2.55E-09	7.02E-10	7.71E-12	1.95E-17	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nb-93m	5.23E-08	4.00E-08	2.68E-08	1.76E-08	1.71E-08	1.71E-08	1.70E-08	1.63E-08	1.08E-08	1.83E-10
Nb-94	6.70E-06	6.69E-06	6.69E-06	6.67E-06	6.63E-06	6.47E-06	4.76E-06	2.20E-07	9.89E-21	0.00E+00
Ni-59	6.34E-05	6.34E-05	6.33E-05	6.33E-05	6.32E-05	6.28E-05	5.78E-05	2.55E-05	6.93E-09	0.00E+00
Np-237	9.32E-09	1.01E-08	1.15E-08	1.87E-08	3.67E-08	6.88E-08	8.41E-08	8.16E-08	6.10E-08	3.33E-09
Np-239	2.49E-08	2.51E-15	2.51E-15	2.49E-15	2.45E-15	2.29E-15	9.82E-16	2.07E-19	9.92E-25	6.65E-25
Pa-231	9.39E-11	9.39E-11	9.38E-11	9.37E-11	9.34E-11	9.21E-11	7.85E-11	3.76E-11	3.49E-11	3.46E-11

Zircaloy Radionuclide Inventory [mol/kgZr]										
Isotope \ Time	0 [a]	10 [a]	30 [a]	100 [a]	300 [a]	10^3 [a]	10^4 [a]	10^5 [a]	10^6 [a]	10^7 [a]
Pa-233	4.34E-10	3.47E-16	3.96E-16	6.45E-16	1.26E-15	2.37E-15	2.90E-15	2.81E-15	2.10E-15	1.15E-16
Pb-210	1.07E-15	7.92E-16	4.25E-16	5.60E-17	1.34E-16	1.46E-15	5.92E-14	5.28E-13	9.60E-13	9.41E-13
Pd-107	9.16E-08	9.16E-08	9.16E-08	9.16E-08	9.16E-08	9.16E-08	9.15E-08	9.07E-08	8.24E-08	3.15E-08
Pm-147	3.01E-08	2.31E-09	1.17E-11	1.08E-19	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Po-210	9.40E-11	1.46E-17	7.25E-18	9.56E-19	2.29E-18	2.50E-17	1.01E-15	9.01E-15	1.64E-14	1.60E-14
Pu-238	1.68E-09	1.90E-09	1.62E-09	9.34E-10	1.93E-10	7.81E-13	3.56E-33	0.00E+00	0.00E+00	0.00E+00
Pu-239	5.15E-07	5.40E-07	5.40E-07	5.39E-07	5.36E-07	5.25E-07	4.07E-07	3.07E-08	3.88E-18	2.48E-18
Pu-240	3.18E-07	3.17E-07	3.17E-07	3.15E-07	3.08E-07	2.86E-07	1.11E-07	8.20E-12	8.79E-17	8.13E-17
Pu-241	7.37E-08	4.54E-08	1.72E-08	5.77E-10	4.35E-14	7.79E-15	3.74E-15	2.43E-18	0.00E+00	0.00E+00
Pu-242	3.74E-08	3.74E-08	3.74E-08	3.74E-08	3.74E-08	3.74E-08	3.67E-08	3.11E-08	5.85E-09	3.26E-16
Ra-223	8.64E-19	2.51E-17	5.55E-17	8.59E-17	8.92E-17	8.81E-17	7.50E-17	3.59E-17	3.34E-17	3.31E-17
Ra-224	2.02E-15	1.27E-14	1.06E-14	5.25E-15	7.03E-16	6.81E-19	6.74E-20	6.83E-20	7.75E-20	1.57E-19
Ra-225	5.62E-18	9.18E-19	1.84E-18	5.05E-18	1.41E-17	4.46E-17	3.15E-16	8.85E-16	1.24E-15	6.33E-17
Ra-226	1.57E-18	1.65E-17	1.06E-16	1.07E-15	9.68E-15	1.05E-13	4.27E-12	3.80E-11	6.92E-11	6.78E-11
Rn-222	9.76E-24	1.08E-22	6.95E-22	7.02E-21	6.33E-20	6.90E-19	2.79E-17	2.49E-16	4.53E-16	4.43E-16
Ru-106	5.10E-08	5.62E-11	6.83E-17	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sb-125	1.42E-05	1.15E-06	7.58E-09	1.74E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sb-126	6.05E-09	6.68E-17	6.68E-17	6.68E-17	6.67E-17	6.66E-17	6.48E-17	4.94E-17	3.28E-18	5.43E-30
Se-79	7.00E-09	6.99E-09	6.99E-09	7.00E-09	6.98E-09	6.98E-09	6.82E-09	5.53E-09	6.67E-10	4.36E-19
Sn-126	3.24E-09	3.24E-09	3.24E-09	3.24E-09	3.24E-09	3.23E-09	3.15E-09	2.40E-09	1.59E-10	2.64E-22
Sr-90	8.80E-08	6.92E-08	4.27E-08	7.92E-09	6.42E-11	3.07E-18	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Tc-99	3.57E-07	3.62E-07	3.62E-07	3.62E-07	3.61E-07	3.61E-07	3.50E-07	2.60E-07	1.36E-08	1.98E-21
Th-227	1.42E-18	4.04E-17	8.94E-17	1.38E-16	1.44E-16	1.42E-16	1.21E-16	5.78E-17	5.38E-17	5.33E-17
Th-228	3.94E-13	2.42E-12	2.03E-12	1.00E-12	1.34E-13	1.30E-16	1.29E-17	1.30E-17	1.48E-17	3.00E-17
Th-229	8.24E-14	1.65E-13	3.31E-13	9.09E-13	2.54E-12	8.02E-12	5.66E-11	1.59E-10	2.23E-10	1.14E-11
Th-230	5.61E-14	2.71E-13	7.13E-13	2.36E-12	7.50E-12	2.63E-11	2.58E-10	1.79E-09	3.26E-09	3.19E-09
Th-234	1.31E-13	2.80E-15	2.80E-15	2.80E-15	2.80E-15	2.80E-15	2.80E-15	2.80E-15	2.80E-15	2.80E-15

Zircaloy Radionuclide Inventory [mol/kgZr]										
Time / Isotope	0 [a]	10 [a]	30 [a]	100 [a]	300 [a]	10^3 [a]	10^4 [a]	10^5 [a]	10^6 [a]	10^7 [a]
U-232	9.56E-11	8.69E-11	7.10E-11	3.51E-11	4.70E-12	4.10E-15	8.82E-20	5.86E-20	9.94E-22	1.94E-39
U-233	1.48E-09	1.91E-09	1.91E-09	1.91E-09	1.91E-09	1.92E-09	2.08E-09	3.40E-09	4.83E-09	2.47E-10
U-234	7.53E-09	7.68E-09	7.96E-09	8.65E-09	9.40E-09	9.59E-09	9.61E-09	9.79E-09	1.04E-08	1.04E-08
U-235	2.08E-07	2.08E-07	2.09E-07	2.10E-07	2.13E-07	2.24E-07	3.44E-07	7.21E-07	7.51E-07	7.44E-07
U-236	1.74E-07	1.75E-07	1.75E-07	1.78E-07	1.84E-07	2.06E-07	3.82E-07	4.91E-07	4.78E-07	3.66E-07
U-238	1.90E-04	1.90E-04	1.90E-04	1.90E-04	1.90E-04	1.90E-04	1.90E-04	1.90E-04	1.90E-04	1.89E-04
Y-90	3.36E-08	1.75E-11	1.08E-11	2.01E-12	1.63E-14	7.79E-22	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Zr-93	1.66E-03	1.66E-03	1.66E-03	1.66E-03	1.66E-03	1.66E-03	1.65E-03	1.58E-03	1.05E-03	1.78E-05

Table 17: 290 MWh/kgU Burnup Fuel Element Inventory

Fuel Element Inventory [mol/kgU]										
Time / Element	0 [a]	10 [a]	30 [a]	100 [a]	300 [a]	10^3 [a]	10^4 [a]	10^5 [a]	10^6 [a]	10^7 [a]
Ag	4.02E-04	4.02E-04	4.02E-04	4.02E-04	4.02E-04	4.02E-04	4.02E-04	4.02E-04	4.02E-04	4.02E-04
Ba	3.59E-03	3.59E-03	3.59E-03	3.59E-03	3.59E-03	3.59E-03	3.59E-03	3.59E-03	3.59E-03	3.59E-03
Cd	2.88E-04	2.88E-04	2.88E-04	2.88E-04	2.88E-04	2.88E-04	2.88E-04	2.88E-04	2.88E-04	2.88E-04
Cr	2.80E-04	2.80E-04	2.80E-04	2.80E-04	2.80E-04	2.80E-04	2.80E-04	2.80E-04	2.80E-04	2.80E-04
Cs	6.95E-03	6.95E-03	6.95E-03	6.95E-03	6.95E-03	6.95E-03	6.95E-03	6.95E-03	6.95E-03	6.95E-03
Hg	2.51E-06	2.51E-06	2.51E-06	2.51E-06	2.51E-06	2.51E-06	2.51E-06	2.51E-06	2.51E-06	2.51E-06
La	3.12E-03	3.12E-03	3.12E-03	3.12E-03	3.12E-03	3.12E-03	3.12E-03	3.12E-03	3.12E-03	3.12E-03
Mo	1.12E-02	1.12E-02	1.12E-02	1.12E-02	1.12E-02	1.12E-02	1.12E-02	1.12E-02	1.12E-02	1.12E-02
Nd	7.99E-03	7.99E-03	7.99E-03	7.99E-03	7.99E-03	7.99E-03	7.99E-03	7.99E-03	7.99E-03	7.99E-03
Pb	4.18E-06	4.18E-06	4.18E-06	4.18E-06	4.18E-06	4.18E-06	4.18E-06	4.18E-06	4.18E-06	4.18E-06
Pd	4.55E-03	4.55E-03	4.55E-03	4.55E-03	4.55E-03	4.55E-03	4.55E-03	4.55E-03	4.55E-03	4.55E-03
Rb	1.25E-03	1.25E-03	1.25E-03	1.25E-03	1.25E-03	1.25E-03	1.25E-03	1.25E-03	1.25E-03	1.25E-03
Rh	1.74E-03	1.74E-03	1.74E-03	1.74E-03	1.74E-03	1.74E-03	1.74E-03	1.74E-03	1.74E-03	1.74E-03
Ru	9.89E-03	9.89E-03	9.89E-03	9.89E-03	9.89E-03	9.89E-03	9.89E-03	9.89E-03	9.89E-03	9.89E-03
Sn	2.01E-04	2.01E-04	2.01E-04	2.01E-04	2.01E-04	2.01E-04	2.01E-04	2.01E-04	2.01E-04	2.01E-04
Te	1.49E-03	1.49E-03	1.49E-03	1.49E-03	1.49E-03	1.49E-03	1.49E-03	1.49E-03	1.49E-03	1.49E-03
U	4.13E+00	4.13E+00	4.13E+00	4.13E+00	4.13E+00	4.13E+00	4.13E+00	4.13E+00	4.13E+00	4.13E+00
Zr	1.29E-02	1.29E-02	1.29E-02	1.29E-02	1.29E-02	1.29E-02	1.29E-02	1.29E-02	1.29E-02	1.29E-02

Table 18: 290MWh/kgU Burnup Zircaloy Element Inventory

Zircaloy Element Inventory [mol/kgZr]										
Element \ Time	0 [a]	10 [a]	30 [a]	100 [a]	300 [a]	10^3 [a]	10^4 [a]	10^5 [a]	10^6 [a]	10^7 [a]
Ag	2.91E-05	2.91E-05	2.91E-05	2.91E-05	2.91E-05	2.91E-05	2.91E-05	2.91E-05	2.91E-05	2.91E-05
Ba	4.41E-06	4.41E-06	4.41E-06	4.41E-06	4.41E-06	4.41E-06	4.41E-06	4.41E-06	4.41E-06	4.41E-06
Cd	1.60E-05	1.60E-05	1.60E-05	1.60E-05	1.60E-05	1.60E-05	1.60E-05	1.60E-05	1.60E-05	1.60E-05
Cr	2.49E-02	2.49E-02	2.49E-02	2.49E-02	2.49E-02	2.49E-02	2.49E-02	2.49E-02	2.49E-02	2.49E-02
Cs	2.09E-06	2.09E-06	2.09E-06	2.09E-06	2.09E-06	2.09E-06	2.09E-06	2.09E-06	2.09E-06	2.09E-06
Hg	1.51E-06	1.51E-06	1.51E-06	1.51E-06	1.51E-06	1.51E-06	1.51E-06	1.51E-06	1.51E-06	1.51E-06
La	7.06E-07	7.06E-07	7.06E-07	7.06E-07	7.06E-07	7.06E-07	7.06E-07	7.06E-07	7.06E-07	7.06E-07
Mo	1.06E-03	1.06E-03	1.06E-03	1.06E-03	1.06E-03	1.06E-03	1.06E-03	1.06E-03	1.06E-03	1.06E-03
Nd	6.29E-07	6.29E-07	6.29E-07	6.29E-07	6.29E-07	6.29E-07	6.29E-07	6.29E-07	6.29E-07	6.29E-07
Pb	5.31E-04	5.31E-04	5.31E-04	5.31E-04	5.31E-04	5.31E-04	5.31E-04	5.31E-04	5.31E-04	5.31E-04
Pd	5.11E-05	5.11E-05	5.11E-05	5.11E-05	5.11E-05	5.11E-05	5.11E-05	5.11E-05	5.11E-05	5.11E-05
Rb	2.15E-06	2.15E-06	2.15E-06	2.15E-06	2.15E-06	2.15E-06	2.15E-06	2.15E-06	2.15E-06	2.15E-06
Rh	1.77E-07	1.77E-07	1.77E-07	1.77E-07	1.77E-07	1.77E-07	1.77E-07	1.77E-07	1.77E-07	1.77E-07
Ru	9.11E-07	9.11E-07	9.11E-07	9.11E-07	9.11E-07	9.11E-07	9.11E-07	9.11E-07	9.11E-07	9.11E-07
Sn	1.43E-01	1.43E-01	1.43E-01	1.43E-01	1.43E-01	1.43E-01	1.43E-01	1.43E-01	1.43E-01	1.43E-01
Te	8.12E-05	8.12E-05	8.12E-05	8.12E-05	8.12E-05	8.12E-05	8.12E-05	8.12E-05	8.12E-05	8.12E-05
U	1.90E-04	1.90E-04	1.90E-04	1.90E-04	1.90E-04	1.90E-04	1.90E-04	1.90E-04	1.90E-04	1.90E-04
Zr	1.07E+01	1.07E+01	1.07E+01	1.07E+01	1.07E+01	1.07E+01	1.07E+01	1.07E+01	1.07E+01	1.07E+01

A.2 Radionuclide Decay and Half-life Data

Table 19 presents the radionuclide decay and half-life data. It is noted that:

- Short-lived daughters whose dose contribution is included in the dose conversion factor of the longer-lived parent are bolded (e.g., $\mathrm{Ac225} \rightarrow \mathbf{Fr221}$ ...**)**
- Stable species are indicated using subscripts (e.g., Bi_{209})
- $\xrightarrow{x}$ indicates a branching ratio of x, note that a branching of 1* indicates a branching ratio conservatively assumed to be one.
- sf indicates a decay via spontaneous fission
- Species with half-lives greater than 1.38x10^{10} years are considered essentially stable.

