Data for Radionuclide and Chemical Element Screening

NWMO TR-2012-11 **December 2012**

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ABSTRACT

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Abstract

Containment and isolation in a deep geologic repository is one approach for the long-term management of used CANDU fuel.

Used nuclear fuel stored in the repository contains hundreds of different radionuclides arising from fission, neutron activation and decay processes. The fuel also contains many chemical elements that are potentially chemically hazardous (e.g., As and U).

However, there is considerable variation in the ability of these various contaminants (radionuclides or chemical elements) to cause harm to humans and the natural environment. Therefore, a simpler screening model can be used to reduce the number of contaminants considered in a detailed postclosure safety assessment for a used fuel repository. For a specific repository design and site, the screening model identifies those radionuclides and chemical elements that would not lead to significant harm (radiological or otherwise) and, hence, that would not require further detailed evaluation.

However, to support such a screening model necessarily requires basic information on a large number of radionuclides and chemical elements. This report describes the data that are needed for screening analyses of those postclosure scenarios in which the main conduit by which contaminants reach the surface is via transport in groundwater. The data included in the report are listed in Section 1.

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1. INTRODUCTION

Used fuel contains hundreds of different radionuclides arising from fission, neutron activation and decay processes. The fuel also contains many chemical elements that are potentially chemically hazardous (e.g., As and U).

However, there is considerable variation in the ability of these various contaminants (radionuclides or chemical elements) to cause harm to humans and the natural environment. Therefore, a simple but conservative screening model, such as the Radionuclide Screening Model (Goodwin et al. 2001), can be used to reduce the number of contaminants that need to be considered in detailed safety assessment calculations for a used fuel repository or other facilities. For a specific repository design and site, a screening model identifies those radionuclides and chemical elements that would not lead to significant harm (radiological or otherwise) and, hence, that would not require further detailed evaluation.

For those postclosure scenarios in which groundwater transport is the only mechanism by which contaminants reach the surface biosphere, radionuclide and chemical element screening generally require the input data listed below.

Radionuclide data:

- Decay schemes,
- Half-life,
- Inventory in the fuel,
- Inventory in the Zircaloy cladding,
- Ground-exposure dose coefficient,
- Air immersion dose coefficient,
- Inhalation dose coefficient,
- Ingestion dose coefficient, and
- Ingestion multiplication factor.

Chemical element data:

- Inventory in the fuel,
- Inventory in the Zircaloy cladding,
- Instant release fractions,
- Solubility limit,
- Volatility,
- Buffer K_d / capacity factor,
- Backfill K_d / capacity factor,
- Rock and fracture K_d,
- Soil K_d, and
- Criteria for environmental concentrations of chemical elements.

These radionuclide and chemical element data, along with site specific information such as the repository design, groundwater flow rates, critical group characteristics, etc. are required to calculate contaminant concentrations in the environment (e.g., well water, soil and air) and radiological dose rates to the critical group. The calculated chemical element concentrations in various environmental media can be compared to chemical toxicity criteria to determine if they pose a safety concern.

In theory, all radionuclides that can be formed while the fuel bundle is in the reactor can be included in the screening database and explicitly modelled. However, a radionuclide with a half-life shorter than 0.1 years and which does not have parents with a half-life greater than 0.1 years would decay before reaching the surface via the groundwater pathway. (Each year, the inventory of a radionuclide with a half-life of 0.1 years decreases by about a factor of 1000.) Thus, the only radionuclides included in the screening database are:

1. Radionuclides with a half-life of greater or equal to 0.1 years, and
2. Radionuclides with a half-life greater than 1 day and less than 0.1 years, if they have a parent with a half-life greater or equal to 0.1 years.

There are 251 radionuclides in the screening database.

Doses from short-lived progeny (i.e., those with half-lives less than 1 day) of longer lived parents can be implicitly accounted for in the dose rate calculations. Specifically, these short lived progeny are assumed to be in secular equilibrium with their precursors throughout the biosphere and their contributions to the dose rate to man are accounted for through their precursors. For both internal and external exposure, the dose coefficients of the short lived radionuclides are added to those of the parents (see Section 2) to derive “effective dose coefficients for the parent radionuclides.

Many chemical elements are present in the fuel. Some arise from fission and neutron activation while the fuel is in the reactor whereas others are initially present in the unirradiated fuel as impurities (Tait et al. 2000).

The screening database contains data on 99 chemical elements. This includes all chemical elements with atomic number less than that of mendelevium (i.e., atomic numbers ≤ 101), except astatine (At) and francium (Fr). These two elements have no isotopes with half-lives greater than 1 day.

Section 2 of the report describes the radionuclide specific data, and Section 3 describes the chemical element specific data. The data tables for Sections 2 and 3 can be found in Appendix A and B, respectively.

2. DATA FOR RADIONUCLIDES

2.1 Decay Chains

The decay schemes for radionuclides with half-lives greater than 1 day are shown in Table A-1. 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, as discussed in Section 2.4. The branching ratios shown in the decay schemes are from ICRP (2008).

The decay schemes in Table A-1 can be combined to create radionuclide decay series or chains. The actinide decay series in particular are quite complex, consisting of long chains with side branches. The Radionuclide Screening Model does not have the capability of handling branched chains. Thus, branched chains must be approximately represented as parallel linear chains, as discussed in detail in Appendix B of Goodwin et al. (2001).

The linear actinide chains are shown in Table A-2. Thus, for example, the 4n actinide decay series is represented by 5 linear chains: 4n(a), 4n(b), 4n(c), 4n(d) and 4n(e), with 4n(a) the main branch.

In addition to the branches listed in Table A-2, the actinide decay series also include stand-alone actinides that, for simplicity, are not modelled as members of any linear chain. The amounts of these nuclides in used fuel are always too small to contribute significantly to the inventory of subsequent progeny, and they need only be modelled explicitly to ensure that their own contribution to any dose impact is included. These stand-alone actinides are:

4n Series: Am-240, Cf-248, Cm-240, Md-260 and Pa-232
4n+1 Series: Bk-245, Cm-241, Fm-253, Pa-229 and Pa-237
4n+2 Series: Ac-226, Bk-246, Cf-246, Cf-254, Es-254m and Np-234
4n+3 Series: Bk-247, Es-251, Es-255, Np-235 and U-231

Each of the different branches in the linear actinide decay series, in theory, must be evaluated separately because they contain common radionuclides. If such a radionuclide is not at the head of a branch, then its initial inventory need be considered in one branch only, and its initial inventory in the other branches can be set to zero. However, if the same radionuclide is at the head of more than one branch, then its inventory must be apportioned according to the branching ratios (see Section 2.2). Finally, the total dose rate for a radionuclide that is common to more than one branch is given by the sum of the dose rate estimates from each branch. (Dose rates are additive since the governing equations in the model are linear.)

Approximations were also made to (conservatively) simplify the non-actinide decay chains. Thus, a branching ratio of one was used whenever it would be more conservative to do so. For example, for the decay chain involving Eu-152, the approximation is made that 100% of the Eu-152 decays to Gd-152 rather than only 28% as indicated in Table A-1 (with 72% of Eu-152 decaying to stable Sm-152). The non-actinide decay chains are shown in Table A-3.

2.2 Radionuclide Inventories in the Fuel and Zircaloy

The safety assessment of a used fuel repository requires information on the radionuclide inventories in a used fuel container.

Radionuclides in the used fuel bundle are present in both the UO_2 fuel and the Zircaloy cladding. In order to allow tracking of the release and transport from the fuel and Zircaloy cladding, contaminants in the screening database are identified as being either from the fuel or the Zircaloy cladding by using the suffix FUEL or ZRLY in the species name.

Radionuclide inventories for CANDU fuel have been calculated by Tait et al. (2000) and Tait and Hanna (2001). The inventories in the UO_2 fuel are given in mol/(kg initial U) and the inventories in the Zircaloy are given in units of mol/(kg Zircaloy). The mass of U in a fuel bundle (19.25 kg) or the mass of Zircaloy in a fuel bundle (2.2 kg) are required to calculate the radionuclide inventories in a fuel bundle.

The radionuclide inventories in fuel bundles depend on the bundle burnup, bundle power history and the methodology and nuclear data used in the inventory calculations, as discussed in Tait et al. (2000). Statistically, because the fuel container holds many fuel bundles, which are assumed to be selected randomly, uncertainties in the inventories in a container that arise from uncertainties in bundle burnups and power histories should be much smaller than for a single fuel bundle and can generally be neglected. Thus, a best estimate for an average container inventory can be calculated using the results for the reference fuel bundle from Tait et al. (2000), i.e., a 37-element Bruce bundle, 220 MW•h/kgU burnup, 455 kW/bundle power rating, and 30 years after discharge from the reactor.

However, systematic errors in the inventories can arise from the methodology and nuclear data used to calculate the inventories. Thus, for conservatism in screening calculations, the inventories for the reference fuel bundle at a burnup of 280 MW•h/kgU are used. This fuel burnup represents approximately the 98th percentile of the discharge burnup distribution for fuel bundles discharged from Ontario Power Generation CANDU reactors (Garisto et al. 2012).

Although radionuclide inventories generally increase with burnup, this is not true for all radionuclides. Therefore, the inventories for a burnup of 280 MW•h/kgU were compared to those for the reference burnup of 220 MW•h/kgU. For the nuclides listed below, the 280 MW•h/kgU inventories are smaller than the corresponding 220 MW•h/kgU inventories by more than 10% (the approximate percentage difference, relative to the 220 MW•h/kgU inventory, is shown in brackets). For these nuclides, the 220 MW•h/kgU inventories should be used in conservative screening analyses.

<u>FUEL Nuclides</u>

Gd-153 (-20%), Hf-174 (-25%), Te-123 (-20%), Th-231 (-35%), U-235(-35%)

<u>ZRLY Nuclides</u>

Eu-152 (-25%), Eu-154(-10%), Eu-155 (-10%), Gd-152 (-60%), Gd-153 (-20%), Hf-174 (-25%), In-115 (-20%), La-138 (-15%)

Radionuclide inventories for the UO_2 fuel and Zircaloy cladding for burnups of 220 MWh/kgU and 280 MWh/kgU can be found in Table A-4.

Inventories for Branching Decay Chains

If the branched actinide chains are modelled as parallel linear chains, as described above, then the inventories of radionuclides appearing in more than one chain must be apportioned between the chains. If a radionuclide heads up more than one chain then the inventories must be apportioned according to the decay schemes. This applies to Np-236 (4n series), Pu-241 (4n+1 series) and Am-242m (4n+2 series) (see Table A-2). For Np-236, 87.3% of the initial inventory should be assigned to the 4n(c) branch and 12.7% should be assigned to the 4n(d) branch. For Pu-241, 0.00245% of the initial inventory should be assigned to the 4n+1(b) branch and the remainder to the 4n+1(a) branch. For Am-242m, 82.33% of the initial inventory should be assigned to the 4n+2(d) branch, 17.22% to the 4n+2(b) branch and 0.45% the 4n+2(c) branch.

For all other radionuclides that appear in more than one branch, the inventory of the radionuclide is assigned to the main branch and the inventory of the nuclide in the other branches is set to zero. For example, the nuclide Th-232 in the 4n(a) actinide branch is assigned the inventory given in Table A-4 whereas the nuclide Th-232 is assigned a zero initial inventory in the 4n(b) and 4n(c) branches.

2.3 Radionuclide Half-Lives

Radionuclide half-life data are taken from the ENDF/B-VII.1 library (Chadwick et al. 2011). The ENDF/B-V11.1 library was developed by the US nuclear data community, coordinated by the Cross Section Evaluation Working Group. It provides data for 3933 nuclides extending from Z=1 to Z=111, where Z is the number of protons in the atomic nucleus.

The ENDF/B-VII.1 library is available on the website of the National Nuclear Data Center, Brookhaven National Laboratory, at http://www.nndc.bnl.gov/exfor/endfb7.1.jsp.

The radionuclide half life data can be found in Table A-4.

2.4 Ground-Exposure Dose Coefficients

Eckerman and Leggett (1996) calculate adult external dose coefficients based on ICRP 60 recommendations (ICRP 1991). These adult data were selected for use in the screening database, unless otherwise stated, because they are consistent with the ICRP (1996) air inhalation and ingestion dose coefficients which are also based on the ICRP 60 recommendations. The Eckerman and Leggett (1996) external dose coefficients do not include contributions from progeny.

The ground-exposure dose coefficients for the screening database were derived from the dose coefficients for soil contaminated with the radionuclide to an infinite depth (Eckerman and Leggett 1996). These latter dose coefficients are given in units of (Sv/s) per unit volume source (Bq/m^3 soil), i.e., (Sv/s)/(Bq/m^3 soil). These units were converted to the database units of (Sv/a)/(Bq/kg) by multiplying by the soil density (1600 kg/m^3) used in Eckerman and Leggett (1996) and the number of seconds in a year (3.156x10^7 s/a).

Ground-exposure dose coefficients for Ar-42 and Bi-208 were not available in Eckerman and Leggett (1996) and were calculated from the air immersion dose coefficient of the radionuclide using the ratio of the ground exposure to air immersion dose coefficients for Ar-39 and Ca-49, respectively. This latter approximation is appropriate because the energies of the beta particles emitted by Ar-39 and Ar-42 are sufficiently similar, as are the energies of the gamma photons emitted by Ca-49 and Bi-208.

Radionuclides with half-lives less than one day are not explicitly included in the screening database. However, their contribution to the total ground-exposure dose is accounted for by adding their ground-exposure dose coefficient (or a fraction thereof, depending on the decay scheme in Table A-1), when available, to that of the parent radionuclide to obtain an effective ground-exposure dose coefficient for the parent nuclide. For example, the effective ground-exposure dose coefficient for Ag-108m includes a contribution from the progeny Ag-108. Since the branching ratio for this decay is 0.087, the contribution of Ag-108 to the effective ground-exposure dose coefficient for Ag-108m is equal to 0.087 times the Ag-108 ground-exposure dose coefficient.

Some of the radionuclides in the screening database do not appear in the compilation of Eckerman and Leggett (1996) or other sources. For these radionuclides, which are listed in Table A-5, the ground-exposure dose coefficients were assumed to be equal to that for Co-56 which has the largest ground-exposure dose coefficient. This likely conservative approximation is adequate for screening purposes. If the ground-exposure dose rate from any of these radionuclides is found to be relatively large, then additional effort to calculate a more accurate ground-exposure dose coefficient could be warranted.

The recommended effective ground-exposure dose coefficients are given in Table A-6.

2.5 Air Immersion Dose Coefficients

Adult air immersion dose coefficients for the screening database were mainly derived from the data in Eckerman and Leggett (1996). The dose coefficients in Eckerman and Leggett are given in units of (Sv/s) per unit volume source (Bq/m^3 air), i.e., (Sv/s)/(Bq/m^3 air). These were converted to the database units of (Sv/a)/(Bq/m^3) by multiplying by the number of seconds in a year (3.156x10^7 s/a). The dose coefficients in Eckerman and Leggett (1996) do not include any contributions from progeny.

ICRP (1996) gives air immersion dose coefficients for the following noble gas radionuclides: Ar-39, Kr-81, and Kr-85. The ICRP values, which agree well with those in Eckerman and Leggett (1996), were selected for the screening database for consistency with the air inhalation and ingestion dose coefficients selected from ICRP (1996).

Air immersion dose coefficients for Ar-42 and Bi-208 were not available in Eckerman and Leggett (1996) and were taken from US DOE (2011).

Radionuclides with half-lives less than one day are not explicitly included the screening database. However, their contribution to the total air immersion dose is accounted for by adding their air immersion dose coefficient (or a fraction thereof, depending on the decay scheme in Table A-1), when available, to that of the parent radionuclide to derive effective air immersion dose coefficients for the parent.

Some of the radionuclides in the screening database do not appear in the compilation of Eckerman and Leggett (1996) or other sources. For these radionuclides, which are listed in Table A-5, the air immersion dose coefficients were assumed to be equal to that for Co-56 which has the largest air immersion dose coefficient. This likely conservative approximation is adequate for screening purposes. If it is found that the air immersion dose rate from any of these radionuclides is relatively large, then additional effort to calculate a more accurate value of the air immersion dose coefficient could be warranted.

The recommended effective air immersion dose coefficients are presented in Table A-6.

2.6 Air Inhalation Dose Coefficients

The adult air inhalation dose coefficients in the screening database were mainly taken from the ICRP (1996) compilation. The ICRP dose coefficients include the dose contributions from progeny that are formed *in vivo* but do not include contributions due to inhalation of the progeny themselves (Phipps and Silk 1999).

The ICRP (1996) compilation does not include air inhalation dose coefficients for noble gases. However, these dose coefficients can be assumed to be zero because noble gases are non-reactive and are not retained in the body for any significant period of time after inhalation (NCRP 1996). The air inhalation dose coefficient for Bi-208, which does not appear in the ICRP compilation, was taken from UD DOE (2011).

Air inhalation dose coefficients depend on the chemical form of the radionuclide. Noble gas (Ar, Kr, Rn and Xe) nuclides are assumed to be in the gas state. Tritium (H-3 or T) is assumed to be in the HTO vapour form. The HTO form should predominate because nuclide releases to the biosphere are assumed to occur via the groundwater pathway. Furthermore, because HTO is also absorbed through the skin at a rate roughly 50% of the intake through the lungs (CSA 2008), the H-3 air inhalation dose coefficient in the database is set equal to 1.5 times the ICRP (1996) value. All other nuclides are assumed to be in a particulate form and, for conservatism, to exist in the chemical form giving the largest air inhalation dose coefficient in the ICRP (1996).

Radionuclides with half-lives less than one day are not explicitly included in the screening database. Instead, their contribution to the total air inhalation dose rate is accounted for by adding their air inhalation dose coefficient (or a fraction thereof, depending on the decay scheme in Table A-1), when available, to that of the parent radionuclide to derive an effective air inhalation dose coefficient for the parent nuclide. This conservative approach assumes that the short-lived progeny (present in air) are in secular equilibrium with their parents and that the progeny and parents are inhaled at the same time.

ICRP (1993) reviewed the dosimetric information for radon and radon progeny nuclides and recommended dose conversion coefficients for exposure to Rn-222 and its progeny. Based on this information, Zach et al. (1996) derived an air inhalation dose coefficient for Rn-222 of 3.5×10^{-9} Sv/Bq, including contributions from Rn-222 progeny inhaled with Rn-222. The progeny contributions are much larger than the contribution of Rn-222 itself (ICRP 1993).

More recently, UNSCEAR (2000) recommended a Rn-222 effective dose coefficient of 9×10^{-9} (Sv/h)/(Bq/m^3), which is higher than the ICRP (1993) value. Using this value and the equilibrium factor for radon progeny relative to Rn-222 of 0.4 for indoor air (UNSCEAR 2000, Chen 2005) and 0.6 for outdoor air (UNSCEAR 2000), the effective air inhalation dose coefficient for Rn-222 was calculated to be 4.0×10^{-9} Sv/Bq, assuming an indoor occupancy factor of 0.80. This dose coefficient should be used in future assessments.

Except for Rn-222, Table A-7 shows the contributions of the progeny (with half-lives less than one day) to the effective air inhalation dose coefficient of the parent. These contributions are generally less than 5%, but some are more than 25% (e.g., Ar-42). Inhalation dose coefficients are not available for all progeny with half-lives less than one day, as indicated in Table A-7. However, based on the results shown at the top of Table A-7, it is expected that these additional contributions could increase calculated inhalation dose rates from exposure to these parent nuclides by less than a factor of 2, and so the present values should be adequate for screening calculations.

Some of the radionuclides in the screening database do not appear in ICRP (1996) or other sources. For these radionuclides, which are listed in Table A-5, the air inhalation dose coefficients were assumed to be equal to that for Ac-227 which has the second largest air inhalation dose coefficient. (It was considered inappropriate to use the air inhalation dose coefficient for Cm-250, which is the largest, because Cm-250 decays mostly by spontaneous fission, which produces energetic heavy particles.) This likely conservative approximation is adequate for screening purposes. 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.

The recommended effective air inhalation dose coefficients are presented in Table A-6.

2.7 Ingestion Dose Coefficients

The adult ingestion coefficients in the screening database were mainly taken from ICRP (1996). These dose coefficients include the dose contributions from progeny that are formed *in vivo* but do not include contributions due to ingestion of the progeny themselves (Phipps and Silk 1999). For some nuclides (e.g., Hg-194, S-35), the ingestion dose coefficients depend on the chemical form of the radionuclide. For conservatism, these nuclides were assumed to have the chemical form giving the largest ingestion dose coefficient in the ICRP (1996) compilation.

ICRP (1996) compilation does not include ingestion dose coefficients for noble gases. However, these dose coefficients can be assumed to be zero because noble gases are non-reactive and are not retained in the body for any significant period of time after ingestion (NCRP 1996). The ingestion dose coefficient for Bi-208, which does not appear in ICRP (1996), was taken from US DOE (2011).

Radionuclides with half-lives less than one day are not explicitly included in the screening database. However, their contribution to the total ingestion dose rate is accounted for by adding their ingestion dose coefficient (or a fraction thereof, depending on the decay scheme in Table A-1), when available, to that of the parent radionuclide to obtain effective ingestion dose coefficients for the parent nuclide. This conservative approach assumes that the short-lived progeny (in the food or water) are in secular equilibrium with their parents and that the progeny and parents are ingested at the same time.

The contributions of the progeny (with half-lives less than one day) to the effective ingestion dose coefficient of the parent, which are shown in Table A-8, are generally less than 5%, but can exceed 25% for some radionuclides such as Ar-42. Ingestion dose coefficients are not available for all progeny with half-lives less than one day, as indicated in Table A-8. However, in view of the results at the top of Table A-8, it is expected that these additional contributions could increase the calculated ingestion dose rates from exposure to these parent nuclides by less than a factor of 2, and so the present values should be adequate for screening calculations.

Some of the radionuclides in the screening database do not appear in ICRP (1996) or other sources. For these radionuclides, which are listed in Table A-5, the ingestion dose coefficients were assumed to be equal that for Po-210 which has the second largest ingestion dose coefficient. (It was considered inappropriate to use the ingestion dose coefficient for Cm-250, which is the largest, because Cm-250 decays mainly by spontaneous fission, which produces energetic heavy particles.) This likely conservative approximation is adequate for screening purposes. 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.

The recommended effective ingestion dose coefficients are presented in Table A-6.

2.8 Ingestion Multiplication Factors

For radionuclide screening purposes, one option is to only consider the well water drinking portion of the total dose from all ingestion pathways, if the well water flow rate was chosen so as to maximize the nuclide concentrations in well water. However, this approach is not necessarily conservative, particularly for short-lived radionuclides for which biosphere concentrations are mainly determined by ingrowth from a long-lived parent nuclide (Garisto 2001).

Hence, the ingestion multiplication factor (IMF) was introduced in the screening models used at the Nuclear Waste Management Organization (NWMO). This parameter is defined such that the product of the IMF and the radionuclide water ingestion dose rate is equal to the radionuclide dose rate arising from all ingestion pathways, that is,

$$D_n^{ING} = IMF_n\, D_n^{W} \qquad (2.1)$$

where D_n^{ING} is the total dose rate for radionuclide n from all ingestion pathways, IMF_n is the ingestion multiplication factor for radionuclide n and D_n^{W} is the water ingestion dose rate from radionuclide n. This approach is used since the NWMO screening models do not include a food chain model.

The ingestion multiplication factor is calculated using a simple biosphere model that accounts for ingrowth and accumulation in the biosphere. This simple biosphere model is conceptually similar to the SR97 well scenario (Bergström et al. 1999) except that human exposures via animal product ingestion pathways are not included in the dose calculations. Based on the results presented in Bergström et al. (1999, Table 4-3), this is a good approximation, with the animal product ingestion pathways contributing a maximum of about 25% of the total dose for any nuclide.

The well scenario consists of compartments for water (the well) and soil (the garden). Water from the well is used for drinking and for irrigating the garden, where the annual consumption of plants is grown. Since the biosphere model uses linear equations, the IMFs are independent of the nuclide concentration in the well. Hence, for convenience, the IMFs are calculated based on a release into the well (from the geosphere) of 1 Bq/a for each nuclide.

The major assumptions used in the biosphere calculations are:

1. biosphere parameters do not change with time,
2. homogeneous mixing of nuclides in all biosphere compartments,
3. annual mean values used for precipitation, net water infiltration rate through soil, and other biosphere parameters,
4. transfer of nuclides in food chains described by steady-state factors,
5. no loss of radionuclides from biosphere compartments due to biological uptake,

6. no loss of radionuclides due to food preparation or water treatment,
7. the Baes and Sharp soil model (Sheppard et al. 1997) is used to calculate nuclide concentrations in the soil compartment, and
8. radionuclide concentrations on plant leaves due to spray irrigation are similar to the model in CSA (2008).

If radionuclide ingrowth in the biosphere is neglected, the ingestion multiplication factor for radionuclide n, IMF_n, for the simple biosphere model, is given by

$$IMF_n = (D_{Wi,n} + D_{Pi,n})/D_{Wi,n} \tag{2.2}$$

where $D_{Wi,n}$ is the dose from the water ingestion pathway and $D_{Pi,n}$ is the dose from the plant ingestion pathways. These doses can be calculated using the following formulae

$$D_{Wi,n} = C_{W,n}\, I^{DW}\, DC_{ing,n} \tag{2.3a}$$

$$D_{Pi,n} = C_{P,n}\, I^{P}\, DC_{ing,n} \tag{2.3b}$$

where $C_{W,n}$ and $C_{P,n}$ are the concentrations of nuclide n in well water and the plant, respectively, I^{DW} and I^{P} are the rate of ingestion of water and plants (kg/a) by the human critical group, and $DC_{ing,n}$ is the ingestion dose coefficient for nuclide n (Sv/Bq). Based on the assumptions outlined above, it is found that

$$C_{W,n} = S_n/VF^{W} \tag{2.4}$$

where,

S_n = nuclide flux rate into the well, defined as 1 Bq/a, and
VF^{W} = water flow rate through well (m^3/a).

$$C_{P,n} = C_{P,leaf,n} + C_{P,root,n} \tag{2.5}$$

where,
$C_{P,leaf,n}$ = nuclide concentration on plant leaves due to spray irrigation (Bq/kg), and
$C_{P,root,n}$ = nuclide concentration in plants due to root uptake from soil (Bq/kg).

$$C_{P,root,n} = C_{soil,n}\, Bv_n \tag{2.6}$$

where,

$C_{soil,n}$ = total nuclide concentration in soil (Bq/kg), and
Bv_n = plant/soil bioconcentration factor ((Bq/kg wet)/(Bq/kg dry)).

$$C_{P,leaf,n} = IR\, C_{W,n}\, fp\, (YP\, \lambda_P)^{-1}\, (1 - \exp(-T_P{*}\lambda_P)) \tag{2.7}$$

where,

IR = irrigation rate averaged over the whole year ($m^3/(m^2{\bullet}a)$),
fp = fraction of irrigation water intercepted by plant (-),
YP = plant yield (kg/m^2),
λ_P = plant weathering rate (a^{-1}), and

T_P = plant lifetime or duration of growing season (a).

$$\lambda_P = \ln(2)/T_{PW} + \lambda_{r.n} \tag{2.8}$$

where,

T_{PW} = plant weathering half-life (a), and
$\lambda_{r,n}$ = radioactive decay constant for nuclide n (a^{-1}).

$$\lambda_{r.n} = \ln(2)/t_{1/2,n} \tag{2.9}$$

where, $t_{1/2,n}$ is the half-life of nuclide n (a).

$$C_{soil,n} = IR\ C_{W,n}\ (H_S\ \rho_{b,S}\ \lambda_{S,n})^{-1}\ (1 - \exp(-T_t{*}\lambda_{S,n})) \tag{2.10}$$

where,

H_S = depth of surface soil layer (m),
$\rho_{b,S}$ = dry bulk density of surface soil (kg/m^3),
$\lambda_{S,n}$ = overall rate constant for removal of nuclide n from surface soil (a^{-1}), and
T_t = time for buildup of radionuclide in soil (a).

$$\lambda_{S,n} = \mathrm{Inf}\ (H_S)^{-1}\ (\rho_{b,S}\ K_{d,S,n} + \theta)^{-1} + \lambda_{r,n} \tag{2.11}$$

where,

Inf = net water infiltration rate through surface soil layer ($m^3/(m^2{\bullet}a)$),
$K_{d,S,n}$ = soil solid-liquid distribution coefficient (m^3/kg), and
θ = volumetric water content of soil ( ).

The analysis above does not account for ingrowth in the biosphere from a (long-lived) parent nuclide. This could be important for short-lived radionuclides such as Y-90 and Pa-233 (Garisto 2001). For these short-lived nuclides, the ingestion multiplication factor $IMF_{d,sl}$ is given by

$$IMF_{d,sl} = IMF_d + IMF_{d,ingrow} \tag{2.12}$$

where the subscript d is used to refer to the short-lived progeny, IMF_d is calculated using Equation 2.2, and $IMF_{d,ingrow}$ is the contribution to the IMF due to ingrowth in the biosphere.

Several different processes contribute $IMF_{d,ingrow}$:

- ingrowth from the long-lived parent nuclide present in or on the plant, and
- ingrowth from the long-lived nuclide present in the soil and subsequent uptake by plants.

The first process is only important if the half-life of the progeny is sufficiently short that secular equilibrium with its parent can be attained during the plant life-time. For conservatism, this contribution to $IMF_{d,ingrow}$ is included for progeny with half-lives less than 2 years.

It should be noted that ingrowth of the short-lived nuclide in the soil layer would also contribute to doses via the air inhalation pathway (due to soil resuspension) and the external ground-exposure pathway. These exposure doses are not included in the calculation of $IMF_{d,ingrow}$.

The calculation of $IMF_{d,ingrow}$ must account for the fact that the parent and its progeny are discharged at different rates into the well. If the two nuclides are in secular equilibrium in the geosphere, then the relative discharge rates of the two nuclides is inversely proportional to the retardation factors of the two nuclides in the geosphere zone closest to surface (Goodwin et al. 2001). That is,

$$REL_p/REL_d = (R_d/R_p) \tag{2.13}$$

where REL_p and REL_d are the discharge rates of the parent and progeny from the last geosphere zone and R_p and R_d are the retardation factors of the parent and progeny in the geosphere zone closest to surface (see Section 3.7).

Assuming that the parent and short-lived progeny are in secular equilibrium in all biosphere compartments, $IMF_{d,ingrow}$ is given by

$$IMF_{d,ingrow} = (R_d^{ZI}/R_p^{ZI})\,(1/D_{Wi,d})\,(C_{P,p} + C_{soil,p}\,Bv_d)\,I^P\,DC_{ing,d} \tag{2.14}$$

where $D_{Wi,d}$ is calculated from Equation 2.3a, $C_{P,p}$ is the total nuclide concentration of the parent in the plant (Bq/kg), as calculated from Equation 2.5, and $C_{soil,p}$ is the total nuclide concentration of the parent in the soil (Bq/kg), as calculated from Equation 2.10.

For some nuclides, the IMF values are sensitive to the soil $K_{d,S}$ values, which depend on soil type. Therefore, a range of IMF values was determined for each nuclide, based on the range of possible $K_{d,S}$ values, using the following procedure:

- IMF values were calculated for each soil type (sand, clay, loam or organic) using the median soil $K_{d,S}$ values listed in Section 3.8.
- For each soil type, IMF values were also calculated for $K_{d,S}$ values equal to 1/10 and 10 times the median $K_{d,S}$ value. In carrying out these calculations, it was assumed that the Bv_n and $K_{d,S}$ values are negatively correlated, with a correlation coefficient of -1.00.
- The IMF values for a nuclide are generally assumed to be uniformly distributed between the minimum and maximum values of the IMFs calculated as described above. However, for some nuclides, the IMF is not sensitive to the $K_{d,S}$ values and, therefore, the IMF value is defined as a constant value. Finally, for noble gas nuclides with no progeny with half-lives less than 1 day, the IMF values were set to 1.

The biosphere parameter values used to calculate the IMF values are shown in Table A-9. The plant bioconcentration factors, Bv_n, were taken from CSA (2008), when available, and from Baes et al. (1984), otherwise. The Bv_n values from these sources are based on the plant dry weight and were converted to a plant wet weight by dividing by 4, i.e., plants are assumed to be 80% water. The plant bioconcentration factors are shown in Table B-13.

The calculated radionuclide IMF values are shown in Table A-10. These provide an approximate accounting for the exposure of humans to ingestion of radionuclides from pathways other that the drinking water pathway.

3. CHEMICAL ELEMENT DATA

The screening database contains data for 96 chemical elements. These data include the inventories of the chemical elements in the UO_2 fuel and the Zircaloy cladding, the instant release fraction, the solubility limit, the volatility, the sorption coefficients (also presented as a capacity factor) of the buffer and backfill materials, the sorption coefficients of the rock and fracture zones, and the soil sorption coefficients. The sources of these data are described in this section.

3.1 Chemical Element Inventories in UO_2 Fuel and Zircaloy

In addition to radionuclides, the UO_2 fuel and Zircaloy cladding contain stable isotopes of many chemical elements. Some of these isotopes were created while the fuel bundle was in the reactor, due to fission, activation, and radionuclide decay. Others were originally present in the fuel as impurities (Tait et al. 2000).

The concentrations of the stable isotopes of the chemical elements are given in Tait et al. (2000). The stable isotope concentrations for each element were summed to determine the total concentrations of the chemical elements in the two waste forms.

The inventories of the chemical elements are presented in Table B-1. It should be emphasized that these inventories do not include the concentrations of the radioactive isotopes of the elements given in Table A-4.

Chemical element toxicity criteria are based on the total concentration of an element in various environmental media (surface water, soil, etc.). Hence, safety assessment calculations of the potential chemical toxicity impacts of a used fuel repository should include both the stable and radioactive isotopes of a chemical element, so that the total chemical element concentration in the various environmental media can be determined for comparison with chemical element toxicity criteria.

The chemical element inventories generally increase with burnup (see Table B-1). However, for the chemical elements listed below, the 280 MW•h/kgU inventories are smaller than the corresponding 220 MW•h/kgU inventories by more than 10% (the approximate percentage difference, relative to the 220 MW•h/kgU inventory, is shown in brackets). For these chemical elements, the 220 MW•h/kgU inventories should be used in conservative screening analyses.

<u>FUEL Elements</u>

Au (-10%), Ir (-15%), Re (-10%), Tm (-20%)

ZRLY Elements

Au (-10%), Eu(-15%), Ir (-15%), Rh (-15%), Tm (-20%)

3.2 Instant Release Fractions

3.2.1 UO_2 Wasteform

Contaminants are released from UO_2 fuel by two processes - instant release and congruent dissolution release. Instant release is the rapid release of nuclides on contact of the used fuel with water. Congruent dissolution is the slower release of nuclides as the UO_2 fuel itself dissolves.

The instant release process considers any contaminant inventory in the fuel-cladding gap or in the UO_2 fuel grain boundaries to be quickly exposed to water and to dissolve into the water. The degree of segregation of a contaminant is dependent on fuel operating parameters such as linear power rating and burnup, as well as on the properties of the contaminant.

The amount of a contaminant that is susceptible to instant release is called the instant release fraction (IRF) and is defined as a fraction of the total inventory of that contaminant within the UO_2 fuel. The IRFs for CANDU UO_2 fuel are described below.

In theory, the IRF can be radionuclide dependent because, for a relatively short-lived radionuclide, the location of the radionuclide in the fuel could depend on the location of the long-lived precursor. However, because a short-lived radionuclide decays rapidly, its concentration in the water within the (failed) container would be independent of the IRF after a relatively short period of time. Thus, for the screening database, instant release fractions are assumed to be only chemical element dependent, i.e., the same IRF is used for all isotopes of the same element.

The instant release fractions for UO_2 fuel are listed in Table B-3. The sources of these data are discussed below.

