Human Intrusion Model for the Mark II Container in Crystalline and Sedimentary Rock Environments: HIMv2.1

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ABSTRACT

Title: **Human Intrusion Model for the Mark II Container in Crystalline and Sedimentary Rock Environments: HIMv2.1**
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Abstract
The Human Intrusion Model for the Mark II Container in Crystalline and Sedimentary Rock Environments (HIMv2.1) is a model for the assessment of the dose consequences from inadvertent human intrusion into a deep geological repository for used nuclear fuel. It is intended for calculating human dose consequences at the surface as a result of a borehole intercepting a Mark II used fuel container in a repository and bringing used fuel debris to the surface.

This report documents the basis for HIMv2.1, which was implemented on the AMBER software platform. It includes the model equations and software documentation. HIMv2.1 calculates the dose consequences to members of two exposure groups:

- A drill crew handling core debris and from contaminated drill slurry (exposure from inhalation, ingestion, groundshine and external irradiation); and
- Residents living in a house on contaminated soil (exposure from groundshine, inhalation, soil and plant ingestion).

Dose consequences are evaluated for a scenario where the used fuel hazard is recognized and the site is completely remediated, and for a scenario where the used fuel hazard is not recognized and the site is not remediated. The dose consequences for the scenario where the fuel hazard is recognized are also evaluated for a higher used fuel burnup.

For the scenario where the fuel hazard is recognized, the estimated peak doses are 90 mSv for the drill crew and 0 mSv for the resident (since the site is assumed to be fully remediated). The estimated peak dose to the drill crew in this scenario for fuel with a higher burnup is 110 mSv. For the scenario where the used fuel hazard is not recognized, the estimated peak doses are 590 mSv per intrusion event for the drill crew and 580 mSv per year for the resident.

The probability of exposure is not estimated in this report. However, the probability of exposure for all scenarios would be small, and even more so for the resident since several very conservative assumptions are embedded in the stylization of the scenario (e.g., the resident is assumed to immediately start growing a garden in the contaminated soil).

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1. INTRODUCTION

The Human Intrusion Model for the Mark II container in crystalline and sedimentary rock environments (HIMv2.1) is a model for the assessment of the dose consequences from inadvertent human intrusion into a deep geological repository for used nuclear fuel. It is intended for calculating human dose consequences at the surface as a result of a borehole intercepting a Mark II used fuel container in a repository and bringing used fuel debris to the surface.

The purpose of this report is to compile the documentation for development and use of HIMv2.1 and to summarize the results of HIMv2.1.

2. PROGRAM ABSTRACT

HIMv2.1 is modelled in AMBERv5.7.1, a commercially-available dynamic compartmental modelling software that is separately developed and maintained by Quintessa Ltd. HIMv2.1 is a use (or application) of AMBERv5.7.1, developed by NWMO.

The first inadvertent human intrusion calculations in Canada were performed as part of the Environmental Impact Statement for a deep geological repository using the GENIE code (Wuschke 1996; Goodwin *et al.* 1994). CNSC Guideline G-320 (CNSC 2006) requires the consideration of human intrusion.

Ontario Power Generation (OPG) considered the impacts of human intrusion using HIMv1.1, a model developed under the SYVAC-CC4 framework (D'Andrea and Gierszewski 2004). HIMv1.1 was developed for the Third Case Study Postclosure Safety Assessment (Gierszewski *et al.* 2004). The NWMO developed HIMv2.0 (Medri 2012) to evaluate the impact of human intrusion for the postclosure safety assessments for an IV-25 container in repositories in crystalline and sedimentary rock (NWMO 2012 and NWMO 2013). It uses a similar set of equations as HIMv1.1, but is built on the AMBER v5.5 platform (selected because of ease of use and maintenance). HIMv2.1 is very similar to HIMv2.0, except that it uses the AMBERv5.7.1 platform, is designed for a different type of used fuel container (namely, the 48 bundle Mark II container rather than the 360 bundle IV-25 container) and considers additional exposure scenarios.

Specifically, HIMv2.1 considers inadvertent intrusion by a drilled borehole that intersects a container, bringing a portion of used fuel directly to the surface. The dose consequences are assessed in terms of the one-time (acute) dose to the drill crew member at the time the material is brought to surface and the annual (chronic) dose to a resident who may live and grow crops near the site after the intrusion occurred. It considers the dose consequences to these exposure groups for three different exposure scenarios; a scenario where the used fuel hazard is recognized and the drill site is completely remediated, a scenario where the used fuel hazard is not recognized and the site is not remediated, and for a scenario similar to the hazard recognition scenario, but for used fuel with a higher discharge burnup. The models do not calculate either the probability of the human intrusion scenario or the resulting risk.

3. THEORY

The following section outlines the HIMv2.1 model and its assumptions and equations. This section focuses on the HIMv2.1 theory, not the AMBERv5.7.1 theory. The AMBER theory is available in the AMBER Reference Guide (Quintessa Ltd. 2014a), which contains a description of the physical problems that AMBER is intended to solve and its solution techniques.