Table 19: Radionuclide Decay Chain and Half-life Data

Isotope	Half-Life [a]	Decay Chain
Ac-225	2.74E-02	$\mathrm{Ac225} \rightarrow \mathbf{Fr221} \rightarrow \mathbf{At217} \xrightarrow{0.9999} \mathbf{Bi213} \xrightarrow{0.9791} \mathbf{Po213}$ / $\xrightarrow{0.0209} \mathbf{Tl209} \rightarrow \mathbf{Pb209} \rightarrow \mathrm{Bi}_{209}$ $\mathbf{At217} \xrightarrow{0.0001} \mathbf{Rn217} \rightarrow \mathbf{Po213} \rightarrow \mathbf{Pb209} \rightarrow \mathrm{Bi}_{209}$
Ac-227	2.18E+01	$\mathrm{Ac227} \xrightarrow{0.0138} \mathbf{Fr223} \rightarrow \mathrm{Ra223}$ ... $\mathrm{Ac227} \xrightarrow{0.9862} \mathrm{Th227}$ ...
Ac-228	7.00E-04	Short lived daughter of Ra228
Ag-105	1.13E-01	$\mathrm{Ag105} \rightarrow \mathrm{Pd}_{105}$
Ag-108	4.53E-06	Short lived daughter of Ag108m
Ag-108m	4.37E+02	$\mathrm{Ag108m} \xrightarrow{0.087} \mathbf{Ag108} \xrightarrow{0.9715} \mathrm{Cd}_{108}$ $\mathbf{Ag108} \xrightarrow{0.0285} \mathrm{Pd}_{108}$
Ag-109m	1.25E-06	$\mathrm{Ag109m} \rightarrow \mathrm{Ag}_{109}$
Ag-110	7.80E-07	Short lived daughter of Ag110m
Ag-110m	6.84E-01	$\mathrm{Ag110m} \xrightarrow{0.0136} \mathbf{Ag110} \xrightarrow{0.997} \mathrm{Cd}_{110}$ $\mathbf{Ag110} \xrightarrow{0.003} \mathrm{Pd}_{110}$
Al-26	7.16E+05	$\mathrm{Al26} \rightarrow \mathrm{Mg}_{26}$
Am-241	4.34E+02	$\mathrm{Am241} \rightarrow \mathrm{Np237}$ ...
Am-242	1.83E-03	Short lived daughter of Am242m
Am-242m	1.41E+02	$\mathrm{Am242m} \xrightarrow{0.9955} \mathbf{Am242} \xrightarrow{0.827} \mathrm{Cm242}$... / $\xrightarrow{0.173} \mathrm{Pu242}$... $\mathrm{Am242m} \xrightarrow{0.0045} \mathrm{Np238}$ ...
Am-243	7.38E+03	$\mathrm{Am242} \rightarrow \mathrm{Np239}$ ...
Am-244	1.15E-03	Short lived daughter of Bk248
Am-245	2.34E-04	Short lived daughter of Bk249
Am-246m	4.75E-05	Short lived daughter of Pu246
Ar-37	9.60E-02	$\mathrm{Ar37} \rightarrow \mathrm{Cl}_{37}$
Ar-39	2.69E+02	$\mathrm{Ar39} \rightarrow \mathrm{K}_{39}$
Ar-42	3.30E+01	$\mathrm{Ar42} \rightarrow \mathbf{K42} \rightarrow \mathrm{Ca}_{42}$
As-73	2.20E-01	$\mathrm{As73} \rightarrow \mathrm{Ge}_{73}$

Isotope	Half-Life [a]	Decay Chain
At-217	1.02E-09	Short lived daughter of Ac225
At-218	4.75E-08	Short lived daughter of Rn222
Au-194	4.34E-03	$\mathrm{Au194} \rightarrow \mathrm{Pt}_{194}$
Au-195	5.10E-01	$\mathrm{Au195} \rightarrow \mathrm{Pt}_{195}$
Ba-133	1.05E+01	$\mathrm{Ba133} \rightarrow \mathrm{Cs}_{133}$
Ba-137m	4.85E-06	Short lived daughter of Cs137
Be-10	1.51E+06	$\mathrm{Be10} \rightarrow \mathrm{B}_{10}$
Bi-207	3.16E+01	$\mathrm{Bi207} \rightarrow \mathrm{Pb}_{207}$
Bi-208	3.68E+05	$\mathrm{Bi208} \rightarrow \mathrm{Pb}_{208}$
Bi-209	1.90E+19	Essentially stable
Bi-210	1.37E-02	$\mathrm{Bi210} \rightarrow \mathrm{Po210}$ ...
Bi-210m	3.04E+06	$\mathrm{Bi210m} \rightarrow \mathbf{Tl206} \rightarrow \mathrm{Pb}_{206}$
Bi-211	4.06E-06	Short lived daughter of Ra223
Bi-212	1.15E-04	Short lived daughter of Ra224
Bi-213	8.68E-05	Short lived daughter of Ac225
Bi-214	3.77E-05	Short lived daughter of Rn222
Bk-247	1.38E+03	$\mathrm{Bk247} \rightarrow \mathrm{Am243}$ ...
Bk-248	9.00E+00	$\mathrm{Bk248} \rightarrow \mathbf{Am244} \rightarrow \mathrm{Cm244}$ ...
Bk-249	8.75E-01	$\mathrm{Bk249} \xrightarrow{1.00*} \mathrm{Cf249}$ ... $\mathrm{Bk249} \xrightarrow{1.5e-5} \mathbf{Am245} \rightarrow \mathrm{Cm245}$ ...
Bk-250	3.68E-04	Short lived daughter of Es254 and Cm250
C-14	5.70E+03	$\mathrm{C14} \rightarrow \mathrm{N}_{14}$
Ca-41	1.02E+05	$\mathrm{Ca41} \rightarrow \mathrm{K}_{41}$
Ca-45	4.44E-01	$\mathrm{Ca45} \rightarrow \mathrm{Sc}_{45}$
Ca-48	2.30E+19	Essentially stable
Cd-109	1.26E+00	$\mathrm{Cd109} \rightarrow \mathrm{Ag}_{109}$
Cd-113	8.05E+15	$\mathrm{Cd113} \rightarrow \mathrm{In}_{113}$
Cd-113m	1.41E+01	$\mathrm{Cd113m} \xrightarrow{0.9986} \mathrm{In}_{113}$ $\mathrm{Cd113m} \xrightarrow{0.0014} \mathrm{Cd113}$..., Essentially Stable
Cd-115m	1.22E-01	$\mathrm{Cd115m} \rightarrow \mathrm{In115}$ ...
Cd-116	3.10E+19	Essentially stable
Ce-139	3.77E-01	$\mathrm{Ce139} \rightarrow \mathrm{La}_{139}$
Ce-141	8.90E-02	$\mathrm{Ce141} \rightarrow \mathrm{Pr}_{141}$
Ce-144	7.80E-01	$\mathrm{Cd144} \xrightarrow{0.0098} \mathbf{Pr144m} \rightarrow \mathbf{Pr144} \rightarrow \mathrm{Nd144}$ ... $\mathrm{Cd144} \xrightarrow{0.9902} \mathbf{Pr144} \rightarrow \mathrm{Nd144}$ ...
Cf-248	9.13E-01	$\mathrm{Cf248} \rightarrow \mathrm{Cm244}$ ...
Cf-249	3.52E+02	$\mathrm{Cf249} \rightarrow \mathrm{Cm245}$ ...
Cf-250	1.31E+01	$\mathrm{Cf250} \rightarrow \mathrm{Cm246}$ ...
Cf-251	8.97E+02	$\mathrm{Cf251} \rightarrow \mathrm{Cm247}$ ...
Cf-252	2.65E+00	$\mathrm{Cf252} \xrightarrow{0.969} \mathrm{Cm248}$ ... $\mathrm{Cf252} \xrightarrow{0.031} \mathrm{sf}$

Isotope	Half-Life [a]	Decay Chain
Cf-254	1.66E-01	Cf254 $\xrightarrow{0.003}$ Cm250 ... $\xrightarrow{0.997}$ sf
Cl-36	3.01E+05	Cl36 $\xrightarrow{0.981}$ Ar_{36} $\xrightarrow{0.019}$ S_{36}
Cm-240	7.38E-02	Cm240 → Pu236 ...
Cm-241	8.97E-02	Cm241 $\xrightarrow{0.99}$ Am241 ... $\xrightarrow{0.01}$ Pu237 ...
Cm-242	4.47E-01	Cm242 → Pu238 ...
Cm-243	2.91E+01	Cm243 $\xrightarrow{0.9976}$ Pu239 ... $\xrightarrow{0.0024}$ Am243 ...
Cm-244	1.81E+01	Cm244 → Pu240 ...
Cm-245	8.49E+03	Cm245 → Pu241 ...
Cm-246	4.75E+03	Cm246 → Pu242 ...
Cm-247	1.56E+07	Cm247 → **Pu243** → Am243 ...
Cm-248	3.49E+05	Cm248 $\xrightarrow{0.916}$ Pu244 ... $\xrightarrow{0.084}$ sf
Cm-250	8.30E+03	$\xrightarrow{0.18}$ Pu246 ... Cm $\xrightarrow{0.08}$ **Bk250** → Cf250 $\xrightarrow{0.74}$ sf
Co-56	2.11E-01	Co56 → Fe_{56}
Co-57	7.45E-01	Co57 → Fe_{57}
Co-58	1.94E-01	Co58 → Fe_{58}
Co-60	5.26E+00	Co60 → Ni_{60}
Co-60m	1.99E-05	Short lived daughter of Fe60
Cr-51	7.57E-02	Cr51 → V_{51}
Cs-134	2.07E+00	Cs134 → Ba_{134}
Cs-135	2.30E+06	Cs135 → Ba_{135}
Cs-137	3.01E+01	Cs137 $\xrightarrow{0.944}$ **Ba137m** → Ba_{137} $\xrightarrow{0.056}$ Ba_{137}
Dy-154	3.00E+06	Dy154 → Gd150 ...
Dy-159	3.96E-01	Dy159 → Tb_{159}
Es-252	1.29E+00	Es252 $\xrightarrow{0.76}$ Bk248 ... $\xrightarrow{0.24}$ Cf252 ...
Es-254	7.54E-01	Es254 → **Bk250** → Cf250 ...
Es-255	1.09E-01	Es255 $\xrightarrow{0.92}$ **Fm255** → Cf251 ... $\xrightarrow{0.08}$ **Bk251** → Cf251 ...
Eu-148	1.49E-01	Eu148 → Sm148 ...
Eu-149	2.55E-01	Eu149 → Sm_{149}