The IRF data for key elements such as I, Sr, and Cs, are based on the work of Stroes-Gascoyne (1996), who used fuel samples with burnups and (peak) peak linear power ratings higher than typical CANDU fuel – thereby providing conservative values of the IRFs for these elements (Garisto et al. 2012). The IRFs of these key elements were reviewed, including the possible implications of newer non-CANDU data (Johnson et al. 2004, SKB 2010). However, for CANDU fuel, Stroes-Gascoyne (1996) remains the best data source.

Stroes-Gascoyne (1996) found that for fuel (the IRF for Cs can be described using a normal distribution with mean 0.039 and standard deviation 0.019. The IRF for I can be described using a normal distribution with mean 0.036 and standard deviation 0.024. This is higher than the IRF used by SKB for LWR fuel (SKB 2010).

The standard deviations in the IRFs found by Stroes-Gascoyne (1996) reflect mainly the differences between the 14 different fuels used in her experiments. For a large quantity of fuel (i.e., the 360 fuel bundles in a used fuel container), the standard deviation for the average IRF would be much smaller. For example, the standard deviation for the IRF of I associated with having 360 bundles in a container, assuming that the measured variability is randomly distributed between fuel bundles, is $0.024/(360)^{1/2} = 0.0013$. However, the measured variability may include systematic biases and not just random measurement uncertainty; therefore, the standard deviation for the average IRF for the fuel in a container has been set to a nominal value of 0.01.

Hence, we assume that the IRF for Cs and I are described by a normal distribution with mean 0.04 and standard deviation 0.01. The limits of the distribution are set at 0.015 to 0.20. The minimum value corresponds approximately to the smallest IRF measured by Stroes-Gascoyne (1996) and the maximum value corresponds approximately to the calculated fission gas release from a high power rating/high burnup fuel (Iglesias et al. 2011).

The IRF for Cl is derived from the Cl-36 release data of Tait et al. (1997), who suggest that most of the Cl-36 in the fuel originates from the fuel-cladding gap and that little is present in the grain boundaries. The IRF for Cl-36 is described as a normal distribution with mean 0.06 and standard deviation of 0.01 (Garisto et al. 2012). This standard deviation accounts for the large quantity of fuel in a used fuel container, as discussed above for I and Cs. The limits of the distribution are set at 0.01 to 0.2, the approximate limits of the IRF data measured by Tait et al. (1997).

Stroes-Gascoyne (1996) found that the IRF of Sr can be described by a normal distribution with a mean of 0.025, a standard deviation of 0.008, and a maximum IRF of about 0.05.

For CANDU fuel, Stroes-Gascoyne et al. (1994) measured C-14 releases from crushed fuel samples. The mean release from the fifteen fuel samples was 0.027, with a standard deviation of 0.016.

The Tc IRF is taken from the review of Garisto and Gierszewski (2002). Their Tc IRF is lognormally distributed with a geometric mean of 0.01 and a geometric standard deviation of 2. This IRF is larger than that used by SKB (2010) since it is based on results of leaching experiments with both slightly preoxidized (UO_{2+x}, $x < 0.25$) and non-oxidized CANDU fuels. This larger value was selected to account for the uncertainty in the amount of Tc that could be leached from the fuel grain boundaries over hundreds of years.

The IRFs of all actinides and lanthanides are taken to be zero, as in other studies (Johnson et al. 2004), since they form non-volatile oxides that are dissolved within the UO_2 fuel matrix.

The IRFs for the elements Sn and Se have not been measured for CANDU fuels. Wilson (1990a, 1990b) attempted to measure the IRFs of Se-79 and Sn-126 for LWR fuels. However, the amount leached was less than the detection limit. From the “less than” data reported by Wilson, it is possible to infer maximum IRFs (Johnson et al. 2004, SKB 2010).

For Se, a semi-volatile element that is non-soluble in the UO_2 fuel, the maximum IRF is less than 15% of the fission gas release. Thus, the IRF for Se is described by a normal distribution with mean 0.006 and standard deviation 0.0015 (i.e., 15% of the I or Cs IRF). The limits of the distribution are set at 0.0023 to 0.03.

For Sn, a non-volatile element that is expected to be present as a metallic precipitate in used fuel (Kleykamp 1985), the maximum IRF, based on the “less than” values from Wilson (1990a, 1990b) is low, i.e., less than 0.0001. Given the uncertainties in the experiments, the differences between CANDU and LWR fuels and the fact that Sn is used as an analog for other elements (see below), it is conservatively assumed that the IRF for Sn is described by a uniform distribution from 0.0 to 0.001, with a median value of 0.0005.

For the many chemical elements for which leaching measurements are not available, the only basis for estimating the IRFs are the diffusion coefficients of the elements in fuel and the chemistry of the elements in fuel. For example, an understanding of which elements form solid solutions with UO_2 and which elements form metallic or oxide precipitates in fuel would be important (Kleykamp 1985). This methodology is used to conservatively estimate the IRFs of elements for which measured data are not available.

Generally, fission products can be approximately classified into 4 groups (Kleykamp 1985):

1. Gases and other volatiles:
   Kr, Xe, Br, I

2. Fission products forming metallic precipitates:
   Mo, Tc, Ru, Rh, Pd, Ag, Cd, In, Sn,. Sb, Te

3. Fission products forming oxide precipitates (often referred to as the “grey phase”):
   Rb, Cs, Ba, Zr, Nb, Mo, Te

4. Fission products dissolved in the fuel matrix:
   Sr, Zr, Nb, Rare Earths, Y, La, Ce, Pr, Nd, Pm, Sm

The key thermodynamic factor that influences the chemical state of the fission products in fuel is the oxygen potential, which in turn depends on the stoichiometry of the fuel, the temperature and burnup. The fuel is initially stoichiometric, i.e., the oxygen potential is very low (Lindemer and Besman 1985), but burnup raises the O/U value because O_2 released by fission of uranium cannot be completely bonded by the fission products (Cordfuncke and Konings 1988). For near-stoichiometric fuels, the oxidation potential in the fuel may be buffered by the Mo/MoO_2 couple (Kleykamp 1985, Cubicciotti and Sanecki 1978), since this couple has an oxidation potential that is similar to that of slightly hyperstoichiometric fuel and the fission yield of Mo is relatively high.

The oxidation potential for formation of the oxide of each element, relative to the oxidation potential of the fuel, was used to assess the chemical state of the elements in fuel (Kleykamp 1985) and, thence, to estimate the instant release fractions of the elements for which no measured values are available. For an element for which measured IRFs are not available, the rationale for the selected instant release fraction is provided in Table B-2.

3.2.2 Zircaloy Cladding

Because the impurities in the Zircaloy cladding are uniformly distributed and the temperature of the cladding during reactor operation is relatively low, the activation products and impurities in the cladding would be expected to be likewise uniformly distributed. Hence, for the Zircaloy cladding, the IRFs should be zero and the chemical elements are released congruently as the Zircaloy corrodes.

However, there is some evidence that C-14 has a higher concentration in the oxide film than in the underlying alloy (Johnson et al. 2004, Yamaguichi et al. 1999). Consequently, the release of carbon from the oxide film on the Zircaloy is assumed to be rapid. This corresponds to an IRF of 0.2 for carbon from the Zircaloy cladding. The remaining carbon in the Zircaloy is released congruently as the Zircaloy corrodes.

Thus, for the Zircaloy cladding, the IRFs are assumed to be zero for all chemical elements except carbon.

3.3 Solubility Limits

In many safety assessment models, including the NWMO screening models, chemical element concentrations in the repository (in particular, within the void volume of the used fuel container) are limited by the solubility of the element. The solubility of the element is dependent on the groundwater composition which, in turn, is dependent of the rock environment in which the repository is located. Recommended solubility limits for crystalline and sedimentary rock environments are described in this section.

3.3.1 Crystalline Rock Environment

For conservatism, numerous elements were assigned a nominal but conservative solubility limit of 2000 mol/m^3. This includes elements with low inventories (i.e., dissolution of the entire inventory of an element into the void volume of the container would result in concentrations less than 0.001 mol/m^3).

Some other elements have high solubilities under the expected repository conditions and, hence, these elements should not precipitate in the container void volume. These elements are also assigned a conservatively high solubility of 2000 mol/m^3.

The noble gases such as Kr are not very soluble. However, if the concentration of say Kr exceeds its solubility limit, then gas bubbles of Kr would form. Since these bubbles could be as mobile as the dissolved Kr, it is recommended that a high solubility of 2000 mol/m^3 be assigned to Kr and the other noble gases.

The list of elements with nominally high solubilities (2000 mol/m^3) includes Ar, Au, B, Bk, Br, Cf, Cl, Cr, Cs, Er, Es, F, Fe, Fm, Ga, Ge, He, Hg, In, Ir, Kr, Li, Lu, Md, Mg, Mn, Na, Os, P, Pt, Rh, Rn, Ru, S, Sc, Ta, Tb, Tc, Ti, Tl, Tm, V, W, Xe, Y, Yb, and Zn.

For a number of elements with relatively low solubilities (Am, As, Bi, C, Cm, Cu, Mo, Nb, Np, Pa, Pb, Pd, Pu, Ra, Se, Sn, Tc, Th, U, and Zr), the solubility values were calculated by Duro et al. (2010) for a selected crystalline groundwater using PHREEQC v2.17.0 (Parkhurst and Appelo, 2001) and the ThermoChimie v.7.b thermodynamic database. The crystalline groundwater is representative of that found in the Canadian Shield at a depth of 500m. The solubility values in the presence of the bentonite buffer and carbon steel container were also calculated. The highest calculated element solubility is recommended for used in the screening database.

For the purposes of the screening database, the approach of Duro et al. (2010) was used to calculate solubility limits for the following elements: Ag, Al, Ba, Cd, Co, Ho, Ni, Sb, Sm, and Sr.

Finally solubility limits for Ac, Be, Ca, Ce, Dy, Eu, Gd, H, Hf, I, K, La, Nd, Pm, Po, Pr, Rb, Re and Si were taken from Johnson et al. (1996).

Element solubilities were compared against those in SKB (2006). The solubilities were found to be comparable for most elements. Notable exceptions include: Ag, for which the solubility is much lower in SKB (2006); and Pa and Th, for which the solubility is somewhat lower (approximately 10x lower) in SKB (2006), likely due to differences in the NWMO and SKB reference groundwaters.

A significant uncertainty in calculating element solubility limits using thermodynamic data is the effect of temperature. The solubilities calculated with the ThermoChemie database are for 25°C, whereas the temperature near a container in a used fuel repository remains high (about 70°C) for tens of thousands of years following closure of the repository. However, there is a scarcity of thermodynamic data at these high temperatures. Since solubilities generally increase with temperature, this suggests that the solubility limits could potentially be underestimated for early times. To account for this uncertainty, the calculated solubilities of the low solubility elements were increased by a factor of 10 for use in the screening database. These conservative values are listed in Table B-4.

3.3.2 Sedimentary Rock Environment

The groundwaters in the sedimentary rock environments of interest to the NWMO have a high salinity, with a total dissolved solid concentration of approximately 270 g/L. The calculation of element solubility limits for such groundwaters are generally not as reliable as those for low salinity groundwaters because of the lack of consistent thermodynamic data, e.g., Pitzer interaction coefficients (Grenthe et al. 1997). Hence, a different approach was used to select solubility values for sedimentary rock environments.

Specifically, most elements were assigned a nominal but conservative solubility limit of 2000 mol/m^3. However, for a number of elements with relatively low solubilities (Am, As, Bi, C, Cm, Cu, Mo, Nb, Np, Pa, Pb, Pd, Pu, Ra, Se, Sn, Tc, Th, U, and Zr), the solubility values were calculated by Duro et al. (2010) for a selected sedimentary groundwater using PHREEQC v2.17.0 (Parkhurst and Appelo, 2001) and the ThermoChimie v.7.b thermodynamic database. The sedimentary groundwater is representative of that found in the Cobourg layer of the Michigan basin formation at a depth of 500 m. The solubility values in the presence of the bentonite buffer and carbon steel container were also calculated. The highest calculated element solubility is recommended for used in the screening database.

As noted above, the solubilities calculated with the ThermoChemie database are for 25°C, whereas the temperature near a container in a used fuel repository remains high (about 70°C) for tens of thousands of years following closure of the repository. To account for the potential effect of temperature, the calculated solubilities of the low solubility elements were increased by a factor of 10 for use in the screening database. These conservative values are listed in Table B−5.

3.4 Element Volatility

In the NWMO screening model, the element concentration in air depends on the volatility of the element (Goodwin et al. 2001). Only Ar, H, Kr, Rn and Xe are considered to be volatile and all other elements in the screening database are assumed to be non-volatile.

3.5 Buffer Sorption Coefficient and Capacity Factor

The buffer capacity factor for element i, r_i^{buf}, is a measure of the amount of storage of a radionuclide within the buffer, including the buffer pore water. It is given by the equation:

$$r_i^{buf} = \varepsilon^{buf} + \rho^{buf} Kd_i^{buf} \tag{3.1}$$

where ε^{buf} and ρ^{buf} are the porosity and bulk density of the buffer, and Kd_i^{buf} is the buffer sorption coefficient for element i. The capacity factor is also related to the retardation factor in the buffer, R_i^{buf}, by the equation

$$r_i^{buf} = \varepsilon^{buf} R_i^{buf} \tag{3.2}$$

The buffer retardation factor is a measure of the degree to which radionuclide transport through the buffer is retarded as a result of radionuclide sorption onto the buffer material.

The buffer sorption coefficients depend on the groundwater composition and, hence, the rock environment in which the repository is located. For a crystalline rock environment, the buffer capacity factors were calculated using the sorption coefficients listed in the SKB (2010). For elements not included in SKB (2010), chemical analogues were used to provide data for chemically similar elements or the sorption coefficient was conservatively set to zero. The buffer sorption coefficients (K_d) and the corresponding capacity factors, calculated with $\varepsilon^{buf} = 0.43$ and $\rho^{buf} = 1571$ kg/m^3 (Garisto et al. 2012) are listed in Table B-6 and Table B-7, respectively.

For a sedimentary rock environment, buffer sorption coefficient values are available for only a few elements due to the lack of measured sorption data at high salinities (total dissolved solids of approximately 270 g/L). For these elements, fairly conservative sorption coefficient values were selected from Walke et al. (2011) and Vilks (2011). Therefore, these sorption coefficients are treated as constant values.

The sorption coefficients (K_d) for a sedimentary rock environment and the corresponding capacity factors, calculated using $\varepsilon^{buf} = 0.48$ and $\rho^{buf} = 1423$ kg/m^3, are listed in Table B−8.

3.6 Backfill Sorption Coefficients and Capacity Factors

The backfill is composed of 5 wt% bentonite, 25 wt% glacial clay and 70 wt% crushed granite aggregate (Garisto et al. 2012).

For a crystalline rock environment, the backfill capacity factors were calculated using Equation 3.1 and K_d data from SKB (2006). Data from SKB (2010) were not used since the backfill in SKB (2010) does not have the same composition as the NWMO backfill. The backfill sorption coefficients and backfill capacity factors are listed in Table B-9 and Table B-10, respectively. The capacity factors were calculated using a backfill porosity and density of 0.20 and 2120 kg/m^3, respectively (Garisto et al. 2012).

For a sedimentary rock environment, the NWMO repository design does not include a backfill. Thus, backfill capacity factors are not required for a sedimentary rock environment and, so, are not listed in this report

3.7 Geosphere Rock and Fracture Sorption Coefficients

In the screening model, the geosphere can consist of several zones with different physical and chemical properties. The sorption coefficient for element i in geosphere zone z, Kd_i^z, is defined as the (equilibrium) ratio of the concentration of the element i adsorbed on the rock in geosphere zone z (in mol/kg) to the concentration of element i in the groundwater in the zone. It is an important parameter because it determines the retardation factor, R_i^z, which controls the rate at which an element is transported through the rock zone. The retardation factor is related to Kd_i^z through the equation

$$R_i^z = 1 + [\rho^z(1-\varepsilon^z)/\varepsilon^z]Kd_i^z \qquad (3.3)$$

where ε^z and ρ^z are the porosity and bulk density in geosphere zone z.

It is important to note that the Kd_i^z values in Equation 3.3 are those for the rock in its natural state, which ranges from intact rock with low porosity (e.g., 0.1%) to a locally higher-porosity fracture zone (e.g., 10%). Sorption coefficients are, however, usually derived from experiments on crushed material with 30-50% porosity. The surface area of the interconnected pore space in intact rock that may be available for sorption of dissolved contaminants is small compared to that for crushed material. Therefore, applying sorption coefficients obtained on crushed material to contaminant migration in intact rock would imply a much greater degree of sorption than is warranted.

In order to correct from experimentally measured sorption data on crushed rock samples to those for intact rock, a normalization factor is applied to the experimental sorption coefficient K_d (Vandergraaf 1997, Vandergraaf and Ticknor 1994) to account for the larger sorption area of the crushed rock, i.e.,

$$Kd_i^z = [(1-\varepsilon_{expt})/\varepsilon_{expt}]\ [(1-\varepsilon^z)/\varepsilon^z]^{-1}\ Kd_{i,m} \qquad (3.4)$$

where, to emphasize the differences between intact and crushed rock, the symbol $Kd_{i,m}$ is used to denote the sorption coefficient for crushed or unconsolidated material. ε^z is the geological material porosity and ε_{expt} is the porosity of the unconsolidated material used in the measurement of $Kd_{i,m}$. Generally, ε_{expt} is assumed to be 50%.

The normalization factors for intact rock and fractures in a granitic host environment can be calculated using data from Garisto et al. (2012).

The normalization factors for sedimentary rock formations can be calculated using data from Walke et al. (2011).

Corrections for converting measured K_d data on crushed rock to intact rock K_d values have also been applied by SKB (2010) and Crawford et al. (2006). Although the approach used by Vandergraaf and Ticknor (1994) is different, it is more conservative since the calculated intact rock K_d values are smaller than obtained using the other approaches.

3.7.1 Crystalline Rock Environment

Crawford et al. (2006) compiled sorption data for a variety of granites and their report was used as the primary reference for the sorption coefficients for intact rock and fractures. For some elements for which Crawford et al. (2006) do not report data, the sorption coefficients were taken from Ticknor and Vandergraaf (1996). Finally, if data were not available in either of these two sources, then the sorption coefficients were estimated using chemical analogues or the sorption coefficient was conservatively assumed to be zero.

The sorption coefficients ($Kd_{i,m}$) for granite are shown Table B-11. In the screening database, no distinction is made between sorption coefficients for granite intact rock and for fractures. This is primarily due to a lack of sorption data for fracture materials and is considered to be conservative as fractures typically have larger surface areas available for sorption.

Sorption coefficients for some elements are sensitive to the salinity of the groundwater and/or the groundwater redox conditions. Hence, when applicable, the sorption coefficients in Table B-11 are identified as being for saline or non-saline conditions and/or for reducing or oxidizing conditions. In this context, saline groundwaters are defined as containing more than 0.5 g/L of total dissolved solids.

It should be noted that while the $Kd_{i,m}$ values are the same for intact rock and fractures, the normalization factor applied to the fracture and intact rock sorption coefficient (Equation 3.4) will be different, resulting in distinct Kd_i^z values for intact rock and fractures. Since, in the screening model, the Kd_i^z value determines the amount of sorption of the contaminant in the geosphere, sorption will be different in intact rock and fractures.

3.7.2 Sedimentary Rock Environment

For the sedimentary formations of interest to the NWMO, the rock layers are primarily composed of argillaceous and limestone lithologies. The groundwaters in such formations are highly saline (total dissolved solids of approximately 270 g/L). Since sorption data for such environments are scarce, for screening purposes, fairly conservative sorption coefficient values were selected. Therefore, these sorption values are treated as constants. For example, the selected sorption coefficients for redox sensitive elements such as U and Np reflect measured values for the weakly sorbing oxidized species even though redox conditions are expected to be reducing at repository depth. The selected sorption coefficients for a sedimentary rock environment, which were taken from Walke et al. (2011) and Vilks (2011), are listed in Table B−12.

3.8 Soil Sorption Coefficients

Soil sorption coefficients are used exclusively in the calculation of the ingestion multiplication factors (see Equation 2.10 and 2.11). The sorption coefficients for the sand, loam, clay and organic soils are presented in Table B-13.

The sorption values for Cl, I, Np, Ra and U are from Sheppard et al. (2002, 2004a, 2004b, 2005a and 2005b, respectively). Soil sorption data from CSA (2008) were used if available. Data were next taken from Sheppard and Thibault (1990) (Ac, Bi, Ca, Cd, K, Pb, Pd, Po, Re, Rn, Si, Sm and Ta). Finally, if data were not available from these two sources, then they were calculated from the plant-to-soil concentration ratios using the correlations in Thibault et al. (1990) and Sheppard and Thibault (1990). The latter approach was explicitly used for Al, Au, B, Bk, Cf, Cu, Dy, Er, Es, F, Fm, Ga, Ge, In, Ir, Li, Lu, Md, Mg, Nd, Os, Pt, Rh, Ti, Tl, Tm, V, W, and Yb.

The correlations used to calculate the soil K_d values from the plant-to-soil concentration ratio were taken from Thibault et al. (1990) and are shown in Equation 3.5.

$$K_d = \exp[4.62 + A - 0.56 \ln(CR)] \qquad (3.5)$$

where A = -2.51, -1.26, -0.84 and 0.0 for sand, loam, clay and organic soils, respectively; and CR is the plant-to-soil concentration ratio on a wet weight basis, i.e., in units of (mol/kg wet plant)/(mol/kg dry soil). Since these correlations were developed using the CR values of Baes et al. (1984), their CR values were used to calculate the soil K_d values. Note that the factor 0.56 in Equation 3.5 is incorrectly shown as 0.5 in Sheppard and Thibault (1990).

3.9 Criteria for Environmental Concentration of Chemical Elements

The criteria for protection of humans and non-human biota from potentially chemically hazardous elements are based on Canadian guideline values for concentrations in environmental media relevant to human health and environmental protection, supplemented as needed.

Specifically, the criteria are based on federal and provincial guideline concentrations for surface water, groundwater, soil and sediment, and in particular Canadian Council of the Environment (CCME 2007a,b,c). In cases where federal guidelines do not currently exist, Ontario Ministry of the Environment guidelines (MoE 2011, MoEE 1994) have been adopted as criteria. Depending on the actual site location, the applicable provincial guidelines would be used.

The environmental concentrations of contaminants calculated by the screening model are compared with the selected criteria. Additive effects are not considered. If any concentrations exceed the criteria or, conservatively, a fraction thereof, these contaminants require further detailed evaluation.

The criteria are listed in Table B−14. The table lists only the chemical elements for which trustworthy criteria were found.

4. SUMMARY

A database of representative radionuclide and chemical element dependent parameters has been compiled for use with screening assessments.

The database includes 96 different chemical elements and 251 radionuclides. For each radionuclide, the database contains the following information: decay schemes, inventory in the fuel, and inventory in the Zircaloy cladding, half-life, ingestion dose coefficient, ground-exposure dose coefficient, air inhalation dose coefficient, air immersion dose coefficient and ingestion multiplication factor. For each chemical element, the database includes the following information: inventory in fuel, inventory in the Zircaloy cladding, instant-release fraction, element solubility limit, element volatility, the sorption coefficient and capacity factor for the buffer, the sorption coefficient and capacity factor for the backfill material, the sorption coefficient for the intact rock and fracture and the soil sorption coefficients.

Since not all required data were available in the literature, conservative approximations and assumptions were made to estimate these missing data. The adequacy of these approximations and assumptions will become clear only after the database is used in several different studies. For example, if it is found that the calculated total radiological dose rates (and, hence, radionuclide rankings) are strongly dependent on these estimated data, then further work, experimental or theoretical, could be warranted to reduce the conservatisms used in estimating these data.

Some of the data compiled in this report are applicable only to specific situations. Specifically, the inventory and instant release fraction data are associated with an assumed burnup and age of fuel typical of CANDU nuclear reactors. Also, the solubility, buffer K_d, backfill K_d and rock K_d values are appropriate either for low salinity groundwaters (i.e., approximately 10 g/L total dissolved solids), typical of granitic Canadian Shield conditions at depths of 500 m, or for high salinity groundwaters (i.e., approximately 300 g/L), typical of sedimentary rocks in the Michigan Basin at depths of 500 m.

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APPENDIX A: RADIONUCLIDE SPECIFIC DATA

LIST OF TABLES

Table A-1: Decay Scheme for Radionuclides	
Nuclide	Radionuclide Decay Scheme. Progeny with Half-lives Less Than 1 Day are Shown in Bold and Stable Isotopes are Indicated Using Subscripts.
Ac-225	$Ac{-}225 \rightarrow \boldsymbol{Fr{-}221} \rightarrow \boldsymbol{At{-}217} \rightarrow \boldsymbol{Bi{-}213} \begin{array}{l} \xrightarrow{0.9791} \boldsymbol{Po{-}213} \\ \xrightarrow{0.0209} \boldsymbol{Tl{-}209} \end{array} \rightarrow \boldsymbol{Pb{-}209} \rightarrow Bi_{209}$
Ac-226	$Ac{-}226 \begin{array}{l} \xrightarrow{0.170} Ra{-}226\ldots \\ \xrightarrow{0.830} \boldsymbol{Th{-}226} \\ \xrightarrow{6.E-5} \boldsymbol{Fr{-}222} \end{array} \rightarrow \boldsymbol{Ra{-}222} \rightarrow \boldsymbol{Rn{-}218} \rightarrow \boldsymbol{Po{-}214} \rightarrow Pb{-}210\cdots$
Ac-227	$Ac{-}227 \begin{array}{l} \xrightarrow{0.0138} \boldsymbol{Fr{-}223} \rightarrow Ra{-}223\cdots \\ \xrightarrow{0.9862} Th{-}227\cdots \end{array}$
Ag-105	$Ag{-}105 \rightarrow Pd_{105}$
Ag-106m	$Ag{-}106m \rightarrow Pd_{106}$
Ag-108m	$Ag{-}108m \xrightarrow{0.087} \boldsymbol{Ag{-}108} \begin{array}{l} \xrightarrow{0.9715} Cd_{108} \\ \xrightarrow{0.0285} Pd_{108} \end{array}$
Ag-110m	$Ag{-}110m \xrightarrow{0.0136} \boldsymbol{Ag{-}110} \begin{array}{l} \xrightarrow{0.997} Cd_{110} \\ \xrightarrow{0.003} Pd_{110} \end{array}$
Ag-111	$Ag{-}111 \rightarrow Cd_{111}$
Al-26	$Al - 26 \rightarrow Mg_{26}$
Am-240	$Am{-}240 \rightarrow Pu{-}240\cdots$
Am-241	$Am{-}241 \rightarrow Np{-}237\cdots$
Am-242m	$Am{-}242m \begin{array}{l} \xrightarrow{0.9955} \boldsymbol{Am{-}242} \begin{array}{l} \xrightarrow{0.827} Cm{-}242\cdots \\ \xrightarrow{0.173} Pu{-}242\cdots \end{array} \\ \xrightarrow{0.0045} Np{-}238\cdots \end{array}$
Am-243	$Am{-}243 \rightarrow Np{-}239\cdots$
Ar-37	$Ar - 37 \rightarrow Cl_{37}$
Ar-39	$Ar - 39 \rightarrow K_{39}$
Ar-42	$Ar{-}42 \rightarrow \boldsymbol{K{-}42} \rightarrow Ca_{42}$
As-71	$As{-}71 \rightarrow Ge{-}71\cdots$
As-72	$As{-}72 \rightarrow Ge_{72}$
As-73	$As{-}73 \rightarrow Ge_{73}$
As-74	$As{-}74 \begin{array}{l} \xrightarrow{0.66} Ge_{74} \\ \xrightarrow{0.34} Se_{74} \end{array}$
As-76	$As{-}76 \rightarrow Se_{76}$
As-77	$As{-}77 \rightarrow Se_{77}$
Au-194	$Au - 194 \rightarrow Pt_{194}$
Au-195	$Au - 195 \rightarrow Pt_{195}$
Au-196	$Au - 196 \begin{array}{l} \xrightarrow{0.928} Pt_{196} \\ \xrightarrow{0.072} Hg_{196} \end{array}$

Table A-1: Decay Scheme for Radionuclides

Nuclide	Radionuclide Decay Scheme. Progeny with Half-lives Less Than 1 Day are Shown in Bold and Stable Isotopes are Indicated Using Subscripts.
Au-198	$Au{-}198 \rightarrow Hg_{198}$
Au-198m	$Au{-}198m \rightarrow Au{-}198\cdots$
Au-199	$Au{-}199 \rightarrow Hg_{199}$
Ba-128	$Ba{-}128 \rightarrow \mathbf{Cs{-}128} \rightarrow Xe_{128}$
Ba-131	$Ba{-}131 \rightarrow Cs{-}131\cdots$
Ba-133	$Ba{-}133 \rightarrow Cs_{133}$
Ba-133m	$Ba{-}133m \rightarrow Ba{-}133\cdots$
Ba-135m	$Ba{-}135m \rightarrow Ba_{135}$
Ba-140	$Ba{-}140 \rightarrow La{-}140\cdots$
Be-7	$Be{-}7 \rightarrow Li_{7}$
Be-10	$Be{-}10 \rightarrow B_{10}$
Bi-205	$Bi{-}205 \rightarrow Pb{-}205\cdots$
Bi-206	$Bi{-}206 \rightarrow Pb_{206}$
Bi-207	$Bi{-}207 \rightarrow Pb_{207}$
Bi-208	$Bi{-}208 \rightarrow Pb_{208}$
Bi-210	$Bi{-}210 \rightarrow Po{-}210\cdots$
Bi-210m	$Bi{-}210m \rightarrow \mathbf{Tl{-}206} \rightarrow Pb_{206}$
Bk-245	$Bk{-}245 \xrightarrow{0.9988} Cm{-}245\cdots$ $\xrightarrow{0.0012} Am{-}241\cdots$
Bk-246	$Bk{-}246 \rightarrow Cm{-}246\cdots$
Bk-247	$Bk{-}247 \rightarrow Am{-}243\cdots$
Bk-248	$Bk{-}248 \xrightarrow{>0.70} \mathbf{Am{-}244} \rightarrow Cm{-}244\cdots$ $\xrightarrow{?}$
Bk-249	$Bk{-}249 \xrightarrow{1.00^{*}} Cf{-}249\cdots$ $\xrightarrow{1.5E-5} \mathbf{Am{-}245} \rightarrow Cm{-}245\cdots$
Br-77	$Br{-}77 \rightarrow Se_{77}$
Br-82	$Br{-}82 \rightarrow Kr_{82}$
C-14	$C{-}14 \rightarrow N_{14}$
Ca-41	$Ca{-}41 \rightarrow K_{41}$
Ca-45	$Ca{-}45 \rightarrow Sc_{45}$
Ca-47	$Ca{-}47 \rightarrow Sc{-}47\cdots$
Cd-109	$Cd{-}109 \rightarrow Ag_{109}$
Cd-113	$Cd{-}113 \rightarrow In_{113}$
Cd-113m	$Cd{-}113m \xrightarrow{0.9986} In_{113}$ $\xrightarrow{0.0014} Cd{-}113\cdots$

Table A-1: Decay Scheme for Radionuclides	
Nuclide	Radionuclide Decay Scheme. Progeny with Half-lives Less Than 1 Day are Shown in Bold and Stable Isotopes are Indicated Using Subscripts.
Cd-115	$Cd\text{–}115 \rightarrow \mathbf{In\text{–}115m} \xrightarrow{0.95} In\text{–}115\cdots$ $\xrightarrow{0.05} Sn_{115}$
Cd-115m	$Cd\text{–}115m \rightarrow In\text{–}115\cdots$
Ce-134	$Ce\text{–}134 \rightarrow \mathbf{La\text{–}134} \rightarrow Ba_{134}$
Ce-137m	$Ce\text{–}137m \xrightarrow{0.9922} \mathbf{Ce\text{–}137} \rightarrow La\text{–}137\cdots$ $\xrightarrow{7.8E-3} La\text{–}137\cdots$
Ce-139	$Ce\text{–}139 \rightarrow La_{139}$
Ce-141	$Ce\text{–}141 \rightarrow Pr_{141}$
Ce-143	$Ce\text{–}143 \rightarrow Pr\text{–}143\cdots$
Ce-144	$Ce\text{–}144 \xrightarrow{0.0098} \mathbf{Pr\text{–}144m} \rightarrow \mathbf{Pr\text{–}144} \rightarrow Nd\text{-}144\cdots$ $\xrightarrow{0.9902} \mathbf{Pr\text{–}144} \rightarrow Nd\text{-}144\cdots$
Cf-246	$Cf\text{–}246 \rightarrow Cm\text{–}242\cdots$
Cf-248	$Cf\text{–}248 \rightarrow Cm\text{–}244\cdots$
Cf-249	$Cf\text{–}249 \rightarrow Cm\text{–}245\cdots$
Cf-250	$Cf\text{–}250 \rightarrow Cm\text{–}246\cdots$
Cf-251	$Cf\text{–}251 \rightarrow Cm\text{–}247\cdots$
Cf-252	$Cf\text{–}252 \xrightarrow{0.969} Cm\text{–}248\cdots$ $\xrightarrow{0.031} sf$
Cf-253	$Cf\text{–}253 \xrightarrow{3.1E-3} \mathbf{Cm\text{–}249} \rightarrow Bk\text{–}249\cdots$ $\xrightarrow{0.9969} Es\text{–}253$
Cf-254	$Cf\text{–}254 \xrightarrow{0.003} Cm\text{–}250\cdots$ $\xrightarrow{0.997} sf$
Cl-36	$Cl\text{–}36 \xrightarrow{0.981} Ar_{36}$ $\xrightarrow{0.019} S_{36}$
Cm-240	$Cm\text{–}240 \rightarrow Pu\text{–}236\cdots$
Cm-241	$Cm\text{–}241 \xrightarrow{0.99} Am\text{–}241\cdots$ $\xrightarrow{0.01} Pu\text{–}237\cdots$
Cm-242	$Cm\text{–}242 \rightarrow Pu\text{–}238\cdots$
Cm-243	$Cm\text{–}243 \xrightarrow{0.9976} Pu\text{–}239\cdots$ $\xrightarrow{0.0024} Am\text{–}243\cdots$
Cm-244	$Cm\text{–}244 \rightarrow Pu\text{–}240\cdots$
Cm-245	$Cm\text{–}245 \rightarrow Pu\text{–}241\cdots$
Cm-246	$Cm\text{–}246 \rightarrow Pu\text{–}242\cdots$
Cm-247	$Cm\text{–}247 \rightarrow \mathbf{Pu\text{–}243} \rightarrow Am\text{–}243\cdots$

Table A-1: Decay Scheme for Radionuclides

Nuclide	Radionuclide Decay Scheme. Progeny with Half-lives Less Than 1 Day are Shown in Bold and Stable Isotopes are Indicated Using Subscripts.
Cm-248	$Cm{-}248 \xrightarrow{0.916} Pu{-}244\cdots$ $\xrightarrow{0.084} sf$
Cm-250	$\xrightarrow{0.18} Pu{-}246\cdots$ $Cm{-}250 \xrightarrow{0.08} \mathbf{Bk{-}250} \rightarrow Cf{-}250\cdots$ $\xrightarrow{0.74} sf$
Co-56	$Co{-}56 \rightarrow Fe_{56}$
Co-57	$Co{-}57 \rightarrow Fe_{57}$
Co-58	$Co{-}58 \rightarrow Fe_{58}$
Co-60	$Co{-}60 \rightarrow Ni_{60}$
Cr-51	$Cr{-}51 \rightarrow V_{51}$
Cs-129	$Cs{-}129 \rightarrow Xe_{129}$
Cs-131	$Cs{-}131 \rightarrow Xe_{131}$
Cs-132	$Cs{-}132 \xrightarrow{0.9813} Xe_{132}$ $\xrightarrow{0.0187} Ba_{132}$
Cs-134	$Cs{-}134 \rightarrow Ba_{134}$
Cs-135	$Cs{-}135 \rightarrow Ba_{135}$
Cs-136	$Cs{-}136 \rightarrow Ba_{136}$
Cs-137	$Cs{-}137 \xrightarrow{0.944} \mathbf{Ba{-}137m} \rightarrow Ba_{137}$ $\xrightarrow{0.056} Ba_{137}$
Cu-67	$Cu{-}67 \rightarrow Zn_{67}$
Dy-154	$Dy{-}154 \rightarrow Gd{-}150\cdots$
Dy-159	$Dy{-}159 \rightarrow Tb_{159}$
Dy-166	$Dy{-}166 \rightarrow Ho{-}166\cdots$
Er-160	$Er{-}160 \rightarrow \mathbf{Ho{-}160} \rightarrow Dy_{160}$
Er-169	$Er{-}169 \rightarrow Tm_{169}$
Er-172	$Er{-}172 \rightarrow Tm{-}172\cdots$
Es-251	$Es{-}251 \xrightarrow{0.995} Cf{-}251\cdots$ $\xrightarrow{0.005} Bk{-}247\cdots$
Es-252	$Es{-}252 \xrightarrow{0.76} Bk{-}248\cdots$ $\xrightarrow{0.24} Cf{-}252\cdots$
Es-253	$Es{-}253 \rightarrow Bk{-}249\cdots$
Es-254	$Es{-}254 \rightarrow \mathbf{Bk{-}250} \rightarrow Cf{-}250\cdots$