3.1 MODEL DESCRIPTIONS AND ASSUMPTIONS

The starting assumption is that at some time after repository closure, an exploratory borehole drill has intercepted a container in the repository and has brought used fuel debris to the surface mixed in with the drill slurry and as a section of intact drill core. Normal practice is for drill mud to be contained at the site initially (for example, in a holding tank), and to be ultimately disposed of properly. However, in HIMv2.1, the slurry is conservatively assumed to be spilled around the drill rig. The contaminated slurry becomes mixed with the surface soil, as well as with subsequent drilled material. The used fuel debris is therefore assumed to be uniformly mixed through a small near-surface volume of material around the rig. The drill crew member handles the core sample for an hour, leading to a direct external exposure. Exposure to the intact core is modelled by the point source approximation.

The intrusion is inadvertent - the presence of the repository and the used fuel is assumed not known. Inadvertent intrusion into the repository would be prevented by institutional controls and even by passive societal memory (and also by the lack of resources at the site). These could be maintained indefinitely, which would prevent any inadvertent intrusion. However for safety assessment purposes, it is assumed that institutional control is maintained until 300 years after repository closure, at which point intrusion becomes possible.

At repository closure, the age of the used fuel is estimated to be 125 years, assuming an age of 30 years[1] at completion of operations (including age at placement and balance of operating period), an extended monitoring period of 70 years and a decommissioning and closure period of 25 years. In the HIMv2.1 standard input data, initial inventories are for 30 year-old fuel, such that repository postclosure period starts 95 years after the start of decay calculations.
Model details and values discussed in Appendix A.

The exposure scenarios are stylized; they include approximate representations of inhalation, ingestion and direct exposure pathways such that the overall dose estimates are indicative of potential doses. Three different exposure scenarios are analysed.

3.1.1 Scenario 1: Recognition of the Used Fuel Hazard

In Scenario 1, drilling operations are assumed to take place for two days after the intrusion event (two 12-hour shifts), at which point the drill crew becomes aware of the hazard, immediately ceases operations, and vacates the site.

In addition to the external exposure to the core sample, the drill crew is exposed through groundshine, inhalation of contaminated dust and inadvertent ingestion of contaminated soil from the mixed volume of near-surface material. The drill crew member is assumed not to wear a mask.

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[1] Because the assumed intrusion occurs about 400 or more years after placement of the used fuel in the repository, the age of the fuel at placement (i.e. 10 years vs. 30 years) has little effect on the results of the assessment since the short-lived radionuclides will have decayed in either case.

The site is then assumed to be completely remediated by qualified experts, whose dose is not considered because they are assumed to take appropriate precautions. Because the site is remediated, the resident is unaffected by the incident.

3.1.2 Scenario 2: No Recognition of the Used Fuel Hazard

In Scenario 2, drilling operations are assumed to continue for 14 working days. The used fuel hazard is not identified and the debris deposited on the surface around the drilling rig is assumed to remain in place without remediation, subject only to radioactive decay and to leaching. Both the one-time acute dose to a drill crew member and the annual (chronic) dose to a local resident are calculated.

In addition to the external exposure to the core sample, the drill crew is exposed through groundshine, inhalation of contaminated dust and ingestion of contaminated soil from the mixed volume of near-surface material. The drill crew member is assumed not to wear a mask.

The resident lives around the contaminated site after the original intrusion, and grows food on the contaminated soil. The resident is exposed to the contaminant through groundshine, dust inhalation and through ingestion of contaminated plants and soil. It is assumed that the contaminated area is relatively small (and therefore has a higher concentration of contaminants), and so an allowance is made for the fraction of time that the resident is exposed to the contaminated site on an annual basis. Because the resident case assumes that the exposure occurs in the first year after intrusion before leaching has any significant effect, leaching is conservatively ignored. Leaching considers the portion of precipitation that draws downwards into the deeper soil (i.e., not the portion within the plant rooting depth that evapotranspires). However, the resident annual dose is also examined for an assumed resident arrival time of 100 years after intrusion, in which case the effect of leaching is included.

3.1.3 Scenario 3: Used Fuel with a Higher Burnup

Scenario 3 is the same as Scenario 1, except that a higher fuel burnup is assumed (i.e., 280 MWh/kgU instead of 220 MWh/kgU). 220 MWh/kgU corresponds to about the 80th percentile burnup of all Canadian used fuel, while 280 MWh/kgU corresponds to about the 99th percentile burnup (Wilk 2013).

3.2 LIMITATIONS

Simple Models: The models used are stylized. They are intended to include the main exposure paths from intrusion, but are approximate. For example, exposures through animals, irrigation water or building materials are not considered. The resulting doses will therefore be indicative and illustrate the importance of the various pathways.

Intrusion Probability: The model does not consider the probability of intrusion into the repository. Thus, the results show the impact of intrusion if intrusion occurs, but do not reflect the likelihood of intrusion as a function of time after placement.

External Irradiation: The model calculates an effective soil concentration assuming the used fuel debris is mixed with drilling mud and deposited in a finite area around the drill site. From this, the groundshine dose is calculated assuming a semi-infinite contamination. External irradiation exposure to the drill crew from the core sample is modelled using a point-source approximation. Neither groundshine nor external radiation geometry assumptions take into account shielding or finite geometry effects.