Isotope	Half-Life [a]	Decay Chain
Eu-150	3.68E+01	$Eu150 \rightarrow Sm_{150}$
Eu-152	1.35E+01	$Eu152 \xrightarrow{0.279} Gd152$ ... $\xrightarrow{0.721} Sm_{152}$
Eu-154	8.59E+00	$Es154 \xrightarrow{0.998} Gd_{154}$ $\xrightarrow{0.002} Sm_{154}$
Eu-155	4.75E+00	$Eu155 \rightarrow Gd_{155}$
Fe-55	2.74E+00	$Fe55 \rightarrow Mn_{55}$
Fe-59	1.22E-01	$Fe59 \rightarrow Co_{59}$
Fe-60	1.50E+06	$Fe60 \rightarrow \mathbf{Co60m} \xrightarrow{0.9976} Co60$ ... $\xrightarrow{0.0024} Ni_{60}$
Fr-221	9.32E-06	Short lived daughter of Ac225
Fr-223	4.18E-05	Short lived daughter of Ac227
Ga-68	1.29E-04	Short lived daughter of Ge68
Gd-148	7.45E+01	$Gd148 \rightarrow Sm_{144}$
Gd-150	1.79E+06	$Gd150 \rightarrow Sm146$ ...
Gd-151	3.39E-01	$Gd151 \rightarrow Eu_{151}$
Gd-152	1.08E+14	$Gd152 \rightarrow Sm148$ ..., Essentially Stable
Gd-153	6.59E-01	$Gd153 \rightarrow Eu_{153}$
Ge-68	7.42E-01	$Ge68 \rightarrow \mathbf{Ga68} \rightarrow Zn_{68}$
Ge-73m	1.58E-08	$Ge73m \rightarrow Ge_{73}$
H-3	1.23E+01	$H3 \rightarrow He_{3}$
Hf-172	1.87E+00	$Hf172 \rightarrow \mathbf{Lu172m} \rightarrow Lu172$ ...
Hf-174	2.00E+15	$Hf174 \rightarrow Y_{170}$, Essentially Stable
Hf-175	1.92E-01	$Hf174 \rightarrow Lu_{175}$
Hf-177m	3.45E-08	$Hf177m \rightarrow Hf_{177}$
Hf-181	1.16E-01	$Hf181 \rightarrow Ta_{181}$
Hf-182	8.90E+06	$Hf182 \rightarrow Ta182$ ...
Hg-194	4.44E+02	$Hg194 \rightarrow Au194$ ...
Hg-203	1.28E-01	$Hg203 \rightarrow Tl_{203}$
Hg-206	1.58E-05	Short Lived daughter of Pb210 ignored due to 1.9×10^{-6}% occurrence
Ho-163	4.56E+03	$Ho163 \rightarrow Dy_{163}$
Ho-166m	1.20E+03	$Ho166m \rightarrow Er_{166}$
I-125	1.63E-01	$I125 \rightarrow Te_{125}$
I-129	1.57E+07	$I129 \rightarrow Xe_{129}$
In-113m	1.89E-04	Short lived daughter of Sn113
In-114	2.28E-06	Short lived daughter of In114m
In-114m	1.36E-01	$In114m \xrightarrow{0.9675} \mathbf{In114} \xrightarrow{0.995} Sn_{114}$ $\mathbf{In114} \xrightarrow{0.05} Cd_{114}$ $In114m \xrightarrow{0.0325} Cd_{114}$

Isotope	Half-Life [a]	Decay Chain
In-115	4.40E+14	$In115 \rightarrow Sn_{115}$, Essentially Stable
In-115m	5.10E-04	$In115m \xrightarrow{0.95} In115 \rightarrow Sn_{115}$ $\xrightarrow{0.05} Sn_{115}$
Ir-192	2.02E-01	$Ir192 \xrightarrow{0.9513} Pt_{192}$ $\xrightarrow{0.0487} Os_{192}$
Ir-194	2.20E-03	Short lived daughter of Os194
K-40	1.25E+09	$K40 \xrightarrow{0.8914} Ca_{40}$ $\xrightarrow{0.1086} Ar_{40}$
K-42	1.41E-03	Short lived daughter of Ar42
Kr-81	2.29E+05	$Kr81 \rightarrow Br_{81}$
Kr-83m	2.09E-04	Short lived daughter of Rb83
Kr-85	1.07E+01	$Kr85 \rightarrow Rb_{85}$
La-137	5.99E+04	$La137 \rightarrow Ba_{137}$
La-138	1.02E+11	$La138 \xrightarrow{0.664} Ba_{138}$, $\xrightarrow{0.336} Ce_{138}$, Essentially Stable
Lu-172	1.83E-02	$Lu172 \rightarrow Yb_{172}$
Lu-172m	7.03E-06	$Lu172m \rightarrow Lu172$ ...
Lu-173	1.37E+00	$Lu173 \rightarrow Yb_{173}$
Lu-174	3.30E+00	$Lu174 \rightarrow Yb_{174}$
Lu-174m	3.90E-01	$Lu174m \xrightarrow{0.9938} Lu174$ ... $\xrightarrow{0.0062} Yb_{174}$
Lu-176	3.77E+10	$Lu176 \rightarrow Hf_{176}$, Essentially Stable
Lu-177	1.82E-02	$Lu177 \rightarrow Hf_{177}$
Lu-177m	4.40E-01	$Lu177m \xrightarrow{0.217} Lu177$ ... $\xrightarrow{0.783} Hf_{177}$
Mn-53	3.71E+06	$Mn53 \rightarrow Cr_{53}$
Mn-54	8.56E-01	$Mn54 \rightarrow Cr_{54}$
Mo-100	7.29E+18	Essentially stable
Mo-93	3.99E+03	$Mo93 \xrightarrow{0.8773} Nb93m$ ... $\xrightarrow{0.1227} Nb_{93}$
Na-22	2.60E+00	$Na22 \rightarrow Ne_{22}$
Nb-91	6.81E+02	$Nb91 \rightarrow Zr_{91}$
Nb-91m	1.67E-01	$Nb91m \xrightarrow{0.966} Nb91$ ... $\xrightarrow{0.034} Zr_{91}$
Nb-92	3.49E+07	$Nb92 \rightarrow Zr_{92}$
Nb-93m	1.61E+01	$Nb93m \rightarrow Nb_{93}$
Nb-94	2.03E+04	$Nb94 \rightarrow Mo_{94}$
Nb-95	9.57E-02	$Nb95 \rightarrow Mo_{95}$

Isotope	Half-Life [a]	Decay Chain
Nb-95m	9.89E-03	$\mathrm{Nb95m} \xrightarrow{0.944} \mathrm{Nb95}$ ... $\xrightarrow{0.054} \mathrm{Mo}_{95}$
Nd-144	2.29E+15	$\mathrm{Nd144} \rightarrow \mathrm{Ce}_{140}$, Essentially stable
Nd-150	7.89E+18	Essentially Stable
Ni-59	7.61E+04	$\mathrm{Ni59} \rightarrow \mathrm{Co}_{59}$
Ni-63	1.01E+02	$\mathrm{Ni63} \rightarrow \mathrm{Cu}_{63}$
Np-235	1.08E+00	$\mathrm{Np235} \xrightarrow{0.996} \mathrm{U236}$ ... $\xrightarrow{0.004} \mathbf{U235m} \rightarrow \mathrm{U235}$ ...
Np-236	1.53E+05	Np2 $\xrightarrow{0.873} \mathrm{U236}$ ... $\xrightarrow{0.125} \mathrm{Pu236}$ ... $\xrightarrow{0.0016} \mathrm{Pa232}$ ...
Np-237	2.15E+06	$\mathrm{Np237} \rightarrow \mathrm{Pa233}$ ...
Np-238	5.80E-03	$\mathrm{Np238} \rightarrow \mathrm{Pu238}$ ...
Np-239	6.46E-03	$\mathrm{Np239} \rightarrow \mathrm{Pu239}$ ...
Np-240	1.18E-04	Short lived daughter of Pu244
Np-240m	1.37E-05	Short lived daughter of Pu244
Os-185	2.56E-01	$\mathrm{Os185} \rightarrow \mathrm{Re}_{185}$
Os-186	2.00E+15	$\mathrm{Os186} \rightarrow \mathrm{W}_{182}$, Essentially Stable
Os-194	5.99E+00	$\mathrm{Os194} \rightarrow \mathbf{Ir194} \rightarrow \mathrm{Pt}_{194}$
P-32	3.90E-02	$\mathrm{P32} \rightarrow \mathrm{S}_{32}$
P-33	6.94E-02	$\mathrm{P33} \rightarrow \mathrm{S}_{33}$
Pa-231	3.26E+04	$\mathrm{Pa231} \rightarrow \mathrm{Ac227}$ ...
Pa-232	3.61E-03	$\mathrm{Pa232} \rightarrow \mathrm{U232}$ ...
Pa-233	7.38E-02	$\mathrm{Pa233} \rightarrow \mathrm{U233}$ ...
Pa-234	7.64E-04	Short lived daughter of Th234
Pa-234m	2.20E-06	Short lived daughter of Th234
Pb-202	5.26E+04	$\mathrm{Pb202} \xrightarrow{0.99} \mathrm{Tl202}$ ... $\xrightarrow{0.01} \mathrm{Hg}_{198}$
Pb-204	1.39E+17	Essentially stable
Pb-205	1.73E+07	$\mathrm{Pb205} \rightarrow \mathrm{Tl}_{205}$
Pb-209	3.71E-04	Short lived daughter of Ac225
Pb-210	2.22E+01	$\mathrm{Pb210} \xrightarrow{1.0*} \mathrm{Bi210}$ ...
Pb-211	6.88E-05	Short lived daughter of Ra223
Pb-212	1.21E-03	Short lived daughter of Ra224
Pb-214	5.10E-05	Short lived daughter of Rn222
Pd-107	6.50E+06	$\mathrm{Pd107} \rightarrow \mathrm{Ag}_{107}$
Pm-143	7.26E-01	$\mathrm{Pm143} \rightarrow \mathrm{Nd}_{143}$
Pm-144	9.95E-01	$\mathrm{Pm144} \rightarrow \mathrm{Nd144}$ ...
Pm-145	1.77E+01	$\mathrm{Pm145} \rightarrow \mathrm{Nd}_{145}$

Isotope	Half-Life [a]	Decay Chain
Pm-146	5.55E+00	$Pm146\ \begin{array}{l} \xrightarrow{0.36} Sm146 \ldots \\ \xrightarrow{0.66} Nd_{146} \end{array}$
Pm-147	2.62E+00	$Pm147 \rightarrow Sm147 \ldots$
Pm-148	1.47E-02	$Pm148 \rightarrow Sm148 \ldots$
Pm-148m	1.13E-01	$Pm148m\ \begin{array}{l} \xrightarrow{0.958} Sm148 \ldots \\ \xrightarrow{0.042} Pm148 \ldots \end{array}$
Po-208	2.90E+00	$Po208\ \begin{array}{l} \xrightarrow{1*} Pb_{204} \\ \xrightarrow{2.2e-5} Bi208 \ldots \end{array}$
Po-209	1.02E+02	$Po209\ \begin{array}{l} \xrightarrow{0.9952} Pb205 \ldots \\ \xrightarrow{0.0048} Bi_{209} \end{array}$
Po-210	3.80E-01	$Po210 \rightarrow Pb_{206}$
Po-211	1.64E-08	Short lived daughter of Ra223
Po-212	3.17E-11	Short lived daughter of Ra224
Po-213	3.17E-11	Short lived daughter of Ac225
Po-214	3.17E-11	Short lived daughter of Rn222
Po-215	5.64E-11	Short lived daughter of Ra223
Po-216	4.59E-09	Short lived daughter of Ra224
Po-218	5.89E-06	Short lived daughter of Rn222
Pr-144	3.30E-05	Short lived daughter of Ce144
Pr-144m	1.37E-05	Short lived daughter of Ce144
Pt-190	6.50E+11	$Pm190 \rightarrow Os186 \ldots$, Essentially Stable
Pt-193	5.01E+01	$Pt193 \rightarrow Ir193 \ldots$
Pu-236	2.86E+00	$Pu236 \rightarrow U232 \ldots$
Pu-237	1.25E-01	$Pu237\ \begin{array}{l} \xrightarrow{1.0*} Np237 \ldots \\ \xrightarrow{4e-5} U233 \ldots \end{array}$
Pu-238	8.78E+01	$Pu238 \rightarrow U234 \ldots$
Pu-239	2.41E+04	$Pu239\ \begin{array}{l} \xrightarrow{0.9994} \mathbf{U235m} \rightarrow U235 \ldots \\ \xrightarrow{0.0006} U235 \ldots \end{array}$
Pu-240	6.56E+03	$Pu240 \rightarrow U236 \ldots$
Pu-241	1.43E+01	$Pu241\ \begin{array}{l} \xrightarrow{1.0*} Am241 \ldots \\ \xrightarrow{2.3e-5} U237 \ldots \end{array}$
Pu-242	3.74E+05	$Pu242 \rightarrow U238 \ldots$
Pu-243	5.64E-04	Short lived daughter of Cm247
Pu-244	8.11E+07	$Pu244\ \begin{array}{l} \xrightarrow{0.999} \mathbf{U240} \rightarrow \mathbf{Np240m}\ \begin{array}{l} \xrightarrow{0.999} Pu240 \rightarrow U236 \ldots \\ \xrightarrow{0.001} \mathbf{Np240} \rightarrow Pu240 \ldots \end{array} \\ \xrightarrow{0.001} sf \end{array}$
Pu-246	2.97E-02	$Pu246 \rightarrow \mathbf{Am246m} \rightarrow Cm246 \ldots$
Ra-223	3.13E-02	$Ra223 \rightarrow \mathbf{Rn219} \rightarrow \mathbf{Po215} \rightarrow \mathbf{Pb211} \rightarrow \mathbf{Bi211}\ \begin{array}{l} \xrightarrow{0.9972} \mathbf{Tl207} \\ \xrightarrow{0.0028} \mathbf{Po211} \end{array} \rightarrow Pb_{207}$
Ra-224	1.00E-02	$Ra224 \rightarrow \mathbf{Rn220} \rightarrow \mathbf{Po216} \rightarrow \mathbf{Pb212} \rightarrow \mathbf{Bi212}\ \begin{array}{l} \xrightarrow{0.64} \mathbf{Po212} \\ \xrightarrow{0.36} \mathbf{Tl208} \end{array} \rightarrow Pb_{208}$
Ra-225	4.09E-02	$Ra225 \rightarrow Ac225 \ldots$