Table A-1: Decay Scheme for Radionuclides

Nuclide	Radionuclide Decay Scheme. Progeny with Half-lives Less Than 1 Day are Shown in Bold and Stable Isotopes are Indicated Using Subscripts.
Es-254m	$Es\text{–}254m \xrightarrow{0.98} \mathbf{Fm\text{–}254} \rightarrow Cf\text{–}250\cdots$ $Es\text{–}254m \xrightarrow{0.0032} \mathbf{Bk\text{–}250} \rightarrow Cf\text{–}250\cdots$ $Es\text{–}254m \xrightarrow{<0.02} Es\text{-}254...$ $Es\text{–}254m \xrightarrow{0.00076} Cf\text{–}254\cdots$
Es-255	$Es\text{–}255 \xrightarrow{0.92} \mathbf{Fm\text{–}255} \rightarrow Cf\text{–}251\cdots$ $Es\text{–}255 \xrightarrow{0.08} \mathbf{Bk\text{–}251} \rightarrow Cf\text{–}251\cdots$
Eu-145	$Eu\text{–}145 \rightarrow Sm\text{–}145\cdots$
Eu-146	$Eu\text{–}146 \rightarrow Sm\text{–}146\cdots$
Eu-147	$Eu\text{–}147 \xrightarrow{1.00^{*}} Sm\text{–}147\cdots$ $Eu\text{–}147 \xrightarrow{2.2E-5} Pm\text{–}143\cdots$
Eu-148	$Eu\text{–}148 \rightarrow Sm\text{–}\ 148\cdots$
Eu-149	$Eu\text{–}149 \rightarrow Sm_{149}$
Eu-150	$Eu\text{–}150 \rightarrow Sm_{150}$
Eu-152	$Eu\text{–}152 \xrightarrow{0.279} Gd\text{–}152\cdots$ $Eu\text{–}152 \xrightarrow{0.721} Sm_{152}$
Eu-154	$Eu\text{–}154 \xrightarrow{0.998} Gd_{154}$ $Eu\text{–}154 \xrightarrow{2.0E-4} Sm_{154}$
Eu-155	$Eu\text{–}155 \rightarrow Gd_{155}$
Eu-156	$Eu\text{–}156 \rightarrow Gd_{156}$
Fe-55	$Fe\text{–}55 \rightarrow Mn_{55}$
Fe-59	$Fe\text{–}59 \rightarrow Co_{59}$
Fe-60	$Fe\text{–}60 \rightarrow \mathbf{Co\text{–}60m} \xrightarrow{0.9976} Co\text{–}60\cdots$ $Fe\text{–}60 \rightarrow \mathbf{Co\text{–}60m} \xrightarrow{0.0024} Ni_{60}$
Fm-253	$Fm\text{–}253 \xrightarrow{0.88} Es\text{–}253\cdots$ $Fm\text{–}253 \xrightarrow{0.12} Cf\text{–}249\cdots$
Fm-257	$Fm\text{–}257 \xrightarrow{0.9979} Cf\text{–}253$ $Fm\text{–}257 \xrightarrow{0.0021} sf$
Ga-67	$Ga\text{–}67 \rightarrow Zn_{67}$
Gd-146	$Gd\text{–}146 \rightarrow Eu\text{–}146\cdots$
Gd-147	$Gd\text{–}147 \rightarrow Eu\text{–}147\cdots$
Gd-148	$Gd\text{–}148 \rightarrow Sm_{144}$
Gd-149	$Gd\text{–}149 \rightarrow Eu\text{–}149\cdots$
Gd-150	$Gd\text{–}150 \rightarrow Sm\text{–}146\cdots$
Gd-151	$Gd\text{–}151 \rightarrow Eu_{151}$

Table A-1: Decay Scheme for Radionuclides

Nuclide	Radionuclide Decay Scheme. Progeny with Half-lives Less Than 1 Day are Shown in Bold and Stable Isotopes are Indicated Using Subscripts.
Gd-152	$Gd-152 \rightarrow Sm-148 \cdots$
Gd-153	$Gd-153 \rightarrow Eu_{153}$
Ge-68	$Ge-68 \rightarrow \mathbf{Ga-68} \rightarrow Zn_{68}$
Ge-69	$Ge-69 \rightarrow Ga_{69}$
Ge-71	$Ge-71 \rightarrow Ga_{71}$
H-3	$H-3 \rightarrow He_{3}$
Hf-172	$Hf-172 \rightarrow \mathbf{Lu-172m} \rightarrow Lu-172 \cdots$
Hf-173	$Hf-173 \rightarrow Lu-173 \cdots$
Hf-174	$Hf-174 \rightarrow Y_{170}$
Hf-175	$Hf-175 \rightarrow Lu_{175}$
Hf-178m	$Hf-178m \rightarrow Hf_{178}$
Hf-179m	$Hf-179m \rightarrow Hf_{179}$
Hf-181	$Hf-181 \rightarrow Ta_{181}$
Hf-182	$Hf-182 \rightarrow Ta-182 \cdots$
Hg-194	$Hg-194 \rightarrow Au-194 \cdots$
Hg-195m	$Hg-195m \begin{array}{l} \xrightarrow{0.542} \mathbf{Hg-195} \rightarrow Au-195 \cdots \\ \xrightarrow{0.458} Au-195 \cdots \end{array}$
Hg-197	$Hg-197 \rightarrow Au_{197}$
Hg-203	$Hg-203 \rightarrow Tl_{203}$
Ho-163	$Ho-163 \rightarrow Dy_{163}$
Ho-166	$Ho-166 \rightarrow Er_{166}$
Ho-166m	$Ho-166m \rightarrow Er_{166}$
I-124	$I-124 \rightarrow Te_{124}$
I-125	$I-125 \rightarrow Te_{125}$
I-126	$I-126 \begin{array}{l} \xrightarrow{0.527} Te_{126} \\ \xrightarrow{0.473} Xe_{126} \end{array}$
I-129	$I-129 \rightarrow Xe_{129}$
I-131	$I-131 \xrightarrow{0.0118} Xe-131m \cdots$
In-111	$In-111 \rightarrow Cd_{111}$
In-114m	$In-114m \begin{array}{l} \xrightarrow{0.9675} \mathbf{In-114} \begin{array}{l} \xrightarrow{0.995} Sn_{114} \\ \xrightarrow{0.005} Cd_{114} \end{array} \\ \xrightarrow{0.0325} Cd_{114} \end{array}$
In-115	$In-115 \rightarrow Sn_{115}$
Ir-188	$Ir-188 \rightarrow Os_{188}$

Table A-1: Decay Scheme for Radionuclides	
Nuclide	Radionuclide Decay Scheme. Progeny with Half-lives Less Than 1 Day are Shown in Bold and Stable Isotopes are Indicated Using Subscripts.
Ir-189	$Ir{-}189 \begin{array}{l} \xrightarrow{0.9257} Os_{189} \\ \xrightarrow{0.0743} \mathbf{Os{-}189m} \rightarrow Os_{189} \end{array}$
Ir-190	$Ir{-}190 \rightarrow Os_{190}$
Ir-192	$Ir{-}192 \begin{array}{l} \xrightarrow{0.9513} Pt_{192} \\ \xrightarrow{0.0487} Os_{192} \end{array}$
Ir-192n	$Ir{-}192n \rightarrow Ir{-}192\cdots$
Ir-193m	$Ir{-}193m \rightarrow Ir_{193}$
Ir-194m	$Ir{-}194m \rightarrow Pt_{194}$
K-40	$K{-}40 \begin{array}{l} \xrightarrow{0.8914} Ca_{40} \\ \xrightarrow{0.1086} Ar_{40} \end{array}$
Kr-79	$Kr{-}79 \rightarrow Br_{79}$
Kr-81	$Kr{-}81 \rightarrow Br_{81}$
Kr-85	$Kr{-}85 \rightarrow Rb_{85}$
La-137	$La{-}137 \rightarrow Ba_{137}$
La-138	$La{-}138 \begin{array}{l} \xrightarrow{0.664} Ba_{138} \\ \xrightarrow{0.336} Ce_{138} \end{array}$
La-140	$La{-}140 \rightarrow Ce_{140}$
Lu-169	$Lu{-}169 \rightarrow Yb{-}169\cdots$
Lu-170	$Lu{-}170 \rightarrow Yb_{170}$
Lu-171	$Lu{-}171 \rightarrow Yb_{171}$
Lu-172	$Lu{-}172 \rightarrow Yb_{172}$
Lu-173	$Lu{-}173 \rightarrow Yb_{173}$
Lu-174	$Lu{-}174 \rightarrow Yb_{174}$
Lu-174m	$Lu{-}174m \begin{array}{l} \xrightarrow{0.9938} Lu{-}174\cdots \\ \xrightarrow{0.0062} Yb_{174} \end{array}$
Lu-176	$Lu{-}176 \rightarrow Hf_{176}$
Lu-177	$Lu{-}177 \rightarrow Hf_{177}$
Lu-177m	$Lu{-}177m \begin{array}{l} \xrightarrow{0.217} Lu{-}177\cdots \\ \xrightarrow{0.783} Hf_{177} \end{array}$
Md-258	$Md{-}258 \rightarrow Es{-}254\cdots$
Md-260	$Md{-}260 \begin{array}{l} \xrightarrow{<0.25} \mathbf{Es{-}256} \rightarrow \mathbf{Fm{-}256} \rightarrow Cf{-}252... \\ \xrightarrow{<0.23} \mathbf{Fm{-}260} \rightarrow sf \\ \xrightarrow{<0.10} \mathbf{No{-}260} \rightarrow sf \\ \xrightarrow{>0.42} sf \end{array}$
Mn-52	$Mn{-}52 \rightarrow Cr_{52}$

Table A-1: Decay Scheme for Radionuclides

Nuclide	Radionuclide Decay Scheme. Progeny with Half-lives Less Than 1 Day are Shown in Bold and Stable Isotopes are Indicated Using Subscripts.
Mn-53	$Mn{-}53 \rightarrow Cr_{53}$
Mn-54	$Mn{-}54 \rightarrow Cr_{54}$
Mo-93	$Mo{-}93 \xrightarrow{0.88} Nb{-}93m\cdots$ $Mo{-}93 \xrightarrow{0.12} Nb_{93}$
Mo-99	$Mo{-}99 \xrightarrow{0.8773} \mathbf{Tc{-}99m} \rightarrow Tc{-}99\cdots$ $Mo{-}99 \xrightarrow{0.1227} Tc{-}99\cdots$
Na-22	$Na{-}22 \rightarrow Ne_{22}$
Nb-91	$Nb{-}91 \rightarrow Zr_{91}$
Nb-91m	$Nb{-}91m \xrightarrow{0.966} Nb{-}91\cdots$ $Nb{-}91m \xrightarrow{0.034} Zr_{91}$
Nb-92	$Nb{-}92 \rightarrow Zr_{92}$
Nb-92m	$Nb{-}92m \rightarrow Zr_{92}$
Nb-93m	$Nb{-}93m \rightarrow Nb_{93}$
Nb-94	$Nb{-}94 \rightarrow Mo_{94}$
Nb-95	$Nb{-}95 \rightarrow Mo_{95}$
Nb-95m	$Nb{-}95m \xrightarrow{0.944} Nb{-}95\cdots$ $Nb{-}95m \xrightarrow{0.056} Mo_{95}$
Nd-140	$Nd{-}140 \rightarrow \mathbf{Pr{-}140} \rightarrow Ce_{140}$
Nd-144	$Nd{-}144 \rightarrow Ce_{140}$
Nd-147	$Nd{-}147 \rightarrow Pm{-}147\cdots$
Ni-56	$Ni{-}56 \rightarrow Co{-}56\cdots$
Ni-57	$Ni{-}57 \rightarrow Co{-}57\cdots$
Ni-59	$Ni{-}59 \rightarrow Co_{59}$
Ni-63	$Ni{-}63 \rightarrow Cu_{63}$
Ni-66	$Ni{-}66 \rightarrow \mathbf{Cu{-}66} \rightarrow Zn_{66}$
Np-234	$Np{-}234 \rightarrow U{-}234\cdots$
Np-235	$Np{-}235 \xrightarrow{0.996} U{-}236\cdots$ $Np{-}235 \xrightarrow{0.004} \mathbf{U{-}235m} \rightarrow U{-}235\cdots$
Np-236	$Np{-}236 \xrightarrow{0.873} U{-}236\cdots$ $Np{-}236 \xrightarrow{0.125} Pu{-}236\ldots$ $Np{-}236 \xrightarrow{0.0016} Pa\text{-}232\ldots$
Np-237	$Np{-}237 \rightarrow Pa{-}233\cdots$
Np-238	$Np{-}238 \rightarrow Pu{-}238\cdots$
Np-239	$Np{-}239 \rightarrow Pu{-}239\cdots$
Os-185	$Os{-}185 \rightarrow Re_{185}$

Table A-1: Decay Scheme for Radionuclides

Nuclide	Radionuclide Decay Scheme. Progeny with Half-lives Less Than 1 Day are Shown in Bold and Stable Isotopes are Indicated Using Subscripts.
Os-186	$Os{-}186 \rightarrow W_{182}$
Os-191	$Os{-}191 \rightarrow Ir_{191}$
Os-193	$Os{-}193 \xrightarrow{0.0035} Ir{-}193m\cdots$ $\xrightarrow{0.9965} Ir_{193}$
Os-194	$Os-194 \rightarrow \mathbf{Ir{-}194} \rightarrow Pt_{194}$
P-32	$P{-}32 \rightarrow S_{32}$
P-33	$P{-}33 \rightarrow S_{33}$
Pa-229	$Pa{-}229 \xrightarrow{0.9952} Th{-}229\cdots$ $\xrightarrow{0.0048} Ac{-}225\cdots$
Pa-230	$Pa{-}230 \xrightarrow{0.916} Th{-}230\cdots$ $\xrightarrow{0.084} U{-}230\cdots$
Pa-231	$Pa{-}231 \rightarrow Ac{-}227\cdots$
Pa-232	$Pa{-}232 \rightarrow U{-}232\cdots$
Pa-233	$Pa{-}233 \rightarrow U{-}233\cdots$
Pb-202	$Pb{-}202 \xrightarrow{0.99} Tl{-}202\cdots$ $\xrightarrow{0.01} Hg_{198}$
Pb-203	$Pb{-}203 \rightarrow Tl_{203}$
Pb-205	$Pb{-}205 \rightarrow Tl_{205}$
Pb-210	$Pb{-}210 \rightarrow Bi{-}210\cdots$
Pd-100	$Pd{-}100 \rightarrow \mathbf{Rh{-}100} \rightarrow Ru_{100}$
Pd-103	$Pd{-}103 \xrightarrow{0.9988} \mathbf{Rh{-}103m} \rightarrow Rh_{103}$ $\xrightarrow{0.0012} Rh_{103}$
Pd-107	$Pd{-}107 \rightarrow Ag_{107}$
Pm-143	$Pm{-}143 \rightarrow Nd_{143}$
Pm-144	$Pm{-}144 \rightarrow Nd{-}144\cdots$
Pm-145	$Pm{-}145 \rightarrow Nd_{145}$
Pm-146	$Pm{-}146 \xrightarrow{0.36} Sm{-}146\cdots$ $\xrightarrow{0.66} Nd_{146}$
Pm-147	$Pm{-}147 \rightarrow Sm{-}147\cdots$
Pm-148	$Pm{-}148 \rightarrow Sm{-}148\cdots$
Pm-148m	$Pm{-}148m \xrightarrow{0.958} Sm{-}148\cdots$ $\xrightarrow{0.042} Pm{-}148\cdots$
Pm-149	$Pm{-}149 \rightarrow Sm_{149}$
Pm-151	$Pm{-}151 \rightarrow Sm{-}151\cdots$

Table A-1: Decay Scheme for Radionuclides

Nuclide	Radionuclide Decay Scheme. Progeny with Half-lives Less Than 1 Day are Shown in Bold and Stable Isotopes are Indicated Using Subscripts.
Po-206	$Po-206 \begin{array}{l} \xrightarrow{0.9455} Bi-206\cdots \\ \xrightarrow{0.0545} Pb-202\cdots \end{array}$
Po-208	$Po-208 \begin{array}{l} \xrightarrow{1^{*}} Pb_{204} \\ \xrightarrow{2.2E-5} Bi-208\cdots \end{array}$
Po-209	$Po-209 \begin{array}{l} \xrightarrow{0.9952} Pb-205\cdots \\ \xrightarrow{0.0048} Bi_{209} \end{array}$
Po-210	$Po-210 \rightarrow Pb_{206}$
Pr-143	$Pr-143 \rightarrow Nd_{143}$
Pt-188	$Pt-188 \rightarrow Ir-188\cdots$
Pt-190	$Pt-190 \rightarrow Os-186\cdots$
Pt-191	$Pt-191 \rightarrow Ir_{191}$
Pt-193	$Pt-193 \rightarrow Ir_{193}$
Pt-193m	$Pt-193m \rightarrow Pt-193\cdots$
Pt-195m	$Pt-195m \rightarrow Pt_{195}$
Pu-236	$Pu-236 \rightarrow U-232\cdots$
Pu-237	$Pu-237 \begin{array}{l} \xrightarrow{1.00^{*}} Np-237\cdots \\ \xrightarrow{4E-5} U-233\cdots \end{array}$
Pu-238	$Pu-238 \rightarrow U-234\cdots$
Pu-239	$Pu-239 \begin{array}{l} \xrightarrow{0.9994} \mathbf{U-235m} \rightarrow U-235... \\ \xrightarrow{0.0006} U-235... \end{array}$
Pu-240	$Pu-240 \rightarrow U-236\cdots$
Pu-241	$Pu-241 \begin{array}{l} \xrightarrow{1.00^{*}} Am-241\cdots \\ \xrightarrow{2.4E-5} U-237\cdots \end{array}$
Pu-242	$Pu-242 \rightarrow U-238\cdots$
Pu-244	$Pu-244 \begin{array}{l} \xrightarrow{0.999} \mathbf{U-240} \rightarrow \mathbf{Np-240m} \rightarrow Pu-240\cdots \\ \xrightarrow{0.001} sf \end{array}$
Pu-246	$Pu-246 \rightarrow \mathbf{Am-246m} \rightarrow Cm-246\cdots$
Ra-223	$Ra-223 \rightarrow \mathbf{Rn-219} \rightarrow \mathbf{Po-215} \rightarrow \mathbf{Pb-211} \rightarrow \mathbf{Bi-211} \begin{array}{l} \xrightarrow{0.9972} \mathbf{Tl-207} \\ \xrightarrow{0.0028} \mathbf{Po-211} \end{array} \rightarrow Pb_{207}$
Ra-224	$Ra-224 \rightarrow \mathbf{Rn-220} \rightarrow \mathbf{Po-216} \rightarrow \mathbf{Pb-212} \rightarrow \mathbf{Bi-212} \begin{array}{l} \xrightarrow{0.64} \mathbf{Po-212} \\ \xrightarrow{0.36} \mathbf{Tl-208} \end{array} \rightarrow Pb_{208}$
Ra-225	$Ra-225 \rightarrow Ac-225\cdots$
Ra-226	$Ra-226 \rightarrow Rn-222\cdots$

Table A-1: Decay Scheme for Radionuclides

Nuclide	Radionuclide Decay Scheme. Progeny with Half-lives Less Than 1 Day are Shown in Bold and Stable Isotopes are Indicated Using Subscripts.
Ra-228	$Ra-228 \rightarrow \mathbf{Ac-228} \rightarrow Th-228\cdots$
Rb-83	$Rb-83 \begin{array}{l} \xrightarrow{0.743} \mathbf{Kr-83m} \rightarrow Kr_{83} \\ \xrightarrow{0.257} \quad Kr_{83} \end{array}$
Rb-84	$Rb-84 \begin{array}{l} \xrightarrow{0.962} Kr_{84} \\ \xrightarrow{0.038} Sr_{84} \end{array}$
Rb-86	$Rb-86 \rightarrow Sr_{86}$
Rb-87	$Rb-87 \rightarrow Sr_{87}$
Re-182	$Re-182 \rightarrow W_{182}$
Re-183	$Re-183 \rightarrow W_{183}$
Re-184	$Re-184 \rightarrow W_{184}$
Re-184m	$Re-184m \begin{array}{l} \xrightarrow{0.754} Re-184\cdots \\ \xrightarrow{0.246} \quad W_{184} \end{array}$
Re-186	$Re-186 \begin{array}{l} \xrightarrow{0.925} Os-186\cdots \\ \xrightarrow{0.075} \quad W_{186} \end{array}$
Re-186m	$Re-186m \rightarrow Re-186\cdots$
Re-187	$Re-187 \rightarrow Os_{187}$
Re-189	$Re-189 \begin{array}{l} \xrightarrow{0.122} \mathbf{Os-189m} \rightarrow Os_{189} \\ \xrightarrow{0.878} \quad Os_{189} \end{array}$
Rh-99	$Rh-99 \rightarrow Ru_{99}$
Rh-101	$Rh-101 \rightarrow Ru_{101}$
Rh-101m	$Rh-101m \begin{array}{l} \xrightarrow{0.064} Rh-101\cdots \\ \xrightarrow{0.936} \quad Ru_{101} \end{array}$
Rh-102	$Rh-102 \begin{array}{l} \xrightarrow{0.78} Ru_{102} \\ \xrightarrow{0.22} Pd_{102} \end{array}$
Rh-102m	$Rh-102m \begin{array}{l} \xrightarrow{0.0023} Rh-102\cdots \\ \xrightarrow{0.9977} \quad Ru_{102} \end{array}$
Rh-105	$Rh-105 \rightarrow Pd_{105}$
Rn-222	$Rn-222 \rightarrow \mathbf{Po-218} \begin{array}{l} \xrightarrow{0.9998} \mathbf{Pb-214} \\ \xrightarrow{2E-4} \mathbf{At-218} \end{array} \rightarrow \mathbf{Bi-214} \rightarrow \mathbf{Po-214} \rightarrow Pb-210\cdots$
Ru-97	$Ru-97 \begin{array}{l} \xrightarrow{1.00*} Tc-97\cdots \\ \xrightarrow{4.22E-4} Tc-97m\cdots \end{array}$
Ru-103	$Ru-103 \begin{array}{l} \xrightarrow{0.9876} \mathbf{Rh-103m} \rightarrow Rh_{103} \\ \xrightarrow{0.0124} \quad Rh_{103} \end{array}$
Ru-106	$Ru-106 \rightarrow \mathbf{Rh-106} \rightarrow Pd_{106}$

Table A-1: Decay Scheme for Radionuclides	
Nuclide	Radionuclide Decay Scheme. Progeny with Half-lives Less Than 1 Day are Shown in Bold and Stable Isotopes are Indicated Using Subscripts.
S-35	$S{-}35 \rightarrow Cl_{36}$
Sb-119	$Sb{-}119 \rightarrow Sn_{119}$
Sb-120m	$Sb{-}120m \rightarrow Sn_{120}$
Sb-122	$Sb{-}122 \begin{array}{l} \xrightarrow{0.976} Te_{122} \\ \xrightarrow{0.024} Sn_{122} \end{array}$
Sb-124	$Sb{-}124 \rightarrow Te_{124}$
Sb-125	$Sb{-}125 \begin{array}{l} \xrightarrow{0.231} Te{-}125m\cdots \\ \xrightarrow{0.769} \quad Te_{125} \end{array}$
Sb-126	$Sb{-}126 \rightarrow Te_{126}$
Sb-127	$Sb{-}127 \begin{array}{l} \xrightarrow{0.823} \mathbf{Te{-}127} \rightarrow I_{127} \\ \xrightarrow{0.177} Te{-}127m\cdots \end{array}$
Sc-44m	$Sc{-}44m \begin{array}{l} \xrightarrow{0.988} \mathbf{Sc{-}44} \rightarrow Ca_{44} \\ \xrightarrow{0.012} \quad Ca_{44} \end{array}$
Sc-46	$Sc{-}46 \rightarrow Ti_{46}$
Sc-47	$Sc{-}47 \rightarrow Ti_{47}$
Sc-48	$Sc{-}48 \rightarrow Ti_{48}$
Se-72	$Se{-}72 \rightarrow As{-}72\cdots$
Se-75	$Se{-}75 \rightarrow As_{75}$
Se-79	$Se{-}79 \rightarrow Br_{79}$
Si-32	$Si{-}32 \rightarrow P{-}32\cdots$
Sm-145	$Sm{-}145 \rightarrow Pm{-}145\cdots$
Sm-146	$Sm{-}146 \rightarrow Nd_{142}$
Sm-147	$Sm{-}147 \rightarrow Nd_{143}$
Sm-148	$Sm{-}148 \rightarrow Nd{-}144\cdots$
Sm-151	$Sm{-}151 \rightarrow Eu_{151}$
Sm-153	$Sm{-}153 \rightarrow Eu_{153}$
Sn-113	$Sn{-}113 \rightarrow \mathbf{In{-}113m} \rightarrow In_{133}$
Sn-117m	$Sn{-}117m \rightarrow Sn_{117}$
Sn-119m	$Sn{-}119m \rightarrow Sn_{119}$
Sn-121	$Sn{-}121 \rightarrow Sb_{121}$
Sn-121m	$Sn{-}121m \begin{array}{l} \xrightarrow{0.776} Sn{-}121\cdots \\ \xrightarrow{0.224} \quad Sb_{121} \end{array}$
Sn-123	$Sn{-}123 \rightarrow Sb_{123}$
Sn-125	$Sn{-}125 \rightarrow Sb{-}125\cdots$

Table A-1: Decay Scheme for Radionuclides

Nuclide	Radionuclide Decay Scheme. Progeny with Half-lives Less Than 1 Day are Shown in Bold and Stable Isotopes are Indicated Using Subscripts.
Sn-126	$Sn{-}126 \rightarrow \mathbf{Sb{-}126m} \begin{array}{l} \xrightarrow{0.14} Sb{-}126\cdots \\ \xrightarrow{0.86} Te_{126} \end{array}$
Sr-82	$Sr{-}82 \rightarrow \mathbf{Rb{-}82} \rightarrow Kr_{82}$
Sr-83	$Sr{-}83 \rightarrow Rb{-}83\cdots$
Sr-85	$Sr{-}85 \rightarrow Rb_{85}$
Sr-89	$Sr{-}89 \rightarrow Y_{89}$
Sr-90	$Sr{-}90 \rightarrow Y{-}90\cdots$
Ta-177	$Ta{-}177 \rightarrow Hf_{177}$
Ta-179	$Ta{-}179 \rightarrow Hf_{179}$
Ta-182	$Ta{-}182 \rightarrow W_{182}$
Ta-183	$Ta{-}183 \rightarrow W_{183}$
Tb-153	$Tb{-}153 \rightarrow Gd{-}153\cdots$
Tb-155	$Tb{-}155 \rightarrow Gd_{155}$
Tb-156	$Tb{-}156 \rightarrow Gd_{156}$
Tb-156m	$Tb{-}156m \rightarrow Tb{-}156\cdots$
Tb-157	$Tb{-}157 \rightarrow Gd_{157}$
Tb-158	$Tb{-}158 \begin{array}{l} \xrightarrow{0.834} Gd_{158} \\ \xrightarrow{0.166} Dy_{158} \end{array}$
Tb-160	$Tb{-}160 \rightarrow Dy_{160}$
Tb-161	$Tb{-}161 \rightarrow Dy_{161}$
Tc-95m	$Tc{-}95m \begin{array}{l} \xrightarrow{0.0388} \mathbf{Tc{-}95} \rightarrow Mo_{95} \\ \xrightarrow{0.9612} Mo_{95} \end{array}$
Tc-96	$Tc{-}96 \rightarrow Mo_{96}$
Tc-97	$Tc{-}97 \rightarrow Mo_{97}$
Tc-97m	$Tc{-}97m \rightarrow Tc{-}97\cdots$
Tc-98	$Tc{-}98 \rightarrow Ru_{98}$
Tc-99	$Tc{-}99 \rightarrow Ru_{99}$
Te-118	$Te{-}118 \rightarrow \mathbf{Sb{-}118} \rightarrow Sn_{118}$
Te-119m	$Te{-}119m \rightarrow Sb{-}119\cdots$
Te-121	$Te{-}121 \rightarrow Sb_{121}$
Te-121m	$Te{-}121m \begin{array}{l} \xrightarrow{0.886} Te{-}121\cdots \\ \xrightarrow{0.114} Sb_{121} \end{array}$
Te-123	$Te{-}123 \rightarrow Sb_{123}$
Te-123m	$Te{-}123m \rightarrow Te{-}123\cdots$
Te-125m	$Te{-}125m \rightarrow Te_{125}$

Table A-1: Decay Scheme for Radionuclides

Nuclide	Radionuclide Decay Scheme. Progeny with Half-lives Less Than 1 Day are Shown in Bold and Stable Isotopes are Indicated Using Subscripts.
Te-127m	$Te{-}127m \begin{array}{l} \xrightarrow{0.976} \boldsymbol{Te{-}127} \rightarrow I_{127} \\ \xrightarrow{0.024} I_{127} \end{array}$
Te-129m	$Te{-}129m \begin{array}{l} \xrightarrow{0.63} \boldsymbol{Te{-}129} \rightarrow I{-}129\cdots \\ \xrightarrow{0.37} I{-}129\cdots \end{array}$
Te-131m	$Te{-}131m \begin{array}{l} \xrightarrow{0.778} I{-}131\cdots \\ \xrightarrow{0.222} \boldsymbol{Te{-}131} \rightarrow I{-}131\cdots \end{array}$
Te-132	$Te{-}132 \rightarrow \boldsymbol{I{-}132} \rightarrow Xe_{132}$
Th-227	$Th{-}227 \rightarrow Ra{-}223\cdots$
Th-228	$Th{-}228 \rightarrow Ra{-}224\cdots$
Th-229	$Th{-}229 \rightarrow Ra{-}225\cdots$
Th-230	$Th{-}230 \rightarrow Ra{-}226\cdots$
Th-231	$Th{-}231 \rightarrow Pa{-}231\cdots$
Th-232	$Th{-}232 \rightarrow Ra{-}228\cdots$
Th-234	$Th{-}234 \rightarrow \boldsymbol{Pa{-}234m} \begin{array}{l} \xrightarrow{0.9984} U{-}234\cdots \\ \xrightarrow{0.0016} \boldsymbol{Pa{-}234} \rightarrow U{-}234\cdots \end{array}$
Ti-44	$Ti{-}44 \rightarrow \boldsymbol{Sc{-}44} \rightarrow Ca_{44}$
Tl-200	$Tl{-}200 \rightarrow Hg_{200}$
Tl-201	$Tl{-}201 \rightarrow Hg_{201}$
Tl-202	$Tl{-}202 \rightarrow Hg_{202}$
Tl-204	$Tl{-}204 \begin{array}{l} \xrightarrow{0.971} Pb_{204} \\ \xrightarrow{0.029} Hg_{204} \end{array}$
Tm-165	$Tm{-}165 \rightarrow \boldsymbol{Er{-}165} \rightarrow Ho_{165}$
Tm-167	$Tm{-}167 \rightarrow Er_{167}$
Tm-168	$Tm{-}168 \xrightarrow{1.0^{*}} Er_{168}$
Tm-170	$Tm{-}170 \begin{array}{l} \xrightarrow{0.9987} Yb_{170} \\ \xrightarrow{0.0013} Er_{170} \end{array}$
Tm-171	$Tm{-}171 \rightarrow Yb_{171}$
Tm-172	$Tm{-}172 \rightarrow Yb_{172}$
U-230	$U{-}230 \rightarrow \boldsymbol{Th{-}226} \rightarrow \boldsymbol{Ra{-}222} \rightarrow \boldsymbol{Rn{-}218} \rightarrow \boldsymbol{Po{-}214} \rightarrow Pb{-}210\cdots$
U-231	$U{-}231 \begin{array}{l} \xrightarrow{1.00^{*}} Pa{-}231\cdots \\ \xrightarrow{4.0E-5} Th{-}227\cdots \end{array}$
U-232	$U{-}232 \rightarrow Th{-}228\cdots$
U-233	$U{-}233 \rightarrow Th{-}229\cdots$
U-234	$U{-}234 \rightarrow Th{-}230\cdots$
U-235	$U{-}235 \rightarrow Th{-}231\cdots$

Table A-1: Decay Scheme for Radionuclides

Nuclide	Radionuclide Decay Scheme. Progeny with Half-lives Less Than 1 Day are Shown in Bold and Stable Isotopes are Indicated Using Subscripts.
U-236	$U{-}236 \rightarrow Th{-}232\cdots$
U-237	$U{-}237 \rightarrow Np{-}237\cdots$
U-238	$U{-}238 \rightarrow Th{-}234\cdots$
V-48	$V{-}48 \rightarrow Ti_{48}$
V-49	$V{-}49 \rightarrow Ti_{49}$
V-50	$V{-}50 \begin{array}{l} \xrightarrow{0.83} Ti_{50} \\ \xrightarrow{0.17} Cr_{50} \end{array}$
W-178	$W{-}178 \rightarrow \mathbf{Ta{-}178} \rightarrow Hf_{178}$
W-181	$W{-}181 \rightarrow Ta_{181}$
W-185	$W{-}185 \rightarrow Re_{185}$
W-188	$W{-}188 \rightarrow \mathbf{Re{-}188} \rightarrow Os_{188}$
Xe-127	$Xe{-}127 \rightarrow I_{127}$
Xe-129m	$Xe{-}129m \rightarrow Xe_{129}$
Xe-131m	$Xe{-}131m \rightarrow Xe_{131}$
Xe-133	$Xe{-}133 \rightarrow Cs_{133}$
Xe-133m	$Xe{-}133m \rightarrow Xe{-}133\cdots$
Y-87	$Y{-}87 \rightarrow \mathbf{Sr{-}87m} \begin{array}{l} \xrightarrow{0.003} Rb{-}87\cdots \\ \xrightarrow{0.997} Sr_{87} \end{array}$
Y-88	$Y{-}88 \rightarrow Sr_{88}$
Y-90	$Y{-}90 \rightarrow Zr_{90}$
Y-91	$Y{-}91 \rightarrow Zr_{91}$
Yb-166	$Yb{-}166 \rightarrow \mathbf{Tm{-}166} \rightarrow Er_{166}$
Yb-169	$Yb{-}169 \rightarrow Tm_{169}$
Yb-175	$Yb{-}175 \rightarrow Lu_{175}$
Zn-65	$Zn{-}65 \rightarrow Cu_{65}$
Zn-72	$Zn{-}72 \rightarrow \mathbf{Ga{-}72} \rightarrow Ge_{72}$
Zr-88	$Zr{-}88 \rightarrow Y{-}88\cdots$
Zr-89	$Zr{-}89 \rightarrow Y_{89}$
Zr-93	$Zr{-}93 \begin{array}{l} \xrightarrow{0.975} Nb{-}93m\cdots \\ \xrightarrow{0.025} Nb_{93} \end{array}$
Zr-95	$Zr{-}95 \begin{array}{l} \xrightarrow{0.9892} Nb{-}95\cdots \\ \xrightarrow{.0108} Nb{-}95m\cdots \end{array}$

Table A-2: Linearized Decay Chains for the Actinide Decay Series

Decay Series	Branch	Linear Actinide Decay Chains. Stable Nuclides and Radionuclides with Half-Lives Less Than One Day are Not Shown.
4n	a	Cf-252→Cm-248 → Pu-244 → Pu-240 → U-236 → Th-232 → Ra-228 → Th-228 → Ra-224
	b	Cm-244 → Pu-240 → U-236 → Th-232 → Ra-228 → Th-228 → Ra-224
	c	Np-236 $\xrightarrow{0873}$ U-236 → Th-232 → Ra-228 → Th-228 → Ra-224
	d	Np-236 $\xrightarrow{0.127}$ Pu-236 → U-232 → Th-228 → Ra-224
	e	Es-252 → Bk-248m
4n+1	a	Bk-249 → Cf-249 → Cm-245 → Pu-241 $\xrightarrow{^{*}0.99+}$ Am-241 → Np-237 → Pa-233 → U-233 → Th-229 → Ra-225 → Ac-225
	b	Pu-241 $\xrightarrow{2.5E-5}$ U-237 → Np-237 → Pa-233 → U-233 → Th-229 → Ra-225 → Ac-225
	c	Fm-257 → Cf-253 → Es-253
4n+2	a	Cf-250 → Cm-246 → Pu-242 → U-238 → Th-234 → U-234 → Th-230 → Ra-226 → Rn-222 → Pb-210 → Bi-210 → Po-210
	b	Am-242m $\xrightarrow{0.1722}$ Pu-242 → U-238 → Th-234 → U-234 → Th-230 → Ra-226 → Rn-222 → Pb-210 → Bi-210 → Po-210
	c	Am-242m $\xrightarrow{4.5E-3}$ Np-238 → Pu-238 → U-234 → Th-230 → Ra-226 → Rn-222 → Pb-210 → Bi-210 → Po-210
	d	Am-242m $\xrightarrow{0.8233}$ Cm-242 → Pu-238 → U-234 → Th-230 → Ra-226 → Rn-222 → Pb-210 → Bi-210 → Po-210
	e	Cm-250 → Pu-246
	f	Pa-230 → U-230
	g	Md-258 → Es-254
4n+3	a	Cf-251 → Cm-247 → Am-243 → Np-239 → Pu-239 → U-235 → Th-231 → Pa-231 → Ac-227 → Th-227 → Ra-223
	b	Cm-243 → Pu-239 → U-235 → Th-231 → Pa-231 → Ac-227 → Th-227 → Ra-223

*The notation 0.99+ indicates a number that is slightly less than 1.0.