Inhalation: The contaminant concentration in dust is based on the local contamination level, and does not include any dilution or dispersion effects from uncontaminated areas.

Closed Borehole: The model assumes that the drill hole is closed and sealed afterwards and does not consider possible long-term leakage through a poorly sealed borehole.

Probabilistic Assessment: The model does not perform probabilistic assessments. Only deterministic cases are evaluated.[2]

3.3 PARAMETERS AND EQUATIONS

3.3.1 Contaminant Transport

HIMv2.1 is based on dynamic compartmental models that represent the migration and fate of contaminants in a system. Contaminants included in the model were selected using a screening approach that is described in Appendix A.3. The model has two compartments, representing a retrieved core sample containing wastes, and a contaminated soil volume containing contaminated drilling slurry.

For a given radionuclide *i*;

$$\frac{dN_{soil}^{i}(t)}{dt} = \lambda^{i+1} N_{soil}^{i+1}(t) - \left(\lambda_{le}^{i} + \lambda^{i}\right) N_{soil}^{i}(t) \tag{3.01}$$

$$\frac{dN_{CS}^{i}(t)}{dt} = \lambda^{i+1} N_{CS}^{i+1}(t) - \lambda^{i} N_{CS}^{i}(t) \tag{3.02}$$

Where;
$N_{soil}^{i}(t)$ is the amount of radionuclide i in the soil compartment [mol];
$N_{CS}^{i}(t)$ is the amount of radionuclide *i* in the drill core sample compartment [mol];
$N_{soil}^{i+1}(t)$ is the amount of parent radionuclide i *+1* in the soil compartment [mol];
$N_{CS}^{i+1}(t)$ is the amount of parent radionuclide i *+1* in the drill core sample compartment [mol];
λ^{i+1} is the decay rate of the parent radionuclide i *+1* [1/a];
λ^{i} is the decay rate of radionuclide i [1/a]; and
λ_{le}^{i} is the leaching rate of radionuclide i (see Section 3.3.3) [1/a].

HIMv2.1 assumes that some of the radionuclides in each container are instantly released to the surface and mixed into the slurry, in proportion to their instant release fraction. The remaining radionuclides which aren't instantly released and brought to the surface are mixed into the slurry in proportion with f_I, the fraction of used fuel in each container that is damaged by the borehole and f_S, the fraction of f_I that comes to the surface as slurry. Initial inventories are taken from Tait et al. (2000) and are presented in mol/kgU and mol/kgZir. The boundary conditions for equations 3.01 and 3.02 are as follows:

$$N_{soil}^{i}(0) = M_{UF}\left(F_U I_U^{i} + F_{ZIR} I_{ZIR}^{i}\right)\left(IRF^{i} + \left(1 - IRF^{i}\right) \cdot f_I \cdot f_S\right) \tag{3.03}$$

[2] AMBER is capable of probabilistic runs, but HIMv2.1 has not been created using this capability.

$$N_{CS}^{i}(0) = M_{UF}\left(F_U I_U^i + F_{ZIR} I_{ZIR}^i\right) \cdot f_I \cdot f_C \qquad (3.04)$$

Where;

M_{UF} is the mass of used fuel in each container (including the Zircaloy cladding) [kgUF];

I_U^i is the initial inventory of radionuclide i in the used fuel [mol/kgU];

I_{ZIR}^i is the initial inventory of radionuclide i in the Zircaloy cladding [mol/kgZir];

F_U is the mass fraction of uranium to used fuel per bundle [kgU/kgUF]

F_{ZIR} is the mass fraction of Zircaloy to used fuel per bundle [kgZir/kgUF];

IRF_i is the instant release fraction for each radionuclide i [-];

f_I is the fraction of used fuel in container that is damaged by the borehole (calculated in Appendix A.1) [-];

f_S is the fraction of f_I that is brought to surface as slurry [-]; and

f_C is the fraction of f_I that is brought to surface as core sample [-].

Equations 3.03 and 3.04 show that radionuclides exist in the soil and the core sample at t=0. While in reality this is not so, the model makes this simplifying assumption since it is numerically convenient and has no effect on the results. The only process affecting the concentration in the soil and the core sample up to the time of intrusion is radioactive decay (and in-growth), which occurs independently of the location of the contaminants. t=0 refers to the time at which the used fuel is placed in the repository.

3.3.2 Branching Ratios

In HIMv2.1, decay into more than one daughter is handled by setting the decay rate to reflect the probability of decay into that daughter. The relative probability of A decaying into B or C is not given explicitly, but is implicit in the decay rates given for the A→B and A→C processes. The decay rate for the production of the daughters is given by BR·λ, where BR is the branching ratio of the decay and λ is the decay rate.

3.3.3 Leaching Rate

Leaching considers contaminant loss with the portion of precipitation that draws downwards into the deeper soil (i.e. beyond the plant rooting depth). This leached contaminant is subject to further dilution and decay such that it is assumed to not significantly contribute to the human dose. The leaching transfer is set to be inactive by default, in order that the dose to the resident in the first year after intrusion may be maximized. In this mode, the model gives the doses as a function of intrusion time. If the effects of leaching on the resident dose rate are desired, the user may activate the leaching transfer. In this mode, the model gives the resident dose as a function of time since intrusion.