Isotope	Half-Life [a]	Decay Chain
Ra-226	1.60E+03	$\mathrm{Ra226} \rightarrow \mathrm{Rn222}$ ...
Ra-228	5.74E+00	$\mathrm{Ra228} \rightarrow \mathbf{Ac228} \rightarrow \mathrm{Th228}$ ...
Rb-83	2.36E-01	$\mathrm{Rb83} \xrightarrow{0.743} \mathbf{Kr83m} \rightarrow \mathrm{Kr}_{83}$ $\mathrm{Rb83} \xrightarrow{0.257} \mathrm{Kr}_{83}$
Rb-84	9.00E-02	$\mathrm{Rb84} \xrightarrow{0.962} \mathrm{Kr}_{84}$ $\mathrm{Rb84} \xrightarrow{0.038} \mathrm{Sr}_{84}$
Rb-87	4.82E+10	$\mathrm{Rb87} \rightarrow \mathrm{Sr}_{87}$, Essentially Stable
Re-183	1.92E-01	$\mathrm{Re183} \rightarrow \mathrm{W}_{183}$
Re-184	9.70E-02	$\mathrm{Re184} \rightarrow \mathrm{W}_{184}$
Re-184m	4.63E-01	$\mathrm{Re184m} \xrightarrow{0.754} \mathrm{Re184}$ ... $\mathrm{Re184m} \xrightarrow{0.246} \mathrm{W}_{184}$
Re-186	1.02E-02	$\mathrm{Re186} \xrightarrow{0.925} \mathrm{Os186}$ ... $\mathrm{Re186} \xrightarrow{0.075} \mathrm{W}_{186}$
Re-186m	2.00E+05	$\mathrm{Re186m} \rightarrow \mathrm{Re186}$ ...
Re-187	4.34E+10	$\mathrm{Re187} \rightarrow \mathrm{Os}_{187}$, Essentially Stable
Re-188	1.94E-03	Short lived daughter of W 188
Rh-101	3.30E+00	$\mathrm{Re101} \rightarrow \mathrm{Ru}_{101}$
Rh-102	5.67E-01	$\mathrm{Rh102} \xrightarrow{0.78} \mathrm{Ru}_{102}$ $\mathrm{Rh102} \xrightarrow{0.22} \mathrm{Pd}_{102}$
Rh-102m	3.74E+00	$\mathrm{Rh102m} \xrightarrow{0.0023} \mathrm{Rh102}$ ... $\mathrm{Rh102m} \xrightarrow{0.9977} \mathrm{Ru}_{102}$
Rh-103m	1.07E-04	Short lived daughter of Ru 103
Rh-106	9.54E-07	Short lived daughter of Ru 106
Rn-217	3.17E-11	Short lived daughter of Ac225
Rn-218	1.11E-09	Short lived daughter of Rn222
Rn-219	1.25E-07	Short lived daughter of Ra223
Rn-220	1.76E-06	Short lived daughter of Ra224
Rn-222	1.05E-02	$\mathrm{Rn222} \rightarrow \mathbf{Po218} \xrightarrow{0.9998} \mathbf{Pb214} \rightarrow \mathbf{Bi214}$ ($\xrightarrow{0.9998} \mathbf{Po214}$; $\xrightarrow{2.1e-4} \mathbf{Tl210}$) $\rightarrow \mathrm{Pb210}$ ... $\mathrm{Rn222} \rightarrow \mathbf{Po218} \xrightarrow{0.0002} \mathbf{At218} \xrightarrow{0.999} \mathbf{Bi214}$ ($\xrightarrow{0.9998} \mathbf{Po214}$; $\xrightarrow{2.1e-4} \mathbf{Tl210}$) $\rightarrow \mathrm{Pb210}$... $\mathbf{At218} \xrightarrow{0.001} \mathbf{Rn218} \rightarrow \mathbf{Po214} \rightarrow \mathrm{Pb210}$...
Ru-103	1.07E-01	$\mathrm{Ru103} \xrightarrow{0.9876} \mathbf{Rh103m} \rightarrow \mathrm{Rh}_{103}$ $\mathrm{Ru103} \xrightarrow{0.0124} \mathrm{Rh}_{103}$
Ru-106	1.02E+00	$\mathrm{Ru106} \rightarrow \mathbf{Rh106} \rightarrow \mathrm{Pd}_{106}$
S-35	2.40E-01	$\mathrm{S35} \rightarrow \mathrm{Cl}_{35}$
Sb-124	1.65E-01	$\mathrm{Sb124} \rightarrow \mathrm{Te}_{124}$
Sb-125	2.76E+00	$\mathrm{Sb125} \xrightarrow{0.231} \mathrm{Te125m}$ ... $\mathrm{Sb125} \xrightarrow{0.769} \mathrm{Te}_{125}$
Sb-126	3.39E-02	$\mathrm{Sb126} \rightarrow \mathrm{Te}_{126}$
Sb-126m	3.64E-05	Short lived daughter of Sn126

Isotope	Half-Life [a]	Decay Chain
Sc-44	4.53E-04	Short lived daughter of Ti44
Sc-45m	1.01E-08	$Sc45m \rightarrow Sc_{45}$
Sc-46	2.29E-01	$Sc46 \rightarrow Ti_{46}$
Se-75	3.26E-01	$Se75 \rightarrow As_{75}$
Se-79	2.95E+05	$Se79 \rightarrow Br_{79}$
Si-32	1.53E+02	$Si32 \rightarrow P32$ ...
Sm-145	9.32E-01	$Sm145 \rightarrow Pm145$ ...
Sm-146	1.03E+08	$Sm146 \rightarrow Nd_{142}$
Sm-147	1.06E+11	$Sm147 \rightarrow Nd_{143}$, Essentially Stable
Sm-148	7.00E+15	$Sm148 \rightarrow Nd144$ ...,Essentially Stable
Sm-151	9.00E+01	$Sm151 \rightarrow Eu_{151}$
Sn-113	3.15E-01	$Sn113 \rightarrow \mathbf{In113m} \rightarrow In_{113}$
Sn-119m	8.02E-01	$Sn119m \rightarrow Sn_{119}$
Sn-121	3.08E-03	$Sn121 \rightarrow Sb_{121}$
Sn-121m	4.40E+01	$Sn121m \xrightarrow{0.776} Sn121$ ... $Sn121m \xrightarrow{0.224} Sb_{121}$
Sn-123	3.55E-01	$Sn123 \rightarrow Sb_{123}$
Sn-126	2.30E+05	$Sn126 \rightarrow \mathbf{Sb126m} \xrightarrow{0.14} Sb126$ ... $\mathbf{Sb126m} \xrightarrow{0.86} Te_{126}$
Sr-85	1.77E-01	$Sr85 \rightarrow Rb_{85}$
Sr-89	1.38E-01	$Sr89 \rightarrow Y_{89}$
Sr-90	2.88E+01	$Sr90 \rightarrow Y90$ ...
Ta-179	1.82E+00	$Ta179 \rightarrow Hf_{179}$
Ta-182	3.14E-01	$Ta182 \rightarrow W_{182}$
Tb-157	7.10E+01	$Tb157 \rightarrow Gd_{157}$
Tb-158	1.80E+02	$Tb158 \xrightarrow{0.834} Gd_{158}$ $Tb158 \xrightarrow{0.116} Dy_{158}$
Tb-160	1.98E-01	$Tb160 \rightarrow Dy_{160}$
Tc-95	2.28E-03	Short lived daughter of Tc95m
Tc-95m	1.67E-01	$Tc95m \xrightarrow{0.0388} \mathbf{Tc95} \rightarrow Mo_{95}$ $Tc95m \xrightarrow{0.9612} Mo_{95}$
Tc-97	4.21E+06	$Tc97 \rightarrow Mo_{97}$
Tc-97m	2.49E-01	$Tc97m \rightarrow Tc97$ ...
Tc-98	4.21E+06	$Tc98 \rightarrow Ru_{98}$
Tc-99	2.11E+05	$Tc99 \rightarrow Ru_{99}$
Te-121	5.26E-02	$Te121 \rightarrow Sb_{121}$

Isotope	Half-Life [a]	Decay Chain
Te-121m	4.50E-01	$\mathrm{Te121m} \begin{array}{l}\xrightarrow{0.886} \mathrm{Te121} \ldots \\ \xrightarrow{0.114} \mathrm{Sb}_{121}\end{array}$
Te-123m	3.26E-01	$\mathrm{Te123m} \rightarrow \mathrm{Te123} \ldots$
Te-125m	1.57E-01	$\mathrm{Te125m} \rightarrow \mathrm{Te}_{125}$
Te-127	1.07E-03	Short lived daughter of Te127m
Te-127m	2.99E-01	$\mathrm{Te127m} \begin{array}{l}\xrightarrow{0.976} \mathbf{Te127} \rightarrow \mathrm{I}_{127} \\ \xrightarrow{0.024} \mathrm{I}_{127}\end{array}$
Te-128	8.81E+18	Essentially stable
Te-129	1.32E-04	Short lived daughter of Te129m
Te-129m	9.19E-02	$\mathrm{Te129m} \begin{array}{l}\xrightarrow{0.63} \mathbf{Te129} \rightarrow \mathrm{I129} \ldots \\ \xrightarrow{0.37} \mathrm{I129} \ldots\end{array}$
Th-227	5.10E-02	$\mathrm{Th227} \rightarrow \mathrm{Ra223} \ldots$
Th-228	1.91E+00	$\mathrm{Th228} \rightarrow \mathrm{Ra224} \ldots$
Th-229	7.35E+03	$\mathrm{Th229} \rightarrow \mathrm{Ra225} \ldots$
Th-230	7.54E+04	$\mathrm{Th230} \rightarrow \mathrm{Ra226} \ldots$
Th-231	2.91E-03	$\mathrm{Th231} \rightarrow \mathrm{Ra227} \ldots$
Th-232	1.40E+10	$\mathrm{Th232} \rightarrow \mathrm{Ra228} \ldots$
Th-234	6.59E-02	$\mathrm{Th234} \rightarrow \mathbf{Pa234m} \begin{array}{l}\xrightarrow{0.9984} \mathrm{U234} \ldots \\ \xrightarrow{0.0016} \mathbf{Pa234} \rightarrow \mathrm{U234} \ldots\end{array}$
Ti-44	5.99E+01	$\mathrm{Ti44} \rightarrow \mathbf{Sc44} \rightarrow \mathrm{Ca}_{44}$
Tl-202	3.36E-02	$\mathrm{Tl202} \rightarrow \mathrm{Hg}_{202}$
Tl-204	3.77E+00	$\mathrm{Tl204} \begin{array}{l}\xrightarrow{0.971} \mathrm{Pb}_{204} \\ \xrightarrow{0.029} \mathrm{Hg}_{204}\end{array}$
Tl-206	7.99E-06	Short lived daughter of Bi210m
Tl-207	9.06E-06	Short lived daughter of Ra223
Tl-208	5.80E-06	Short lived daughter of Ra224
Tl-209	4.18E-06	Short lived daughter of Ac225
Tl-210	2.47E-06	Short lived daughter of Rn222
Tm-168	2.55E-01	$\mathrm{Tm168} \xrightarrow{1.0*} \mathrm{Er}_{168}$
Tm-170	3.52E-01	$\mathrm{Tm170} \begin{array}{l}\xrightarrow{0.9987} \mathrm{Yb}_{170} \\ \xrightarrow{0.0013} \mathrm{Er}_{170}\end{array}$
Tm-171	1.92E+00	$\mathrm{Tm171} \rightarrow \mathrm{Yb}_{171}$
U-232	6.88E+01	$\mathrm{U232} \rightarrow \mathrm{Th228} \ldots$
U-233	1.59E+05	$\mathrm{U233} \rightarrow \mathrm{Th229} \ldots$
U-234	2.46E+05	$\mathrm{U234} \rightarrow \mathrm{Th230} \ldots$
U-235	7.03E+08	$\mathrm{U235} \rightarrow \mathrm{Th231} \ldots$
U-236	2.34E+07	$\mathrm{U236} \rightarrow \mathrm{Th232} \ldots$
U-237	1.85E-02	$\mathrm{U237} \rightarrow \mathrm{Np237} \ldots$
U-238	4.47E+09	$\mathrm{U238} \rightarrow \mathrm{Th234} \ldots$
U-240	1.61E-03	Short lived daughter of Pu244

Isotope	Half-Life [a]	Decay Chain
V-49	9.03E-01	$V49 \rightarrow Ti_{49}$
V-50	1.40E+17	$V50 \xrightarrow{0.83} Ti_{50}$, $\xrightarrow{0.17} Cr_{50}$, Essentially Stable
W-180	1.80E+18	Essentially stable
W-181	3.33E-01	$W181 \rightarrow Ta_{181}$
W-185	2.06E-01	$W185 \rightarrow Re_{185}$
W-186	1.70E+20	Essentially stable
W-188	1.91E-01	$W188 \rightarrow \mathbf{Re188} \rightarrow Os_{188}$
Xe-127	9.95E-02	$Xe127 \rightarrow I_{127}$
Y-88	2.92E-01	$Y88 \rightarrow Sr_{88}$
Y-89m	4.98E-07	$Y89m \rightarrow Y_{89}$
Y-90	7.29E-03	$Y90 \rightarrow Zr_{90}$
Y-91	1.60E-01	$Y91 \rightarrow Zr_{91}$
Yb-169	8.78E-02	$Yb169 \rightarrow Tm_{169}$
Zn-65	6.69E-01	$Zn65 \rightarrow Cu_{65}$
Zr-88	2.28E-01	$Zr88 \rightarrow Y88$ ...
Zr-93	1.53E+06	$Zr93 \xrightarrow{0.975} Nb93m$ ... $\xrightarrow{0.025} Nb_{93}$
Zr-95	1.75E-01	$Zr95 \xrightarrow{0.9892} Nb95$ ... $\xrightarrow{0.0108} Nb95m$ ...
Zr-96	2.00E+19	Essentially stable

A.3 Dose Conversion Factor Data

Human dose conversion factor data was taken from ICRP publication 119 (ICRP 2012) for inhalation and ingestion and ICRP publication 144 (ICRP 2019) for water immersion, air immersion and groundshine. Table 20 lists the final set of dose conversion factors described in Section 2.3.1 through Section 2.3.5. Table 21 shows the contribution to the parent dose conversion factor as a result of the short lived daughters.