Table A-3: Fission Product Decay Chains

Number	Decay Chain
1*	$Cd{-}115m \rightarrow In{-}115 \rightarrow Sn_{115}$
2	$Dy{-}154 \rightarrow Gd{-}150 \rightarrow Sm{-}146 \rightarrow Nd_{142}$
3	$Eu{-}148 \rightarrow Sm{-}148 \rightarrow Nd{-}144 \rightarrow Ce_{140}$
4*	$Eu{-}152 \rightarrow Gd{-}152 \rightarrow Sm{-}148 \rightarrow Nd{-}144 \rightarrow Ce_{140}$
5	$Fe{-}60 \rightarrow Co{-}60 \rightarrow Ni_{60}$
6	$Gd{-}146 \rightarrow Eu{-}146 \rightarrow Sm{-}146 \rightarrow Nd_{142}$
7	$Hf{-}172 \rightarrow Lu{-}172 \rightarrow Yb_{172}$
8	$Hf{-}182 \rightarrow Ta{-}182 \rightarrow W_{182}$
9	$Hg{-}194 \rightarrow Au{-}194 \rightarrow Pt_{194}$
10	$Ir{-}192n \rightarrow Ir{-}192 \rightarrow Pt_{192}$
11	$Lu{-}174m \rightarrow Lu{-}174 \rightarrow Yb_{174}$
12*	$Lu{-}177m \rightarrow Lu{-}177 \rightarrow Hf_{177}$
13*	$Mo{-}93 \rightarrow Nb{-}93m \rightarrow Nb_{93}$
14*	$Nb{-}91m \rightarrow Nb{-}91 \rightarrow Zr_{91}$
15	$Pb{-}202 \rightarrow Tl{-}202 \rightarrow Hg_{202}$
16*	$Pm{-}146 \rightarrow Sm{-}146 \rightarrow Nd_{142}$
17	$Pm{-}147 \rightarrow Sm{-}147 \rightarrow Nd_{143}$
18*	$Pm{-}148m \rightarrow Sm{-}148 \rightarrow Nd{-}144 \rightarrow Ce_{140}$
19	$Po{-}209 \rightarrow Pb{-}205 \rightarrow Tl_{205}$
20	$Pt{-}190 \rightarrow Os{-}186 \rightarrow W_{182}$
21*	$Re{-}184m \rightarrow Re{-}184 \rightarrow W_{184}$
22	$Re{-}186m \rightarrow Re{-}186 \rightarrow Os{-}186 \rightarrow W_{182}$
23*	$Rh{-}102m \rightarrow Rh{-}102 \rightarrow Ru_{102}$
24*	$Sb{-}125 \rightarrow Te{-}125m \rightarrow Te_{125}$
25	$Si{-}32 \rightarrow P{-}32 \rightarrow S_{32}$
26	$Sm{-}145 \rightarrow Pm{-}145 \rightarrow Nd_{145}$
27*	$Sn{-}121m \rightarrow Sn{-}121 \rightarrow Sb_{121}$
28*	$Sn{-}126 \rightarrow Sb{-}126 \rightarrow Te_{126}$
29	$Sr{-}90 \rightarrow Y{-}90 \rightarrow Zr_{90}$
30	$Tc{-}97m \rightarrow Tc{-}97 \rightarrow Mo_{97}$
31*	$Te{-}121m \rightarrow Te{-}121 \rightarrow Sb_{121}$
32	$Te{-}123m \rightarrow Te{-}123 \rightarrow Sb_{123}$
33	$Zr{-}88 \rightarrow Y{-}88 \rightarrow Sr_{88}$
34*	$Zr{-}93 \rightarrow Nb{-}93m \rightarrow Nb_{93}$
35*	$Zr{-}95 \rightarrow Nb{-}95 \rightarrow Mo_{95}$

*Chain has been simplified relative to the decay scheme in Table A-1.

Table A-4: Half-Life and Inventory Data[*]

Species	Half-Life [a]	280 MWh/kg U Fuel [mol/kg U]	220 MWh/kg U Fuel [mol/kg U]	280 MWh/kg U Zircaloy [mol/kg Zr]	220 MWh/kg U Zircaloy [mol/kg Zr]
Ac-225	2.738E-02	1.86E-14	1.66E-14	1.00E-25	1.00E-25
Ac-227	2.177E+01	1.85E-11	1.56E-11	1.00E-25	1.00E-25
Ag-105	1.130E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Ag-108m	4.380E+02	3.89E-08	3.06E-08	3.86E-07	3.03E-07
Ag-110m	6.838E-01	1.43E-19	8.40E-20	2.84E-20	2.67E-20
Al-26	7.170E+05	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Am-241	4.326E+02	1.18E-03	8.81E-04	1.00E-25	1.00E-25
Am-242m	1.410E+02	2.98E-07	1.81E-07	1.00E-25	1.00E-25
Am-243	7.370E+03	5.57E-05	2.34E-05	1.00E-25	1.00E-25
Ar-39	2.690E+02	6.97E-08	6.28E-08	3.50E-09	3.14E-09
Ar-42	3.290E+01	8.24E-16	6.25E-16	7.98E-16	6.09E-16
As-73	2.198E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Au-194	4.337E-03	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Au-195	5.095E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Ba-133	1.052E+01	2.45E-09	1.91E-09	2.43E-12	1.90E-12
Be -7	1.457E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Be-10	1.510E+06	6.47E-09	5.01E-09	3.33E-07	2.58E-07
Bi-207	3.155E+01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Bi-208	3.680E+05	4.22E-10	3.28E-10	2.19E-11	1.69E-11
Bi-210	1.372E-02	5.23E-18	5.30E-18	1.00E-25	1.00E-25
Bi-210m	3.040E+06	6.56E-09	5.08E-09	3.40E-10	2.61E-10
Bk-247	1.380E+03	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Bk-248	8.994E+00	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Bk-249	8.761E-01	5.52E-25	5.43E-26	1.00E-25	1.00E-25
C-14	5.700E+03	7.91E-06	6.13E-06	2.46E-05	1.90E-05
Ca-41	1.020E+05	3.04E-06	2.35E-06	6.03E-08	4.67E-08
Ca-45	4.452E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Cd-109	1.263E+00	3.10E-17	2.31E-17	2.88E-16	2.11E-16
Cd-113	8.040E+15	2.98E-07	2.77E-07	9.64E-11	9.47E-11
Cd-113m	1.410E+01	1.01E-07	7.09E-08	1.02E-09	7.89E-10

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[*] Inventories are for 30 year old Bruce used fuel. A value of 1.0E-25 is used if Tait et al. (2001) do no report an inventory value for the nuclide.

Table A-4: Half-Life and Inventory Data*

Species	Half-Life [a]	280 MWh/kg U Fuel [mol/kg U]	220 MWh/kg U Fuel [mol/kg U]	280 MWh/kg U Zircaloy [mol/kg Zr]	220 MWh/kg U Zircaloy [mol/kg Zr]
Cd-115m	1.220E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Ce-139	3.768E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Ce-144	7.800E-01	3.48E-15	3.14E-15	1.00E-25	1.00E-25
Cf-248	9.131E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Cf-249	3.510E+02	1.12E-14	1.10E-15	1.00E-25	1.00E-25
Cf-250	1.308E+01	5.52E-16	4.59E-17	1.00E-25	1.00E-25
Cf-251	8.980E+02	8.06E-16	6.03E-17	1.00E-25	1.00E-25
Cf-252	2.645E+00	2.36E-19	1.31E-20	1.00E-25	1.00E-25
Cf-253	4.876E-02	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Cf-254	1.656E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Cl-36	3.010E+05	1.25E-05	9.86E-06	1.49E-05	1.17E-05
Cm-242	4.461E-01	7.75E-10	4.70E-10	1.00E-25	1.00E-25
Cm-243	2.910E+01	6.18E-08	2.44E-08	1.00E-25	1.00E-25
Cm-244	1.811E+01	2.11E-06	6.66E-07	1.00E-25	1.00E-25
Cm-245	8.500E+03	5.14E-08	1.43E-08	1.00E-25	1.00E-25
Cm-246	4.760E+03	9.46E-09	1.93E-09	1.00E-25	1.00E-25
Cm-247	1.560E+07	5.45E-11	8.61E-12	1.00E-25	1.00E-25
Cm-248	3.480E+05	2.29E-12	2.71E-13	1.00E-25	1.00E-25
Cm-250	8.300E+03	1.87E-20	1.62E-21	1.00E-25	1.00E-25
Co-56	2.115E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Co-57	7.440E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Co-58	1.940E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Co-60	5.271E+00	6.67E-07	5.33E-07	6.63E-07	5.30E-07
Cs-134	2.065E+00	6.98E-09	4.50E-09	2.56E-11	2.20E-11
Cs-135	2.300E+06	3.46E-04	2.68E-04	1.53E-07	9.85E-08
Cs-137	3.008E+01	1.64E-03	1.29E-03	4.04E-13	1.89E-13
Dy-154	3.000E+06	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Dy-159	3.953E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Es-252	1.291E+00	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Es-253	5.604E-02	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Es-254	7.548E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Es-255	1.090E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Eu-146	1.257E-02	1.00E-25	1.00E-25	1.00E-25	1.00E-25

Table A-4: Half-Life and Inventory Data*

Species	Half-Life [a]	280 MWh/kg U Fuel [mol/kg U]	220 MWh/kg U Fuel [mol/kg U]	280 MWh/kg U Zircaloy [mol/kg Zr]	220 MWh/kg U Zircaloy [mol/kg Zr]
Eu-148	1.492E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Eu-149	2.549E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Eu-150	3.690E+01	1.21E-14	8.61E-15	1.00E-25	1.00E-25
Eu-152	1.354E+01	8.95E-10	8.39E-10	5.81E-14	7.63E-14
Eu-154	8.601E+00	2.77E-06	1.83E-06	4.81E-09	5.43E-09
Eu-155	4.753E+00	1.67E-07	1.20E-07	2.38E-10	2.65E-10
Fe-55	2.744E+00	7.28E-10	5.82E-10	6.92E-09	5.54E-09
Fe-59	1.218E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Fe-60	1.500E+06	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Fm-257	2.752E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Gd-146	1.322E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Gd-148	7.460E+01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Gd-150	1.790E+06	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Gd-151	3.395E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Gd-152	1.080E+14	3.51E-08	3.51E-08	1.79E-09	4.55E-09
Gd-153	6.582E-01	2.17E-21	2.67E-21	7.40E-22	9.33E-22
Ge-68	7.418E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
H-3	1.232E+01	3.04E-06	2.67E-06	2.89E-07	2.46E-07
Hf-172	1.870E+00	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Hf-174	2.000E+15	2.54E-08	3.38E-08	2.57E-07	3.41E-07
Hf-175	1.916E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Hf-178m	3.100E+01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Hf-181	1.161E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Hf-182	8.900E+06	1.28E-08	9.17E-09	1.26E-07	9.03E-08
Hg-194	4.440E+02	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Hg-203	1.276E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Ho-163	4.570E+03	5.08E-10	4.05E-10	1.68E-10	1.34E-10
Ho-166m	1.200E+03	2.73E-08	2.13E-08	8.92E-09	7.00E-09
I-125	1.626E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
I-129	1.570E+07	5.49E-04	4.23E-04	3.26E-09	2.55E-09
In-114m	1.356E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
In-115	4.410E+14	1.17E-05	1.08E-05	3.09E-06	3.84E-06
Ir-192	2.021E-01	6.15E-13	5.93E-13	6.14E-13	5.93E-13

Table A-4: Half-Life and Inventory Data[*]

Species	Half-Life [a]	280 MWh/kg U Fuel [mol/kg U]	220 MWh/kg U Fuel [mol/kg U]	280 MWh/kg U Zircaloy [mol/kg Zr]	220 MWh/kg U Zircaloy [mol/kg Zr]
Ir-192n	2.410E+02	7.32E-10	7.06E-10	7.31E-10	7.05E-10
Ir-194m	4.682E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
K-40	1.248E+09	3.37E-06	2.65E-06	1.51E-07	1.19E-07
Kr-81	2.290E+05	3.74E-08	2.26E-08	7.36E-09	4.45E-09
Kr-85	1.076E+01	1.28E-05	1.07E-05	2.13E-14	8.06E-15
La-137	6.000E+04	6.06E-09	4.73E-09	6.01E-11	4.69E-11
La-138	1.020E+11	5.67E-08	5.68E-08	3.42E-10	3.94E-10
Lu-172	1.834E-02	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Lu-173	1.370E+00	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Lu-174	3.310E+00	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Lu-174m	3.888E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Lu-176	3.760E+10	4.82E-09	4.97E-09	3.06E-09	2.84E-09
Lu-177	1.820E-02	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Lu-177m	4.393E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Md-258	1.410E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Mn-53	3.700E+06	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Mn-54	8.543E-01	6.56E-19	5.63E-19	6.22E-18	5.34E-18
Mo-93	4.000E+03	3.86E-09	2.99E-09	2.39E-08	1.86E-08
Na-22	2.603E+00	6.77E-18	6.82E-18	6.78E-19	6.82E-19
Nb-91	6.800E+02	2.01E-13	1.56E-13	1.94E-12	1.51E-12
Nb-91m	1.666E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Nb-92	3.470E+07	5.61E-10	4.36E-10	4.89E-09	3.81E-09
Nb-93m	1.613E+01	1.58E-08	1.28E-08	4.21E-08	3.29E-08
Nb-94	2.030E+04	6.21E-07	4.85E-07	6.14E-06	4.80E-06
Nb-95	9.580E-02	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Nb-95m	9.884E-03	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Nd-144	2.290E+15	3.22E-03	2.45E-03	2.17E-07	2.09E-07
Ni-59	7.600E+04	8.01E-06	6.44E-06	9.28E-06	7.46E-06
Ni-63	1.012E+02	1.19E-06	9.33E-07	1.38E-06	1.08E-06
Np-235	1.085E+00	9.00E-21	5.54E-21	1.00E-25	1.00E-25
Np-236	1.530E+05	5.78E-11	3.38E-11	1.00E-25	1.00E-25
Np-237	2.144E+06	2.22E-04	1.71E-04	1.00E-25	1.00E-25
Np-238	5.796E-03	5.50E-14	3.34E-14	1.00E-25	1.00E-25

Table A-4: Half-Life and Inventory Data[*]

Species	Half-Life [a]	280 MWh/kg U Fuel [mol/kg U]	220 MWh/kg U Fuel [mol/kg U]	280 MWh/kg U Zircaloy [mol/kg Zr]	220 MWh/kg U Zircaloy [mol/kg Zr]
Np-239	6.450E-03	4.87E-11	2.05E-11	1.00E-25	1.00E-25
Os-185	2.563E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Os-186	2.000E+15	1.00E-06	8.38E-07	1.22E-06	9.58E-07
Os-194	6.000E+00	7.49E-12	5.78E-12	7.37E-12	5.69E-12
P-32	3.905E-02	1.37E-17	1.05E-17	1.98E-17	1.51E-17
Pa-231	3.276E+04	4.47E-08	3.78E-08	1.00E-25	1.00E-25
Pa-233	7.385E-02	7.66E-12	5.90E-12	1.00E-25	1.00E-25
Pb-202	5.250E+04	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Pb-205	1.730E+07	1.66E-08	1.29E-08	2.15E-08	1.66E-08
Pb-210	2.220E+01	8.49E-15	8.60E-15	1.00E-25	1.00E-25
Pd-107	6.500E+06	9.87E-04	6.90E-04	8.03E-08	6.22E-08
Pm-143	7.255E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Pm-144	9.938E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Pm-145	1.770E+01	9.56E-11	5.92E-11	1.15E-11	9.10E-12
Pm-146	5.530E+00	1.04E-10	6.81E-11	1.00E-25	1.00E-25
Pm-147	2.623E+00	2.36E-07	2.08E-07	1.29E-13	1.09E-13
Pm-148	1.470E-02	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Pm-148m	1.130E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Po-208	2.898E+00	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Po-209	1.020E+02	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Po-210	3.789E-01	1.44E-16	1.46E-16	1.00E-25	1.00E-25
Pt-190	6.500E+11	4.38E-10	4.82E-10	4.39E-10	4.83E-10
Pt-193	5.000E+01	3.34E-08	2.25E-08	3.31E-08	2.23E-08
Pu-236	2.858E+00	4.85E-14	2.99E-14	1.00E-25	1.00E-25
Pu-237	1.250E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Pu-238	8.770E+01	3.79E-05	2.26E-05	1.00E-25	1.00E-25
Pu-239	2.411E+04	1.15E-02	1.12E-02	1.00E-25	1.00E-25
Pu-240	6.561E+03	6.79E-03	5.34E-03	1.00E-25	1.00E-25
Pu-241	1.429E+01	3.65E-04	2.74E-04	1.00E-25	1.00E-25
Pu-242	3.735E+05	7.63E-04	4.18E-04	1.00E-25	1.00E-25
Pu-244a	8.110E+07	1.29E-16	1.53E-17	1.00E-25	1.00E-25
Pu-246	2.968E-02	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Ra-223	3.129E-02	2.67E-14	2.24E-14	1.00E-25	1.00E-25

Table A-4: Half-Life and Inventory Data[*]

Species	Half-Life [a]	280 MWh/kg U Fuel [mol/kg U]	220 MWh/kg U Fuel [mol/kg U]	280 MWh/kg U Zircaloy [mol/kg Zr]	220 MWh/kg U Zircaloy [mol/kg Zr]
Ra-224	1.002E-02	1.66E-12	1.10E-12	1.00E-25	1.00E-25
Ra-225	4.079E-02	2.75E-14	2.46E-14	1.00E-25	1.00E-25
Ra-226	1.600E+03	2.28E-12	2.35E-12	1.00E-25	1.00E-25
Ra-228	5.750E+00	8.31E-13	8.37E-13	1.00E-25	1.00E-25
Rb-83	2.360E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Rb-87	4.810E+10	8.55E-04	7.14E-04	3.25E-06	3.25E-06
Re-183	1.916E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Re-184	9.692E-02	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Re-184m	4.627E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Re-186	1.018E-02	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Re-186m	2.000E+05	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Re-187	4.330E+10	4.95E-06	4.67E-06	2.61E-05	2.19E-05
Rh-101	3.300E+00	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Rh-102	5.676E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Rh-102m	3.742E+00	6.79E-14	5.17E-14	1.39E-15	1.20E-15
Rn-222	1.047E-02	1.49E-17	1.54E-17	1.00E-25	1.00E-25
Ru-103	1.075E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Ru-106	1.018E+00	1.25E-12	9.52E-13	3.63E-23	3.00E-23
S -35	2.396E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Sb-124	1.648E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Sb-125	2.759E+00	1.51E-08	1.16E-08	5.79E-09	4.65E-09
Sb-126	3.381E-02	3.36E-12	2.46E-12	1.00E-25	1.00E-25
Sc-46	2.294E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Se-75	3.280E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Se-79	2.950E+05	2.22E-05	1.76E-05	6.69E-09	5.16E-09
Si-32	1.530E+02	6.03E-14	4.61E-14	8.72E-14	6.65E-14
Sm-145	9.309E-01	4.00E-20	2.58E-20	4.51E-21	3.89E-21
Sm-146	1.030E+08	3.16E-09	1.83E-09	7.24E-12	5.17E-12
Sm-147	1.060E+11	7.70E-04	6.55E-04	7.49E-08	8.00E-08
Sm-148	7.000E+15	1.51E-04	9.63E-05	9.99E-08	9.50E-08
Sm-151	9.000E+01	1.60E-05	1.46E-05	9.32E-10	1.00E-09
Sn-113	3.151E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Sn-119m	8.022E-01	2.46E-19	1.90E-19	2.10E-16	1.80E-16

Table A-4: Half-Life and Inventory Data*

Species	Half-Life [a]	280 MWh/kg U Fuel [mol/kg U]	220 MWh/kg U Fuel [mol/kg U]	280 MWh/kg U Zircaloy [mol/kg Zr]	220 MWh/kg U Zircaloy [mol/kg Zr]
Sn-121	3.084E-03	5.05E-12	3.69E-12	7.39E-12	5.73E-12
Sn-121m	4.390E+01	1.16E-07	8.47E-08	1.70E-07	1.32E-07
Sn-123	3.537E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Sn-126	2.300E+05	7.06E-05	5.18E-05	1.00E-25	1.00E-25
Sr-85	1.775E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Sr-89	1.383E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Sr-90	2.879E+01	8.97E-04	7.56E-04	7.36E-11	4.78E-11
Ta-179	1.820E+00	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Ta-182	3.141E-01	4.47E-16	3.21E-16	4.40E-15	3.16E-15
Tb-157	7.100E+01	3.25E-10	2.65E-10	1.08E-10	8.77E-11
Tb-158	1.800E+02	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Tb-160	1.979E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Tc-95m	1.670E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Tc-97	4.210E+06	1.68E-09	1.31E-09	8.33E-09	6.48E-09
Tc-97m	2.491E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Tc-98	4.200E+06	1.50E-09	9.70E-10	1.18E-14	7.12E-15
Tc-99	2.111E+05	3.02E-03	2.41E-03	2.90E-08	2.27E-08
Te-121	5.248E-02	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Te-121m	4.496E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Te-123	9.200E+16	1.25E-08	1.58E-08	2.84E-08	2.62E-08
Te-123m	3.264E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Te-125m	1.572E-01	2.14E-10	1.64E-10	8.23E-11	6.60E-11
Te-127m	2.984E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Th-227	5.114E-02	4.31E-14	3.62E-14	1.00E-25	1.00E-25
Th-228	1.912E+00	3.16E-10	2.10E-10	1.00E-25	1.00E-25
Th-229	7.340E+03	5.34E-09	4.78E-09	1.00E-25	1.00E-25
Th-230	7.538E+04	1.57E-08	1.64E-08	1.00E-25	1.00E-25
Th-231	2.911E-03	1.93E-14	2.94E-14	1.00E-25	1.00E-25
Th-232	1.405E+10	2.08E-03	2.10E-03	1.00E-25	1.00E-25
Th-234	6.598E-02	6.07E-11	6.09E-11	1.00E-25	1.00E-25
Ti-44	6.000E+01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Tl-202	3.370E-02	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Tl-204	3.783E+00	2.22E-10	1.79E-10	2.20E-11	1.77E-11

Table A-4: Half-Life and Inventory Data[*]

Species	Half-Life [a]	280 MWh/kg U Fuel [mol/kg U]	220 MWh/kg U Fuel [mol/kg U]	280 MWh/kg U Zircaloy [mol/kg Zr]	220 MWh/kg U Zircaloy [mol/kg Zr]
Tm-168	2.549E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Tm-170	3.521E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Tm-171	1.920E+00	1.83E-12	1.45E-12	6.02E-13	4.77E-13
U-232	6.890E+01	1.12E-08	7.43E-09	1.00E-25	1.00E-25
U-233	1.592E+05	4.00E-05	3.61E-05	1.00E-25	1.00E-25
U-234	2.455E+05	1.79E-04	1.86E-04	1.00E-25	1.00E-25
U-235	7.038E+08	4.67E-03	7.12E-03	1.00E-25	1.00E-25
U-236	2.342E+07	3.85E-03	3.50E-03	1.00E-25	1.00E-25
U-237	1.848E-02	1.13E-11	8.44E-12	1.00E-25	1.00E-25
U-238	4.468E+09	4.11E+00	4.13E+00	1.00E-25	1.00E-25
V-49	9.035E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
V-50	1.400E+17	7.89E-07	8.29E-07	2.03E-06	2.12E-06
W-181	3.318E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
W-185	2.056E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
W-188	1.910E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Y-88	2.919E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Y-90	7.301E-03	2.33E-07	1.97E-07	1.91E-14	1.24E-14
Y-91	1.602E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Zn-65	6.678E-01	6.48E-21	5.61E-21	3.95E-22	3.26E-22
Zr-88	2.283E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25
Zr-93	1.530E+06	1.67E-03	1.37E-03	1.80E-03	1.40E-03
Zr-95	1.753E-01	1.00E-25	1.00E-25	1.00E-25	1.00E-25

Table A-5: Nuclides in the Screening Database for Which the Air Inhalation, Air Immersion, Ground-Exposure and Ingestion Dose Coefficients Were Estimated

Bk-248m Dy-154 Es-252 Es-255 Gd-150 Hf-174
Ho-163 Nb-91 Nb-91m Nb-92 Nd-144 Os-186
Po-208 Po-209 Pt-190 Re-183 Sm-148 Tm-168
V-50

Table A-6: Effective Dose Coefficients

Nuclide	Ground-Exposure (Sv/a)/(Bq/kg)	Air Immersion (Sv/a)/(Bq/m^3)	Air Inhalation (Sv/Bq)	Ingestion (Sv/Bq)
Ac-225*	3.18E-07	3.23E-07	8.53E-06	2.43E-08
Ac-227*	7.97E-10	1.12E-09	5.50E-04	1.10E-06
Ag-105	7.32E-07	7.13E-07	8.10E-10	4.70E-10
Ag-108m*	2.44E-06	2.29E-06	3.70E-08	2.30E-09
Ag-110m*	4.38E-06	4.01E-06	1.20E-08	2.80E-09
Al-26	4.46E-06	4.04E-06	2.00E-08	3.50E-09
Am-241	1.00E-08	2.13E-08	9.60E-05	2.00E-07
Am-242m*	1.25E-08	1.99E-08	9.20E-05	1.90E-07
Am-243	3.36E-08	5.84E-08	9.60E-05	2.00E-07
Ar-39	2.17E-10	4.02E-09	0.00E+00	0.00E+00
Ar-42*	4.97E-07	4.71E-07	1.20E-10	4.30E-10
As-73	2.12E-09	4.89E-09	1.00E-09	2.60E-10
Au-194	1.67E-06	1.56E-06	2.40E-10	4.20E-10
Au-195	4.90E-08	8.62E-08	1.70E-09	2.50E-10
Ba-133	4.92E-07	5.11E-07	1.00E-08	1.50E-09
Be- 7	7.27E-08	6.91E-08	5.50E-11	2.80E-11
Be-10	2.72E-10	4.35E-09	3.50E-08	1.10E-09
Bi-207	2.39E-06	2.22E-06	5.60E-09	1.30E-09
Bi-208	4.76E-06	4.26E-06	4.48E-09	1.16E-09
Bi-210	1.47E-09	8.14E-09	9.30E-08	1.30E-09
Bi-210m*	3.48E-07	3.66E-07	3.40E-06	1.50E-08
Bk-247	1.07E-07	1.33E-07	6.90E-05	3.50E-07
Bk-248m	6.06E-06	5.46E-06	5.50E-04	1.20E-06
Bk-249*	1.55E-12	1.55E-11	1.60E-07	9.70E-10
C-14	2.97E-12	8.20E-11	5.80E-09	5.80E-10
Ca-41	0.00E+00	0.00E+00	1.80E-10	1.90E-10
Ca-45	1.44E-11	4.83E-10	3.70E-09	7.10E-10
Cd-109	3.30E-09	7.20E-09	8.10E-09	2.00E-09
Cd-113	2.65E-11	7.98E-10	1.20E-07	2.50E-08
Cd-113m	1.63E-10	2.86E-09	1.10E-07	2.30E-08
Cd-115m	3.98E-08	4.67E-08	7.70E-09	3.30E-09

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[*] Indicates a nuclide for which the effective dose coefficients include contributions from progeny with half-lives less than 1 day.

Table A-6: Effective Dose Coefficients

Nuclide	Ground-Exposure (Sv/a)/(Bq/kg)	Air Immersion (Sv/a)/(Bq/m^3)	Air Inhalation (Sv/Bq)	Ingestion (Sv/Bq)
Ce-139	1.57E-07	1.88E-07	1.90E-09	2.60E-10
Ce-144*	8.97E-08	1.08E-07	5.30E-08	5.25E-09
Cf-248	2.37E-11	1.03E-10	8.80E-06	2.80E-08
Cf-249	4.66E-07	4.58E-07	7.00E-05	3.50E-07
Cf-250	2.25E-11	9.75E-11	3.40E-05	1.60E-07
Cf-251	1.30E-07	1.58E-07	7.10E-05	3.60E-07
Cf-252	3.68E-11	1.15E-10	2.00E-05	9.00E-08
Cf-253*	1.08E-10	6.52E-10	1.30E-06	1.40E-09
Cf-254	7.32E-14	3.19E-13	4.10E-05	4.00E-07
Cl-36	6.72E-10	5.24E-09	7.30E-09	9.30E-10
Cm-242	3.47E-11	1.27E-10	5.90E-06	1.20E-08
Cm-243	1.44E-07	1.67E-07	6.90E-05	1.50E-07
Cm-244	2.42E-11	1.07E-10	5.70E-05	1.20E-07
Cm-245	8.28E-08	1.10E-07	9.90E-05	2.10E-07
Cm-246	2.24E-11	9.78E-11	9.80E-05	2.10E-07
Cm-247*	4.67E-07	4.66E-07	9.00E-05	1.90E-07
Cm-248	1.69E-11	7.42E-11	3.60E-04	7.70E-07
Cm-250*	1.14E-07	1.04E-07	2.10E-03	4.40E-06
Co-56	6.06E-06	5.46E-06	6.70E-09	2.50E-09
Co-57	1.23E-07	1.57E-07	1.00E-09	2.10E-10
Co-58	1.51E-06	1.40E-06	2.10E-09	7.40E-10
Co-60	4.17E-06	3.76E-06	3.10E-08	3.40E-09
Cs-134	2.41E-06	2.23E-06	2.00E-08	1.90E-08
Cs-135	8.68E-12	3.00E-10	8.60E-09	2.00E-09
Cs-137*	8.63E-07	8.04E-07	3.90E-08	1.30E-08
Dy-154	6.06E-06	5.46E-06	5.50E-04	1.20E-06
Dy-159	1.21E-08	3.13E-08	3.70E-10	1.00E-10
Es-252	6.06E-06	5.46E-06	5.50E-04	1.20E-06
Es-253	4.35E-10	5.05E-10	2.70E-06	6.10E-09
Es-254*	1.42E-06	1.31E-06	8.60E-06	2.81E-08
Es-255	6.06E-06	5.46E-06	5.50E-04	1.20E-06
Eu-146	3.93E-06	3.63E-06	8.00E-10	1.30E-09
Eu-148	3.34E-06	3.10E-06	2.60E-09	1.30E-09

Table A-6: Effective Dose Coefficients				
Nuclide	Ground-Exposure (Sv/a)/(Bq/kg)	Air Immersion (Sv/a)/(Bq/m^3)	Air Inhalation (Sv/Bq)	Ingestion (Sv/Bq)
Eu-149	4.96E-08	6.15E-08	2.90E-10	1.00E-10
Eu-150	2.21E-06	2.10E-06	5.30E-08	1.30E-09
Eu-152	1.79E-06	1.67E-06	4.20E-08	1.40E-09
Eu-154	1.96E-06	1.81E-06	5.30E-08	2.00E-09
Eu-155	4.37E-08	6.75E-08	6.90E-09	3.20E-10
Fe-55	0.00E+00	0.00E+00	7.70E-10	3.30E-10
Fe-59	1.96E-06	1.77E-06	4.00E-09	1.80E-09
Fe-60*	6.26E-09	6.37E-09	2.80E-07	1.10E-07
Fm-257	1.06E-07	1.31E-07	7.10E-06	1.50E-08
Gd-146	1.94E-07	2.72E-07	6.40E-09	9.60E-10
Gd-148	0.00E+00	0.00E+00	2.60E-05	5.60E-08
Gd-150	6.06E-06	5.46E-06	5.50E-04	1.20E-06
Gd-151	4.20E-08	5.93E-08	8.60E-10	2.00E-10
Gd-152	0.00E+00	0.00E+00	1.90E-05	4.10E-08
Gd-153	5.76E-08	9.81E-08	2.10E-09	2.70E-10
Ge-68*	1.42E-06	1.35E-06	1.40E-08	1.40E-09
H-3	0.00E+00	0.00E+00	2.70E-11[#]	1.80E-11
Hf-172	5.81E-08	1.07E-07	3.20E-08	1.00E-09
Hf-174	6.06E-06	5.46E-06	5.50E-04	1.20E-06
Hf-175	4.65E-07	4.86E-07	1.20E-09	4.10E-10
Hf-178m	3.27E-06	3.25E-06	2.60E-07	4.70E-09
Hf-181	7.62E-07	7.64E-07	5.00E-09	1.10E-09
Hf-182	3.12E-07	3.25E-07	3.10E-07	3.00E-09
Hg-194	2.88E-12	1.97E-11	1.40E-08	5.10E-08
Hg-203	3.16E-07	3.28E-07	2.40E-09	1.90E-09
Ho-163	6.06E-06	5.46E-06	5.50E-04	1.20E-06
Ho-166m	2.61E-06	2.47E-06	1.20E-07	2.00E-09
I-125	3.21E-09	1.18E-08	5.10E-09	1.50E-08
I-129	2.58E-09	8.87E-09	3.60E-08	1.10E-07
In-114m*	1.27E-07	1.28E-07	9.30E-09	4.10E-09
In-115	9.59E-11	2.07E-09	3.90E-07	3.20E-08

[#] The air inhalation dose coefficient for H-3, which is assumed to exist as HTO in the atmosphere, is set equal to 1.5 times the ICRP72 value to account for absorption of HTO through the skin (CSA 2008).