The leaching rate [1/a] is computed as:

$$\lambda_{le}^{i} = \frac{Q_{infl}}{(WCs+\rho_S \cdot KD_S^i)\cdot Z_R} \cdot f(t_{intr}) \qquad (3.05)$$

Where:

Q_{infl} is the net infiltration rate of water through the soil [m/a];

WCs is the water content of soil [m^3/m^3];

ρ_s is the surface soil bulk dry density [kg$_{soil}$/m^3];

KD_S^i is the soil distribution coefficient for radionuclide i [m^3/kg_{soil}];
Z_R is the depth of contaminated soil in the resident case [m]; and
$f(t_{intr})$ is a time-dependent parameter with value 0 before intrusion and 1 after intrusion [-].

3.3.4 Concentration Equations

A. Soil Concentration

The total contaminant concentration [mol/kg_{soil}] of radionuclide i in the soil for each case j (j = DC for drill crew and j = R for resident) is computed as:

$$Csoil_j^i = \frac{N_{soil}^i(t)}{A_j Z_j \rho_s} \tag{3.06}$$

Where:
A_j is the surface area of the contaminated soil in each case j [m^2]
Z_j is the depth of contaminated soil in each case j [m].

Because radon is a gas, and the fuel debris is assumed to be in shallow soil, it is assumed that Rn-222 will have been released into the atmosphere and dispersed. Therefore, the contribution from Rn-222 and its short-lived daughters is not considered for the resident exposure. Long-lived daughters of Rn-222 are present in the fuel debris and are assumed to remain in the soil.

B. Air Concentration

The concentration [mol/m^3] of radionuclide i in the air for each cases j is computed as:

$$Cair_j^i = Csoil_j^i \cdot ADL_j \tag{3.07}$$

Where:
ADL_j is the atmospheric dust loading for each case j [kg_{soil}/m^3], which is assumed to originate completely from the contaminated soil.

C. Plant Concentration

The concentration [mol/kg_{plant}] of radionuclide i in plant for the resident case is computed as:

$$Cplant_R^i = Csoil_R^i \cdot BV^i \tag{3.08}$$

Where:
BV^i is the (wet)plant/(dry)soil concentration ratio [kg_{soil}/kg_{plant}].

3.3.5 Dose Equations

The dose to the drill crew member is a one-time (acute) dose, while the dose to the resident is received over the course of a year (chronic). Doses from each pathway (inhalation, ingestion, groundshine and external) are calculated individually and then summed.

A. Inhalation Dose

The inhalation dose [Sv] due to radionuclide i for case j is calculated as follows:

$$Dinh_j^i = Cair_j^i \cdot DF_{inh}^i \cdot INH \cdot T_j \cdot \lambda^i \cdot Na \tag{3.09}$$

Where:
DF_{inh}^i is the inhalation dose coefficient for radionuclide i [Sv/Bq];
INH is the inhalation rate [m^3/a];
T_j is the exposure time for case j [a];
λ^i is the decay rate of radionuclide i [1/a]; and
Na is Avogadro's Number [1/mol].

B. Ingestion Dose

The ingestion doses [Sv] due to radionuclide i for each case are:

$$Ding_{DC}^i = Usoil_{DC} \cdot Csoil_{DC}^i \cdot DF_{ing}^i \cdot \lambda^i \cdot Na \tag{3.10}$$

$$Ding_R^i = \left(Usoil_R \cdot Csoil_R^i \cdot f_R + Uplant \cdot Cplant_R^i \cdot f_{Lf}\right) \cdot DF_{ing}^i \cdot \lambda^i \cdot Na \tag{3.11}$$

Where:
$Usoil_{DC}$ is amount of soil ingested by the drill crew member [kg_{soil}];
DF_{ing}^i is the ingestion dose coefficient for radionuclide i [Sv/Bq];
$Usoil_R$ is the amount of soil ingested by the resident in a year [kg_{soil}];
f_R is the fraction of soil ingested by the resident that is contaminated [-];
$Uplant$ is the amount of plant food consumed in a year by resident [kg_{plant}]; and
f_{Lf} is the fraction of plant food grown locally on contaminated soil [-].

C. Groundshine Dose

The groundshine dose is modelled assuming semi-infinite contamination. The dose [Sv] due to groundshine for each radionuclide i and each case j is computed as:

$$Dgrd_j^i = Csoil_j^i \cdot DF_{grd}^i \cdot T_j \cdot \lambda^i \cdot Na \tag{3.12}$$

Where:
DF_{grd}^i is the groundshine dose coefficient for radionuclide i [(Sv/a)/(Bq/kg_{soil})].