Non-human biota dose conversion factor data was taken from ICRP publication 136 (ICRP 2017) as described in Section 2.3.6. Internal, water immersion, soil immersion, on-ground, above ground and air immersion dose conversion factors are presented in Table 22. Values presented are the maximum of the bee, wild grass, earth worm, frog, rat, duck, deer, pine tree, brown seaweed, crab, trout and flatfish dose conversion factors for each exposure pathway.

Table 20: Radionuclide Dose Conversion Factors

Isotope	Inhalation	Ingestion	Water Immersion	Air Immersion	Groundshine
	Sv/Bq	Sv/Bq	(nSv/hr)/(Bq/m^3)	(nSv/hr)/(Bq/m^3)	(nSv/hr)/(Bq/m^2)
Ac-225	1.68E-07	5.95E-05	1.15E-04	5.31E-02	1.82E-03
Ac-227	1.10E-06	5.50E-04	2.26E-07	1.04E-04	6.16E-06
Ac-228	Included in Ra 228 DCFs				
Ag-105	4.70E-10	8.10E-10	1.62E-04	7.37E-02	1.64E-03
Ag-108	Included in Ag 108m DCFs				
Ag-108m	4.60E-09	7.40E-08	5.38E-04	2.45E-01	5.39E-03
Ag-109m	1.10E-07	1.60E-05	1.08E-06	4.74E-04	2.99E-05
Ag-110	Included in Ag 110m DCFs				
Ag-110m	5.60E-09	2.40E-08	9.73E-04	4.44E-01	8.93E-03
Al-26	3.50E-09	2.00E-08	9.90E-04	4.50E-01	8.56E-03
Am-241	2.00E-07	9.60E-05	4.44E-06	1.89E-03	7.04E-05
Am-242	Included in Am242m DCF				
Am-242m	1.90E-07	9.20E-05	4.04E-06	1.81E-03	1.46E-04
Am-243	2.00E-07	9.60E-05	1.26E-05	5.61E-03	1.66E-04
Am-244	Included in Bk 248 DCFs				
Am-245	Included in Bk 249 DCFs				
Am-246m	Included in Pu 246 DCFs				
Ar-37	0.00E+00	0.00E+00	0.00E+00	1.71E-07	0.00E+00
Ar-39	0.00E+00	0.00E+00	4.68E-07	4.58E-04	1.37E-04
Ar-42	8.60E-10	2.40E-10	1.20E-04	5.67E-02	2.28E-03
As-73	2.60E-10	1.00E-09	1.03E-06	4.40E-04	1.68E-05
At-217	Included in Ac 225 DCFs				
At-218	Included in Rn 222 DCFs				
Au-194	4.20E-10	2.40E-10	3.67E-04	1.67E-01	3.23E-03
Au-195	2.50E-10	1.70E-09	1.77E-05	7.70E-03	2.35E-04
Ba-133	1.50E-09	1.00E-08	1.16E-04	5.30E-02	1.27E-03

Isotope	Inhalation	Ingestion	Water Immersion	Air Immersion	Groundshine
	Sv/Bq	Sv/Bq	(nSv/hr)/(Bq/m^3)	(nSv/hr)/(Bq/m^3)	(nSv/hr)/(Bq/m^2)
Ba-137m	Included in Cs 137 DCFs				
Be-10	1.10E-09	3.50E-08	5.70E-07	4.35E-04	1.63E-04
Bi-207	1.30E-09	5.60E-09	5.39E-04	2.43E-01	4.94E-03
Bi-208	1.10E-07	1.60E-05	1.05E-03	4.82E-01	7.47E-03
Bi-209	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Bi-210	1.30E-09	9.30E-08	1.19E-06	8.41E-04	2.49E-04
Bi-210m	3.00E-08	6.80E-06	8.30E-05	3.85E-02	1.21E-03
Bi-211	Included in Ra 223 DCFs				
Bi-212	Included in Ra 224 DCFs				
Bi-213	Included in Ac 225 DCFs				
Bi-214	Included in Rn 222 DCFs				
Bk-247	3.50E-07	6.90E-05	4.12E-05	1.85E-02	4.80E-04
Bk-248	9.20E-10	7.40E-09	5.36E-04	2.46E-01	5.40E-03
Bk-249	9.70E-10	1.60E-07	2.09E-09	1.32E-06	1.26E-06
Bk-250	Included in Es 254 and Cm 250 DCFs				
C-14	5.80E-10	5.80E-09	9.50E-09	6.29E-06	6.25E-06
Ca-41	1.90E-10	1.80E-10	0.00E+00	0.00E+00	0.00E+00
Ca-45	7.10E-10	3.70E-09	5.57E-08	3.73E-05	2.50E-05
Ca-48	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cd-109	2.00E-09	8.10E-09	1.62E-06	7.15E-04	5.61E-05
Cd-113	2.50E-08	1.20E-07	9.30E-08	6.54E-05	3.71E-05
Cd-113m	2.30E-08	1.10E-07	3.83E-07	2.84E-04	1.11E-04
Cd-115m	3.30E-09	7.70E-09	1.43E-05	7.06E-03	4.96E-04
Cd-116	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ce-139	2.60E-10	1.90E-09	4.10E-05	1.85E-02	4.92E-04
Ce-141	7.10E-10	3.80E-09	2.11E-05	9.46E-03	3.22E-04
Ce-144	1.05E-08	1.06E-07	2.43E-05	1.28E-02	1.14E-03
Cf-248	2.80E-08	8.80E-06	1.56E-07	7.07E-05	2.96E-06
Cf-249	3.50E-07	7.00E-05	1.04E-04	4.71E-02	1.07E-03
Cf-250	1.60E-07	3.40E-05	3.71E-06	1.70E-03	3.51E-05
Cf-251	3.60E-07	7.10E-05	3.30E-05	1.45E-02	4.33E-04
Cf-252	9.00E-08	2.00E-05	1.72E-04	7.86E-02	1.60E-03
Cf-254	4.00E-07	4.10E-05	6.36E-03	2.91E+00	6.02E-02
Cl-36	9.30E-10	7.30E-09	7.23E-07	5.25E-04	1.76E-04
Cm-240	7.60E-09	3.50E-06	3.84E-08	1.72E-05	2.14E-06
Cm-241	9.10E-10	3.70E-08	1.54E-04	6.90E-02	1.65E-03
Cm-242	1.20E-08	5.90E-06	3.33E-08	1.49E-05	1.90E-06
Cm-243	1.50E-07	6.90E-05	3.68E-05	1.63E-02	4.42E-04
Cm-244	1.20E-07	5.70E-05	3.37E-08	1.52E-05	1.67E-06

Isotope	Inhalation	Ingestion	Water Immersion	Air Immersion	Groundshine
	Sv/Bq	Sv/Bq	(nSv/hr)/(Bq/m^3)	(nSv/hr)/(Bq/m^3)	(nSv/hr)/(Bq/m^2)
Cm-245	2.10E-07	9.90E-05	2.70E-05	1.15E-02	3.20E-04
Cm-246	2.10E-07	9.80E-05	1.38E-06	6.32E-04	1.38E-05
Cm-247	1.90E-07	9.00E-05	1.07E-04	4.87E-02	1.20E-03
Cm-248	7.70E-07	3.60E-04	4.94E-04	2.27E-01	4.66E-03
Cm-250	4.40E-06	2.10E-03	5.06E-03	2.32E+00	4.84E-02
Co-56	2.50E-09	6.70E-09	1.36E-03	6.23E-01	1.11E-02
Co-57	2.10E-10	1.00E-09	3.37E-05	1.44E-02	3.70E-04
Co-58	7.40E-10	2.10E-09	3.32E-04	1.53E-01	3.21E-03
Co-60	3.40E-09	3.10E-08	9.36E-04	4.23E-01	7.76E-03
Co-60m	Included in Fe 60 DCFs				
Cr-51	3.80E-11	3.70E-11	1.00E-05	4.59E-03	1.02E-04
Cs-134	1.90E-08	2.00E-08	5.29E-04	2.42E-01	5.22E-03
Cs-135	2.00E-09	8.60E-09	8.01E-08	5.46E-05	3.37E-05
Cs-137	2.60E-08	7.80E-08	1.89E-04	8.65E-02	2.02E-03
Dy-154	1.20E-06	5.50E-04	0.00E+00	0.00E+00	0.00E+00
Dy-159	1.00E-10	3.70E-10	6.75E-06	2.96E-03	1.25E-04
Es-252	1.20E-06	5.50E-04	2.01E-03	9.31E-01	1.61E-02
Es-254	2.81E-08	8.60E-06	3.26E-04	1.47E-01	3.00E-03
Es-255	6.90E-09	7.45E-07	2.84E-06	1.27E-03	8.52E-05
Eu-148	1.30E-09	2.60E-09	7.61E-04	3.45E-01	7.25E-03
Eu-149	1.00E-10	2.90E-10	1.44E-05	6.53E-03	1.95E-04
Eu-150	1.30E-09	5.30E-08	5.16E-04	2.34E-01	5.05E-03
Eu-152	1.40E-09	4.20E-08	4.13E-04	1.87E-01	3.74E-03
Eu-154	2.00E-09	5.30E-08	4.44E-04	2.02E-01	4.08E-03
Eu-155	3.20E-10	6.90E-09	1.44E-05	6.20E-03	1.88E-04
Fe-55	3.30E-10	7.70E-10	4.52E-14	1.94E-11	4.94E-13
Fe-59	1.80E-09	4.00E-09	4.41E-04	1.99E-01	3.73E-03
Fe-60	1.10E-07	2.80E-07	1.50E-06	6.80E-04	2.89E-05
Fr-221	Included in Ac 225 DCFs				
Fr-223	Included in Ac 227 DCFs				
Ga-68	Included in Ge 68 DCFs				
Gd-148	5.60E-08	2.60E-05	0.00E+00	0.00E+00	0.00E+00
Gd-150	1.10E-07	1.60E-05	0.00E+00	0.00E+00	0.00E+00
Gd-151	2.00E-10	8.60E-10	1.48E-05	6.70E-03	2.10E-04
Gd-152	4.10E-08	1.90E-05	0.00E+00	0.00E+00	0.00E+00
Gd-153	2.70E-10	2.10E-09	2.09E-05	8.93E-03	3.04E-04
Ge-68	1.40E-09	1.40E-08	3.18E-04	1.44E-01	3.63E-03
Ge-73m	1.10E-07	1.60E-05	2.01E-03	9.31E-01	1.61E-02
H-3	4.20E-11	2.60E-10	9.09E-13	9.05E-10	5.99E-11

Isotope	Inhalation	Ingestion	Water Immersion	Air Immersion	Groundshine
	Sv/Bq	Sv/Bq	(nSv/hr)/(Bq/m^3)	(nSv/hr)/(Bq/m^3)	(nSv/hr)/(Bq/m^2)
Hf-172	2.00E-09	6.40E-08	2.06E-05	8.82E-03	2.94E-04
Hf-174	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hf-175	4.10E-10	1.20E-09	1.05E-04	4.77E-02	1.14E-03
Hf-177m	8.10E-11	9.00E-11	7.00E-04	3.19E-01	7.51E-03
Hf-181	1.10E-09	5.00E-09	1.69E-04	7.60E-02	1.82E-03
Hf-182	3.00E-09	3.10E-07	7.30E-05	3.34E-02	7.75E-04
Hg-194	5.10E-08	1.40E-08	7.18E-09	3.37E-06	7.11E-07
Hg-203	1.90E-09	2.40E-09	7.32E-05	3.36E-02	7.93E-04
Hg-206	Short lived daughter of Pb210 with a very low (1.9E-6%) chance of occurrence				
Ho-163	1.10E-07	1.60E-05	0.00E+00	0.00E+00	0.00E+00
Ho-166m	2.00E-09	1.20E-07	5.39E-04	2.48E-01	5.34E-03
I-125	1.50E-08	5.10E-09	2.65E-06	1.17E-03	9.23E-05
I-129	1.10E-07	3.60E-08	2.00E-06	8.83E-04	6.71E-05
In-113m	Included in Sn 113 DCFs				
In-114	Included in In 114m DCFs				
In-114m	8.20E-09	1.86E-08	2.78E-05	1.35E-02	8.37E-04
In-115	3.20E-08	3.90E-07	2.60E-07	1.97E-04	8.54E-05
In-115m	8.60E-11	5.90E-11	4.98E-05	2.29E-02	6.39E-04
Ir-192	1.40E-09	6.60E-09	2.62E-04	1.19E-01	2.78E-03
Ir-194	Included in Os 194 DCFs				
K-40	6.20E-09	2.10E-09	6.14E-05	2.83E-02	8.16E-04
K-42	Included in Ar42 DCFs				
Kr-81	0.00E+00	0.00E+00	2.91E-07	8.75E-04	6.08E-06
Kr-83m	Included in Rb 83 DCFs				
Kr-85	0.00E+00	0.00E+00	1.33E-06	9.17E-04	1.66E-04
La-137	8.10E-11	8.70E-09	2.16E-06	9.53E-04	6.19E-05
La-138	1.10E-09	1.50E-07	4.53E-04	2.06E-01	3.84E-03
Lu-172	1.30E-09	1.60E-09	6.88E-04	3.12E-01	6.16E-03
Lu-172m	Included in Hf 172 DCFs				
Lu-173	2.60E-10	2.40E-09	4.47E-05	1.99E-02	5.49E-04
Lu-174	2.70E-10	4.20E-09	3.34E-05	1.49E-02	3.42E-04
Lu-174m	5.30E-10	4.20E-09	1.21E-05	5.28E-03	1.72E-04
Lu-176	1.80E-09	7.00E-08	1.45E-04	6.65E-02	1.66E-03
Lu-177	5.30E-10	1.20E-09	1.02E-05	4.62E-03	1.82E-04
Lu-177m	1.70E-09	1.60E-08	2.99E-04	1.35E-01	3.23E-03
Mn-53	3.00E-11	5.40E-11	0.00E+00	0.00E+00	0.00E+00
Mn-54	7.10E-10	1.50E-09	2.88E-04	1.33E-01	2.72E-03
Mo-100	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Mo-93	3.10E-09	2.30E-09	1.61E-07	7.31E-05	1.09E-05