Table A-6: Effective Dose Coefficients

Nuclide	Ground-Exposure (Sv/a)/(Bq/kg)	Air Immersion (Sv/a)/(Bq/m^3)	Air Inhalation (Sv/Bq)	Ingestion (Sv/Bq)
Ir-192	1.16E-06	1.14E-06	6.60E-09	1.40E-09
Ir-192n	1.86E-07	2.16E-07	3.90E-08	3.10E-10
Ir-194m	3.44E-06	3.28E-06	1.30E-08	2.10E-09
K-40	2.69E-07	2.50E-07	2.10E-09	6.20E-09
Kr-81	7.47E-09	7.67E-09	0.00E+00	0.00E+00
Kr-85	3.65E-09	8.04E-09	0.00E+00	0.00E+00
La-137	2.82E-09	9.47E-09	8.70E-09	8.10E-11
La-138	2.04E-06	1.84E-06	1.50E-07	1.10E-09
Lu-172	2.93E-06	2.73E-06	1.60E-09	1.30E-09
Lu-173	1.01E-07	1.39E-07	2.40E-09	2.60E-10
Lu-174	1.45E-07	1.56E-07	4.20E-09	2.70E-10
Lu-174m	3.48E-08	5.81E-08	4.20E-09	5.30E-10
Lu-176	6.31E-07	6.66E-07	7.00E-08	1.80E-09
Lu-177	3.92E-08	4.73E-08	1.20E-09	5.30E-10
Lu-177m	1.25E-06	1.34E-06	1.60E-08	1.70E-09
Md-258	5.03E-10	1.23E-09	5.90E-06	1.30E-08
Mn-53	0.00E+00	0.00E+00	5.40E-11	3.00E-11
Mn-54	1.31E-06	1.21E-06	1.50E-09	7.10E-10
Mo-93	1.13E-10	5.46E-10	2.30E-09	3.10E-09
Na-22	3.49E-06	3.22E-06	1.30E-09	3.20E-09
Nb-91	6.06E-06	5.46E-06	5.50E-04	1.20E-06
Nb-91m	6.06E-06	5.46E-06	5.50E-04	1.20E-06
Nb-92	6.06E-06	5.46E-06	5.50E-04	1.20E-06
Nb-93m	1.99E-11	9.63E-11	1.80E-09	1.20E-10
Nb-94	2.46E-06	2.27E-06	4.90E-08	1.70E-09
Nb-95	1.20E-06	1.10E-06	1.80E-09	5.80E-10
Nb-95m	7.93E-08	8.65E-08	8.80E-10	5.60E-10
Nd-144	6.06E-06	5.46E-06	5.50E-04	1.20E-06
Ni-59	0.00E+00	0.00E+00	4.40E-10	6.30E-11
Ni-63	0.00E+00	0.00E+00	1.30E-09	1.50E-10
Np-235	1.48E-09	2.14E-09	3.46E-08	2.41E-10
Np-236	1.13E-07	1.50E-07	8.00E-06	1.70E-08
Np-237	1.88E-08	2.80E-08	5.00E-05	1.10E-07

Table A-6: Effective Dose Coefficients				
Nuclide	Ground-Exposure (Sv/a)/(Bq/kg)	Air Immersion (Sv/a)/(Bq/m^3)	Air Inhalation (Sv/Bq)	Ingestion (Sv/Bq)
Np-238	8.79E-07	8.08E-07	3.50E-09	9.10E-10
Np-239	1.86E-07	2.19E-07	1.00E-09	8.00E-10
Os-185	1.06E-06	1.00E-06	1.60E-09	5.10E-10
Os-186	6.06E-06	5.46E-06	5.50E-04	1.20E-06
Os-194*	1.42E-07	1.50E-07	8.56E-08	3.70E-09
P-32	5.50E-09	1.69E-08	3.40E-09	2.40E-09
Pa-231	4.77E-08	4.95E-08	1.40E-04	7.10E-07
Pa-233	2.54E-07	2.70E-07	3.90E-09	8.70E-10
Pb-202	1.98E-12	1.57E-11	1.20E-08	8.80E-09
Pb-205	2.22E-12	1.72E-11	8.50E-10	2.80E-10
Pb-210	5.35E-10	1.41E-09	5.60E-06	6.90E-07
Pd-107	0.00E+00	0.00E+00	5.90E-10	3.70E-11
Pm-143	4.49E-07	4.26E-07	1.50E-09	2.30E-10
Pm-144	2.34E-06	2.19E-06	8.20E-09	9.70E-10
Pm-145	6.26E-09	1.73E-08	3.60E-09	1.10E-10
Pm-146	1.12E-06	1.05E-06	2.10E-08	9.00E-10
Pm-147	1.16E-11	2.74E-10	5.00E-09	2.60E-10
Pm-148	9.44E-07	8.71E-07	2.20E-09	2.70E-09
Pm-148m	3.04E-06	2.84E-06	5.70E-09	1.70E-09
Po-208	6.06E-06	5.46E-06	5.50E-04	1.20E-06
Po-209	6.06E-06	5.46E-06	5.50E-04	1.20E-06
Po-210	1.33E-11	1.23E-11	4.30E-06	1.20E-06
Pt-190	6.06E-06	5.46E-06	5.50E-04	1.20E-06
Pt-193	1.71E-12	1.28E-11	2.10E-11	3.10E-11
Pu-236	4.90E-11	1.48E-10	4.00E-05	8.70E-08
Pu-237	3.92E-08	5.55E-08	3.90E-10	1.00E-10
Pu-238	3.15E-11	1.10E-10	1.10E-04	2.30E-07
Pu-239	7.12E-11	1.10E-10	1.20E-04	2.50E-07
Pu-240	3.04E-11	1.08E-10	1.20E-04	2.50E-07
Pu-241	1.43E-12	2.00E-12	2.30E-06	4.80E-09
Pu-242	2.68E-11	9.15E-11	1.10E-04	2.40E-07
Pu-244*	5.15E-07	4.91E-07	1.10E-04	2.41E-07
Pu-246*	1.77E-06	1.66E-06	8.02E-09	3.33E-09

Table A-6: Effective Dose Coefficients

Nuclide	Ground-Exposure (Sv/a)/(Bq/kg)	Air Immersion (Sv/a)/(Bq/m^3)	Air Inhalation (Sv/Bq)	Ingestion (Sv/Bq)
Ra-223*	3.76E-07	4.11E-07	8.71E-06	1.00E-07
Ra-224*	2.62E-06	2.41E-06	3.62E-06	7.13E-08
Ra-225	2.33E-09	7.57E-09	7.70E-06	9.90E-08
Ra-226	7.88E-09	8.96E-09	9.50E-06	2.80E-07
Ra-228*	1.53E-06	1.42E-06	1.60E-05	6.90E-07
Rb-83*	7.42E-07	6.97E-07	6.90E-10	1.90E-09
Rb-87	3.28E-11	1.04E-09	5.00E-10	1.50E-09
Re-183	6.06E-06	5.46E-06	5.50E-04	1.20E-06
Re-184	1.33E-06	1.26E-06	1.90E-09	1.00E-09
Re-184m	5.15E-07	5.27E-07	6.50E-09	1.50E-09
Re-186	1.94E-08	3.15E-08	1.10E-09	1.50E-09
Re-186m	6.36E-09	1.31E-08	1.20E-08	2.20E-09
Re-187	0.00E+00	0.00E+00	6.30E-12	5.10E-12
Rh-101	3.04E-07	3.44E-07	5.40E-09	5.50E-10
Rh-102	3.29E-06	3.05E-06	1.70E-08	2.60E-09
Rh-102m	7.17E-07	6.78E-07	7.10E-09	1.20E-09
Rn-222*	2.86E-06	2.63E-06	4.00E-09	2.50E-10
Ru-103*	6.97E-07	6.57E-07	3.00E-09	7.34E-10
Ru-106*	3.37E-07	3.35E-07	6.60E-08	7.00E-09
S-35	3.31E-12	9.81E-11	1.90E-09	7.70E-10
Sb-124	2.99E-06	2.72E-06	8.60E-09	2.50E-09
Sb-125	6.16E-07	5.90E-07	1.20E-08	1.10E-09
Sb-126	4.34E-06	4.04E-06	3.20E-09	2.40E-09
Sc-46	3.24E-06	2.95E-06	6.80E-09	1.50E-09
Se-75	4.95E-07	5.30E-07	1.30E-09	2.60E-09
Se-79	4.14E-12	1.24E-10	6.80E-09	2.90E-09
Si-32	8.03E-12	2.74E-10	1.10E-07	5.60E-10
Sm-145	1.47E-08	3.98E-08	1.60E-09	2.10E-10
Sm-146	0.00E+00	0.00E+00	1.10E-05	5.40E-08
Sm-147	0.00E+00	0.00E+00	9.60E-06	4.90E-08
Sm-148	6.06E-06	5.46E-06	5.50E-04	1.20E-06
Sm-151	1.83E-13	7.76E-13	4.00E-09	9.80E-11
Sn-113*	3.68E-07	3.63E-07	2.72E-09	7.58E-10

Table A-6: Effective Dose Coefficients				
Nuclide	Ground-Exposure (Sv/a)/(Bq/kg)	Air Immersion (Sv/a)/(Bq/m^3)	Air Inhalation (Sv/Bq)	Ingestion (Sv/Bq)
Sn-119m	5.66E-10	2.22E-09	2.20E-09	3.40E-10
Sn-121	4.63E-11	1.23E-09	2.30E-10	2.30E-10
Sn-121m	3.87E-10	1.65E-09	4.50E-09	3.80E-10
Sn-123	1.43E-08	2.20E-08	8.10E-09	2.10E-09
Sn-126*	2.39E-06	2.27E-06	2.80E-08	4.74E-09
Sr-85	7.47E-07	7.07E-07	8.10E-10	5.60E-10
Sr-89	4.08E-09	1.38E-08	7.90E-09	2.60E-09
Sr-90	1.75E-10	3.10E-09	1.60E-07	2.80E-08
Ta-179	1.32E-08	2.84E-08	5.60E-10	6.50E-11
Ta-180m	6.97E-07	7.42E-07	2.60E-08	8.40E-10
Ta-182	2.03E-06	1.89E-06	1.00E-08	1.50E-09
Tb-157	6.26E-10	1.69E-09	1.20E-09	3.40E-11
Tb-158	1.21E-06	1.13E-06	4.60E-08	1.10E-09
Tb-160	1.77E-06	1.64E-06	7.00E-09	1.60E-09
Tc-95m*	1.04E-06	9.89E-07	1.20E-09	5.67E-10
Tc-97	1.52E-10	7.13E-10	1.80E-09	6.80E-11
Tc-97m	4.15E-10	1.17E-09	4.10E-09	5.50E-10
Tc-98	2.18E-06	2.02E-06	4.50E-08	2.00E-09
Tc-99	2.93E-11	9.06E-10	1.30E-08	6.40E-10
Te-121	8.38E-07	7.89E-07	4.10E-10	4.30E-10
Te-121m	2.68E-07	2.84E-07	5.70E-09	2.30E-09
Te-123	1.25E-09	4.77E-09	3.90E-09	4.40E-09
Te-123m	1.55E-07	1.83E-07	5.10E-09	1.40E-09
Te-125m	3.00E-09	1.06E-08	4.20E-09	8.70E-10
Te-127m*	8.17E-09	1.38E-08	9.94E-09	2.47E-09
Th-227	1.30E-07	1.40E-07	1.00E-05	8.80E-09
Th-228	1.94E-09	2.56E-09	4.00E-05	7.20E-08
Th-229	7.83E-08	1.06E-07	2.40E-04	4.90E-07
Th-230	2.89E-10	4.67E-10	1.00E-04	2.10E-07
Th-231	8.68E-09	1.45E-08	3.30E-10	3.40E-10
Th-232	1.23E-10	2.28E-10	1.10E-04	2.30E-07
Th-234*	3.71E-08	5.19E-08	7.70E-09	3.40E-09
Ti-44*	3.45E-06	3.26E-06	1.20E-07	6.15E-09

Table A-6: Effective Dose Coefficients

Nuclide	Ground-Exposure (Sv/a)/(Bq/kg)	Air Immersion (Sv/a)/(Bq/m^3)	Air Inhalation (Sv/Bq)	Ingestion (Sv/Bq)
Tl-202	6.31E-07	6.31E-07	1.90E-10	4.50E-10
Tl-204	1.05E-09	5.40E-09	3.90E-10	1.20E-09
Tm-168	6.06E-06	5.46E-06	5.50E-04	1.20E-06
Tm-170	3.81E-09	1.16E-08	7.00E-09	1.30E-09
Tm-171	2.54E-10	5.59E-10	1.40E-09	1.10E-10
U-232	2.14E-10	3.69E-10	3.70E-05	3.30E-07
U-233	3.42E-10	4.48E-10	9.60E-06	5.10E-08
U-234	9.29E-11	1.93E-10	9.40E-06	4.90E-08
U-235	1.78E-07	2.04E-07	8.50E-06	4.70E-08
U-236	4.80E-11	1.22E-10	8.70E-06	4.70E-08
U-237	1.30E-07	1.67E-07	1.90E-09	7.60E-10
U-238	2.15E-11	7.89E-11	8.00E-06	4.50E-08
V-49	0.00E+00	0.00E+00	3.40E-11	1.80E-11
V-50	6.06E-06	5.46E-06	5.50E-04	1.20E-06
W-181	1.76E-08	3.66E-08	2.70E-11	7.60E-11
W-185	1.04E-10	1.57E-09	1.20E-10	4.40E-10
W-188*	8.67E-08	1.02E-07	1.11E-09	3.50E-09
Y-88	4.57E-06	4.10E-06	4.40E-09	1.30E-09
Y-90	1.09E-08	2.50E-08	1.50E-09	2.70E-09
Y-91	1.02E-08	1.96E-08	8.90E-09	2.40E-09
Zn-65	9.49E-07	8.58E-07	2.20E-09	3.90E-09
Zr-88	5.66E-07	5.46E-07	3.60E-09	4.50E-10
Zr-93	0.00E+00	0.00E+00	2.50E-08	1.10E-09
Zr-95	1.15E-06	1.06E-06	5.90E-09	9.50E-10

Table A-7: Progeny Contribution to Parent Effective Air Inhalation Dose Coefficient

Nuclide	ICRP72 (1996) Air Inhalation Dose Coefficient (Sv/Bq)	Progeny Contribution (Sv/Bq)	Progeny Contribution As Percent of ICRP72 Value	Effective Air Inhalation Dose Coefficient (Sv/Bq)
All Progeny Contributions are Included.				
Ac-227	5.50E-04	1.23E-11	0.00	5.50E-04
Am-242m	9.20E-05	1.99E-08	0.02	9.20E-05
Ar-42	0.0	1.20E-10	----	1.20E-10
Bk-249	1.60E-07	8.40E-16	0.00	1.60E-07
Cf-253	1.30E-06	1.24E-13	0.00	1.30E-06
Cm-247	9.00E-05	8.60E-11	0.00	9.00E-05
Cm-250	2.10E-03	1.40E-10	0.00	2.10E-03
Es-254	8.60E-06	1.00E-09	0.01	8.60E-06
Fe-60	2.80E-07	1.40E-12	0.00	2.80E-07
Ge-68	1.40E-08	4.90E-11	0.35	1.40E-08
Os-194	8.50E-08	5.60E-10	0.66	8.56E-08
Pu-246	8.00E-09	2.30E-11	0.29	8.02E-09
Ra-228	1.60E-05	2.50E-08	0.16	1.60E-05
Ru-103	3.00E-09	2.69E-12	0.09	3.00E-09
Sn-113	2.70E-09	2.00E-11	0.74	2.72E-09
Sn-126	2.80E-08	2.00E-11	0.07	2.80E-08
Tc-95m	1.20E-09	4.40E-12	0.37	1.20E-09
Te-127m	9.80E-09	1.37E-10	1.39	9.94E-09
Ti-44	1.20E-07	1.80E-10	0.15	1.20E-07
W-188	5.70E-10	5.40E-10	94.74	1.11E-09
Not all Progeny Contributions are Available				
Ac-225	8.50E-06	3.01E-08	0.35	8.53E-06
Ag-108m	3.70E-08	0.00E+00	0.00	3.70E-08
Ag-110m	1.20E-08	0.00E+00	0.00	1.20E-08
Bi-210m	3.40E-06	0.00E+00	0.00	3.40E-06
Ce-144	5.30E-08	1.80E-11	0.03	5.30E-08
Cs-137	3.90E-08	0.00E+00	0.00	3.90E-08
Hf-172	3.20E-08	0.00E+00	0.00	3.20E-08
In-114m	9.30E-09	0.00E+00	0.00	9.30E-09
Pu-239	5.00E-05	0.00E+00	0.00	5.00E-05
Pu-244	1.10E-04	5.79E-10	0.001	1.10E-04
Ra-223	8.70E-06	1.20E-08	0.14	8.71E-06
Ra-224	3.40E-06	2.21E-07	6.50	3.62E-06
Rb-83	6.90E-10	0.00E+00	0.00	6.90E-10
Ru-106	6.60E-08	0.00E+00	0.00	6.60E-08
Th-234	7.70E-09	1.32E-12	0.02	7.70E-09

Table A-8: Progeny Contribution to Parent Effective Ingestion Dose Coefficient

Nuclide	ICRP72 (1996) Ingestion Dose Coefficient (Sv/Bq)	Progeny Contribution (Sv/Bq)	Progeny Contribution As Percent of ICRP72 Value	Effective Ingestion Dose Coefficient (Sv/Bq)
All Progeny Contributions are Included				
Ac-227	1.10E-06	3.31E-11	0.003	1.10E-06
Am-242m	1.90E-07	2.99E-10	0.16	1.90E-07
Ar-42	0.0	4.30E-10	----	4.30E-10
Bk-249	9.70E-10	9.30E-16	0.00	9.70E-10
Cf-253	1.40E-09	9.61E-14	0.01	1.40E-09
Cm-247	1.90E-07	8.50E-11	0.05	1.90E-07
Cm-250	4.40E-06	1.96E-11	0.00	4.40E-06
Es-254	2.80E-08	1.40E-10	0.50	2.81E-08
Fe-60	1.10E-07	1.70E-12	0.002	1.10E-07
Ge-68	1.30E-09	1.00E-10	7.69	1.40E-09
Os-194	2.40E-09	1.30E-09	54.17	3.70E-09
Pu-246	3.30E-09	3.40E-11	1.03	3.33E-09
Ra-228	6.90E-07	4.30E-10	0.06	6.90E-07
Ru-103	7.30E-10	3.79E-12	0.52	7.34E-10
Sn-113	7.30E-10	2.80E-11	3.84	7.58E-10
Sn-126	4.70E-09	3.60E-11	0.77	4.74E-09
Tc-95m	5.60E-10	7.20E-12	1.29	5.67E-10
Te-127m	2.30E-09	1.66E-10	7.21	2.47E-09
Ti-44	5.80E-09	3.50E-10	6.03	6.15E-09
W-188	2.10E-09	1.40E-09	66.67	3.50E-09
Not all Progeny Contributions are Available				
Ac-225	2.40E-08	2.57E-10	1.07	2.43E-08
Ag-108m	2.30E-09	0.00E+00	0.00	2.30E-09
Ag-110m	2.80E-09	0.00E+00	0.00	2.80E-09
Bi-210m	1.50E-08	0.00E+00	0.00	1.50E-08
Ce-144	5.20E-09	5.00E-11	0.96	5.25E-09
Cs-137	1.30E-08	0.00E+00	0.00	1.30E-08
Hf-172	1.00E-09	0.00E+00	0.00	1.00E-09
In-114m	4.10E-09	0.00E+00	0.00	4.10E-09
Pu-239	2.50E-07	0.00E+00	0.00	2.50E-07
Pu-244	2.40E-07	1.10E-09	0.46	2.41E-07
Ra-223	1.00E-07	1.80E-10	0.18	1.00E-07
Ra-224	6.50E-08	6.26E-09	9.63	7.13E-08
Rb-83	1.90E-09	0.00E+00	0.00	1.90E-09
Rn-222	0.0	2.50E-10	----	2.50E-10
Ru-106	7.00E-09	0.00E+00	0.00	7.00E-09
Th-234	3.40E-09	1.68E-12	0.05	3.40E-09

Table A-9: Ingestion Multiplication Factor Data

Symbol	Description	Value	Units	Reference
fp	Fraction of irrigation water intercepted by plants	0.2	-	Actual value is 0.05 (Garisto et al. 2012) but this was multiplied by 4 because irrigation only occurs during growing season
H_S	Soil depth	0.2	m	Garisto et al. (2012)
I^{DW}	Water Ingestion Rate	0.84	m^3/a	90th Percentile CSA (2008)
I^P	Plant Ingestion Rate	704	kg/a	Garisto et al (2012)
IR	Irrigation Rate	0.115	$m^3/m^2/a$	Average for soil types in Garisto et al. (2012)
Kd_{rock}	Shallow Geosphere K_d	Element Dependent	-	See Table B-11
Inf	Net water Infiltration rate	0.31	m^3/a	Garisto et al. (2012)
$t_{1/2,n}$	Half-Life	Nuclide Dependent	a	See Table A-4
T_P	Plant Lifetime	0.274 (100 days)	a	Garisto et al. (2012)
T_{PW}	Plant Weathering Time	0.033 (12 days)	a	Garisto et al. (2012)
T_t	Soil Buildup Time	10^4	a	Bergström et al. (1999)
VF^W	Well Flow Rate	110	m^3/a	Domestic water demand for 1 person (Garisto et al. 2012)
YP	Plant Yield	0.8	kg/m^2	Garisto et al. (2012)
θ ( )	Soil Porosity	0.25	-	Average for soil types in Garisto et al. (2012)
$\rho_{b,S}$	Soil Density	1150	kg/m^3	Average for soil types in Garisto et al. (2012)
Kd_{soil}	Soil Adsorption Coefficient	Element Dependent	m^3/kg	See Table B-13

Table A-10: Radionuclide Ingestion Multiplication Factor

Nuclide[1]	Lower Limit[2]	Upper Limit
Ac-225a	6.1	84.9
Ac-225b	6.1	84.9
Ac-227a	2.5	7.6
Ac-227b	2.5	7.6
Ag-105	1.9	
Ag-108m	3.0	107.7
Ag-110m	2.1	2.3
Al-26	2.3	3.6
Am-241a	2.1	2.5
Am-242ma	2.2	
Am-242my	2.2	
Am-242mz	2.2	
Am-243a	2.2	4.9
Ar-39	1.0	
Ar-42	2.1	
As-73	2.0	
Au-194	3.8	24.6
Au-195	2.1	2.4
Ba-133	2.1	2.5
Be-7	1.9	
Be-10	2.9	11.5
Bi-207	2.2	3.3
Bi-208	2.4	6.2
Bi-210a	1.3	
Bi-210b	1.3	
Bi-210c	1.3	
Bi-210d	1.3	
Bi-210m	2.4	6.2
Bk-247	2.2	2.7
Bk-248	2.1	
Bk-249a	2.1	
C -14	3.9	125.5
Ca-41	3.5	27.4
Ca-45	2.1	4.2
Cd-109	2.1	3.1
Cd-113	3.8	36.4
Cd-113m	2.2	10.9
Cd-115m	2.0	
Ce-139	2.1	
Ce-144	2.1	
Cf-248	2.1	
Cf-249a	2.1	2.4
Cf-250a	2.1	
Cf-251a	2.1	2.6
Cf-252a	2.1	
Cf-253	1.7	
Cf-254	2.0	
Cl-36	2.3	2534.5
Cm-242d	2.3	
Cm-243b	2.1	
Cm-244b	2.1	
Cm-245a	2.2	2.4
Cm-246a	2.1	2.4
Cm-247a	2.2	2.4
Cm-248a	2.2	2.4
Cm-250	2.2	2.4
Co-56	2.0	
Co-57	2.1	
Co-58	2.0	
Co-60	2.6	17.4
Cs-134	2.2	
Cs-135	3.2	20.3
Cs-137	2.2	4.3
Dy-154	2.3	4.4
Dy-159	2.1	
Es-252	2.1	
Es-253	1.7	
Es-254	2.1	
Es-255	1.9	
Eu-146	1.3	
Eu-148	1.9	
Eu-149	2.0	
Eu-150	2.1	2.8
Eu-152	2.1	2.4
Eu-154	2.1	2.3
Eu-155	2.2	
Fe-55	2.1	
Fe-59	1.9	

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[1] The letters a, b,c and d that follow the nuclide name indicates the actinide series branch to which the nuclide belongs (see Table A-2). Nb-93my and Nb-93mz are the decay products of Mo-93 and Zr-93, respectively.

[2] The ingestion multiplication factor is described by a uniform or constant distribution. The uniform distribution is described by the lower and upper limits. For the constant distribution, the lower limit represents the constant value.

Table A-10: Radionuclide Ingestion Multiplication Factor

Nuclide[1]	Lower Limit[2]	Upper Limit
Fe-60	2.2	4.0
Fm-257	2.0	
Gd-146	1.9	
Gd-148	2.2	3.6
Gd-150	2.4	4.8
Gd-151	2.0	
Gd-152	2.4	4.8
Gd-153	2.1	
Ge-68	2.1	2.5
H-3	2.1	
Hf-172	2.1	
Hf-174	2.7	8.9
Hf-175	2.0	
Hf-178m	2.1	2.8
Hf-181	1.9	
Hf-182	2.7	8.9
Hg-194	3.3	18.5
Hg-203	1.9	2.1
Ho-163	2.3	4.4
Ho-166m	2.2	4.2
I-125	2.0	
I-129	2.2	
In-114m	1.9	
In-115	2.3	3.6
Ir-192	3.4	10.9
Ir-192n	2.3	6.0
Ir-194m	2.1	
K-40	3.3	17.9
Kr-81	1.0	
Kr-85	1.0	
La-137	2.3	3.7
La-138	2.3	3.7
Lu-172	1.4	
Lu-173	2.1	
Lu-174	2.2	
Lu-174m	2.1	
Lu-176	2.3	4.4
Lu-177	1.4	
Lu-177m	2.1	
Md-258	1.9	
Mn-53	3.5	21.8
Mn-54	2.1	2.5
Mo-93	2.4	5.7
Na-22	2.1	2.6
Nb-91	2.3	6.1
Nb-91m	2.0	
Nb-92	2.5	6.7
Nb-93my	62.4	775.6
Nb-93mz	3.4	19.2
Nb-94	2.5	6.6
Nb-95	1.9	
Nb-95m	1.3	
Nd-144	2.3	4.4
Ni-59	12.8	42.4
Ni-63	2.8	27.9
Np-235	2.1	
Np-236c	2.1	2.6
Np-236d	2.1	2.6
Np-237a	2.1	2.6
Np-237b	2.1	2.6
Np-238c	1.2	
Np-239a	1.2	
Os-185	2.0	
Os-186	2.4	4.8
Os-194	2.2	
P-32	7.6	109.0
Pa-231a	3.5	21.4
Pa-231b	3.5	21.4
Pa-233a	64.3	171.9
Pa-233b	64.3	171.9
Pb-202	3.0	75.7
Pb-205	3.1	77.2
Pb-210a	2.2	3.6
Pb-210b	2.2	3.6
Pb-210c	2.2	3.6
Pb-210d	2.2	3.6
Pd-107	2.8	10.0
Pm-143	2.1	
Pm-144	2.1	
Pm-145	2.1	2.5
Pm-146	2.2	
Pm-147	2.2	
Pm-148	1.4	
Pm-148m	1.9	
Po-208	2.1	
Po-209	2.1	2.4
Po-210a	2.1	
Po-210b	2.1	

Table A-10: Radionuclide Ingestion Multiplication Factor

Nuclide[1]	Lower Limit[2]	Upper Limit
Po-210c	2.1	
Po-210d	2.1	
Pt-190	2.6	8.2
Pt-193	2.2	5.4
Pu-236d	2.1	3.7
Pu-237	1.9	
Pu-238c	2.1	
Pu-238d	2.1	
Pu-239a	2.2	
Pu-239b	2.2	
Pu-240a	2.2	
Pu-240b	2.2	
Pu-241a	2.2	2.4
Pu-241b	2.1	
Pu-242a	2.2	
Pu-242b	2.2	
Pu-244a	2.2	
Pu-246	3.5	4.2
Ra-223a	6.6	53.2
Ra-223b	6.6	53.2
Ra-224a	7.3	292.6
Ra-224b	7.3	292.6
Ra-224c	7.3	292.6
Ra-224d	230.0	788.6
Ra-225a	6.1	212.4
Ra-225b	6.1	212.4
Ra-226a	2.3	
Ra-226b	2.3	
Ra-226c	2.3	
Ra-226d	2.3	
Ra-228a	6.3	268.8
Ra-228b	6.3	268.8
Ra-228c	6.3	268.8
Rb-83	2.0	2.2
Rb-87	4.7	34.0
Re-183	2.0	2.4
Re-184	1.9	2.1
Re-184m	2.1	3.1
Re-186	4.7	37.9
Re-186m	3.3	19.9
Re-187	3.3	19.9
Rh-101	2.1	2.8
Rh-102	2.1	2.9
Rh-102m	2.1	

Table A-10: Radionuclide Ingestion Multiplication Factor

Nuclide[1]	Lower Limit[2]	Upper Limit
Rn-222a	1.3	
Rn-222b	1.3	
Rn-222c	1.3	
Rn-222d	1.3	
Ru-103	1.9	
Ru-106	2.2	
S-35	2.0	2.8
Sb-124	2.0	
Sb-125	2.1	
Sb-126	3.0	15.7
Sc-46	2.0	
Se-75	2.0	2.3
Se-79	7.4	65.2
Si-32	2.6	11.8
Sm-145	2.1	
Sm-146	2.3	4.5
Sm-147	2.3	4.5
Sm-148	2.3	4.5
Sm-151	2.2	3.0
Sn-113	2.0	2.2
Sn-119m	2.1	2.6
Sn-121	2.7	37.7
Sn-121m	2.4	19.9
Sn-123	2.0	2.3
Sn-126	6.3	53.2
Sr-85	2.0	2.2
Sr-89	1.9	2.1
Sr-90	2.4	10.2
Ta-179	2.1	
Ta-180m	2.3	4.7
Ta-182	4.0	14.1
Tb-157	2.2	3.5
Tb-158	2.2	4.1
Tb-160	2.0	
Tc-95m	2.0	2.4
Tc-97	2.2	3.2
Tc-97m	2.0	2.6
Tc-98	2.2	3.2
Tc-99	2.2	3.2
Te-121	1.7	
Te-121m	2.1	
Te-123	2.8	11.5
Te-123m	2.1	
Te-125m	2.0	

Table A-10: Radionuclide Ingestion Multiplication Factor

Nuclide[1]	Lower Limit[2]	Upper Limit
Te-127m	2.0	
Th-227a	4.3	23.8
Th-227b	4.3	23.8
Th-228a	3.8	39.1
Th-228b	3.8	39.1
Th-228c	3.8	39.1
Th-228d	174.0	271.1
Th-229a	2.3	15.1
Th-229b	2.3	15.1
Th-230a	2.4	19.4
Th-230b	2.4	19.4
Th-230c	2.4	19.4
Th-230d	2.4	19.4
Th-231a	176.8	431.6
Th-231b	176.8	431.6
Th-232a	2.4	20.1
Th-232b	2.4	20.1
Th-232c	2.4	20.1
Th-234a	177.5	432.3
Th-234b	177.5	432.3
Ti-44	2.1	2.5
Tl-202	1.6	1.8
Tl-204	2.1	
Tm-168	2.0	
Tm-170	2.0	
Tm-171	2.1	
U-232d	2.1	2.6
U-233a	2.2	3.3
U-233b	2.2	3.3
U-234a	2.2	3.3
U-234b	2.2	3.3
U-234c	2.2	3.3
U-234d	2.2	3.3
U-235a	2.2	3.3
U-235b	2.2	3.3
U-236a	2.2	3.3
U-236b	2.2	3.3
U-236c	2.2	3.3
U-237b	1.4	
U-238a	2.2	3.3
U-238b	2.2	3.3
V-49	2.1	
V-50	2.3	3.9
W-181	2.0	
W-185	2.0	
W-188	2.0	
Y-88	2.0	
Y-90	212.0	1412.5
Y-91	1.9	
Zn-65	2.1	3.4
Zr-88	2.0	
Zr-93	2.3	4.0
Zr-95	2.0	

APPENDIX B: ELEMENT SPECIFIC DATA

LIST OF TABLES

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Table B-1: Inventories of the Chemical Elements[1]

Element	280 MWh/Kg U Fuel [mol/kg U]	220 MWh/kg U Fuel [mol/kg U]	280 MWh/kg U Zircaloy [mol/kg Zr]	220 MWh/kg U Zircaloy [mol/kg Zr]
Ag	4.63E-04	3.35E-04	7.25E-05	7.64E-05
Al	3.70E-03	3.70E-03	2.78E-03	2.78E-03
Ar	2.64E-06	2.60E-06	2.55E-06	2.54E-06
As	4.03E-05	4.02E-05	1.31E-05	1.31E-05
Au	3.02E-06	3.39E-06	3.09E-07	3.45E-07
B	4.46E-05	4.46E-05	4.52E-05	4.51E-05
Ba	5.85E-03	4.74E-03	1.51E-06	1.36E-06
Be	1.12E-05	1.11E-05	1.11E-02	1.11E-02
Bi	9.60E-05	9.60E-05	5.23E-06	5.13E-06
Br	1.48E-04	1.31E-04	1.21E-05	1.22E-05
C	1.68E-02	1.68E-02	3.50E-01	3.50E-01
Ca	2.49E-03	2.49E-03	4.98E-05	4.98E-05
Cd	2.87E-04	1.91E-04	2.74E-05	2.33E-05
Ce	6.00E-03	4.77E-03	7.31E-07	7.27E-07
Cl	1.29E-04	1.31E-04	1.54E-04	1.57E-04
Co	3.01E-04	3.09E-04	3.02E-04	3.10E-04
Cr	9.64E-04	9.64E-04	2.49E-02	2.50E-02
Cs	3.29E-03	2.63E-03	6.59E-06	6.78E-06
Cu	3.11E-04	3.12E-04	7.77E-04	7.79E-04
Dy	4.02E-06	3.17E-06	4.46E-07	4.51E-07
Er	2.48E-06	2.33E-06	8.17E-07	7.70E-07
Eu	2.45E-04	1.75E-04	3.42E-07	3.95E-07
F	1.58E-03	1.58E-03	3.16E-04	3.16E-04
Fe	4.48E-03	4.48E-03	4.29E-02	4.29E-02
Ga	4.26E-05	4.27E-05	7.05E-05	7.08E-05
Gd	2.42E-04	1.55E-04	4.18E-06	4.11E-06
Ge	4.36E-05	4.31E-05	1.49E-05	1.46E-05
H	1.01E-03	1.01E-03	2.50E-02	2.50E-02
He	2.75E-04	2.12E-04	2.95E-05	2.56E-05
Hf	5.52E-05	5.54E-05	5.49E-04	5.51E-04

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[1] Inventories are for 30 year old Bruce used fuel. The inventories shown here include only the concentrations of the stable isotopes of the element. The total inventory of an element in fuel is obtained by adding the concentrations of the radioactive isotopes of the element (shown in Table A-4) to the inventory in this table.