D. External Dose

Only the drill crew member is directly exposed to the core sample. The core sample is modelled as a point-source. The dose conversion coefficients assume that the core is one meter away and do not take into account self-shielding. The dose [Sv] due to direct external exposure to the drill crew member for radionuclide i is:

$$Dext_{DC}^i = N_{CS}^i(t) \cdot DF_{ext}^i \cdot T_{CS} \cdot \lambda^i \cdot Na \tag{3.13}$$

Where:
DF_{ext}^{i} is the external dose coefficient for radionuclide i [(Sv/a)/Bq]; and
T_{CS} is the exposure time of the drill crew member to the core sample [a].

E. Total Dose

The doses [Sv] from all pathways for each radionuclide i and case j is computed as:

$$Dall_j^i = Dinh_j^i + Ding_j^i + Dext_j^i + Dgrd_j^i \tag{3.14}$$

The total dose [Sv] for each case j from all pathways and contaminants i is computed as:

$$TD_j = \sum_i Dall_j^i \tag{3.15}$$

4. VERIFICATION

4.1 AMBERv5.7.1

AMBERv5.7.1 was independently verified and the results are documented in the AMBERv5.7.1 verification summary (Quintessa Ltd. 2014c).

4.2 VERIFICATION WITH HIMv1.1

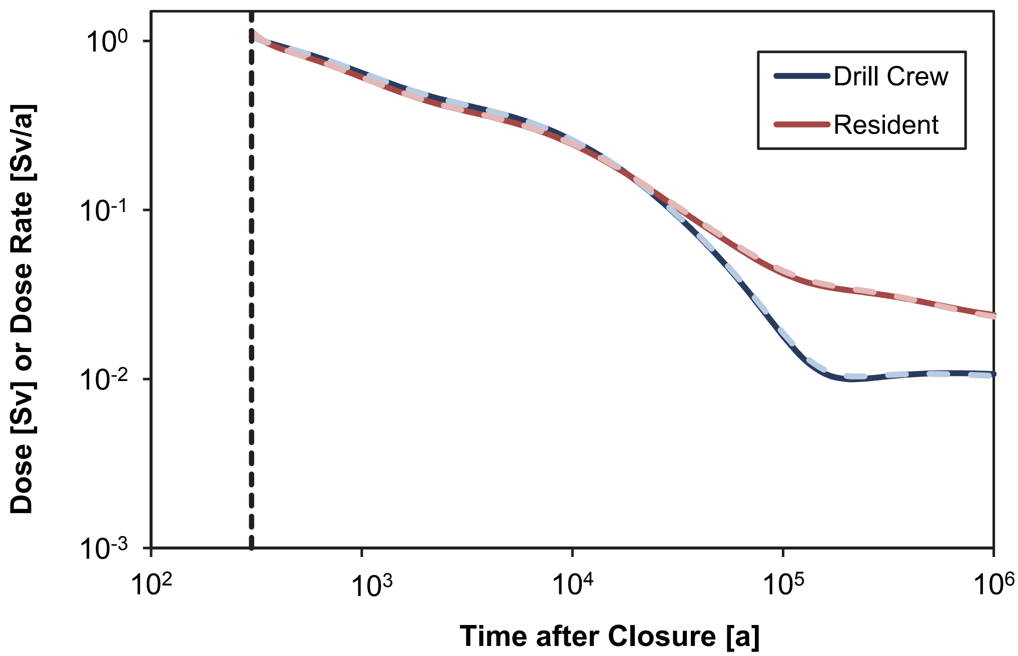
HIMv2.1 has not been directly verified against the human intrusion model developed for the Third Case Study (D'Andrea and Gierszewski 2004). This was done for HIMv2.0 (Medri 2012). However, because of the abundant similarities between HIMv2.0 and HIMv2.1, and because consistency between HIMv2.0 and HIM2.1 is demonstrated in the next Section (see Section 4.3), direct verification of HIMv2.1 with HIMv1.1 is not required.

4.3 VERIFICATION WITH HIMv2.0

Scenario 2 of HIMv2.1 was verified against the previous Human Intrusion Model (HIMv2.0, Medri 2012). To ensure that the model equations, parameters, contaminants and decays are correctly implemented in HIMv2.1, the model was run with the following changes to reflect the parameterization of HIMv2.0 (see Appendix A):

- The mass of used fuel in the container (M_{UF}) was changed to 8650 kg from 1150 kg;
- The fraction of used fuel in each container that is damaged by the borehole (f_i) was changed to 0.04 from 0.17; and
- The soil concentration of Rn-222 for the Resident exposure was included in the model (i.e., $Csoil_j^i$ for Rn-222 was set to default equation).

The results of the comparison between HIMv2.1 and HIMv2.0 are shown in Figure 4-1.