Isotope	Inhalation	Ingestion	Water Immersion	Air Immersion	Groundshine
	Sv/Bq	Sv/Bq	(nSv/hr)/(Bq/m^3)	(nSv/hr)/(Bq/m^3)	(nSv/hr)/(Bq/m^2)
Na-22	3.20E-09	1.30E-09	7.81E-04	3.53E-01	7.09E-03
Nb-91	1.10E-07	1.60E-05	6.64E-07	3.00E-04	1.50E-05
Nb-91m	1.10E-07	1.60E-05	9.39E-06	4.24E-03	1.06E-04
Nb-92	1.10E-07	1.60E-05	5.20E-04	2.36E-01	4.84E-03
Nb-93m	1.20E-10	1.80E-09	2.88E-08	1.31E-05	1.95E-06
Nb-94	1.70E-09	4.90E-08	5.36E-04	2.47E-01	5.19E-03
Nb-95	5.80E-10	1.80E-09	2.60E-04	1.20E-01	2.53E-03
Nb-95m	5.60E-10	8.80E-10	1.96E-05	9.08E-03	3.13E-04
Nd-144	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nd-150	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ni-59	6.30E-11	4.40E-10	5.13E-09	2.32E-06	5.15E-08
Ni-63	1.50E-10	1.30E-09	6.73E-11	4.10E-08	3.09E-09
Np-235	1.06E-10	1.26E-09	4.26E-07	1.83E-04	1.32E-05
Np-236	1.70E-08	8.00E-06	3.77E-05	1.63E-02	4.92E-04
Np-237	1.10E-07	5.00E-05	5.79E-06	2.52E-03	8.18E-05
Np-238	9.10E-10	3.50E-09	2.11E-04	9.56E-02	1.95E-03
Np-239	8.00E-10	1.00E-09	5.05E-05	2.23E-02	6.48E-04
Np-240	Included in Pu 244 DCFs				
Np-240m	Included in Pu 244 DCFs				
Os-185	5.10E-10	1.60E-09	2.27E-04	1.03E-01	2.27E-03
Os-186	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Os-194	3.70E-09	8.56E-08	3.49E-05	1.68E-02	8.56E-04
P-32	2.40E-09	3.40E-09	2.95E-06	2.01E-03	4.56E-04
P-33	2.40E-10	1.50E-09	5.25E-08	3.50E-05	2.41E-05
Pa-231	7.10E-07	1.40E-04	1.03E-05	4.72E-03	1.22E-04
Pa-232	7.20E-10	1.00E-08	3.24E-04	1.47E-01	3.04E-03
Pa-233	8.70E-10	3.90E-09	6.56E-05	2.97E-02	7.71E-04
Pa-234	Included in Th 234 DCFs				
Pa-234m	Included in Th 234 DCFs				
Pb-202	8.80E-09	1.20E-08	9.15E-09	4.47E-06	1.08E-06
Pb-204	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pb-205	2.80E-10	8.50E-10	9.27E-09	4.53E-06	1.09E-06
Pb-209	Included in Ac 225 DCFs				
Pb-210	6.90E-07	5.60E-06	3.25E-07	1.43E-04	7.28E-06
Pb-211	Included in Ra 223 DCFs				
Pb-212	Included in Ra 224 DCFs				
Pb-214	Included in Rn 222 DCFs				
Pd-107	3.70E-11	5.90E-10	8.69E-12	6.41E-09	4.46E-10
Pm-143	2.30E-10	1.50E-09	1.00E-04	4.62E-02	1.03E-03

Isotope	Inhalation	Ingestion	Water Immersion	Air Immersion	Groundshine
	Sv/Bq	Sv/Bq	(nSv/hr)/(Bq/m^3)	(nSv/hr)/(Bq/m^3)	(nSv/hr)/(Bq/m^2)
Pm-144	9.70E-10	8.20E-09	5.18E-04	2.36E-01	5.18E-03
Pm-145	1.10E-10	3.60E-09	3.74E-06	1.66E-03	8.37E-05
Pm-146	9.00E-10	2.10E-08	2.47E-04	1.13E-01	2.53E-03
Pm-147	2.60E-10	5.00E-09	3.18E-08	2.07E-05	1.54E-05
Pm-148	2.70E-09	2.20E-09	2.13E-04	9.75E-02	2.32E-03
Pm-148m	1.70E-09	5.70E-09	6.73E-04	3.05E-01	6.64E-03
Po-208	1.20E-06	5.50E-04	6.90E-09	3.14E-06	7.02E-08
Po-209	1.20E-06	5.50E-04	2.05E-06	9.38E-04	2.00E-05
Po-210	1.20E-06	4.30E-06	3.33E-09	1.54E-06	3.20E-08
Po-211	Included in Ra 223 DCFs				
Po-212	Included in Ra 224 DCFs				
Po-213	Included in Ac 225 DCFs				
Po-214	Included in Rn 222 DCFs				
Po-215	Included in Ra 223 DCFs				
Po-216	Included in Ra 224 DCFs				
Po-218	Included in Rn 222 DCFs				
Pr-144	Included in Ce 144 DCFs				
Pr-144m	Included in Ce 144 DCFs				
Pt-190	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pt-193	3.10E-11	2.10E-11	5.07E-09	2.43E-06	5.57E-07
Pu-236	8.70E-08	4.00E-05	3.72E-08	1.66E-05	2.01E-06
Pu-237	1.00E-10	3.90E-10	1.20E-05	5.03E-03	1.43E-04
Pu-238	2.30E-07	1.10E-04	2.99E-08	1.35E-05	1.78E-06
Pu-239	5.00E-07	2.40E-04	5.82E-08	2.58E-05	1.88E-06
Pu-240	2.50E-07	1.20E-04	2.91E-08	1.31E-05	1.69E-06
Pu-241	4.80E-09	2.30E-06	4.14E-10	1.77E-07	5.13E-09
Pu-242	2.40E-07	1.10E-04	5.29E-08	2.41E-05	1.71E-06
Pu-243	Included in Cm 247 DCFs				
Pu-244	4.81E-07	2.20E-04	1.21E-04	5.55E-02	1.60E-03
Pu-246	3.33E-09	8.02E-09	3.89E-04	1.77E-01	3.83E-03
Ra-223	6.00E-07	5.22E-05	9.89E-05	4.58E-02	1.63E-03
Ra-224	3.31E-07	1.72E-05	1.02E-03	4.66E-01	8.65E-03
Ra-225	9.90E-08	7.70E-06	1.62E-06	7.47E-04	7.15E-05
Ra-226	2.80E-07	9.50E-06	2.14E-06	9.73E-04	2.45E-05
Ra-228	6.90E-07	1.60E-05	3.06E-04	1.40E-01	2.99E-03
Rb-83	3.80E-09	1.38E-09	1.61E-04	7.25E-02	1.61E-03
Rb-84	2.80E-09	1.00E-09	3.12E-04	1.43E-01	3.04E-03
Rb-87	1.50E-09	5.00E-10	1.33E-07	9.32E-05	5.20E-05
Re-183	1.10E-07	1.60E-05	3.74E-05	1.65E-02	4.72E-04

Isotope	Inhalation	Ingestion	Water Immersion	Air Immersion	Groundshine
	Sv/Bq	Sv/Bq	(nSv/hr)/(Bq/m^3)	(nSv/hr)/(Bq/m^3)	(nSv/hr)/(Bq/m^2)
Re-184	1.00E-09	1.90E-09	3.00E-04	1.37E-01	2.87E-03
Re-184m	1.50E-09	6.50E-09	1.20E-04	5.43E-02	1.21E-03
Re-186	1.50E-09	1.10E-09	6.24E-06	2.98E-03	2.72E-04
Re-186m	2.20E-09	1.20E-08	2.82E-06	1.20E-03	4.41E-05
Re-187	5.10E-12	6.30E-12	0.00E+00	0.00E+00	0.00E+00
Re-188	Included in W 188 DCFs				
Rh-101	5.50E-10	5.40E-09	8.10E-05	3.64E-02	8.78E-04
Rh-102	1.20E-09	7.10E-09	1.67E-04	7.56E-02	1.75E-03
Rh-102m	2.60E-09	1.70E-08	7.36E-04	3.34E-01	6.98E-03
Rh-103m	Included in Ru 103 DCFs				
Rh-106	Included in Ru 106 DCFs				
Rn-217	Included in Ac 226 DCFs				
Rn-218	Included in Rn 222 DCFs				
Rn-219	Included in Ra 223 DCFs				
Rn-220	Included in Ra 224 DCFs				
Rn-222	1.51E-09	1.64E-07	6.31E-04	2.87E-01	6.04E-03
Ru-103	7.34E-10	3.00E-09	1.64E-04	7.39E-02	1.66E-03
Ru-106	1.40E-08	1.32E-07	8.18E-05	3.92E-02	1.90E-03
S-35	7.70E-10	1.90E-09	1.11E-08	7.32E-06	6.98E-06
Sb-124	2.50E-09	8.60E-09	6.77E-04	3.08E-01	6.08E-03
Sb-125	1.10E-09	1.20E-08	1.40E-04	6.35E-02	1.47E-03
Sb-126	2.40E-09	3.20E-09	9.30E-04	4.26E-01	9.32E-03
Sb-126m	Included in Sn 126 DCFs				
Sc-44	Included in Ti 44 DCFs				
Sc-45m	1.10E-07	1.60E-05	2.01E-03	9.31E-01	1.61E-02
Sc-46	1.50E-09	6.80E-09	7.26E-04	3.30E-01	6.37E-03
Se-75	2.60E-09	1.30E-09	1.16E-04	5.27E-02	1.22E-03
Se-79	2.90E-09	6.80E-09	1.11E-08	7.36E-06	7.38E-06
Si-32	5.60E-10	1.10E-07	3.78E-08	2.48E-05	1.87E-05
Sm-145	2.10E-10	1.60E-09	8.33E-06	3.67E-03	1.74E-04
Sm-146	5.40E-08	1.10E-05	0.00E+00	0.00E+00	0.00E+00
Sm-147	4.90E-08	9.60E-06	0.00E+00	0.00E+00	0.00E+00
Sm-148	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-151	9.80E-11	4.00E-09	3.18E-10	1.58E-07	2.10E-08
Sn-113	7.58E-10	2.72E-09	8.51E-05	3.88E-02	9.89E-04
Sn-119m	3.40E-10	2.20E-09	6.82E-07	3.01E-04	2.84E-05
Sn-121	2.30E-10	2.30E-10	1.52E-07	1.12E-04	5.54E-05
Sn-121m	3.80E-10	4.50E-09	3.44E-07	1.63E-04	2.41E-05
Sn-123	2.10E-09	8.10E-09	4.44E-06	2.46E-03	3.57E-04

Isotope	Inhalation	Ingestion	Water Immersion	Air Immersion	Groundshine
	Sv/Bq	Sv/Bq	(nSv/hr)/(Bq/m^3)	(nSv/hr)/(Bq/m^3)	(nSv/hr)/(Bq/m^2)
Sn-126	4.74E-09	2.80E-08	5.33E-04	2.43E-01	5.73E-03
Sr-85	5.60E-10	8.10E-10	1.63E-04	7.34E-02	1.64E-03
Sr-89	2.60E-09	7.90E-09	2.30E-06	1.57E-03	3.79E-04
Sr-90	2.80E-08	1.60E-07	3.98E-07	3.03E-04	1.20E-04
Ta-179	6.50E-11	5.60E-10	4.59E-06	1.96E-03	6.89E-05
Ta-182	1.50E-09	1.00E-08	4.64E-04	2.09E-01	4.06E-03
Tb-157	3.40E-11	1.20E-09	6.64E-07	2.93E-04	1.29E-05
Tb-158	1.10E-09	4.60E-08	2.76E-04	1.26E-01	2.56E-03
Tb-160	1.60E-09	7.00E-09	3.99E-04	1.81E-01	3.68E-03
Tc-95	Included in Tc 95m DCFs				
Tc-95m	5.67E-10	1.20E-09	2.36E-04	1.09E-01	2.32E-03
Tc-97	6.80E-11	1.80E-09	1.97E-07	8.83E-05	1.26E-05
Tc-97m	5.50E-10	4.10E-09	2.75E-07	1.24E-04	2.37E-05
Tc-98	2.00E-09	4.50E-08	4.78E-04	2.19E-01	4.76E-03
Tc-99	6.40E-10	1.30E-08	1.07E-07	7.48E-05	4.25E-05
Te-121	4.30E-10	4.10E-10	1.87E-04	8.41E-02	1.90E-03
Te-121m	2.30E-09	5.70E-09	6.39E-05	2.92E-02	6.77E-04
Te-123m	1.40E-09	5.10E-09	3.97E-05	1.79E-02	4.60E-04
Te-125m	8.70E-10	4.20E-09	2.33E-06	1.03E-03	9.89E-05
Te-127	Included in Te 127m DCFs				
Te-127m	2.47E-09	9.94E-09	2.79E-06	1.41E-03	1.86E-04
Te-128	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Te-129	Included in Te129m DCF				
Te-129m	3.04E-09	7.92E-09	2.47E-05	1.17E-02	6.00E-04
Th-227	8.80E-09	1.00E-05	3.67E-05	1.67E-02	4.06E-04
Th-228	7.20E-08	4.00E-05	5.62E-07	2.52E-04	8.17E-06
Th-229	4.90E-07	2.40E-04	2.24E-05	9.84E-03	2.75E-04
Th-230	2.10E-07	1.00E-04	1.06E-07	4.71E-05	2.19E-06
Th-231	3.40E-10	3.30E-10	3.08E-06	1.37E-03	7.56E-05
Th-232	2.30E-07	1.10E-04	5.68E-08	2.49E-05	1.51E-06
Th-234	6.80E-09	1.54E-08	1.29E-05	6.71E-03	6.57E-04
Ti-44	6.15E-09	1.20E-07	7.88E-04	3.56E-01	7.61E-03
Tl-202	4.50E-10	1.90E-10	1.45E-04	6.56E-02	1.51E-03
Tl-204	1.20E-09	3.90E-10	8.38E-07	5.39E-04	1.51E-04
Tl-206	Included in Bi 210m DCFs				
Tl-207	Included in Ra 223 DCFs				
Tl-208	Included in Ra 224 DCFs				
Tl-209	Included in Ac 225 DCFs				
Tl-210	Included in Rn 222 DCFs				