Table B-1: Inventories of the Chemical Elements[1]

Element	280 MWh/Kg U Fuel [mol/kg U]	220 MWh/kg U Fuel [mol/kg U]	280 MWh/kg U Zircaloy [mol/kg Zr]	220 MWh/kg U Zircaloy [mol/kg Zr]
Hg	7.11E-06	6.72E-06	7.21E-07	6.80E-07
Ho	2.09E-06	2.09E-06	6.40E-07	6.63E-07
I	1.54E-04	1.14E-04	7.53E-06	7.61E-06
In	7.01E-07	6.00E-07	2.14E-05	1.83E-05
Ir	2.00E-06	2.37E-06	2.01E-06	2.38E-06
K	5.08E-04	5.09E-04	2.54E-05	2.54E-05
Kr	1.26E-03	1.04E-03	4.33E-07	3.39E-07
La	3.07E-03	2.46E-03	7.01E-07	7.05E-07
Li	1.45E-04	1.46E-04	2.48E-05	2.49E-05
Lu	1.55E-06	1.58E-06	1.10E-06	1.04E-06
Mg	2.47E-03	2.47E-03	8.23E-04	8.23E-04
Mn	3.51E-04	3.54E-04	8.90E-04	8.95E-04
Mo	1.20E-02	9.49E-03	1.36E-03	1.16E-03
N	1.07E-03	1.07E-03	4.62E-03	4.62E-03
Na	8.68E-04	8.69E-04	8.68E-05	8.69E-05
Nb	1.07E-04	1.07E-04	1.07E-03	1.07E-03
Nd	6.26E-03	5.11E-03	5.00E-07	5.03E-07
Ne	7.30E-08	5.66E-08	1.66E-08	1.29E-08
Ni	1.05E-03	1.04E-03	1.22E-03	1.22E-03
O	8.37E+00	8.37E+00	9.37E-02	9.37E-02
Os	6.28E-06	6.01E-06	1.06E-05	8.89E-06
P	1.93E-03	1.94E-03	1.93E-03	1.94E-03
Pb	4.82E-04	4.82E-04	6.27E-04	6.27E-04
Pd	4.43E-03	3.09E-03	1.15E-04	1.11E-04
Pr	2.74E-03	2.18E-03	6.85E-07	6.91E-07
Pt	8.30E-06	7.93E-06	8.30E-06	7.92E-06
Rb	4.16E-04	3.46E-04	1.17E-05	1.17E-05
Re	1.18E-06	1.32E-06	2.84E-05	2.42E-05
Rh	2.14E-03	1.71E-03	2.61E-05	2.99E-05
Ru	7.80E-03	5.96E-03	4.95E-05	4.95E-05
S	6.24E-04	6.23E-04	6.24E-04	6.23E-04
Sb	3.69E-05	2.98E-05	1.18E-04	1.10E-04
Sc	4.11E-04	4.19E-04	2.06E-04	2.09E-04

Table B-1: Inventories of the Chemical Elements[1]

Element	280 MWh/Kg U Fuel [mol/kg U]	220 MWh/kg U Fuel [mol/kg U]	280 MWh/kg U Zircaloy [mol/kg Zr]	220 MWh/kg U Zircaloy [mol/kg Zr]
Se	4.57E-04	4.19E-04	1.29E-05	1.29E-05
Si	4.27E-03	4.27E-03	1.14E-02	1.14E-02
Sm	1.25E-03	9.66E-04	3.83E-07	4.07E-07
Sn	1.21E-04	9.24E-05	1.43E-01	1.43E-01
Sr	1.21E-03	1.01E-03	1.56E-05	1.47E-05
Ta	4.70E-05	4.87E-05	9.30E-04	9.66E-04
Tb	8.07E-06	6.14E-06	5.63E-07	5.78E-07
Te	1.35E-03	1.05E-03	2.57E-05	2.15E-05
Ti	4.51E-04	4.44E-04	1.06E-03	1.06E-03
Tl	4.85E-06	4.86E-06	4.85E-07	4.86E-07
Tm	7.25E-07	8.85E-07	2.43E-07	2.97E-07
V	3.88E-04	3.88E-04	1.01E-03	1.01E-03
W	6.09E-05	5.96E-05	7.01E-04	6.68E-04
Xe	1.48E-02	1.16E-02	3.25E-07	2.54E-07
Y	1.58E-03	1.33E-03	1.15E-05	1.14E-05
Yb	2.70E-06	2.56E-06	8.98E-07	8.51E-07
Zn	3.07E-04	3.06E-04	1.98E-05	1.88E-05
Zr	1.08E-02	8.85E-03	1.06E+01	1.06E+01

Table B-2: Basis for the Selected Instant Release Fractions

Element	Chemical State of Element in Fuel	Boiling Point of Element (K)	Rationale for Selected Instant Release Fraction
Actinides*	Oxides dissolved in the fuel matrix	-----	Actinides are present in solid solution in the fuel matrix. Assume IRF=0 for all actinides (Johnson and Tait 1997)
Ag	Metallic precipitate alloyed with other noble metals such as Cd and Sn (Kleykamp 1985).	2435	Boiling point of Ag is similar to that of Sn (2875 K). Since Ag is likely alloyed with Sn and other similar metals in fuel, assume IRF for Ag is the same as that for Sn.
Al	Oxide in fuel; but, Al_2O_3 is not soluble in UO_2 fuel matrix (Kashibe and Une 1998).	-----	Oxide is non-volatile and insoluble in UO_2. Although Al_2O_3 should precipitate at grain boundaries during fuel sintering, there is no evidence for this. Perhaps at typical Al levels in UO_2 (< 0.005 g/kgU, Tait et al. 2000) Al_2O_3 can be accommodated in the fuel matrix. However, at the recommended inventory, Al_2O_3 could partition to grain boundaries. For conservatism, IRF for Al is set to 1.
Ar	Non-reactive gas	-----	Ar is a noble gas. The IRFs of I and the noble gases are similar. Set IRF for Ar to that of I.
As	In elemental form in fuel	887	Boiling point of As is similar to that of Se, so assume IRF of As is the same as that of Se.
Au	In elemental form in fuel	3129	Since the boiling point of Au is similar to that of Sn, for conservatism, assume that the IRF of Au is the same as that of Sn.
B	Oxide in fuel.	-----	Oxide is non-volatile and B is present in fuel as an impurity at very low concentrations. Assume boron oxide can be accommodated in fuel matrix, so IRF of B is set to zero.
Ba	Oxide in fuel. BaO is slightly soluble in fuel and is found associated with oxide precipitates (“grey phase”) in fuel (Kleykamp 1985)	-----	Sr and Ba are both alkaline earth elements. Assume IRF for Ba is the same as that of Sr.
Be	Oxide in fuel. BeO is not soluble in the UO_2 fuel matrix.	-----	Oxide is non-volatile and Be is present in fuel as an impurity at very low concentrations. Assume BeO can be accommodated in fuel matrix, so IRF of Be is set to zero.

Table B-2: Basis for the Selected Instant Release Fractions			
Element	Chemical State of Element in Fuel	Boiling Point of Element (K)	Rationale for Selected Instant Release Fraction
Bi	Metallic precipitate in fuel	1837	Boiling point of Bi is lower than that of Sn and higher than that of Se. For conservatism, assume IRF is same as that of Se.
Br	Volatile, reactive gas	-----	Halogen like Cl and I. Assume IRF of Br is equal to the IRF of Cl, which is larger than that of I.
C	Gaseous oxide (CO or CO2).	-----	Measured value (see text)
Ca	Oxide in fuel. CaO is soluble in fuel matrix	-----	CaO is likely present in solid solution in the UO_2 fuel matrix, so the IRF of Ca is set to zero.
Cd	Metallic precipitate in fuel, alloyed with, e.g., Ag, Sn and Pd.	1040	Boiling point of Cd is similar to that of Se, so assume IRF of Cd is that same as that of Se.
Cl	Volatile, reactive gas	-----	Measured value (see text)
Co	Metallic precipitate in fuel.	3200	Boiling point of Co is somewhat higher than that of Sn; but, for conservatism, assume IRF for Co is the same as that for Sn.
Cr	Oxide in fuel, Cr_2O_3, with limited solubility in UO_2 (0.06 wt% at 1600°C).	-----	The amount of Cr in fuel does not exceed the solubility limit of Cr_2O_3 in fuel; therefore Cr is likely present in solid solution in the UO_2 fuel matrix and so the IRF of Cr is set to zero.
Cs	Found in various forms in fuel – dissolved in fuel, as Cs uranates, in grey phase and reacted with other fission products such as I and Te (Kleykamp 1985).	-----	Measured (see text)
Cu	Metallic precipitate in fuel, alloyed with other metals	2853	Boiling point of Cu is similar to that of Sn, so assume IRF for Cu is the same as that for Sn.
F	Volatile, reactive gas	-----	Halogen like Cl and I. Assume IRF of F is equal to the IRF of Cl, which is larger than that of I.
Fe	Oxide in fuel, dissolved in the fuel matrix	-----	FeO is likely present in solid solution in the UO_2 fuel matrix, so assume that the IRF of Fe is equal to zero.

Table B-2: Basis for the Selected Instant Release Fractions

Element	Chemical State of Element in Fuel	Boiling Point of Element (K)	Rationale for Selected Instant Release Fraction
Ga	Oxide in fuel, Ga_2O_3. Oxide is slightly soluble in PuO_2 so assume same for UO_2	-----	Given small amount of Ga in fuel, Ga_2O_3 is likely present in solid solution in the UO_2 fuel matrix, so assume IRF for Ga is set equal to zero.
Ge	In elemental form in fuel	3106	Boiling point of Ge is somewhat higher than that of Sn. For conservatism, assume IRF for Ge is the same as that for Sn.
H	Gaseous H_2, which diffuses rapidly in UO_2. Pickup of H_2 by the cladding significantly reduces the gap inventory of H_2.	-----	IRF for H is described by uniform distribution from 0 to 0.001 (Johnson et al. 1996).
He	Non-reactive gas	-----	He is a noble gas. The IRFs of I and noble gases are similar. IRF for He is set equal to that of I.
Hf	Oxide dissolved in fuel matrix	-----	Hf is present in solid solution in the fuel matrix, so assume IRF of Hf is equal to zero.
Hg	Metallic precipitate in fuel, alloyed with other elements	630	The volatility of Hg is quite high at the temperature of fuel in the reactor; therefore, assume IRF is similar to that of noble gases such as Rn.
I	Volatile, reactive gas	-----	Measured (see text)
In	Metallic precipitate in fuel, alloyed with other metals such as Sn.	2345	Boiling point of In is similar to that of Sn. Assume IRF for In is that same as that of Sn.
Ir	Metallic precipitate in fuel, alloyed with other metals	4701	Non-volatile, non-reactive metal. Since Ir concentration in fuel is so low, assume it can be accommodated in fuel matrix so IRF is set equal to zero.
K	Assume in oxide form in fuel, either in fuel matrix or in grey phase	-----	K is an alkali metal. Assume it behaves similarly to Cs in the fuel so IRF of K is set equal to that of Cs.
Kr	Non-reactive gas	-----	Kr is a noble gas like Ar. IRF for Kr is set equal to that of Ar.
Lanthanides	Oxides dissolved in the fuel matrix	-----	Lanthanides are present in solid solution in the fuel matrix. Assume IRF=0 for all lanthanides (Johnson and Tait 1997)

Table B-2: Basis for the Selected Instant Release Fractions

Element	Chemical State of Element in Fuel	Boiling Point of Element (K)	Rationale for Selected Instant Release Fraction
Li	Oxide in fuel, either in fuel matrix or in grey phase	-----	Li is an alkali metal like Cs. Assume it behaves similarly to Cs in the fuel so IRF of Li is set equal to that of Cs.
Mg	Oxide in fuel. The solubility of MgO in UO_2 is 0.8 at% at 1700°C, and higher at lower temperatures. It is also more soluble in UO_{2+x} than in UO_2 (Kashibe and Une 1998).	-----	MgO is non-volatile. Given small amount of Mg in fuel, solubility limit of MgO in UO_2 is not exceeded so MgO is present in solid solution in the UO_2 fuel matrix. IRF is set to zero.
Mn	Oxide in fuel. Assume it is slightly soluble in fuel matrix, like Fe and Cr.	-----	Given small amount of Mn in fuel, MnO is likely present in solid solution in the UO_2 fuel matrix, so IRF of Mn is set to zero.
Mo	Metallic precipitate alloyed with Tc, Ru, Rh and Pd, and dissolved in fuel matrix as oxide.	4912	Found in grain boundaries of fuel alloyed with Tc in epsilon particles. Assume IRF of Mo is the same as for Tc.
Na	Oxide in fuel, either in fuel matrix or in grey phase	-----	Na is an alkali metal like Cs. Assume it behaves similarly to Cs in the fuel so IRF of Na is set equal to that of Cs.
Nb	Oxide in fuel. Nb_2O5_b solubility in UO_2 is about 0.5 wt% (Harada 1996).	-----	Given small amount of Nb in fuel, Nb_2O_5 is likely present in solid solution in the UO_2 fuel matrix, so IRF of Nb is set to zero.
Ni	Metallic precipitate in fuel.	3186	Boiling point of Ni is somewhat higher than that of Sn; but, for conservatism, assume IRF for Ni is the same as that for Sn.
Os	Metallic precipitate in fuel, alloyed with other metals.	5285	Non-volatile, non-reactive metal. Since Os concentration in fuel is so low, assume it can be accommodated in the fuel matrix. Thus, IRF of Os is set equal to zero.
P	Chemistry of P in fuel is uncertain. Phosphates could form in fuel, perhaps in the grey phase (Kleykamp 1985).	-----	Assume P behaves like As, another Group VB element, in fuel; so, IRF of P is set equal to that of As.

Table B-2: Basis for the Selected Instant Release Fractions

Element	Chemical State of Element in Fuel	Boiling Point of Element (K)	Rationale for Selected Instant Release Fraction
Pb	Metallic precipitate in fuel	2022	Boiling point of Pb is lower than that of Sn and higher than that of Se. For conservatism, assume IRF is same as that of Se.
Pd	Metallic precipitate alloyed with a wide variety of metals in fuel, e.g., found in epsilon particles with Tc, Ru, Rh and Mo.	3236	Found in grain boundaries of fuel alloyed with Tc in epsilon particles. Assume IRF of Pd is the same as for Tc,
Po	Chemistry is similar to that of Bi and Te.	-----	Po has only short-lived isotopes, so for conservatism assume that IRF of Po is the same as for noble gases such as Rn.
Pt	Metallic precipitate in fuel.	4098	Non-volatile, non-reactive metal. Since Pt concentration in fuel is small, assume it can be accommodated in fuel matrix. Thus, IRF of Pt is set equal to zero.
Ra	Oxide in fuel.	-----	Ra is likely dissolved in the fuel matrix. However, for conservatism assume Ra behaves like Sr in fuel, since both are alkaline earth elements. Thus, assume IRF of Ra is the same as that of Sr.
Rb	Oxide in fuel either in fuel matrix or in grey phase	-----	Rb is an alkali metal like Cs. Assume it behaves similarly to Cs in the fuel, so IRF of Rb is set equal to that of Cs.
Re	Metallic precipitate in fuel, alloyed with other metals	5869	Non-volatile, non-reactive metal. Since Re concentration in fuel is so small, assume it can be accommodated in fuel matrix. Thus, IRF of Re is set equal to zero.
Rh	Metallic precipitate alloyed with Tc, Ru, Mo and Pd (Kleykamp 1985)	3968	Found in grain boundaries of fuel alloyed with Tc in epsilon particles. Assume IRF of Rh is the same as for Tc,
Rn	Non-reactive gas	-----	Rn is a noble gas like Ar. Therefore, IRF for Rn is set equal to that Ar.
Ru	Metallic precipitate alloyed with Tc, Rh, Mo and Pd (Kleykamp 1985)	4423	Ru is since found in grain boundaries of fuel alloyed with Tc in epsilon particles. Assume IRF of Ru is the same as for Tc.
S	Chemistry of S in fuel is uncertain. It could form sulphates, depending of the oxidation potential, and be present in grey phase.	-----	Assume S behaves similarly to Se, another Group VIB element, in fuel. Therefore, IRF of S is set equal to that of Se.

Table B-2: Basis for the Selected Instant Release Fractions

Element	Chemical State of Element in Fuel	Boiling Point of Element (K)	Rationale for Selected Instant Release Fraction
Sb	Metallic precipitate alloyed with Pd, Sn and other metals	1860	Boiling point of Sb is lower than that of Sn and higher than that of Se; but, for conservatism, assume IRF is same as that of Se.
Sc	Oxide in fuel, dissolved in the UO_2 matrix	-----	Sc_2O_3 is present in solid solution in the fuel matrix; thus, assume IRF for Sc is equal to zero.
Se	Likely in elemental form in fuel, alloyed with other fission products	958	Measured value (see text). Note that although boiling point of Se is relatively low, the measured values of the IRF are not high. Perhaps alloys or compounds formed by Se are stable.
Si	Oxide in fuel. Solubility of SiO_2 in UO_2 fuel is very low, about 0.045 wt% (Kashibe and Une 1998).	-----	SiO_2 is non-volatile. Given the small amount of Si in fuel, the solubility limit of SiO_2 in UO_2 is not exceeded. Thus, SiO_2 should be present in solid solution in the UO_2 fuel matrix, so IRF of Si is set to zero.
Sn	Metallic precipitate in fuel alloyed with other metals, e.g., Cd and Ag.	2875	Measured value (see text)
Sr	Oxide in fuel, dissolved in fuel matrix. Some evidence that it is also found in the grey oxide phase (Kleykamp 1985).	-----	Measured value. The IRF of Sr-90 is non-zero even though SrO dissolves in the fuel matrix. This could be due to the volatile precursors of Sr-90 (Stroes-Gascoyne 1996).
Ta	Oxide in fuel.	-----	Ta_2O_5 is probably somewhat soluble in UO_2. In this case, since Ta concentration in fuel is small, Ta would be dissolved in fuel matrix. Thus, IRF of Ta is equal to zero.
Tc	Metallic precipitate in fuel alloyed with Mo, Pd, Ru and Rh.	4538	Measured value (see text)
Te	Chemistry of Te is complex – it dissolves in UO_2, forms alloys with Pd and Sn, forms oxide precipitates (e.g., $BaTeO_3$) and forms non-oxide compounds (e.g., Cs_2Te) (Kleykamp 1985).	1261	Assume Te behaves similarly to Se in the fuel. Therefore, the IRF of Te is set equal to that of Se.

Table B-2: Basis for the Selected Instant Release Fractions

Element	Chemical State of Element in Fuel	Boiling Point of Element (K)	Rationale for Selected Instant Release Fraction
Ti	Oxide formed in fuel. TiO_2 is slightly soluble in UO_2 (0.13 wt%)	-----	TiO_2 is present in solid solution in the UO_2 fuel matrix, since Ti concentration is sufficiently low that solubility limit of TiO_2 in UO_2 is not exceeded. Thus, IRF of Ti is equal to zero.
Tl	Metallic precipitate in fuel.	1746	Boiling point of Tl is lower than that of Sn and higher than that of Se. For conservatism, assume IRF is same as that of Se.
V	Oxide in fuel. Assume dissolved in fuel matrix	-----	Assume V_2O_3 is present in solid solution in the UO_2 fuel matrix. Thus, IRF of V is set equal to zero.
W	Metallic precipitate in fuel.	5828	Non-volatile, non-reactive metal. Since W concentration in fuel is so small, assume it can be accommodated in fuel matrix. Thus IRF of W is equal to zero.
Xe	Non-reactive gas.	-----	Xe is a noble gas like Ar. Therefore, IRF for Xe is set equal to that of Ar.
Y	Oxide in fuel, dissolved in UO_2 fuel matrix	-----	Y is present in solid solution in the fuel matrix. Assume IRF=0 for Y (Johnson and Tait 1997)
Zn	Could be metallic precipitate in fuel or an oxide (ZnO_2), depending on the oxidation potential of the fuel.	1180	Assume Zn is in metallic precipitates in fuel. Boiling point of Zn is lower than that of Sn and higher than that of Se. For conservatism, assume IRF is same as that of Se.
Zr	Oxide in fuel. It is partially dissolved in fuel matrix (maximum solubility of ZrO_2 in UO_2 is about 0.4 mol% at 1473 K, and increases with temperature (Kleykamp 1993)) but is mostly found associated with Ba in oxide precipitates (grey phase) (Kleykamp 1985).	-----	If Zr were all dissolved in the fuel matrix then the IRF would be zero. However, some Zr does precipitate in the grey oxide phase as, e.g., $BaZrO_3$ (Kleykamp 1985). For conservatism, assume IRF of Zr is the same as that for Ba.

Table B-3: Instant Release Fractions[1]

Element	Distribution Type	Attribute A[2]	Attribute B[3]	Lower Bound	Upper Bound
Ac	constant	0			
Ag	uniform			0	0.001
Al	constant	1			
Am	constant	0			
Ar	normal	0.04	0.01	0.015	0.2
As	normal	0.006	0.0015	0.0023	0.03
Au	uniform			0	0.001
B	constant	0			
Ba	normal	0.025	0.008	0.001	0.05
Be	constant	0			
Bi	normal	0.006	0.0015	0.0023	0.03
Bk	constant	0			
Br	normal	0.06	0.01	0.01	0.2
C	normal	0.027	0.016	0.0005	0.075
Ca	constant	0			
Cd	normal	0.006	0.0015	0.0023	0.03
Ce	constant	0			
Cf	constant	0			
Cl	normal	0.06	0.01	0.01	0.2
Cm	constant	0			
Co	uniform			0	0.001
Cr	constant	0			
Cs	normal	0.04	0.01	0.015	0.2
Cu	uniform			0	0.001
Dy	constant	0			
Er	constant	0			
Es	constant	0			
Eu	constant	0			
F	normal	0.06	0.01	0.01	0.2
Fe	constant	0			
Fm	constant	0			

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[1] The basis of the instant release fraction values is provided in Table B-2.

[2] Attribute A refers to the mean if the distribution is normal, the geometric mean if the distribution is lognormal, and the value if the distribution is constant.

[3] Attribute B refers to the standard deviation if the distribution is normal, and the geometric standard deviation if the distribution is lognormal.

Table B-3: Instant Release Fractions[1]

Element	Distribution Type	Attribute A[2]	Attribute B[3]	Lower Bound	Upper Bound
Ga	constant	0			
Gd	constant	0			
Ge	uniform			0	0.001
H	uniform	0.00001	0.001		
He	normal	0.04	0.01	0.015	0.2
Hf	constant	0			
Hg	normal	0.04	0.01	0.015	0.2
Ho	constant	0			
I	normal	0.04	0.01	0.015	0.2
In	uniform	0	0.001		
Ir	constant	0			
K	normal	0.04	0.01	0.015	0.2
Kr	normal	0.04	0.01	0.015	0.2
La	constant	0			
Li	normal	0.04	0.01	0.015	0.2
Lu	constant	0			
Md	constant	0			
Mg	constant	0			
Mn	constant	0			
Mo	lognormal	0.01	2	0.0005	0.05
N	normal	0.04	0.01	0.015	0.2
Na	normal	0.04	0.01	0.015	0.2
Nb	constant	0			
Nd	constant	0			
Ne	normal	0.04	0.01	0.015	0.2
Ni	uniform			0	0.001
Np	constant	0			
O	constant	0			
Os	constant	0			
P	normal	0.006	0.0015	0.0023	0.03
Pa	constant	0			
Pb	normal	0.006	0.0015	0.0023	0.03
Pd	lognormal	0.01	2	0.0005	0.05
Pm	constant	0			
Po	normal	0.06	0.01	0.01	0.2
Pr	constant	0			
Pt	constant	0			
Pu	constant	0			

Table B-3: Instant Release Fractions[1]					
Element	Distribution Type	Attribute A[2]	Attribute B[3]	Lower Bound	Upper Bound
Ra	normal	0.025	0.008	0.001	0.05
Rb	normal	0.04	0.01	0.015	0.2
Re	constant	0			
Rh	lognormal	0.01	2	0.0005	0.05
Rn	normal	0.04	0.01	0.015	0.2
Ru	lognormal	0.01	2	0.0005	0.05
S	normal	0.006	0.0015	0.0023	0.03
Sb	normal	0.006	0.0015	0.0023	0.03
Sc	constant	0			
Se	normal	0.006	0.0015	0.0023	0.03
Si	constant	0			
Sm	constant	0			
Sn	uniform			0	0.001
Sr	normal	0.025	0.008	0.001	0.05
Ta	constant	0			
Tb	constant	0			
Tc	lognormal	0.01	2	0.0005	0.05
Te	normal	0.006	0.0015	0.0023	0.03
Th	constant	0			
Ti	constant	0			
Tl	normal	0.006	0.0015	0.0023	0.03
Tm	constant	0			
U	constant	0			
V	constant	0			
W	constant	0			
Xe	normal	0.04	0.01	0.015	0.2
Y	constant	0			
Yb	constant	0			
Zn	normal	0.006	0.0015	0.0023	0.03
Zr	normal	0.025	0.008	0.001	0.049

Table B-4: Solubility of the Chemical Elements in a Crystalline Environment[1]				
Element	Distribution Type	Solubility [mol/m^3][2]	GSD	Justification / Reference
Ac	Constant	2.00E+03		Assigned high value for conservatism
Ag	Lognormal	1.10E-01	3.2	Calculated with SIT database. AgCl(s) is controlling solid.
Al	Lognormal	5.30E-03	3.2	Calculated with SIT database. Gibbsite ($Al(OH)_3$) is controlling solid.
Am	Lognormal	2.23E-01	3.2	Duro et al. (2010). $AmOHCO_3$ controls solubility.
Ar	Constant	2.00E+03		Noble gas, does not precipitate
As	Constant	2.00E+03		Duro et al. (2010)
Au	Constant	2.00E+03		Low inventory, assigned high value for conservatism
B	Constant	2.00E+03		Low inventory, assigned high value for conservatism
Ba	Lognormal	2.60E-03	3.2	Calculated with SIT database. Barite, $BaSO_4$(s), is controlling solid
Be	Constant	2.00E+03		Assigned high value for conservatism
Bi	Lognormal	1.17E-01	3.2	Duro et al. (2010)
Bk	Constant	2.00E+03		Low inventory, assigned high value for conservatism
Br	Constant	2.00E+03		High solubility element
C	Lognormal	8.29E+00	3.2	Duro et al. (2010)
Ca	Constant	2.00E+03		Assigned high value for conservatism
Cd	Lognormal	7.60E-01	3.2	Calculated with SIT database. $CdCO_3$ is controlling solid (Berner 2002)
Ce	Lognormal	1.00E+00	3.2	Johnson et al. (1996)
Cf	Constant	2.00E+03		Low inventory, assigned high value for conservatism
Cl	Constant	2.00E+03		High solubility element
Cm	Lognormal	2.23E-01	3.2	Cm and Am have similar chemical properties, assume same solubility as Am as per Duro et al. (2006)
Co	Lognormal	1.00E+00	3.2	Calculated with SIT database. $CoCO_3$ is controlling solid (Berner 2002)
Cr	Constant	2.00E+03		Low inventory, assigned high value for conservatism
Cs	Constant	2.00E+03		High solubility element
Cu	Lognormal	1.36E-04	3.2	Duro et al. (2010). Cu(s) controls solubility.

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[1] The solubility values shown here and used in screening calculations are 10-fold larger than those calculated at 25°C in order to account for the higher temperatures expected in the used fuel container and other uncertainties.

[2] The solubility is described by a constant or lognormal probability distribution function. The table gives the geometric mean of the solubility for lognormal distributions. Constant distributions with a nominal value of 2000 mol/m^3 are used as an arbitrarily high value for species that are not solubility limited.

Table B-4: Solubility of the Chemical Elements in a Crystalline Environment[1]				
Element	Distribution Type	Solubility $[\mathrm{mol/m^3}]^2$	GSD	Justification / Reference
Dy	Lognormal	1.00E+00	3.2	Johnson et al. (1996)
Er	Constant	2.00E+03		Low inventory, assigned high value for conservatism
Es	Constant	2.00E+03		Low inventory, assigned high value for conservatism
Eu	Lognormal	1.00E+00	3.2	Johnson et al. (1996)
F	Constant	2.00E+03		High solubility element
Fe	Constant	2.00E+03		High solubility element
Fm	Constant	2.00E+03		Low inventory, assigned high value for conservatism
Ga	Constant	2.00E+03		Low inventory, assigned high value for conservatism
Gd	Lognormal	1.00E+00	3.2	Johnson et al. (1996)
Ge	Constant	2.00E+03		Low inventory, assigned high value for conservatism
H	Constant	2.00E+03		High solubility element
He	Constant	2.00E+03		Noble gas, does not precipitate
Hf	Constant	2.00E+03		Assigned high value for conservatism
Hg	Constant	2.00E+03		Low inventory, assigned high value for conservatism
Ho	Lognormal	6.70E-02	3.2	Calculated with SIT database. $Ho_2(CO3)_3(s)$ is controlling solid (Duro et al. 2006)
I	Constant	2.00E+03		High solubility element
In	Constant	2.00E+03		Assigned high value for conservatism
Ir	Constant	2.00E+03		Low inventory, assigned high value for conservatism
K	Constant	2.00E+03		High solubility element
Kr	Constant	2.00E+03		Noble gas, does not precipitate
La	Lognormal	1.00E+00	3.2	Johnson et al. (1996)
Li	Constant	2.00E+03		Alkali metals have high solubility
Lu	Constant	2.00E+03		Low inventory, assigned high value for conservatism
Md	Constant	2.00E+03		Low inventory, assigned high value for conservatism
Mg	Constant	2.00E+03		Alkaline metals can have high solubility
Mn	Constant	2.00E+03		Low inventory, assigned high value for conservatism
Mo	Lognormal	3.00E-03	3.2	Duro et al. (2010). For conservatism, CaMoO4(s) is controlling solid.
N	Constant	2.00E+03		Assigned high value for conservatism
Na	Constant	2.00E+03		High solubility element

Table B-4: Solubility of the Chemical Elements in a Crystalline Environment[1]

Element	Distribution Type	Solubility [mol/m^3]^2	GSD	Justification / Reference
Nb	Lognormal	1.30E-01	10.0	Duro et al. (2010). Nb_2O_5(s) controls solubility. Large gsd of 10 used since solubility sensitive to pH, and lack of thermodynamic data.
Nd	Lognormal	1.00E+00	3.2	Johnson et al. (1996)
Ne	Constant	2.00E+03		Noble gas does not precipitate.
Ni	Lognormal	2.90E+01	3.2	Calculated with SIT database. $Ni(OH)_2$(s) is controlling solid
Np	Lognormal	1.08E-05	3.2	Duro et al. (2010). NpO_2(am) is controlling solid.
O	Constant	2.00E+03		Assigned high value for conservatism
Os	Constant	2.00E+03		Assigned high value for conservatism
P	Constant	2.00E+03		Low inventory, assigned high value for conservatism
Pa	Lognormal	2.22E-05	10.0	Duro et al. (2010). Pa_2O_5(s) is controlling solid. gsd = 10 since solubility sensitive to oxidation and lack of thermodynamic data.
Pb	Lognormal	7.96E-02	3.2	Duro et al. (2010). $Pb_3(CO_3)_2(OH)_2$ is controlling solid.
Pd	Lognormal	4.11E-02	3.2	Duro et al. (2010). $Pd(OH)_2$(s) is controlling solid.
Pm	Lognormal	1.00E+00	3.2	Johnson et al. (1996)
Po	Constant	2.00E+03		Assigned high value for conservatism
Pr	Lognormal	1.00E+00	3.2	Johnson et al. (1996)
Pt	Constant	2.00E+03		Low inventory, assigned high value for conservatism
Pu	Lognormal	9.10E-04	3.2	Duro et al. (2010) use PuO_2 is controlling solid. Formation of phosphate solid would reduce solubility.
Ra	Lognormal	1.56E-03	3.2	Duro et al. (2010). $RaSO_4$ is controlling solid.
Rb	Constant	2.00E+03		High solubility element
Re	Constant	2.00E+03		Assigned high value for conservatism
Rh	Constant	2.00E+03		Low inventory, assigned high value for conservatism
Rn	Constant	2.00E+03		Noble gas, does not precipitate
Ru	Constant	2.00E+03		Short half-life, assigned high value for conservatism
S	Constant	2.00E+03		High solubility element
Sb	Lognormal	5.70E-01	3.2	Calculated with SIT database. Sb_2O_3(s) is controlling solid (Berner 2002)

Table B-4: Solubility of the Chemical Elements in a Crystalline Environment[1]				
Element	Distribution Type	Solubility [mol/m^3][2]	GSD	Justification / Reference
Sc	Constant	2.00E+03		Low inventory, assigned high value for conservatism
Se	Lognormal	1.26E-04	3.2	Duro et al. (2010). β-FE$_{1.04}$Se is controlling solid
Si	Lognormal	5.00E+02	3.2	Johnson et al. (1996)
Sm	Lognormal	2.40E-02	3.2	Calculated with SIT database. $Sm_2(CO_3)_3(s)$ is controlling solid (Duro et al. 2006)
Sn	Lognormal	9.63E-03	3.2	Duro et al. (2010). SnO_2 is controlling solid
Sr	Lognormal	5.50E+00	3.2	Calculated using SIT database. Celestite controls solubility.
Ta	Constant	2.00E+03		Low inventory, assigned high value for conservatism
Tb	Constant	2.00E+03		Low inventory, assigned high value for conservatism
Tc	Lognormal	4.10E-05	3.2	Duro et al. (2010). TcO_2:1.6H_2O is controlling solid
Te	Constant	2.00E+03		Low inventory, assigned high value for conservatism
Th	Lognormal	2.49E-04	3.2	Duro et al. (2010). ThO_2(fresh) is controlling solid. Aging of solid would reduce solubility.
Ti	Constant	2.00E+03		Low inventory, assigned high value for conservatism
Tl	Constant	2.00E+03		Low inventory, assigned high value for conservatism
Tm	Constant	2.00E+03		Low inventory, assigned high value for conservatism
U	Lognormal	3.45E-05	3.2	Duro et al. (2010). UO_2(am) is controlling solid. Aging of solid would reduce solubility.
V	Constant	2.00E+03		Assigned high value for conservatism
W	Constant	2.00E+03		Low inventory, assigned high value for conservatism
Xe	Constant	2.00E+03		Nobel gas, does not precipitate
Y	Constant	2.00E+03		Short half-life, assigned high value for conservatism
Yb	Constant	2.00E+03		Low inventory, assigned high value for conservatism
Zn	Constant	2.00E+03		High solubility element
Zr	Lognormal	1.82E-04	3.2	Duro et al. (2010) $Zr(OH)_4$(am) is controlling solid.

Table B-5: Solubility of the Chemical Elements in a Sedimentary Environment[1]

Element	Distribution Type	Solubility [mol/m^3][2]	GSD	Justification / Reference
Am	Constant	2.00E+03		Duro et al. (2010).
As	Constant	2.00E+03		Duro et al. (2010)
Bi	Constant	2.00E+03		Duro et al. (2010)
C	Lognormal	2.22E+01	3.2	Duro et al. (2010)
Cu	Lognormal	2.64E-01	3.2	Duro et al. (2010). Cu(s) controls solubility.
Mo	Lognormal	2.34E-09	3.2	Duro et al. (2010). For conservatism, CaMoO4(s) is controlling solid.
Nb	Lognormal	2.01E-03	10.0	Duro et al. (2010). Nb_2O_5(s) controls solubility. Large gsd of 10 used since solubility sensitive to pH, and lack of thermodynamic data.
Np	Lognormal	1.72E-05	3.2	Duro et al. (2010). NpO_2(am) is controlling solid.
Pa	Lognormal	3.20E-04	10.0	Duro et al. (2010). Pa_2O_5(s) is controlling solid. gsd = 10 since solubility sensitive to oxidation and lack of thermodynamic data.
Pb	Constant	2.00E+03		Duro et al. (2010)
Pd	Constant	2.00E+03		Duro et al. (2010)
Pu	Constant	2.00E+03		Duro et al. (2010)
Ra	Lognormal	1.68E-01	3.2	Duro et al. (2010). $RaSO_4$ is controlling solid.
Se	Lognormal	3.43E-05	3.2	Duro et al. (2010). $FeSe_2$ is controlling solid
Sn	Lognormal	9.06E-04	3.2	Duro et al. (2010). SnO_2 is controlling solid
Tc	Lognormal	4.39E-05	3.2	Duro et al. (2010). TcO_2:1.6H_2O is controlling solid
Th	Lognormal	1.45E-03	3.2	Duro et al. (2010). ThO_2(fresh) is controlling solid.
U	Lognormal	4.52E-05	3.2	Duro et al. (2010). UO_2(am) is controlling solid.
Zr	Lognormal	1.82E-04	3.2	Duro et al. (2010) $Zr(OH)_4$(am) is controlling solid.
Other	Constant	2.00E+03		Conservatively assume a nominally high solubility

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[1] The solubility values shown here and used in screening calculations are 10-fold larger than those calculated at 25°C in order to account for the higher temperatures expected in the used fuel container and other uncertainties.