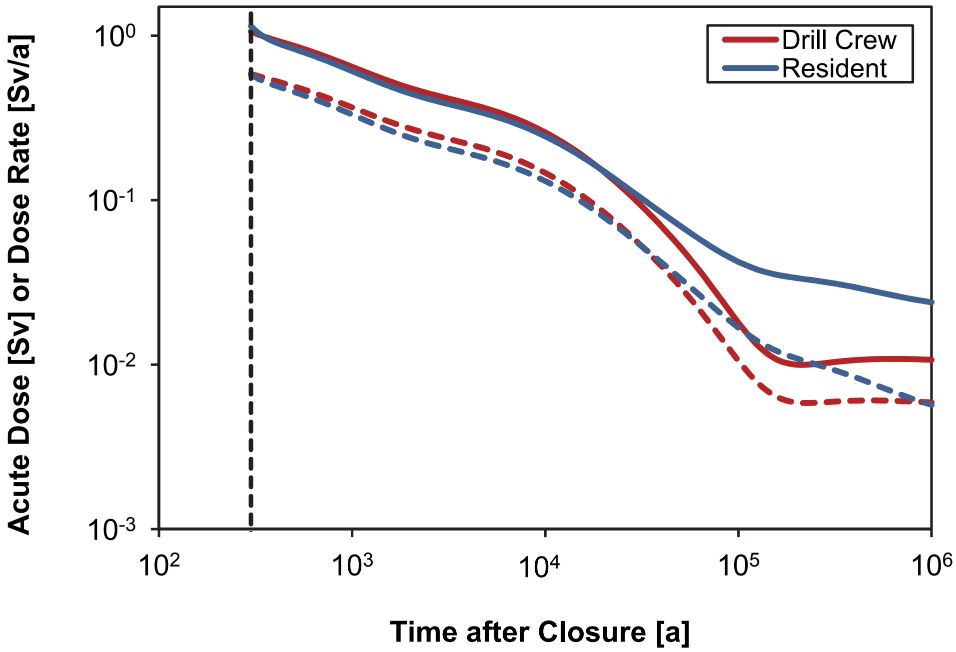


Note: HIMv2.0 results are shown with a solid line and HIMv2.1 results are shown with dotted line.

Figure 4-1: Comparison of Calculated Exposure for HIMv2.0 and HIMv2.1 using Input Values from HIMv2.0

The results of the two models are very similar. The very slight deviation that can be seen at later times is due to a correction of the Sb-125 and Sn-126 decay chains (see Table A.7 of this report compared to Table A.7 of Medri (2012), as well as Appendix A.1.4). The radionuclide screening methodology is also slightly different between the two models; however this has no effect on the resulting doses.

Figure 4-2 shows a comparison of the doses from HIMv2.0 and Scenario 2 of HIMv2.1, with both models run using their respective M_{UF}, f_i and $Csoil_j^i$ parameter values. As expected, the doses in HIMv2.1 are smaller than the doses in HIMv2.0 by a factor of approximately 1.8. This factor corresponds roughly to the ratio of intercepted and damaged used fuel masses for both models. However, because the amount of used fuel that is instantly released to the surface upon interception of the borehole depends on the amount of used fuel in the entire container (rather than the amount of used fuel that is intercepted and damaged, see Equation 3.03), the ratio of doses between the two models is not exactly equal to the ratio of damaged used fuel masses. Therefore, in HIMv2.1, radionuclides that are instantly released will contribute less significantly to total doses than in HIMv2.0, because the volume of the container is smaller in HIMv2.1. Also, the dose rate drops off more significantly after 10^5 years for the resident in HIMv2.1 since the contribution from Rn-222 in soil is not considered (see Section 3.3.4).



Note: The drill crew receives a one-time (acute) dose, while the resident receives a (chronic) dose rate. HIMv2.0 results are shown with a solid line and HIMv2.1 results are shown with dotted line.

Figure 4-2: Dose and Dose Rate Comparison between HIMv2.0 and HIMv2.1

HIMv2.1 has been verified by an independent reviewer. The following has been checked:

- Equations properly interpreted from the theory;
- Data properly copied from references;
- Data and equations properly implemented in the AMBER model;
- Additional data for Scenarios 1 and 3 have been properly implemented in the AMBER model; and
- Changes between HIM v2.0 and HIMv2.1, as described in Appendix A, properly implemented.

Given that the differences between the results of HIMv2.0 and HIMv2.1 are well understood and that the update between models was independently reviewed, HIMv2.1 is considered to be verified.

4.4 COMPARISON WITH OTHER HUMAN INTRUSION SCENARIOS

In order to determine whether the human intrusion model has been adequately stylized, a comparison with other human intrusion models from the safety assessments of various organizations is included herein.

Table 4-1 contains of brief descriptions of each of the models, including the key features that are highlighted in the models. HIMv2.0 (Medri 2012) is included in the table for comparison, although the stylization is identical to Scenario 2 of HIMv2.1.

With respect to other waste management organizations, HIMv2.1 is most similar to the SKB model. The main difference is that the SKB model also includes an open or poorly sealed borehole and subsequent use of the borehole for drinking water and irrigation as a dose pathway, where HIMv2.1 does not. However, as reported in SKB (2011), the dose consequences from using the well were insignificant compared to the dose consequences from other pathways considered; therefore the most significant SKB human intrusion dose pathways are included in HIMv2.1.