Isotope	Inhalation	Ingestion	Water Immersion	Air Immersion	Groundshine
	Sv/Bq	Sv/Bq	(nSv/hr)/(Bq/m^3)	(nSv/hr)/(Bq/m^3)	(nSv/hr)/(Bq/m^2)
Tm-168	1.10E-07	1.60E-05	4.08E-04	1.87E-01	4.04E-03
Tm-170	1.30E-09	7.00E-09	1.71E-06	9.95E-04	2.14E-04
Tm-171	1.10E-10	1.40E-09	1.13E-07	4.83E-05	1.88E-06
U-232	3.30E-07	3.70E-05	7.95E-08	3.49E-05	2.39E-06
U-233	5.10E-08	9.60E-06	7.61E-08	3.40E-05	1.60E-06
U-234	4.90E-08	9.40E-06	4.78E-08	2.10E-05	1.86E-06
U-235	4.70E-08	8.50E-06	4.73E-05	2.14E-02	5.08E-04
U-236	4.70E-08	8.70E-06	3.14E-08	1.39E-05	1.51E-06
U-237	7.60E-10	1.90E-09	3.59E-05	1.57E-02	4.61E-04
U-238	4.50E-08	8.00E-06	2.67E-08	1.19E-05	1.22E-06
U-240	Included in Pu 244 DCFs				
V-49	1.80E-11	3.40E-11	0.00E+00	0.00E+00	0.00E+00
V-50	0.00E+00	0.00E+00	5.38E-04	2.45E-01	4.37E-03
W-180	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
W-181	7.60E-11	2.70E-11	7.58E-06	3.24E-03	1.11E-04
W-185	4.40E-10	1.20E-10	1.97E-07	1.43E-04	6.49E-05
W-186	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
W-188	3.50E-09	1.11E-09	2.38E-05	1.15E-02	7.64E-04
Xe-127	0.00E+00	0.00E+00	7.90E-05	3.60E-02	8.73E-04
Y-88	1.30E-09	4.40E-09	1.01E-03	4.62E-01	8.21E-03
Y-89m	1.10E-07	1.60E-05	3.19E-04	1.46E-01	2.88E-03
Y-90	2.70E-09	1.50E-09	5.26E-06	3.53E-03	6.63E-04
Y-91	2.40E-09	8.90E-09	3.56E-06	2.17E-03	4.01E-04
Yb-169	7.10E-10	3.00E-09	8.10E-05	3.60E-02	1.01E-03
Zn-65	3.90E-09	2.20E-09	2.13E-04	9.60E-02	1.80E-03
Zr-88	4.50E-10	3.60E-09	1.23E-04	5.61E-02	1.26E-03
Zr-93	1.10E-09	2.50E-08	8.15E-11	5.02E-08	8.00E-09
Zr-95	9.50E-10	5.90E-09	2.48E-04	1.15E-01	2.48E-03
Zr-96	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table 21: Contribution of Short-Lived Daughters (SLD) to Precursor Dose Conversion Factors

	Inhalation DCF			Ingestion DCF			Water Immersion DCF			Air Immersion DCF			Groundshine DCF		
Isotope	Precursor	w/ SLD	Ratio	Precursor	w/ SLD	Ratio	Precursor	w/ SLD	Ratio	Precursor	w/ SLD	Ratio	Precursor	w/ SLD	Ratio
Ac-225	8.50E-06	5.95E-05	7.0E+00	2.40E-08	1.68E-07	7.0E+00	3.88E-06	1.15E-04	3.0E+01	1.71E-03	5.31E-02	3.1E+01	4.58E-05	1.82E-03	4.0E+01
Ac-227	5.50E-04	5.50E-04	1.0E+00	1.10E-06	1.10E-06	1.0E+00	2.70E-08	2.26E-07	8.4E+00	1.20E-05	1.04E-04	8.7E+00	7.55E-07	6.16E-06	8.2E+00
Ag-108m	3.70E-08	7.40E-08	2.0E+00	2.30E-09	4.60E-09	2.0E+00	5.37E-04	5.38E-04	1.0E+00	2.45E-01	2.45E-01	1.0E+00	5.35E-03	5.39E-03	1.0E+00
Ag-110m	1.20E-08	2.40E-08	2.0E+00	2.80E-09	5.60E-09	2.0E+00	9.73E-04	9.73E-04	1.0E+00	4.44E-01	4.44E-01	1.0E+00	8.92E-03	8.93E-03	1.0E+00
Am-242m	9.20E-05	9.20E-05	1.0E+00	1.90E-07	1.90E-07	1.0E+00	1.51E-07	4.04E-06	2.7E+01	6.66E-05	1.81E-03	2.7E+01	5.95E-06	1.46E-04	2.5E+01
Ar-42	1.20E-10	2.40E-10	2.0E+00	4.30E-10	8.60E-10	2.0E+00	5.18E-07	1.20E-04	2.3E+02	3.93E-04	5.67E-02	1.4E+02	1.47E-04	2.28E-03	1.5E+01
Bi-210m	3.40E-06	6.80E-06	2.0E+00	1.50E-08	3.00E-08	2.0E+00	8.10E-05	8.30E-05	1.0E+00	3.71E-02	3.85E-02	1.0E+00	8.61E-04	1.21E-03	1.4E+00
Bk-248	3.70E-09	7.40E-09	2.0E+00	4.60E-10	9.20E-10	2.0E+00	2.68E-04	5.36E-04	2.0E+00	1.23E-01	2.46E-01	2.0E+00	2.70E-03	5.40E-03	2.0E+00
Bk-249	1.60E-07	1.60E-07	1.0E+00	9.70E-10	9.70E-10	1.0E+00	1.95E-09	2.09E-09	1.1E+00	1.25E-06	1.32E-06	1.1E+00	1.26E-06	1.26E-06	1.0E+00
Ce-144	5.30E-08	1.06E-07	2.0E+00	5.20E-09	1.05E-08	2.0E+00	4.91E-06	2.43E-05	5.0E+00	2.17E-03	1.28E-02	5.9E+00	8.95E-05	1.14E-03	1.3E+01
Cm-247	9.00E-05	9.00E-05	1.0E+00	1.90E-07	1.90E-07	1.0E+00	1.01E-04	1.07E-04	1.1E+00	4.58E-02	4.87E-02	1.1E+00	1.03E-03	1.20E-03	1.2E+00
Cm-250	2.10E-03	2.10E-03	1.0E+00	4.40E-06	4.40E-06	1.0E+00	5.03E-03	5.06E-03	1.0E+00	2.31E+00	2.32E+00	1.0E+00	4.82E-02	4.84E-02	1.0E+00
Cs-137	3.90E-08	7.80E-08	2.0E+00	1.30E-08	2.60E-08	2.0E+00	3.88E-07	1.89E-04	4.9E+02	2.91E-04	8.65E-02	3.0E+02	1.12E-04	2.02E-03	1.8E+01
Es-254	8.60E-06	8.60E-06	1.0E+00	2.80E-08	2.81E-08	1.0E+00	1.07E-06	3.26E-04	3.0E+02	4.78E-04	1.47E-01	3.1E+02	2.68E-05	3.00E-03	1.1E+02
Es-255	2.48E-07	7.45E-07	3.0E+00	2.30E-09	6.90E-09	3.0E+00	3.17E-07	2.84E-06	9.0E+00	1.59E-04	1.27E-03	8.0E+00	2.78E-05	8.52E-05	3.1E+00
Fe-60	2.80E-07	2.80E-07	1.0E+00	1.10E-07	1.10E-07	1.0E+00	2.47E-08	1.50E-06	6.1E+01	1.61E-05	6.80E-04	4.2E+01	1.43E-05	2.89E-05	2.0E+00
Ge-68	1.40E-08	1.40E-08	1.0E+00	1.30E-09	1.40E-09	1.1E+00	1.88E-09	3.18E-04	1.7E+05	9.43E-07	1.44E-01	1.5E+05	2.44E-07	3.63E-03	1.5E+04
Hf-172	3.20E-08	6.40E-08	2.0E+00	1.00E-09	2.00E-09	2.0E+00	2.06E-05	2.06E-05	1.0E+00	8.82E-03	8.82E-03	1.0E+00	2.94E-04	2.94E-04	1.0E+00
In-114m	9.30E-09	1.86E-08	2.0E+00	4.10E-09	8.20E-09	2.0E+00	2.34E-05	2.78E-05	1.2E+00	1.07E-02	1.35E-02	1.3E+00	3.26E-04	8.37E-04	2.6E+00
Np-235	6.30E-10	1.26E-09	2.0E+00	5.30E-11	1.06E-10	2.0E+00	2.13E-07	4.26E-07	2.0E+00	9.17E-05	1.83E-04	2.0E+00	6.61E-06	1.32E-05	2.0E+00
Os-194	8.50E-08	8.56E-08	1.0E+00	2.40E-09	3.70E-09	1.5E+00	3.47E-07	3.49E-05	1.0E+02	1.54E-04	1.68E-02	1.1E+02	7.29E-06	8.56E-04	1.2E+02
Pu-239	1.20E-04	2.40E-04	2.0E+00	2.50E-07	5.00E-07	2.0E+00	2.91E-08	5.82E-08	2.0E+00	1.29E-05	2.58E-05	2.0E+00	9.41E-07	1.88E-06	2.0E+00
Pu-244	1.10E-04	2.20E-04	2.0E+00	2.40E-07	4.81E-07	2.0E+00	7.49E-06	1.21E-04	1.6E+01	3.43E-03	5.55E-02	1.6E+01	7.25E-05	1.60E-03	2.2E+01
Pu-246	8.00E-09	8.02E-09	1.0E+00	3.30E-09	3.33E-09	1.0E+00	3.72E-05	3.89E-04	1.0E+01	1.65E-02	1.77E-01	1.1E+01	4.37E-04	3.83E-03	8.8E+00
Ra-223	8.70E-06	5.22E-05	6.0E+00	1.00E-07	6.00E-07	6.0E+00	3.99E-05	9.89E-05	2.5E+00	1.80E-02	4.58E-02	2.5E+00	4.57E-04	1.63E-03	3.6E+00
Ra-224	3.40E-06	1.72E-05	5.1E+00	6.50E-08	3.31E-07	5.1E+00	3.15E-06	1.02E-03	3.2E+02	1.45E-03	4.66E-01	3.2E+02	3.40E-05	8.65E-03	2.5E+02

Isotope	Inhalation DCF			Ingestion DCF			Water Immersion DCF			Air Immersion DCF			Groundshine DCF		
	Precursor	w/ SLD	Ratio	Precursor	w/ SLD	Ratio	Precursor	w/ SLD	Ratio	Precursor	w/ SLD	Ratio	Precursor	w/ SLD	Ratio
Ra-228	1.60E-05	1.60E-05	1.0E+00	6.90E-07	6.90E-07	1.0E+00	3.06E-08	3.06E-04	1.0E+04	1.40E-05	1.40E-01	1.0E+04	2.23E-06	2.99E-03	1.3E+03
Rb-83	6.90E-10	1.38E-09	2.0E+00	1.90E-09	3.80E-09	2.0E+00	1.61E-04	1.61E-04	1.0E+00	7.25E-02	7.25E-02	1.0E+00	1.61E-03	1.61E-03	1.0E+00
Rn-222	1.50E-08	1.64E-07	1.1E+01	1.40E-10	1.51E-09	1.1E+01	1.28E-07	6.31E-04	4.9E+03	5.80E-05	2.87E-01	5.0E+03	1.30E-06	6.04E-03	4.6E+03
Ru-103	3.00E-09	3.00E-09	1.0E+00	7.30E-10	7.34E-10	1.0E+00	1.64E-04	1.64E-04	1.0E+00	7.39E-02	7.39E-02	1.0E+00	1.66E-03	1.66E-03	1.0E+00
Ru-106	6.60E-08	1.32E-07	2.0E+00	7.00E-09	1.40E-08	2.0E+00	1.08E-11	8.18E-05	7.6E+06	7.76E-09	3.92E-02	5.1E+06	5.44E-10	1.90E-03	3.5E+06
Sn-113	2.70E-09	2.72E-09	1.0E+00	7.30E-10	7.58E-10	1.0E+00	2.47E-06	8.51E-05	3.4E+01	1.12E-03	3.88E-02	3.5E+01	5.18E-05	9.89E-04	1.9E+01
Sn-126	2.80E-08	2.80E-08	1.0E+00	4.70E-09	4.74E-09	1.0E+00	1.20E-05	5.33E-04	4.4E+01	5.25E-03	2.43E-01	4.6E+01	1.89E-04	5.73E-03	3.0E+01
Tc-95m	1.20E-09	1.20E-09	1.0E+00	5.60E-10	5.67E-10	1.0E+00	2.26E-04	2.36E-04	1.0E+00	1.04E-01	1.09E-01	1.0E+00	2.22E-03	2.32E-03	1.0E+00
Te-127m	9.80E-09	9.94E-09	1.0E+00	2.30E-09	2.47E-09	1.1E+00	7.69E-07	2.79E-06	3.6E+00	3.44E-04	1.41E-03	4.1E+00	3.50E-05	1.86E-04	5.3E+00
Te-129m	7.90E-09	7.92E-09	1.0E+00	3.00E-09	3.04E-09	1.0E+00	1.13E-05	2.47E-05	2.2E+00	5.38E-03	1.17E-02	2.2E+00	2.64E-04	6.00E-04	2.3E+00
Th-234	7.70E-09	1.54E-08	2.0E+00	3.40E-09	6.80E-09	2.0E+00	2.13E-06	1.29E-05	6.0E+00	9.13E-04	6.71E-03	7.3E+00	3.52E-05	6.57E-04	1.9E+01
Ti-44	1.20E-07	1.20E-07	1.0E+00	5.80E-09	6.15E-09	1.1E+00	3.20E-05	7.88E-04	2.5E+01	1.42E-02	3.56E-01	2.5E+01	4.12E-04	7.61E-03	1.8E+01
W-188	5.70E-10	1.11E-09	1.9E+00	2.10E-09	3.50E-09	1.7E+00	6.75E-07	2.38E-05	3.5E+01	3.37E-04	1.15E-02	3.4E+01	4.86E-05	7.64E-04	1.6E+01

* Red font indicates ratio > 10.