[2] The solubility is described by a constant or lognormal probability distribution function. The table gives the geometric mean of the solubility for lognormal distributions. Constant distributions with a nominal value of 2000 mol/m^3 are used as an arbitrarily high value for species that are not solubility limited.

Table B-6: Buffer Sorption Coefficients in a Crystalline Environment (m^3/kg)					
Element	Distribution Type	Attribute A[1]	Lower Bound	Upper Bound	Justification / Reference
Ac	Triangle	6.1E+01	1.0E+01	3.8E+02	Assume K_d is the same as for Am, both trivalent actinides
Ag	Triangle	0.0E+00	0.0E+00	1.5E+01	SKB (2010), Ag(I) value
Al	Constant	0.0E+00			For conservatism assume K_d=0
Am	Triangle	6.1E+01	1.0E+01	3.8E+02	SKB (2010), Am(III) value
Ar	Constant	0.0E+00			Assume K_d =0 for noble gases
As	Constant	3.0E-01			Vilks et al. (2011), As(III) value
Au	Constant	0.0E+00			For conservatism assume K_d=0.
B	Constant	0.0E+00			Assume K_d=0 since B forms neutral $B(OH)_3$ or anion $B(OH)_4^-$ in solution
Ba	Triangle	4.5E-03	7.5E-04	2.7E-02	Assume K_d is the same as for Sr, another alkaline earth element
Be	Triangle	4.5E-03	7.5E-04	2.7E-02	Assume K_d is the same as for Sr, another alkaline earth element
Bi	Lognormal	3.5E+01 (1.6)	2.5E+01	5.0E+01	Vilks et al. (2011), Bi(III) value
Bk	Triangle	6.1E+01	1.0E+01	3.8E+02	Assume K_d is the same as for Am, both trivalent actinides
Br	Constant	0.0E+00			Halogen element like I, assume K_d is the same as for I
C	Constant	0.0E+00			SKB (2010)
Ca	Triangle	4.5E-03	7.5E-04	2.7E-02	Assume K_d is the same as for Sr, another alkaline earth element
Cd	Triangle	4.5E-03	7.5E-04	2.7E-02	Cd^{2+} cation present in solution, assume same K_d as Sr
Ce	Triangle	8.0E+00	8.0E-01	9.3E+01	SKB (2010), Ce(III) value
Cf	Triangle	6.1E+01	1.0E+01	3.8E+02	Assume K_d is the same as for Am, another trivalent actinide
Cl	Constant	0.0E+00			SKB (2010), Cl(-I) value
Cm	Triangle	6.1E+01	1.0E+01	3.8E+02	SKB (2010), Cm(III) value
Co	Triangle	4.5E-03	7.5E-04	2.7E-02	Co(II) oxidation state is stable, so assume same K_d is the same as for Sr
Cr	Triangle	4.5E-03	7.5E-04	2.7E-02	Cr(III) is stable as $Cr(OH)^{2+}$. Assume K_d is the same as for Sr (Johnson et al. 1996)
Cs	Triangle	9.3E-02	1.5E-02	5.6E-01	SKB (2010), Cs(I) Value

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[1] Attribute A represents the peak if the distribution is triangular; the geometric mean, with the geometric standard deviation in brackets, if the distribution is lognormal; and the value if the distribution is constant.

Table B-6: Buffer Sorption Coefficients in a Crystalline Environment (m^3/kg)					
Element	Distribution Type	Attribute A^1	Lower Bound	Upper Bound	Justification / Reference
Cu	Lognormal	2.2E-02 (4)	7.0E-03	2.6E-01	Vilks et al. (2011)
Dy	Triangle	8.0E+00	8.0E-01	9.3E+01	Assume K_d is the same as for Ce, both lanthanides
Er	Triangle	8.0E+00	8.0E-01	9.3E+01	Assume K_d is the same as for Ce, another lanthanide
Es	Triangle	6.1E+01	1.0E+01	3.8E+02	Assume K_d is the same as for Am, both trivalent actinides
Eu	Triangle	8.0E+00	8.0E-01	9.3E+01	SKB (2010), Eu(III) value
F	Constant	0.0E+00			Halide so assume same as iodine
Fe	Triangle	4.5E-03	7.5E-04	2.7E-02	Fe^{2+} stable under vault conditions, so assume K_d is the same as for Sr, a weakly sorbed cation
Fm	Triangle	6.1E+01	1.0E+01	3.8E+02	Assume K_d is the same as for Am, both trivalent actinides
Ga	Constant	0.0E+00			For conservatism assume K_d=0.
Gd	Triangle	8.0E+00	8.0E-01	9.3E+01	Assume K_d is the same as for Ce, both lanthanides
Ge	Triangle	6.3E+01	2.3E+00	1.8E+03	Ge(IV) stable oxidation state, like Sn(IV). Assume K_d is the same as for Sn
H	Constant	0.0E+00			Assume K_d=0
He	Constant	0.0E+00			For conservatism assume K_d=0.
Hf	Triangle	4.0E+00	1.0E-01	1.0E+02	Assume K_d is the same as for Zr, since chemically similar (Johnson et al. 1996)
Hg	Constant	0.0E+00			For conservatism assume K_d=0.
Ho	Triangle	8.0E+00	8.0E-01	9.3E+01	SKB (2010), Ho (III) value
I	Constant	0.0E+00			SKB (2010), I(-I) Value
In	Constant	0.0E+00			For conservatism assume K_d=0.
Ir	Constant	0.0E+00			For conservatism assume K_d=0.
K	Triangle	9.3E-02	1.5E-02	5.6E-01	Alkali metal, assume K_d is the same as for Cs
Kr	Constant	0.0E+00			Assume K_d=0
La	Triangle	8.0E+00	8.0E-01	9.3E+01	Assume K_d is the same as for Ce, another lanthanide
Li	Triangle	4.5E-03	7.5E-04	2.7E-02	Assume K_d is the same as for Na (Oscarson et al. 1995)
Lu	Triangle	8.0E+00	8.0E-01	9.3E+01	Assume K_d is the same as for Ce, another lanthanide
Md	Triangle	6.1E+01	1.0E+01	3.8E+02	Assume K_d is the same as for Am, both trivalent actinides

Table B-6: Buffer Sorption Coefficients in a Crystalline Environment (m^3/kg)					
Element	Distribution Type	Attribute A[1]	Lower Bound	Upper Bound	Justification / Reference
Mg	Triangle	4.5E-03	7.5E-04	2.7E-02	Assume K_d is the same as for Sr, both alkaline earth elements
Mn	Triangle	4.5E-03	7.5E-04	2.7E-02	Assume K_d is the same as for Sr, since both 2+ ions under reducing conditions
Mo	Triangle	8.9E-02	1.0E-02	4.0E-01	Vilks (2011). Mo (VI) anion is stable oxidation state.
N	Constant	0.0E+00			For conservatism assume K_d=0.
Na	Triangle	4.5E-03	7.5E-04	2.7E-02	Assume K_d is the same as for Sr (Oscarson et al. 1995)
Nb	Triangle	3.0E+00	2.0E-01	4.5E+01	SKB (2010)
Nd	Triangle	8.0E+00	8.0E-01	9.3E+01	Assume K_d is the same as for Ce, another lanthanide
Ne	Constant	0.0E+00			Noble gas, so K_d=0.
Ni	Triangle	3.0E-01	3.0E-02	3.3E+00	SKB (2010), Ni(II) value
Np	Triangle	6.3E+01	4.0E+00	1.1E+03	SKB (2010), Np(IV) value
O	Constant	0.0E+00			For conservatism assume K_d=0.
Os	Constant	0.0E+00			Assume Kd is same as Ru, since have similar chemistries
P	Constant	0.0E+00			Anions PO_3 and PO_4 are stable in aqueous solution. Assume K_d=0
Pa	Triangle	3.0E+00	2.0E-01	4.5E+01	SKB (2010), Pa(IV) value
Pb	Triangle	7.4E+01	1.2E+01	4.6E+02	SKB (2010), Pb(II) value
Pd	Triangle	5.0E+00	3.0E-01	7.5E+01	SKB (2010), Pd(II) value
Pm	Triangle	8.0E+00	8.0E-01	9.3E+01	Assume K_d is the same as for Ce, another lanthanide
Po	Triangle	6.0E-02	8.0E-03	5.0E-01	Nagra (2003)
Pr	Triangle	8.0E+00	8.0E-01	9.3E+01	Assume K_d is the same as for Ce, another lanthanide
Pt	Triangle	5.0E+00	3.0E-01	7.5E+01	Assume K_d is the same as for Pd, another noble metal in II oxidation state
Pu	Triangle	6.3E+01	4.0E+00	1.1E+03	SKB (2010), Pu(IV) value
Ra	Triangle	4.5E-03	7.5E-04	2.7E-02	SKB (2010), Ra(II) value
Rb	Triangle	9.3E-02	1.5E-02	5.6E-01	Assume K_d is the same as for Cs (Oscarson et al. 1995)
Re	Triangle	6.3E+01	2.3E+00	1.8E+03	Assume K_d is the same as for Tc under reducing conditions
Rh	Constant	0.0E+00			For conservatism assume K_d=0.
Rn	Constant	0.0E+00			Noble gas, so K_d=0.

Table B-6: Buffer Sorption Coefficients in a Crystalline Environment (m^3/kg)					
Element	Distribution Type	Attribute A[1]	Lower Bound	Upper Bound	Justification / Reference
Ru	Constant	0.0E+00			Assume K_d=0, for conservatism
S	Constant	0.0E+00			Assume K_d=0, for conservatism
Sb	Triangle	4.5E-03	7.5E-04	2.7E-02	Assume K_d is the same as for Sr (Johnson et al. 1996)
Sc	Triangle	8.0E+00	8.0E-01	9.3E+01	Assume K_d is the same as for Ce, since Sc behaves like lanthanides
Se	Constant	0.0E+00			For conservatism assume Se(-II) in solution. SKB (2010), Se(-II) value.
Si	Constant	0.0E+00			$Si(OH)_4$ in aqueous solution. Assume low K_d because of presence of Si in buffer porewater.
Sm	Triangle	8.0E+00	8.0E-01	9.3E+01	SKB (2010), Sm(III) value
Sn	Triangle	6.3E+01	2.3E+00	1.8E+03	SKB (2010), Sn(IV) value
Sr	Triangle	4.5E-03	7.5E-04	2.7E-02	SKB (2010), Sr(II) value
Ta	Triangle	3.0E+00	2.0E-01	4.5E+01	Assume K_d is the same as for Nb another Group VA element
Tb	Triangle	8.0E+00	8.0E-01	9.3E+01	Assume K_d is the same as for Ce, another lanthanide
Tc	Triangle	6.3E+01	2.3E+00	1.8E+03	SKB (2010), Tc(IV) values
Te	Constant	0.0E+00			Assume K_d=Se another Group VIB element
Th	Triangle	6.3E+01	6.0E+00	7.0E+02	SKB (2010)
Ti	Triangle	6.3E+01	2.3E+00	1.8E+03	Assume K_d is the same as for Sn since Ti(IV) and Sn(IV) behave similarly
Tl	Constant	0.0E+00			Chemistry of Th(I), which is stable in aqueous solution, similar to that of Ag(I) and alkalis. For conservatism use K_d=0.
Tm	Triangle	8.0E+00	8.0E-01	9.3E+01	Assume K_d is the same as for Ce, another lanthanide
U	Triangle	6.3E+01	3.6E+00	1.1E+03	SKB (2010), U(IV) value
V	Triangle	4.5E-03	7.5E-04	2.7E-02	Assume K_d is the same as for Sr (both 2+ anions in solution)
W	Triangle	8.9E-02	1.0E-02	4.0E-01	Assume K_d is the same as for Mo since Mo and W are chemically similar
Xe	Constant	0.0E+00			Noble gas, so K_d=0.

Table B-6: Buffer Sorption Coefficients in a Crystalline Environment (m^3/kg)					
Element	Distribution Type	Attribute A^1	Lower Bound	Upper Bound	Justification / Reference
Y	Triangle	8.0E+00	8.0E-01	9.3E+01	Assume K_d similar to that of lanthanides, since Y has similar chemistry
Yb	Triangle	8.0E+00	8.0E-01	9.3E+01	Assume K_d is the same as for Ce, another lanthanide
Zn	Triangle	4.5E-03	7.5E-04	2.7E-02	Assume K_d is the same as for Sr, another 2+ anion (Johnson et al. 1996)
Zr	Triangle	4.0E+00	1.0E-01	1.0E+02	SKB (2010)

Table B-7: Buffer Capacity Factors in a Crystalline Environment[1]

Element	Distribution Type	Attribute A[2]	Lower Bound	Upper Bound
Ac	Triangle	9.6E+04	1.6E+04	5.9E+05
Ag	Triangle	4.3E-01	4.3E-01	2.4E+04
Al	Constant	4.3E-01		
Am	Triangle	9.6E+04	1.6E+04	5.9E+05
Ar	Constant	4.3E-01		
As	Constant	4.7E+02		
Au	Constant	4.3E-01		
B	Constant	4.3E-01		
Ba	Triangle	7.5E+00	1.6E+00	4.3E+01
Be	Triangle	7.5E+00	1.6E+00	4.3E+01
Bi	Lognormal	5.5E+04 (1.6)	3.9E+04	7.9E+04
Bk	Triangle	9.6E+04	1.6E+04	5.9E+05
Br	Constant	1.7E-01		
C	Constant	4.3E-01		
Ca	Triangle	7.5E+00	1.6E+00	4.3E+01
Cd	Triangle	7.5E+00	1.6E+00	4.3E+01
Ce	Triangle	1.3E+04	1.3E+03	1.5E+05
Cf	Triangle	9.6E+04	1.6E+04	5.9E+05
Cl	Constant	1.7E-01		
Cm	Triangle	9.6E+04	1.6E+04	5.9E+05
Co	Triangle	7.5E+00	1.6E+00	4.3E+01
Cr	Triangle	7.5E+00	1.6E+00	4.3E+01
Cs	Triangle	1.5E+02	2.4E+01	8.8E+02
Cu	Lognormal	3.5E+01 (4)	1.1E+01	4.1E+02
Dy	Triangle	1.3E+04	1.3E+03	1.5E+05
Er	Triangle	1.3E+04	1.3E+03	1.5E+05
Es	Triangle	9.6E+04	1.6E+04	5.9E+05
Eu	Triangle	1.3E+04	1.3E+03	1.5E+05
F	Constant	1.7E-01		
Fe	Triangle	7.5E+00	1.6E+00	4.3E+01
Fm	Triangle	9.6E+04	1.6E+04	5.9E+05
Ga	Constant	4.3E-01		

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[1] Calculated from the buffer sorption coefficients in Table B-6.

[2] Attribute A represents the peak if the distribution is triangular; the geometric mean, with the geometric standard deviation shown in brackets, if the distribution is lognormal; and the value if the distribution is constant.

Table B-7: Buffer Capacity Factors in a Crystalline Environment[1]

Element	Distribution Type	Attribute A[2]	Lower Bound	Upper Bound
Gd	Triangle	1.3E+04	1.3E+03	1.5E+05
Ge	Triangle	9.9E+04	3.6E+03	2.8E+06
H	Constant	4.3E-01		
He	Constant	4.3E-01		
Hf	Triangle	6.3E+03	1.6E+02	1.6E+05
Hg	Constant	4.3E-01		
Ho	Triangle	1.3E+04	1.3E+03	1.5E+05
I	Constant	1.7E-01		
In	Constant	4.3E-01		
Ir	Constant	4.3E-01		
K	Triangle	1.5E+02	2.4E+01	8.8E+02
Kr	Constant	4.3E-01		
La	Triangle	1.3E+04	1.3E+03	1.5E+05
Li	Triangle	7.5E+00	1.6E+00	4.3E+01
Lu	Triangle	1.3E+04	1.3E+03	1.5E+05
Md	Triangle	9.6E+04	1.6E+04	5.9E+05
Mg	Triangle	7.5E+00	1.6E+00	4.3E+01
Mn	Triangle	7.5E+00	1.6E+00	4.3E+01
Mo	Triangle	1.4E+02	1.6E+01	6.3E+02
N	Constant	4.3E-01		
Na	Triangle	7.5E+00	1.6E+00	4.3E+01
Nb	Triangle	4.7E+03	3.2E+02	7.1E+04
Nd	Triangle	1.3E+04	1.3E+03	1.5E+05
Ne	Constant	4.3E-01		
Ni	Triangle	4.7E+02	4.8E+01	5.2E+03
Np	Triangle	9.9E+04	6.3E+03	1.8E+06
O	Constant	4.3E-01		
Os	Constant	4.3E-01		
P	Constant	1.7E-01		
Pa	Triangle	4.7E+03	3.2E+02	7.1E+04
Pb	Triangle	1.2E+05	1.9E+04	7.2E+05
Pd	Triangle	7.9E+03	4.7E+02	1.2E+05
Pm	Triangle	1.3E+04	1.3E+03	1.5E+05
Po	Triangle	9.4E+01	1.3E+01	7.9E+02
Pr	Triangle	1.3E+04	1.3E+03	1.5E+05
Pt	Triangle	7.9E+03	4.7E+02	1.2E+05
Pu	Triangle	9.9E+04	6.3E+03	1.8E+06
Ra	Triangle	7.5E+00	1.6E+00	4.3E+01
Rb	Triangle	1.5E+02	2.4E+01	8.8E+02

Table B-7: Buffer Capacity Factors in a Crystalline Environment[1]				
Element	Distribution Type	Attribute A[2]	Lower Bound	Upper Bound
Re	Triangle	9.9E+04	3.6E+03	2.8E+06
Rh	Constant	4.3E-01		
Rn	Constant	4.3E-01		
Ru	Constant	4.3E-01		
S	Constant	1.7E-01		
Sb	Triangle	7.5E+00	1.6E+00	4.3E+01
Sc	Triangle	1.3E+04	1.3E+03	1.5E+05
Se	Constant	1.7E-01		
Si	Constant	4.3E-01		
Sm	Triangle	1.3E+04	1.3E+03	1.5E+05
Sn	Triangle	9.9E+04	3.6E+03	2.8E+06
Sr	Triangle	7.5E+00	1.6E+00	4.3E+01
Ta	Triangle	4.7E+03	3.2E+02	7.1E+04
Tb	Triangle	1.3E+04	1.3E+03	1.5E+05
Tc	Triangle	9.9E+04	3.6E+03	2.8E+06
Te	Constant	1.7E-01		
Th	Triangle	9.9E+04	9.4E+03	1.1E+06
Ti	Triangle	9.9E+04	3.6E+03	2.8E+06
Tl	Constant	4.3E-01		
Tm	Triangle	1.3E+04	1.3E+03	1.5E+05
U	Triangle	9.9E+04	5.7E+03	1.8E+06
V	Triangle	7.5E+00	1.6E+00	4.3E+01
W	Triangle	1.4E+02	1.6E+01	6.3E+02
Xe	Constant	4.3E-01		
Y	Triangle	1.3E+04	1.3E+03	1.5E+05
Yb	Triangle	1.3E+04	1.3E+03	1.5E+05
Zn	Triangle	7.5E+00	1.6E+00	4.3E+01
Zr	Triangle	6.3E+03	1.6E+02	1.6E+05

Table B-8: Buffer Sorption Coefficients and Capacity Factors in a Sedimentary Environment

Element	Distribution Type	K_d (m^3/kg)	Capacity Factor (-)	Justification / Reference
Am	Constant	2.3E-01	3.3E+02	Lower bound K_d value from Vilks (2011)
Cu	Constant	7.0E-03	1.0E+01	Lower bound K_d value from Vilks (2011)
Nb	Constant	1.0E-01	1.4E+02	NWMO DGR-TR-2011-32
Np	Constant	4.0E-03	6.2E+00	NWMO DGR-TR-2011-32
Pa	Constant	1.7E-02	2.5E+01	Np(V) used as analog. Lower bound K_d value of Np(V) from Vilks (2011)
Pb	Constant	1.0E-03	1.9E+00	NWMO DGR-TR-2011-32
Pu	Constant	5.0E-01	7.1E+02	NWMO DGR-TR-2011-32
U	Constant	1.4E-02	2.0E+01	Conservatively use lower bound K_d value of U(VI) from Vilks (2011).
Zr	Constant	5.0E-02	7.2E+01	NWMO DGR-TR-2011-32
Other	Constant	0.0E+00	4.8E-01	Conservatively assume $K_d = 0$

Table B-9: Backfill Sorption Coefficients in a Crystalline Environment (m^3/kg)

Element	Distribution Type	Attribute A[1]	Lower Bound	Upper Bound	Justification / Reference
Ac	Triangle	1.9E+01	3.2E+00	1.1E+02	Assume the K_d is the same as for Am, both trivalent actinides
Ag	Triangle	3.5E-03	7.0E-04	4.5E+00	SKB (2006)
Al	Constant	0.0E+00			For conservatism assume K_d=0.
Am	Triangle	1.9E+01	3.2E+00	1.1E+02	SKB (2006)
Ar	Constant	0.0E+00			Assume K_d =0 for noble gases
As	Constant	0.0E+00			Anion AsO_3 is stable form, assume K_d=0
Au	Constant	0.0E+00			Anionic species stable, assume K_d is the same as for iodine, i.e., K_d=0
B	Constant	0.0E+00			Assume K_d=0 since B forms neutral $B(OH)_3$ or anion $B(OH)_4^-$ in solution
Ba	Triangle	1.5E-03	2.8E-04	9.7E-03	Assume K_d is the same as for Sr, another alkaline earth element
Be	Triangle	1.5E-03	2.8E-04	9.7E-03	Assume K_d is the same as for Sr, another alkaline earth element
Bi	Triangle	2.5E+00	3.1E-01	2.8E+01	Assume K_d is the same as for Eu (Vilks et al. 2011)
Bk	Triangle	1.9E+01	3.2E+00	1.1E+02	Assume K_d is the same as for Am, both trivalent actinides
Br	Constant	0.0E+00			Assume K_d is the same as for I, since both halides
C	Constant	0.0E+00			SKB (2006)
Ca	Triangle	1.5E-03	2.8E-04	9.7E-03	Assume K_d is the same as for Sr, both alkaline earths
Cd	Triangle	1.5E-03	2.8E-04	9.7E-03	Cd^{2+} cation formed in solution, assume K_d is the same as for Sr
Ce	Triangle	2.4E+00	2.4E-01	2.8E+01	SKB (2006)
Cf	Triangle	1.9E+01	3.2E+00	1.1E+02	Assume K_d is the same as for Am, both trivalent actinides
Cl	Constant	0.0E+00			SKB (2006)
Cm	Triangle	1.9E+01	3.1E+00	1.2E+02	SKB (2006)
Co	Triangle	1.5E-03	2.8E-04	9.7E-03	Co(II) oxidation state is stable so assume K_d is the same as for Sr
Cr	Triangle	1.5E-03	2.8E-04	9.7E-03	Cr(III) forms $Cr(OH)^{2+}$ in solution, so assume K_d is the same as for Sr (Johnson et al. 1996)
Cs	Triangle	3.6E-02	6.1E-03	1.9E-01	SKB (2006)
Cu	Constant	0.0E+00			For conservatism assume K_d=0

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[1] Attribute A represents the peak if the distribution is triangular and the value if the distribution is constant.

Table B-9: Backfill Sorption Coefficients in a Crystalline Environment (m^3/kg)					
Element	Distribution Type	Attribute A^1	Lower Bound	Upper Bound	Justification / Reference
Dy	Triangle	2.4E+00	2.4E-01	2.8E+01	Assume K_d is the same as for Ce, another lanthanide
Er	Triangle	2.4E+00	2.4E-01	2.8E+01	Assume K_d is the same as for Ce, another lanthanide
Es	Triangle	1.9E+01	3.2E+00	1.1E+02	Assume K_d is the same as for Am, both trivalent actinides
Eu	Triangle	2.5E+00	3.1E-01	2.8E+01	SKB (2006)
F	Constant	0.0E+00			Halide so same as iodine
Fe	Triangle	1.5E-03	2.8E-04	9.7E-03	Fe^{2+} stable under vault conditions, so assume K_d is the same as for Sr, a weakly sorbed cation
Fm	Triangle	1.9E+01	3.2E+00	1.1E+02	Assume K_d is the same as for Am, both trivalent actinides
Ga	Constant	0.0E+00			For conservatism assume K_d=0.
Gd	Triangle	2.4E+00	2.4E-01	2.8E+01	Assume K_d is the same as for Ce, another lanthanide
Ge	Triangle	1.9E+01	6.9E-01	5.3E+02	Ge(IV) is stable oxidation state which behaves like Sn(IV), so assume K_d is the same as for Sn.
H	Constant	0.0E+00			For conservatism assume K_d=0
He	Constant	0.0E+00			For conservatism assume K_d=0
Hf	Triangle	1.3E+00	6.5E-02	3.1E+01	Assume K_d is the same as for Zr, since chemically similar (Johnson et al. 1996)
Hg	Constant	0.0E+00			For conservatism assume K_d=0
Ho	Triangle	2.5E+00	3.1E-01	2.8E+01	SKB (2006)
I	Constant	0.0E+00			SKB (2006)
In	Constant	0.0E+00			For conservatism assume K_d=0
Ir	Constant	0.0E+00			For conservatism assume K_d=0
K	Triangle	3.6E-02	6.1E-03	1.9E-01	Alkali metal, assume K_d is the same as for Cs (Oscarson et al. 1995)
Kr	Constant	0.0E+00			For conservatism assume K_d=0
La	Triangle	2.4E+00	2.4E-01	2.8E+01	Assume K_d is the same as for Ce, another lanthanide
Li	Triangle	1.5E-03	2.8E-04	9.7E-03	Assume same as for Na, another alkali
Lu	Triangle	2.4E+00	2.4E-01	2.8E+01	Assume K_d is the same as for Ce, another lanthanide
Md	Triangle	1.9E+01	3.2E+00	1.1E+02	Assume K_d is the same as for Am, both trivalent actinides

Table B-9: Backfill Sorption Coefficients in a Crystalline Environment (m^3/kg)					
Element	Distribution Type	Attribute A[1]	Lower Bound	Upper Bound	Justification / Reference
Mg	Triangle	1.5E-03	2.8E-04	9.7E-03	Alkaline earth element, assume K_d is the same as for Sr
Mn	Triangle	1.5E-03	2.8E-04	9.7E-03	Assume K_d is the same as for Sr, since both 2+ ions under reducing conditions
Mo	Constant	0.0E+00			For conservatism assume K_d=0
N	Constant	0.0E+00			For conservatism assume K_d=0
Na	Triangle	1.5E-03	2.8E-04	9.7E-03	Assume K_d is the same as for Sr (Oscarson et al 1995)
Nb	Triangle	9.7E-01	9.5E-02	1.4E+01	SKB (2006)
Nd	Triangle	2.4E+00	2.4E-01	2.8E+01	Assume K_d is the same as for Ce, another lanthanide
Ne	Constant	0.0E+00			Noble gas, so assumed K_d=0
Ni	Triangle	9.1E-02	9.6E-03	9.9E-01	SKB (2006)
Np	Triangle	1.9E+01	1.2E+00	3.3E+02	SKB (2006)
O	Constant	0.0E+00			For conservatism assume K_d=0
Os	Constant	0.0E+00			For conservatism assume K_d=0
P	Constant	0.0E+00			Anions PO_3 and PO_4 are stable species in aqueous solution, so assume K_d=0
Pa	Triangle	9.7E-01	9.5E-02	1.4E+01	SKB (2006)
Pb	Triangle	2.2E+01	3.6E+00	1.4E+02	SKB (2006)
Pd	Triangle	1.5E+00	9.0E-02	2.3E+01	SKB (2006)
Pm	Triangle	2.4E+00	2.4E-01	2.8E+01	Assume K_d is the same as for Ce, another lanthanide
Po	Triangle	6.1E-02	7.9E-03	5.2E-01	SKB (2006)
Pr	Triangle	2.4E+00	2.4E-01	2.8E+01	Assume K_d is the same as for Ce, both lanthanides
Pt	Triangle	1.5E+00	9.0E-02	2.3E+01	Assume K_d is the same as for Pd (another noble metal in II oxidation state)
Pu	Triangle	1.9E+01	1.3E+00	3.3E+02	SKB (2006)
Ra	Triangle	1.5E-01	7.0E-03	1.7E-01	SKB (2006)
Rb	Triangle	3.6E-02	6.1E-03	1.9E-01	Assume K_d is the same as for Cs (Oscarson et al. 1995)
Re	Triangle	1.9E+01	7.3E-01	5.3E+02	Assume same as Tc under reducing conditions
Rh	Constant	0.0E+00			For conservatism assume K_d=0
Rn	Constant	0.0E+00			SKB (2006)
Ru	Constant	0.0E+00			Assume K_d=0, for conservatism

Table B-9: Backfill Sorption Coefficients in a Crystalline Environment (m^3/kg)					
Element	Distribution Type	Attribute A^1	Lower Bound	Upper Bound	Justification / Reference
S	Constant	0.0E+00			Assume K_d is the same as for I, since S forms stable anion in solution
Sb	Triangle	1.5E-03	2.8E-04	9.7E-03	Assume K_d is the same as for Sr (Johnson et al. 1996)
Sc	Triangle	2.4E+00	2.4E-01	2.8E+01	Assume K_d is the same as for Ce, since Sc behaves like lanthanides
Se	Triangle	1.2E-02	9.4E-04	1.2E-01	SKB (2006)
Si	Constant	0.0E+00			$Si(OH)_4$ forms in aqueous solution. Assume low K_d because of presence of Si in buffer porewater.
Sm	Triangle	2.5E+00	3.1E-01	2.8E+01	SKB (2006)
Sn	Triangle	1.9E+01	6.9E-01	5.3E+02	SKB (2006)
Sr	Triangle	1.5E-03	2.8E-04	9.7E-03	SKB (2006)
Ta	Triangle	9.7E-01	9.5E-02	1.4E+01	Assume K_d is the same as for Nb, another Group VA element
Tb	Triangle	2.4E+00	2.4E-01	2.8E+01	Assume K_d is the same as for Ce, both lanthanides
Tc	Triangle	1.9E+01	7.3E-01	5.3E+02	SKB (2006)
Te	Triangle	1.2E-02	9.4E-04	1.2E-01	Assume K_d is the same as for Se, another Group VIB element
Th	Triangle	1.9E+01	1.9E+00	2.1E+02	SKB (2006)
Ti	Triangle	1.9E+01	6.9E-01	5.3E+02	Assume K_d is the same as for Sn since Ti(IV) and Sn(IV) behave similarly
Tl	Constant	0.0E+00			Chemistry of Th(I), which is stable in aqueous solution, similar to that of Ag(I) and alkali. For conservatism use K_d=0.
Tm	Triangle	2.4E+00	2.4E-01	2.8E+01	Assume K_d is the same as for Ce (another lanthanide)
U	Triangle	1.9E+01	1.2E+00	3.3E+02	SKB (2006)
V	Triangle	1.5E-03	2.8E-04	9.7E-03	Assume K_d is the same as for Sr, since both form 2+ anions in solution
W	Constant	0.0E+00			Assume K_d is the same as for Mo since Mo and W are chemically similar
Xe	Constant	0.0E+00			Noble gas, so K_d=0.
Y	Triangle	2.4E+00	2.4E-01	2.8E+01	Assume K_d is the same as for Ce, since Y behaves like lanthanides

Table B-9: Backfill Sorption Coefficients in a Crystalline Environment (m^3/kg)					
Element	Distribution Type	Attribute A[1]	Lower Bound	Upper Bound	Justification / Reference
Yb	Triangle	2.4E+00	2.4E-01	2.8E+01	Assume K_d is the same as for Ce, both lanthanide
Zn	Triangle	1.5E-03	2.8E-04	9.7E-03	Assume K_d is the same as for Sr, another 2+ anion (Johnson et al. 1996)
Zr	Triangle	1.3E+00	6.5E-02	3.1E+01	SKB (2006)

Table B-10: Backfill Capacity Factors in a Crystalline Environment[1]				
Element	Distribution Type	Attribute A[2]	Lower Bound	Upper Bound
Ac	Triangle	4.0E+04	6.8E+03	2.3E+05
Ag	Triangle	7.6E+00	1.7E+00	9.5E+03
Al	Constant	2.0E-01		
Am	Triangle	4.0E+04	6.8E+03	2.3E+05
Ar	Constant	2.0E-01		
As	Constant	2.0E-01		
Au	Constant	2.0E-01		
B	Constant	2.0E-01		
Ba	Triangle	3.4E+00	7.9E-01	2.1E+01
Be	Triangle	3.4E+00	7.9E-01	2.1E+01
Bi	Triangle	5.3E+03	6.6E+02	5.9E+04
Bk	Triangle	4.0E+04	6.8E+03	2.3E+05
Br	Constant	8.0E-02		
C	Constant	2.0E-01		
Ca	Triangle	3.4E+00	7.9E-01	2.1E+01
Cd	Triangle	3.4E+00	7.9E-01	2.1E+01
Ce	Triangle	5.1E+03	5.1E+02	5.9E+04
Cf	Triangle	4.0E+04	6.8E+03	2.3E+05
Cl	Constant	8.0E-02		
Cm	Triangle	4.0E+04	6.6E+03	2.5E+05
Co	Triangle	3.4E+00	7.9E-01	2.1E+01
Cr	Triangle	3.4E+00	7.9E-01	2.1E+01
Cs	Triangle	7.7E+01	1.3E+01	4.0E+02
Cu	Constant	2.0E-01		
Dy	Triangle	5.1E+03	5.1E+02	5.9E+04
Er	Triangle	5.1E+03	5.1E+02	5.9E+04
Es	Triangle	4.0E+04	6.8E+03	2.3E+05
Eu	Triangle	5.3E+03	6.6E+02	5.9E+04
F	Constant	8.0E-02		
Fe	Triangle	3.4E+00	7.9E-01	2.1E+01
Fm	Triangle	4.0E+04	6.8E+03	2.3E+05
Ga	Constant	2.0E-01		
Gd	Triangle	5.1E+03	5.1E+02	5.9E+04

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[1] Calculated from the backfill sorption coefficients in Table B-9.

[2] Attribute A represents the peak if the distribution is triangular; the geometric mean, with the geometric standard deviation shown in brackets, if the distribution is lognormal; and the value if the distribution is constant.