Table 4-1: Human Intrusion Pathways Considered in Recent Used Fuel Repository Safety Assessments

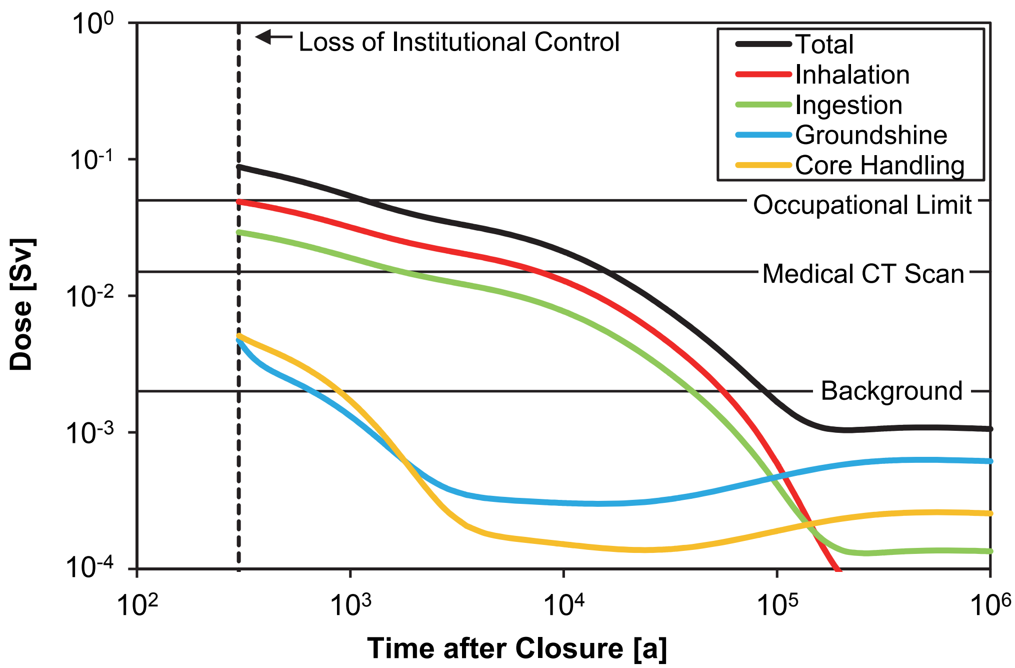
Assessment	Exposure Cases Considered	Type of Exposure	Exposure Source
SKB 2011 (Sweden)	• Drill crew[a] • Family that settles on contaminated land	• External exposure • Ingestion of water and plants • Inhalation of soil dust • External exposure (groundshine) to contaminated soil	• Cuttings, drilling water and fuel pieces on the ground. • Cuttings and slurry are spread into the soil on which the family lives. • Vegetable garden grown on contaminated soil and irrigated with contaminated water. • Open borehole used as a well.
DOE 2008 (USA)	• Reasonable Maximally Exposed Individual (resident)	• Inhalation of soil dust • Ingestion of contaminated plants, animals and water • External exposure to groundshine and cloudshine	• Open borehole leading to contamination of the aquifer and accessed by resident through well or at a surface-water discharge point and used directly for drinking or in the human food chain (such as through irrigation or watering livestock).
Gierszewski *et al.* 2004[b] (Canada)	• Drill crew • Core examination technician • Construction worker • Resident[a]	• Inhalation of soil dust • Ingestion of soil and plants • External exposure to contaminated soil	• Extracted core and slurry spread around the drill rig. • Cuttings and slurry spread into the soil on which resident lives. • Vegetable garden grown on contaminated soil.
Nagra 2002 (Switzerland)	• Resident	• Inhalation of soil dust • Ingestion of contaminated plants and animals • Ingestion of water • External exposure from soil	• Open borehole leading to contamination of the aquifer and accessed by resident through well or at a surface-water discharge point and used directly for drinking or in the human food chain (such as through irrigation or watering livestock).
JNC 2000 (Japan)	• Excavation workers	• External exposure to core sample • Inhalation of core dust	• Extracted core from borehole
Medri 2012[c] (Canada)	• Drill crew • Resident[a]	• Inhalation of soil dust • Ingestion of soil and plants • Groundshine exposure to contaminated soil • External exposure to core sample	• Extracted core and slurry spread around the drill rig. • Cuttings and slurry spread into the soil on which the resident lives. • Vegetable garden grown on contaminated soil.

a Most limiting exposure case.
b Refers to HIMv1.1 model.
c Refers to HIMv2.0 model.