Table 22: Non-Human Biota Dose Conversion Factors

Isotope	Internal	Water Immersion	Soil Immersion	On Ground	Above Ground	Air Immersion
	(µGy/hr)/ (Bq/kg)	(µGy/hr)/ (Bq/L)	(µGy/hr)/ (Bq/kg)	(µGy/hr)/ (Bq/kg)	(µGy/hr)/ (Bq/kg)	(µGy/hr)/ (Bq/m^3)
Ag110	9.80E-04	1.60E-03	1.50E-03	5.90E-04	5.40E-04	7.50E-04
Am241	3.20E-03	1.50E-05	5.70E-06	3.00E-06	2.00E-06	5.30E-06
Ba140	1.30E-03	1.50E-03	1.30E-03	5.50E-04	5.00E-04	7.60E-04
C14	2.90E-05	1.30E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ca45	4.40E-05	4.40E-07	3.40E-13	4.20E-13	6.50E-14	1.40E-12
Cd109	6.20E-05	1.30E-05	3.50E-06	2.20E-06	1.60E-06	6.20E-06
Ce141	1.30E-04	4.60E-05	2.70E-05	1.30E-05	1.20E-05	1.70E-05
Ce144	7.60E-04	2.60E-04	2.10E-05	9.00E-06	8.10E-06	1.30E-05
Cf252	7.10E-03	3.20E-04	2.30E-04	8.90E-05	8.00E-05	1.20E-04
Cl36	1.60E-04	9.70E-06	7.50E-08	3.70E-08	3.60E-08	4.50E-08
Cm242	3.60E-03	6.40E-07	1.70E-07	1.30E-07	5.70E-08	3.80E-07
Cm243	3.50E-03	7.50E-05	5.00E-05	2.40E-05	2.30E-05	3.20E-05
Cm244	3.40E-03	5.60E-07	1.50E-07	1.20E-07	5.10E-08	3.30E-07
Co57	6.30E-05	6.90E-05	4.00E-05	2.10E-05	1.70E-05	2.40E-05
Co58	3.60E-04	5.50E-04	5.20E-04	2.50E-04	2.30E-04	3.10E-04
Co60	8.50E-04	1.40E-03	1.30E-03	5.10E-04	4.60E-04	6.80E-04
Cr51	1.50E-05	1.80E-05	1.60E-05	8.50E-06	8.30E-06	1.00E-05
Cs134	6.30E-04	8.90E-04	8.30E-04	3.50E-04	3.30E-04	4.40E-04
Cs135	5.10E-05	6.10E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cs136	8.00E-04	1.20E-03	1.10E-03	4.90E-04	4.50E-04	6.30E-04
Cs137	3.40E-04	3.30E-04	3.00E-04	1.40E-04	1.30E-04	1.70E-04
Eu152	4.70E-04	6.70E-04	5.90E-04	2.30E-04	2.10E-04	3.00E-04
Eu154	5.70E-04	7.20E-04	6.40E-04	2.70E-04	2.40E-04	3.60E-04
Eu155	6.40E-05	3.40E-05	1.60E-05	9.20E-06	9.00E-06	1.40E-05
H3	3.30E-06	2.60E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00
I125	3.40E-05	2.20E-05	5.60E-06	3.20E-06	2.50E-06	9.70E-06
I129	5.10E-05	1.30E-05	3.60E-06	1.90E-06	1.30E-06	5.20E-06
I131	2.50E-04	2.20E-04	1.90E-04	8.20E-05	7.90E-05	9.80E-05
I132	1.00E-03	1.30E-03	1.20E-03	4.70E-04	4.40E-04	6.00E-04
I133	4.50E-04	3.70E-04	3.20E-04	1.50E-04	1.40E-04	1.80E-04
Ir192	4.30E-04	4.70E-04	4.10E-04	1.80E-04	1.70E-04	2.10E-04
K40	3.50E-04	1.30E-04	8.00E-05	2.90E-05	2.60E-05	3.90E-05
La140	1.00E-03	1.40E-03	1.20E-03	5.10E-04	4.60E-04	7.10E-04
Mn54	2.90E-04	4.70E-04	4.40E-04	2.00E-04	1.90E-04	2.50E-04
Nb94	6.30E-04	8.90E-04	8.30E-04	3.40E-04	3.20E-04	4.30E-04
Nb95	2.90E-04	4.30E-04	4.10E-04	1.50E-04	1.30E-04	1.70E-04
Ni59	4.00E-06	2.00E-07	1.00E-07	1.20E-07	6.40E-09	5.70E-08

Isotope	Internal	Water Immersion	Soil Immersion	On Ground	Above Ground	Air Immersion
	(µGy/hr)/ (Bq/kg)	(µGy/hr)/ (Bq/L)	(µGy/hr)/ (Bq/kg)	(µGy/hr)/ (Bq/kg)	(µGy/hr)/ (Bq/kg)	(µGy/hr)/ (Bq/m^3)
Ni63	1.00E-05	1.10E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Np237	2.90E-03	1.70E-05	7.40E-06	4.10E-06	3.50E-06	7.10E-06
P32	4.00E-04	7.20E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
P33	4.40E-05	4.20E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pa231	3.00E-03	2.20E-05	1.60E-05	7.10E-06	6.70E-06	9.70E-06
Pb210	2.50E-04	2.50E-05	6.10E-07	4.10E-07	1.60E-07	6.10E-07
Po210	3.10E-03	5.50E-09	5.20E-09	2.50E-09	2.30E-09	3.20E-09
Pu238	3.20E-03	6.10E-07	1.70E-07	1.40E-07	6.00E-08	3.70E-07
Pu239	3.00E-03	2.90E-07	9.30E-08	6.70E-08	3.60E-08	1.90E-07
Pu240	3.00E-03	5.70E-07	1.60E-07	1.30E-07	5.70E-08	3.50E-07
Pu241	3.10E-06	9.40E-10	4.80E-10	2.60E-10	2.10E-10	3.50E-10
Ra226	1.50E-02	1.10E-03	8.90E-04	3.30E-04	3.00E-04	4.40E-04
Ra228	5.60E-04	5.20E-04	4.50E-04	1.70E-04	1.60E-04	2.20E-04
Ru103	2.40E-04	2.80E-04	2.60E-04	1.00E-04	8.50E-05	1.10E-04
Rh106	8.80E-04	4.30E-04	1.10E-04	4.60E-05	4.40E-05	5.70E-05
S35	2.80E-05	1.40E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sb124	8.20E-04	1.10E-03	9.70E-04	3.70E-04	3.30E-04	5.00E-04
Sb125	2.20E-04	2.50E-04	2.20E-04	9.40E-05	9.10E-05	1.20E-04
Se75	1.60E-04	2.20E-04	1.70E-04	8.60E-05	8.40E-05	1.00E-04
Se79	3.00E-05	1.40E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sr89	3.40E-04	5.30E-05	4.60E-08	1.80E-08	1.60E-08	2.20E-08
Sr90	6.50E-04	1.40E-04	1.20E-10	9.40E-11	3.10E-11	2.70E-10
Tc99	5.80E-05	8.20E-07	1.70E-10	9.40E-11	8.40E-11	1.50E-10
Te129m	3.80E-04	9.00E-05	3.60E-05	1.50E-05	1.40E-05	1.90E-05
Te132	1.20E-03	1.50E-03	1.30E-03	5.20E-04	4.90E-04	6.50E-04
Th227	3.60E-03	7.20E-05	5.40E-05	2.50E-05	2.40E-05	3.20E-05
Th228	2.00E-02	9.30E-04	7.40E-04	2.90E-04	2.60E-04	4.20E-04
Th229	3.00E-03	5.10E-05	2.80E-05	1.40E-05	1.30E-05	2.10E-05
Th230	2.70E-03	5.70E-07	2.10E-07	1.40E-07	7.60E-08	2.70E-07
Th231	1.10E-04	1.20E-05	4.30E-06	2.60E-06	2.20E-06	5.40E-06
Th232	2.40E-03	4.40E-07	1.40E-07	1.10E-07	4.80E-08	2.20E-07
Th234	5.20E-04	1.20E-04	1.20E-05	5.20E-06	4.90E-06	7.20E-06
U233	2.80E-03	4.10E-07	1.70E-07	1.10E-07	6.40E-08	2.20E-07
U234	2.80E-03	5.80E-07	1.70E-07	1.40E-07	6.00E-08	3.30E-07
U235	2.80E-03	1.10E-04	7.10E-05	3.20E-05	3.10E-05	4.40E-05
U238	2.50E-03	4.00E-07	1.20E-07	9.50E-08	3.80E-08	2.30E-07
Zn65	1.90E-04	3.30E-04	3.00E-04	1.20E-04	1.10E-04	1.60E-04
Zr95	3.20E-04	4.20E-04	3.90E-04	1.50E-04	1.40E-04	1.80E-04

A.4 Non-Radiological Hazard Criteria

Chemical hazard criteria described in Section 2.4 are presented in Table 23. Criteria are threshold values below which elements are not considered harmful to humans and non-human biota. Values highlighted in blue have criteria derived by methodology described in Fernandes (2019) or by adopting criteria from a chemically analogous element.

Table 23: Chemical Hazard Acceptance Criteria in Environmental Media

Element	Surface Water	Groundwater	Soil	Sediment	Air
	µg/L	µg/L	µg/g	µg/g	µg/m3
Ag	0.1	0.1	20	0.5	0.01
Al	15	15	50	50	5
As	5	25	12	5.9	0.003
Au	6	60	0.1	150	2.5
B	500	500	2	2	2
Ba	1000	500	500	20	0.5
Be	100	100	4	1.1	0.002
Bi	140	1400	20	65000	5
Br	2	20	10	20	0.7
Ca	1000000	1000000	10000	10000	100
Cd	0.04	5.1	1.4	0.6	0.005
Ce	22.1	221	53	18800	30000
Cl	100000	100000	30	500	1.5
Co	50	50	40	50	0.02
Cr	1	4.9	0.38	37.3	0.00007
Cs	2500	2500	2	2	5600
Cu	2	200	63	35.7	1
Dy	9.3	93	2200	2200	30000
Er	1.8	18	7500	7500	30000
Eu	1.8	18	7500	7500	30000
F	120	1000	30	500	0.34
Fe	300	5000	10	20000	4
Ga	18	18	50	50	30000
Gd	7.1	71	1800	1800	30000
Ge	25	250	5	900	3200
Hf	4	4	97	97	0.5
Hg	0.004	3	6.6	0.17	0.025
Ho	1.8	18	7500	7500	12000
I	100	100	4	4	0.67
In	41	41	7.3	5050	0.1
Ir	10	100	2.2	2700	0.1
K	53000	530000	2	2	2

Element	Surface Water	Groundwater	Soil	Sediment	Air
	µg/L	µg/L	µg/g	µg/g	µg/m3
La	0.04	0.4	50	4700	30000
Li	2500	2500	2	2	0.2
Lu	1.8	18	7500	7500	30000
Mg	82000	400000	4	1.1	100
Mn	90	200	100	460	0.1
Mo	10	10	5	3	3
Na	200000	200000	2	2	13000
Nb	600	6000	9	9	5
Nd	1.8	18	7500	7500	30000
Ni	25	200	45	16	0.02
Os	0.067	0.067	1	30	0.002
P	5	25	12	5.9	0.1
Pb	1	100	70	35	0.2
Pd	0.068	0.68	0.012	4.1	5
Pm	1.8	18	7500	7500	30000
Pr	9.1	91	5800	5800	1200
Pt	0.61	6.1	0.012	55	0.2
Rb	2500	2500	2	2	2.5
Re	5.8	5.8	2	31	0.1
Rh	10	10	2.2	600	0.1
Ru	10	100	1	390	3
S	1000000	1000000	2	130	5
Sb	6	1.5	20	2	0.5
Sc	1.8	18	7500	7500	30000
Se	1	20	1	0.7	0.2
Sm	8.2	82	2500	2500	30000
Sn	25	250	5	900	2
Sr	7000	7000	32875	32875	2
Ta	600	600	9	9	5
Tb	1.8	18	7500	7500	1200
Te	5.8	5.8	2	31	0.1
Ti	4	100	1000	1000	5
Tl	0.3	0.3	1	1	0.1
Tm	1.8	18	7500	7500	30000
U	10	10	23	32	0.03
V	100	100	130	27.3	2
W	30	30	400	960	5
Y	6.4	64	1400	1400	1
Yb	1.8	18	7500	7500	30000

Element	Surface Water	Groundwater	Soil	Sediment	Air
	µg/L	µg/L	µg/g	µg/g	µg/m3
Zn	1.7	1000	250	120	2
Zr	4	4	97	97	5