Table B-10: Backfill Capacity Factors in a Crystalline Environment[1]				
Element	Distribution Type	Attribute A[2]	Lower Bound	Upper Bound
Ge	Triangle	4.0E+04	1.5E+03	1.1E+06
H	Constant	2.0E-01		
He	Constant	2.0E-01		
Hf	Triangle	2.8E+03	1.4E+02	6.6E+04
Hg	Constant	2.0E-01		
Ho	Triangle	5.3E+03	6.6E+02	5.9E+04
I	Constant	8.0E-02		
In	Constant	2.0E-01		
Ir	Constant	2.0E-01		
K	Triangle	7.7E+01	1.3E+01	4.0E+02
Kr	Constant	2.0E-01		
La	Triangle	5.1E+03	5.1E+02	5.9E+04
Li	Triangle	3.4E+00	7.9E-01	2.1E+01
Lu	Triangle	5.1E+03	5.1E+02	5.9E+04
Md	Triangle	4.0E+04	6.8E+03	2.3E+05
Mg	Triangle	3.4E+00	7.9E-01	2.1E+01
Mn	Triangle	3.4E+00	7.9E-01	2.1E+01
Mo	Constant	2.0E-01		
N	Constant	2.0E-01		
Na	Triangle	3.4E+00	7.9E-01	2.1E+01
Nb	Triangle	2.1E+03	2.0E+02	3.0E+04
Nd	Triangle	5.1E+03	5.1E+02	5.9E+04
Ne	Constant	2.0E-01		
Ni	Triangle	1.9E+02	2.1E+01	2.1E+03
Np	Triangle	4.0E+04	2.5E+03	7.0E+05
O	Constant	2.0E-01		
Os	Constant	2.0E-01		
P	Constant	2.0E-01		
Pa	Triangle	2.1E+03	2.0E+02	3.0E+04
Pb	Triangle	4.7E+04	7.6E+03	3.0E+05
Pd	Triangle	3.2E+03	1.9E+02	4.9E+04
Pm	Triangle	5.1E+03	5.1E+02	5.9E+04
Po	Triangle	1.3E+02	1.7E+01	1.1E+03
Pr	Triangle	5.1E+03	5.1E+02	5.9E+04
Pt	Triangle	3.2E+03	1.9E+02	4.9E+04
Pu	Triangle	4.0E+04	2.8E+03	7.0E+05
Ra	Triangle	3.2E+02	1.5E+01	3.6E+02
Rb	Triangle	7.7E+01	1.3E+01	4.0E+02

Table B-10: Backfill Capacity Factors in a Crystalline Environment[1]

Element	Distribution Type	Attribute A[2]	Lower Bound	Upper Bound
Re	Triangle	4.0E+04	1.6E+03	1.1E+06
Rh	Constant	2.0E-01		
Rn	Constant	2.0E-01		
Ru	Constant	2.0E-01		
S	Constant	8.0E-02		
Sb	Triangle	3.4E+00	7.9E-01	2.1E+01
Sc	Triangle	5.1E+03	5.1E+02	5.9E+04
Se	Triangle	2.6E+01	2.2E+00	2.6E+02
Si	Constant	2.0E-01		
Sm	Triangle	5.3E+03	6.6E+02	5.9E+04
Sn	Triangle	4.0E+04	1.5E+03	1.1E+06
Sr	Triangle	3.4E+00	7.9E-01	2.1E+01
Ta	Triangle	2.1E+03	2.0E+02	3.0E+04
Tb	Triangle	5.1E+03	5.1E+02	5.9E+04
Tc	Triangle	4.0E+04	1.6E+03	1.1E+06
Te	Triangle	2.6E+01	2.2E+00	2.6E+02
Th	Triangle	4.0E+04	4.0E+03	4.5E+05
Ti	Triangle	4.0E+04	1.5E+03	1.1E+06
Tl	Constant	2.0E-01		
Tm	Triangle	5.1E+03	5.1E+02	5.9E+04
U	Triangle	4.0E+04	2.5E+03	7.0E+05
V	Triangle	3.4E+00	7.9E-01	2.1E+01
W	Constant	2.0E-01		
Xe	Constant	2.0E-01		
Y	Triangle	5.1E+03	5.1E+02	5.9E+04
Yb	Triangle	5.1E+03	5.1E+02	5.9E+04
Zn	Triangle	3.4E+00	7.9E-01	2.1E+01
Zr	Triangle	2.8E+03	1.4E+02	6.6E+04

Table B-11: Rock and Fracture Sorption Coefficients in a Crystalline Environment [m^3/kg]						
Element	Distribution Type	Attribute A[1]	GSD[2]	Lower Bound	Upper Bound	Justification / Reference
Ac	Lognormal	3.0E+00	1.4	1.0E+00	5.0E+00	Crawford et al. (2006)
Ag Saline[3]	Lognormal	5.0E-02	1.7	1.0E-02	1.0E-01	Crawford et al. (2006)
Ag Non-Saline	Lognormal	5.0E-01	1.7	1.0E-01	1.0E+00	Crawford et al. (2006)
Al	Constant	0.0E+00				Conservatively assume K_d=0
Am	Lognormal	1.3E+01	3.9	2.2E-01	1.9E+02	Crawford et al. (2006)
Ar	Constant	0.0E+00				Ticknor and Vandergraaf (1996)
As	Constant	0.0E+00				Conservatively assume K_d=0
Au	Constant	0.0E+00				Conservatively assume K_d=0, since anionic species are stable in solution
B	Constant	0.0E+00				Conservatively assume K_d=0, $B(OH)_3$ is stable species in groundwater
Ba Saline	Lognormal	9.8E-05	1.9	1.4E-05	5.0E-04	Assume K_d is the same as for Sr, both alkaline earth elements
Ba Non-Saline	Lognormal	1.3E-02	2.4	1.0E-03	6.1E-01	Assume K_d is the same as for Sr, both alkaline earth elements
Be Saline	Lognormal	9.8E-05	1.9	1.4E-05	5.0E-04	Assume K_d is the same as for Sr, both alkaline earth elements
Be Non-Saline	Lognormal	1.3E-02	2.4	1.0E-03	6.1E-01	Assume K_d is the same as for Sr, both alkaline earth elements
Bi	Lognormal	1.0E-03	2.2	1.0E-04	1.0E-02	Ticknor and Vandergraaf (1996)
Bk	Lognormal	3.0E+00	1.4	1.0E+00	5.0E+00	Assume K_d is the same as for Cm (both elements are trivalent actinides)
Br	Constant	0.0E+00				Ticknor and Vandergraaf (1996)
C	Lognormal	1.0E-03	1.3	5.0E-04	2.0E-03	Crawford et al. (2006)

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[1] Attribute A represents the geometric mean for lognormal distributions and the value for constant distributions.

[2] Geometric Standard Deviation (GSD) only applies to lognormal distributions.

[3] Saline groundwaters, as defined here, have a total dissolved solid concentration > 0.5 g/L.

Table B-11: Rock and Fracture Sorption Coefficients in a Crystalline Environment [m^3/kg]						
Element	Distribution Type	Attribute A^1	GSD^2	Lower Bound	Upper Bound	Justification / Reference
Ca Saline	Lognormal	9.8E-05	1.9	1.4E-05	5.0E-04	Assume K_d is the same as for Sr, both alkaline earth elements
Ca Non-Saline	Lognormal	1.3E-02	2.4	1.0E-03	6.1E-01	Assume K_d is the same as for Sr, both alkaline earth elements
Cd Saline	Lognormal	2.0E-02	1.3	1.0E-02	1.0E-01	Crawford et al. (2006)
Cd Non-Saline	Lognormal	1.0E-01	1.3	5.0E-02	5.0E-01	Crawford et al. (2006)
Ce	Lognormal	2.0E+00	1.3	1.0E+00	5.0E+00	Assume K_d is the same as the other lanthanides (Sm, Eu)
Cf	Lognormal	3.0E+00	1.4	1.0E+00	5.0E+00	Assume K_d is the same as for Cm (another trivalent actinide)
Cl	Constant	0.0E+00				Crawford et al. (2006)
Cm	Lognormal	3.0E+00	1.4	1.0E+00	5.0E+00	Crawford et al. (2006)
Co Saline	Lognormal	2.0E-02	1.3	1.0E-02	1.0E-01	Crawford et al. (2006)
Co Non-Saline	Lognormal	1.0E-01	1.3	5.0E-02	5.0E-01	Crawford et al. (2006)
Cr	Lognormal	2.0E+00	1.3	1.0E+00	5.0E+00	Ticknor and Vandergraaf (1996) use Ce data to provide estimate
Cs Saline	Lognormal	4.2E-02	4.7	4.0E-04	2.0E+00	Crawford et al. (2006)
Cs Non-Saline	Lognormal	1.8E-01	4.7	1.7E-03	9.6E+00	Crawford et al. (2006)
Cu Saline	Lognormal	9.8E-05	1.9	1.4E-05	5.0E-04	Assume K_d is the same as for Sr, both form stable 2+ cations in solution
Cu Non-Saline	Lognormal	1.3E-02	2.4	1.0E-03	6.1E-01	Assume K_d is the same as for Sr, both form stable 2+ cations solution
Dy	Lognormal	2.0E+00	1.3	1.0E+00	5.0E+00	Assume K_d is same as for other lanthanides such as Ce, Eu
Er	Lognormal	2.0E+00	1.3	1.0E+00	5.0E+00	Assume K_d is same as for other lanthanides such as Ce
Es	Lognormal	3.0E+00	1.4	1.0E+00	5.0E+00	Assume K_d is the same as for Cm (both trivalent actinides)

Table B-11: Rock and Fracture Sorption Coefficients in a Crystalline Environment [m^3/kg]						
Element	Distribution Type	Attribute A[1]	GSD[2]	Lower Bound	Upper Bound	Justification / Reference
Eu	Lognormal	2.0E+00	1.3	1.0E+00	5.0E+00	Crawford et al. (2006) (non-saline conditions)
F	Constant	0.0E+00				For conservatism assume K_d=0
Fe Saline	Lognormal	1.0E-02	1.7	2.0E-03	8.7E-02	Ticknor and Vandergraaf (1996) use Ni as analog
Fe Non-Saline	Lognormal	1.2E-01	1.9	1.8E-02	5.4E-01	Ticknor and Vandergraaf (1996) use Ni as analog
Fm	Lognormal	3.0E+00	1.4	1.0E+00	5.0E+00	Assume K_d is the same as for Cm, another trivalent actinide
Ga	Constant	0.0E+00				Conservatively assume K_d = 0
Gd	Lognormal	2.0E+00	1.3	1.0E+00	5.0E+00	Assume K_d is same as for other lanthanides such as Ce
Ge	Constant	0.0E+00				Assume K_d is the same as for Si, another Group IVB element
H	Constant	0.0E+00				Ticknor and Vandergraaf (1996)
He	Constant	0.0E+00				K_d=0, for noble gases
Hf	Lognormal	1.0E+00	1.3	5.0E-01	3.0E+00	Assume K_d is the same as for Zr since Hf and Zr have similar chemistries
Hg	Constant	0.0E+00				Conservatively assume K_d = 0
Ho	Lognormal	2.0E+00	1.3	1.0E+00	5.0E+00	Crawford et al. (2006)
I	Constant	0.0E+00				Crawford et al. (2006)
In	Constant	0.0E+00				Ticknor and Vandergraaf (1996)
Ir	Constant	0.0E+00				Ticknor and Vandergraaf (1996)
K Saline	Lognormal	4.2E-03	4.7	4.0E-05	2.0E-01	Ticknor and Vandergraaf (1996) set K_d value to 1/10 Cs value
K Non-Saline	Lognormal	1.8E-02	4.7	1.7E-04	9.6E-01	Ticknor and Vandergraaf (1996) set K_d value to 1/10 Cs value
Kr	Constant	0.0E+00				Ticknor and Vandergraaf (1996)
La	Lognormal	2.0E+00	1.3	1.0E+00	5.0E+00	Assume K_d is the same as for other lanthanides such Ce.

Table B-11: Rock and Fracture Sorption Coefficients in a Crystalline Environment [m^3/kg]

Element	Distribution Type	Attribute A[1]	GSD[2]	Lower Bound	Upper Bound	Justification / Reference
Li	Constant	0.0E+00				Conservatively assume K_d = 0
Lu	Lognormal	2.0E+00	1.3	1.0E+00	5.0E+00	Assume K_d is the same as for other lanthanides such Ce
Md	Lognormal	3.0E+00	1.4	1.0E+00	5.0E+00	Assume K_d is the same as for Cm, another trivalent actinide
Mg Saline	Lognormal	9.8E-05	1.9	1.4E-05	5.0E-04	Assume K_d is the same as for Sr, another alkaline earth element
Mg Non-Saline	Lognormal	1.3E-02	2.4	1.0E-03	6.1E-01	Assume K_d is the same as for Sr, another alkaline earth element
Mn Saline	Lognormal	9.8E-05	1.9	1.4E-05	5.0E-04	Assume K_d is the same as for Sr, both form stable 2+ cations in solution
Mn Non-Saline	Lognormal	1.3E-02	2.4	1.0E-03	6.1E-01	Assume K_d is the same as for Sr, both form stable 2+ cations in solution
Mo	Constant	0.0E+00				Conservatively assume K_d = 0
N	Constant	0.0E+00				Conservatively assume K_d = 0, since N forms anionic species in solution
Na Saline	Lognormal	4.2E-04	4.7	4.0E-06	2.0E-02	Assume K_d is 1% of the Cs value, weakly sorbed
Na Non-Saline	Lognormal	1.8E-03	4.7	1.7E-05	9.6E-02	Assume K_d is 10% of the K value, weakly sorbed
Nb	Lognormal	1.0E+00	1.3	5.0E-01	3.0E+00	Crawford et al. (2006) (non-saline)
Nd	Lognormal	2.0E+00	1.3	1.0E+00	5.0E+00	Assume K_d is same as for other lanthanides such Ce
Ne	Constant	0.0E+00				Assume K_d = 0, since Ne is a noble gas
Ni Saline	Lognormal	1.0E-02	1.7	2.0E-03	8.7E-02	Crawford et al. (2006)
Ni Non-Saline	Lognormal	1.2E-01	1.9	1.8E-02	5.4E-01	Crawford et al. (2006)
Np Reducing	Lognormal	9.6E-01	2.7	4.7E-02	2.0E+01	Crawford et al. (2006), Np (IV) value
Np Oxidizing	Lognormal	1.8E-02	2.1	2.0E-03	2.2E-01	Crawford et al. (2006), Np (V) value
O	Constant	0.0E+00				Conservatively assume K_d = 0.

Table B-11: Rock and Fracture Sorption Coefficients in a Crystalline Environment [m^3/kg]						
Element	Distribution Type	Attribute A[1]	GSD[2]	Lower Bound	Upper Bound	Justification / Reference
Os	Constant	0.0E+00				Ticknor and Vandergraaf (1996)
P	Constant	0.0E+00				Ticknor and Vandergraaf (1996)
Pa	Lognormal	1.0E+00	1.3	5.0E-01	5.0E+00	Crawford et al. (2006)
Pb Saline	Lognormal	1.0E-02	1.7	2.0E-03	8.7E-02	Ticknor and Vandergraaf (1996) use Ni data as analog
Pb Non-Saline	Lognormal	1.2E-01	1.9	1.8E-02	5.4E-01	Ticknor and Vandergraaf (1996) use Ni data used as analog
Pd Saline	Lognormal	1.0E-02	2.2	1.0E-03	5.0E-02	Crawford et al. (2006)
Pd Non-Saline	Lognormal	1.0E-01	2.2	1.0E-02	5.0E-01	Crawford et al. (2006)
Pm	Lognormal	2.0E+00	1.3	1.0E+00	5.0E+00	Assume K_d is same as for other lanthanides such as Ce
Po	Lognormal	1.0E-01	2.2	1.0E-02	1.0E+00	Based on data in Baston et al. (1999) and Sheppard and Thibault (1990)
Pr	Lognormal	2.0E+00	1.3	1.0E+00	5.0E+00	Assume K_d is same as for other lanthanides such Ce
Pt	Constant	0.0E+00				Ticknor and Vandergraaf (1996)
Pu	Lognormal	5.0E+00	1.7	1.0E+00	1.0E+01	Crawford et al. (2006), Pu(IV) falues (non-saline)
Ra Saline	Lognormal	2.1E+00	6.9	6.4E-04	2.6E+00	Crawford et al. (2006)
Ra Non-Saline	Lognormal	1.3E+00	2.7	6.3E-02	1.1E+01	Crawford et al. (2006)
Rb Saline	Lognormal	2.1E-02	4.7	2.0E-04	1.0E+00	Assume 50% of the Cs value, as in Ticknor and Vandergraaf (1996)
Rb Non-Saline	Lognormal	9.0E-02	4.7	8.5E-04	4.8E+00	Assume 50% of the Cs values, as in Ticknor and Vandergraaf (1996)
Re Reducing	Lognormal	1.0E+00	1.3	5.0E-01	3.0E+00	Assume K_d is the same as for Tc, since Tc and Re have similar chemistries
Re Oxidizing	Constant	0.0E+00				Assume K_d is the same as for Tc, since Tc and Re have similar chemistries
Rh	Constant	0.0E+00				Ticknor and Vandergraaf (1996)

Table B-11: Rock and Fracture Sorption Coefficients in a Crystalline Environment [m^3/kg]						
Element	Distribution Type	Attribute A[1]	GSD[2]	Lower Bound	Upper Bound	Justification / Reference
Rn	Constant	0.0E+00				Assume K_d=0, Rn is noble gas
Ru	Lognormal	5.0E-04	2.2	5.0E-05	5.0E-03	Ticknor and Vandergraaf (1996)
S	Constant	0.0E+00				Conservatively assume K_d = 0, i.e., SO_4^{2-} is non-sorbing
Sb	Constant	0.0E+00				Ticknor and Vandergraaf (1996)
Sc	Lognormal	2.0E+00	1.3	1.0E+00	5.0E+00	Assumed K_d is same as for lanthanides since has similar chemistry
Se	Lognormal	1.0E-03	1.3	5.0E-04	5.0E-03	Crawford et al. (2006), Se (IV, VI) non-saline value
Si	Constant	0.0E+00				Ticknor and Vandergraaf (1996)
Sm	Lognormal	2.0E+00	1.3	1.0E+00	5.0E+00	Crawford et al. (2006)
Sn	Lognormal	1.0E-03	4.6	0.0E+00	1.0E-02	Crawford et al. (2006)
Sr Saline	Lognormal	9.8E-05	1.9	1.4E-05	5.0E-04	Crawford et al. (2006)
Sr Non-Saline	Lognormal	1.3E-02	2.4	1.0E-03	6.1E-01	Crawford et al. (2006)
Ta	Lognormal	1.0E+00	1.3	5.0E-01	3.0E+00	Assume K_d is the same as for Nb, another Group VA element
Tb	Lognormal	2.0E+00	1.3	1.0E+00	5.0E+00	Assumed K_d is same as for lanthanides since has similar chemistry
Tc Reducing	Lognormal	1.0E+00	1.3	5.0E-01	3.0E+00	Crawford et al. (2006), Tc(IV) value
Tc Oxidizing	Constant	0.0E+00				Crawford et al. (2006), Tc(VII) values
Te	Constant	0.0E+00				Conservatively assume K_d = 0
Th	Lognormal	1.0E+00	1.3	5.0E-01	1.0E+01	Crawford et al. (2006) Th(IV)
Ti	Lognormal	1.0E-03	4.6	0.0E+00	1.0E-02	Assume K_d is same as for Sn since Ti(IV) and Sn(IV) behave similarly
Tl	Constant	0.0E+00				Conservatively assume K_d = 0
Tm	Lognormal	2.0E+00	1.3	1.0E+00	5.0E+00	Assumed K_d is same as for lanthanides since has similar chemistry

Table B-11: Rock and Fracture Sorption Coefficients in a Crystalline Environment [m^3/kg]						
Element	Distribution Type	Attribute A[1]	GSD[2]	Lower Bound	Upper Bound	Justification / Reference
U Reducing	Lognormal	6.3E+00	5.1	4.8E-02	2.8E+02	Crawford et al. (2006), U(IV) value
U Oxidizing	Lognormal	6.3E-03	2.3	5.0E-04	1.2E-01	Crawford et al. (2006), U(VI) value (non-saline)
V Saline	Lognormal	9.8E-05	1.9	1.4E-05	5.0E-04	Assume K_d is the same as for Sr since both 2+ cations
V Non-Saline	Lognormal	1.3E-02	2.4	1.0E-03	6.1E-01	Assume K_d is the same as for Sr since both 2+ cations
W	Constant	0.0E+00				Assume K_d is the same as for Mo since two elements have similar chemistries
Xe	Constant	0.0E+00				Assume K_d = 0, since Xe a noble gas
Y	Lognormal	2.0E+00	1.3	1.0E+00	5.0E+00	Assume K_d is same as for lanthanides since has similar chemistry
Yb	Lognormal	2.0E+00	1.3	1.0E+00	5.0E+00	Assumed K_d is same as for other lanthanides
Zn Saline	Lognormal	9.8E-05	1.9	1.4E-05	5.0E-04	Assume K_d is the same as for Sr since both are 2+ cations in solution
Zn Non-Saline	Lognormal	1.3E-02	2.4	1.0E-03	6.1E-01	Assume K_d is the same as for Sr since both are 2+ cations in solution
Zr	Lognormal	1.0E+00	1.3	5.0E-01	3.0E+00	Crawford et al. (2006), Zr(IV) (non-saline) value

Table B-12: Rock Sorption Coefficients in a Sedimentary Environment

Element	Distribution Type	K_d (m^3/kg)		Justification / Reference
		Shale	Limestone	
Am	Constant	2.3E-01	2.0E-02	Lower bound K_d value from Vilks (2011)
Cd	Constant	5.0E-02	0.0E+00	NWMO DGR-TR-2011-32
Cu	Constant	1.0E-04	2.0E-04	Lower bound K_d value from Vilks (2011)
Nb	Constant	5.0E-02	0.0E+00	NWMO DGR-TR-2011-32
Np	Constant	3.0E-02	1.0E-03	NWMO DGR-TR-2011-32
Pa	Constant	7.5E-03	1.0E-03	Np(V) used as analog (Vilks 2011). Lower bound K_d value of Np(V) from Vilks (2011).
Pb	Constant	3.0E-02	0.0E+00	NWMO DGR-TR-2011-32
Pu	Constant	2.0E-01	2.0E-02	NWMO DGR-TR-2011-32
Th	Constant	0.0E+00	7.0E-01	Lower bound K_d values from Vilks (2011). Assume K_d = 0 for shale since measured values are at low ionic strengths.
U	Constant	2.0E-03	2.0E-03	Conservatively use lower bound K_d values of U(VI) from Vilks (2011).
Zr	Constant	1.0E-02	0.0E+00	NWMO DGR-TR-2011-32
Other	Constant	0.0E+00	0.0E+00	Conservatively assume K_d = 0

Table B-13: Plant to Soil Bioconcentration Factors and Soil Sorption Coefficients[1]

Element	Bv (Bq/kg wet) (Bq/ kg dry)$^{-1}$	Sand K_d (m^3/kg)	Loam K_d (m^3/kg)	Clay K_d (m^3/kg)	Organic K_d (m^3/kg)	Reference
Ac	8.80E-04	0.45	1.5	2.4	5.4	Sheppard and Thibault (1990)
Ag	6.25E-02	0.09	0.12	0.18	15	CSA (2008)
Al	1.00E-03	0.39	1.38	2.10	4.86	Calculated from Bv value (see text)
Am	1.60E-04	2	9.6	8.1	110	CSA (2008)
Ar	0.00E+00	0	0	0	0	Noble gas, assume all values are 0
As	6.25E-02	0.001	0.006	0.01	0.01	CSA (2008)
Au	1.00E-01	0.03	0.10	0.16	0.37	Calculated from Bv value (see text)
B	1.00E+00	0.0083	0.029	0.044	0.10	Calculated from Bv value (see text)
Ba	7.00E-03	0.099	0.344	0.524	1.213	CSA (2008)
Be	1.00E-02	0.240	0.810	1.3	3	CSA (2008)
Bi	8.80E-03	0.1	0.45	0.6	1.5	Sheppard and Thibault (1990)
Bk	2.13E-04	0.94	3.28	4.99	11.56	Calculated from Bv value (see text)
Br	4.50E-01	0.015	0.049	0.074	0.18	CSA (2008)
C	5.50E+00	0.005	0.02	0.001	0.07	CSA (2008)
Ca	8.80E-01	0.005	0.03	0.05	0.09	Sheppard and Thibault (1990)
Cd	1.38E-01	0.08	0.04	0.56	0.8	Sheppard and Thibault (1990)
Ce	2.33E-02	0.49	8.1	20	3	CSA (2008)
Cf	2.13E-04	0.94	3.28	4.99	11.56	Calculated from Bv value (see text)
Cl	3.70E+00	0.0001	0.0001	0.0001	2.2	Sheppard et al. (2002)
Cm	5.25E-05	4	18	5.4	12	CSA (2008)
Co	1.18E-02	0.06	1.3	0.54	0.99	CSA (2008)
Cr	2.05E-03	0.067	0.03	1.5	0.27	CSA (2008)
Cs	1.33E-02	0.27	4.4	1.8	0.27	CSA (2008)
Cu	1.00E-01	0.03	0.10	0.16	0.37	Calculated from Bv value (see text)
Dy	2.50E-03	0.24	0.82	1.26	2.91	Calculated from Bv value (see text)
Er	2.50E-03	0.24	0.82	1.26	2.91	Calculated from Bv value (see text)
Es	2.13E-04	0.94	3.28	4.99	11.56	Calculated from Bv value (see text)

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[1] Data were not found for oxygen (O).

Table B-13: Plant to Soil Bioconcentration Factors and Soil Sorption Coefficients[1]						
Element	Bv (Bq/kg wet) (Bq/ kg dry)$^{-1}$	Sand K_d (m^3/kg)	Loam K_d (m^3/kg)	Clay K_d (m^3/kg)	Organic K_d (m^3/kg)	Reference
Eu	4.50E-03	0.123	0.429	0.653	1.513	CSA (2008)
F	1.50E-02	0.087	0.30	0.46	1.07	Calculated from Bv value (see text)
Fe	1.25E-03	0.22	0.81	0.16	4.9	CSA (2008)
Fm	2.13E-04	0.94	3.28	4.99	11.56	Calculated from Bv value (see text)
Ga	1.00E-03	0.39	1.38	2.10	4.86	Calculated from Bv value (see text)
Gd	7.00E-03	0.099	0.344	0.524	1.213	CSA (2008)
Ge	1.00E-01	0.03	0.10	0.16	0.37	Calculated from Bv value (see text)
H	0.00E+00	0	0	0	0	CSA (2008)
He	0.00E+00	0	0	0	0	Noble gas, assume all values are 0
Hf	4.00E-03	0.45	1.5	2.4	5.4	CSA (2008)
Hg	2.75E-01	0.016	0.055	0.084	0.194	CSA (2008)
Ho	2.50E-03	0.25	0.8	1.3	3	Calculated from Bv value (see text)
I	5.00E-03	0.008	0.018	0.012	0.076	Sheppard et al. (2004a)
In	1.00E-03	0.39	1.38	2.10	4.86	Calculated from Bv value (see text)
Ir	1.38E-02	0.09	0.32	0.48	1.12	Calculated from Bv value (see text)
K	2.50E-01	0.015	0.055	0.075	0.2	Sheppard and Thibault (1990)
Kr	0.00E+00	0	0	0	0	Noble gas, assume all values are 0
La	2.50E-03	0.165	0.576	0.876	2.030	CSA (2008)
Li	6.25E-03	0.14	0.49	0.75	1.74	Calculated from Bv value (see text)
Lu	2.50E-03	0.24	0.82	1.26	2.91	Calculated from Bv value (see text)
Md	2.13E-04	0.94	3.28	4.99	11.56	Calculated from Bv value (see text)
Mg	2.50E-01	0.018	0.063	0.095	0.22	Calculated from Bv value (see text)
Mn	8.75E-02	0.049	0.72	0.18	0.49	CSA (2008)
Mo	9.00E-02	0.01	0.125	0.09	0.025	CSA (2008)
N	6.25E+00	0	0	0	0	CSA (2008)
Na	3.00E-02	0.048	0.166	0.253	0.586	CSA (2008)
Nb	7.25E-03	0.16	0.55	0.9	2	CSA (2008)
Nd	2.50E-03	0.24	0.82	1.26	2.91	Calculated from Bv value (see text)

Table B-13: Plant to Soil Bioconcentration Factors and Soil Sorption Coefficients[1]

Element	Bv (Bq/kg wet) (Bq/ kg dry)$^{-1}$	Sand K_d (m^3/kg)	Loam K_d (m^3/kg)	Clay K_d (m^3/kg)	Organic K_d (m^3/kg)	Reference
Ne	0.00E+00	0	0	0	0	Noble gas, assume all values are 0
Ni	1.18E-01	0.40	0.30	0.67	1.1	CSA (2008)
Np	2.50E-03	0.0025	0.013	0.021	0.53	Sheppard et al. 2004b
Os	3.75E-03	0.19	0.66	1.00	2.32	Calculated from Bv value (see text)
P	8.75E-01	0.009	0.03	0.049	0.11	CSA (2008)
Pa	9.50E-03	0.54	1.8	2.7	6.6	CSA (2008)
Pb	1.10E-02	0.27	16	0.55	22	Sheppard and Thibault (1990)
Pd	3.75E-02	0.055	0.18	0.27	0.67	Sheppard and Thibault (1990)
Pm	4.50E-03	0.123	0.429	0.653	1.513	CSA (2008)
Po	6.30E-04	0.15	0.4	3	7.3	Sheppard and Thibault (1990)
Pr	6.25E-03	0.104	0.364	0.554	1.284	CSA (2008)
Pt	2.38E-02	0.07	0.23	0.36	0.82	Calculated from Bv value (see text)
Pu	3.50E-05	0.54	1.2	4.9	1.8	CSA (2008)
Ra	9.50E-03	0.047	0.047	0.047	0.047	Sheppard et al. (2005a)
Rb	1.53E-01	0.055	0.18	0.27	0.67	CSA (2008)
Re	3.75E-01	0.01	0.04	0.06	0.15	Sheppard and Thibault (1990)
Rh	3.75E-02	0.043	0.149	0.226	0.524	CSA (2008)
Rn	0.00E+00	0	0	0	0	Noble gas, assume all values are 0
Ru	2.40E-02	0.055	0.99	0.4	66	CSA (2008)
S	5.75E-01	0.011	0.038	0.058	0.134	CAS (2008)
Sb	3.75E-04	0.045	0.15	0.24	0.54	CSA (2008)
Sc	3.75E-03	0.135	0.470	0.716	1.657	CSA (2008)
Se	1.13E-01	0.15	0.49	0.74	1.8	CSA (2008)
Si	8.75E-02	0.035	0.11	0.18	0.4	Sheppard and Thibault (1990)
Sm	2.50E-03	0.245	0.8	1.3	3	Sheppard and Thibault (1990)
Sn	1.03E-01	0.13	0.45	0.67	1.6	CSA (2008)
Sr	2.18E-01	0.013	0.02	0.11	0.15	CSA (2008)
Ta	2.50E-03	0.22	0.9	1.2	3.3	Sheppard and Thibault (1990)
Tb	7.00E-03	0.099	0.344	0.524	1.213	CSA (2008)
Tc	9.25E-01	0.00014	0.0001	0.0012	0.0015	CSA (2008)
Te	1.58E-02	0.125	0.5	0.72	1.9	CSA (2008)
Th	8.30E-04	3	3.3	5.4	89	CSA (2008)

Table B-13: Plant to Soil Bioconcentration Factors and Soil Sorption Coefficients[1]

Element	Bv (Bq/kg wet) (Bq/ kg dry)$^{-1}$	Sand K_d (m^3/kg)	Loam K_d (m^3/kg)	Clay K_d (m^3/kg)	Organic K_d (m^3/kg)	Reference
Ti	1.38E-03	0.33	1.15	1.75	4.06	Calculated from Bv value (see text)
Tl	1.00E-03	0.39	1.38	2.10	4.86	Calculated from Bv value (see text)
Tm	2.50E-03	0.24	0.82	1.26	2.91	Calculated from Bv value (see text)
U	1.70E-03	0.042	0.22	0.18	2.2	Sheppard et al. (2005b)
V	1.38E-03	0.33	1.15	1.75	4.06	Calculated from Bv value (see text)
W	1.13E-02	0.10	0.36	0.54	1.25	Calculated from Bv value (see text)
Xe	0.00E+00	0	0	0	0	Noble gas, assume all values are 0
Y	5.50E-03	0.17	0.72	1	2.6	CSA (2008)
Yb	2.50E-03	0.24	0.82	1.26	2.91	Calculated from Bv value (see text)
Zn	3.25E-01	0.2	1.3	2.4	1.6	CSA (2008)
Zr	8.00E-04	0.6	2.2	3.3	7.3	CSA (2008)

Table B-14: Criteria for Protection of Humans and Non-Human Biota from Non-Radiological Impacts

Species	Ground-water (µg L^{-1})	Note	Surface Water (µg L^{-1})	Note	Soil (µg g^{-1})	Note	Sediment (µg g^{-1})	Note
Ag	0.3	a	0.1	b, c	0.5	a	0.5	a
Al	-	-	5	c	50	g	-	-
As	13	a	5	b, c	11	a	5.9	f
B	1700	a	200	b	2	e	-	-
Ba	610	a	4	g, i	210	a	-	-
Be	0.5	a	11	b	2.5	a	-	-
Bi	-	-	-	-	20	g	-	-
Br	-	-	1700	k	10	g	-	-
Ca	-	-	1000000	d	-	-	-	-
Cd	0.5	a	0.017	c	1	a	0.6	a
Ce	-	-	22	h	53	h	19000	h
Cl	790000	a, q	120000	b, q	-	-	-	-
Co	3.8	a	0.9	b	19	a	50	a
Cr	11	a,k	1	b,l	0.4	e, l	26	a,k
Cu	5	a	1	b	62	a	16	a
Eu	-	-	10.1	j	50	j	4700	j
F	-	-	120	c	200	e, o	-	-
Fe	-	-	300	b, c	200	g, s	-	-
Gd	-	-	7.1	h	50	j	1800	h
Hf	-	-	4	n	-	-	-	-
Hg	0.1	a	0.004	c,m	0.16	a	0.17	f
I	-	-	100	b	4	g	-	-
K	-	-	53000	g, i	-	-	-	-
La	-	-	10.1	h	50	g	4700	h
Li	-	-	2500	d	2	g	-	-
Mg	-	-	82000	g, i	50	j	-	-
Mn	-	-	200	d	100	g	1100	g
Mo	23	a	40	b	2	a	-	-
Nd	-	-	1.8	h	50	j	7500	h
Nb	-	-	600	g	9	g	-	-
Ni	14	a	25	b	37	a	16	a
P	-	-	4	c	-	-	-	-
Pb	1.9	a	1	b, c	45	a	31	a
Pr	-	-	9.1	h	50	j	5800	h
S	-	-	-	-	500	e	-	-
Sb	1.5	a	20	b	1	a	3	g
Sc	-	-	1.8	p	50	j	-	-
Se	5	a	1	c	1	e, g	-	-
Sn	-	-	73	i, g	5	e	-	-
Sr	-	-	1500	i, g	33000	g	-	-
Te	-	-	20	r	250	g, t	-	-
Ti	-	-	-	-	1000	g	-	-
Tl	0.5	a	0.3	b	1	a, e	-	-
U	8.9	a	5	b	1.9	a	-	-
V	3.9	a	6	b	86	a	-	-
W	-	-	30	b	400	g	-	-

Table B-14: Criteria for Protection of Humans and Non-Human Biota from Non-Radiological Impacts

Species	Ground-water ($\mu g\ L^{-1}$)	Note	Surface Water ($\mu g\ L^{-1}$)	Note	Soil ($\mu g\ g^{-1}$)	Note	Sediment ($\mu g\ g^{-1}$)	Note
Y	-	-	6.4	h	50	j	1400	h
Zn	160	a	20	b	290	a	120	a
Zr	-	-	4	b	97	g	-	-

a ‘Full Depth Background Site Condition Standard’ for Ontario from MoE (2011). Used ‘Agricultural or Other Property Use’ values for soil.

b Lowest available Provincial Water Quality Objective(PWQO)/Interim PWQO from MoEE (1994).

c Freshwater value from from CCME (2007c).

d Irrigation water value from CCME (2007b).

e Lowest available soil value from CCME (2007a)

f Freshwater values from the Canadian Sediment Quality Guidelines for the Protection of Aquatic Life (CCME 2002).

g Lowest available for each media from ODEQ (2001).

h Maximum Permissible Concentration (MPC) from Sneller et al. (2000).

i Tier II secondary chronic value from Suter and Tsoa (1996).

j Value for La used

k Values for total chromium used.

l Values for Cr VI used.

m Values for methylmercury used

n Value for Zr used.

o Value for Fluoride used.

p Value for Nd used (lowest for all rare earth).

q Value for chloride used.

k Based on oral mouse LD50 value for Te.

s Based on value for invertebrates.

t Converted from soil solution concentration to soil concentration using K_d for sand of 0.125 m^3/kg.

\- No value available