5. RESULTS

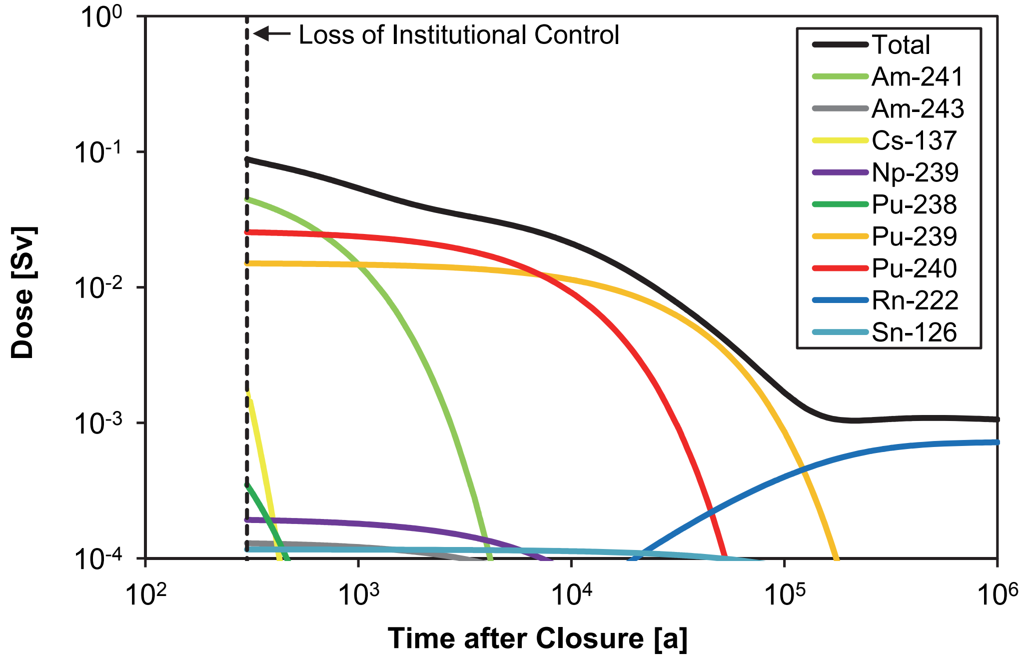
5.1 SCENARIO 1: RECOGNITION OF THE USED FUEL HAZARD

Scenario 1 is described in Section 3.1.1. Figure 5-1 shows the calculated acute dose to a drill crew member as a function of time after closure, showing a breakdown of contributing pathways. The resident is unaffected by this scenario because the site is assumed to be completely remediated. The maximum one-time dose to the drill crew, occurring at the earliest time of intrusion, is 90 mSv. Figure 5-2 shows that the total dose is dominated by Am-241 for the first 300 to 1000 years, by Pu-239 and Pu-240 from 10^3 to 10^5 years, and by the U-238 decay chain for longer times.



Note: Drill crew receives a one-time (acute) dose.

Figure 5-1: Pathways for Drill Crew Intrusion Exposure in Scenario 1

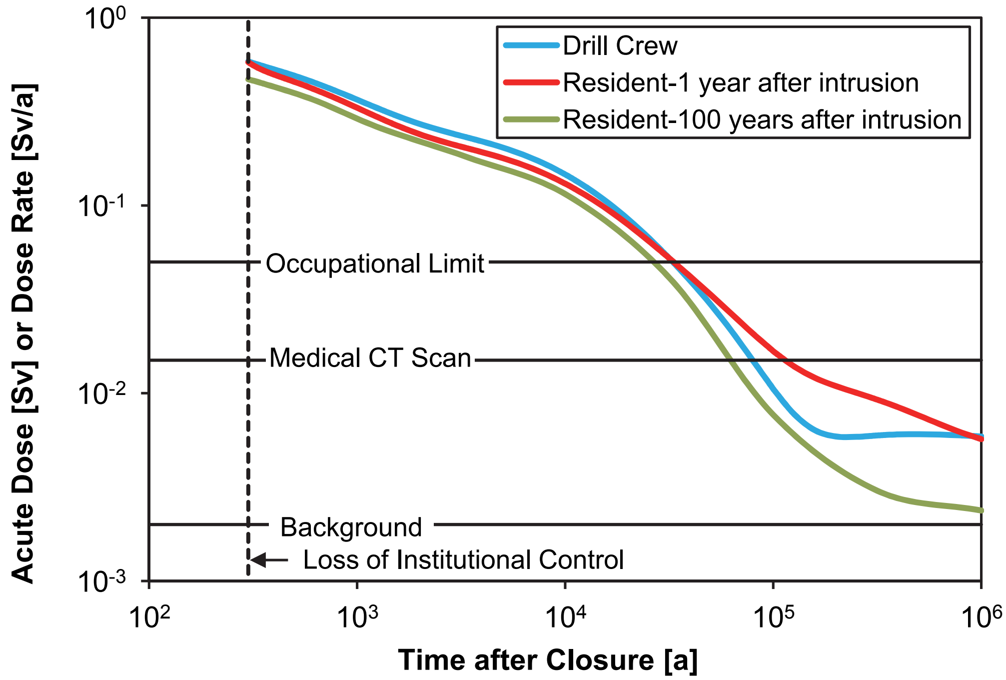


Note: Drill crew receives a one-time (acute) dose.

Figure 5-2: Radionuclides Breakdown of Drill Crew Exposure in Scenario 1

5.2 SCENARIO 2: NO RECOGNITION OF THE USED FUEL HAZARD

Scenario 2 is described in Section 3.1.2. Figure 5-3 shows the calculated acute dose to the drill crew member and chronic dose rate to the resident as a function of assumed time of intrusion after repository closure. The resident annual dose is also examined for an assumed resident arrival time of 100 years after intrusion, in which case the effect of leaching is included.



Note: The drill crew receives a one-time (acute) dose, while the resident receives a (chronic) dose rate.

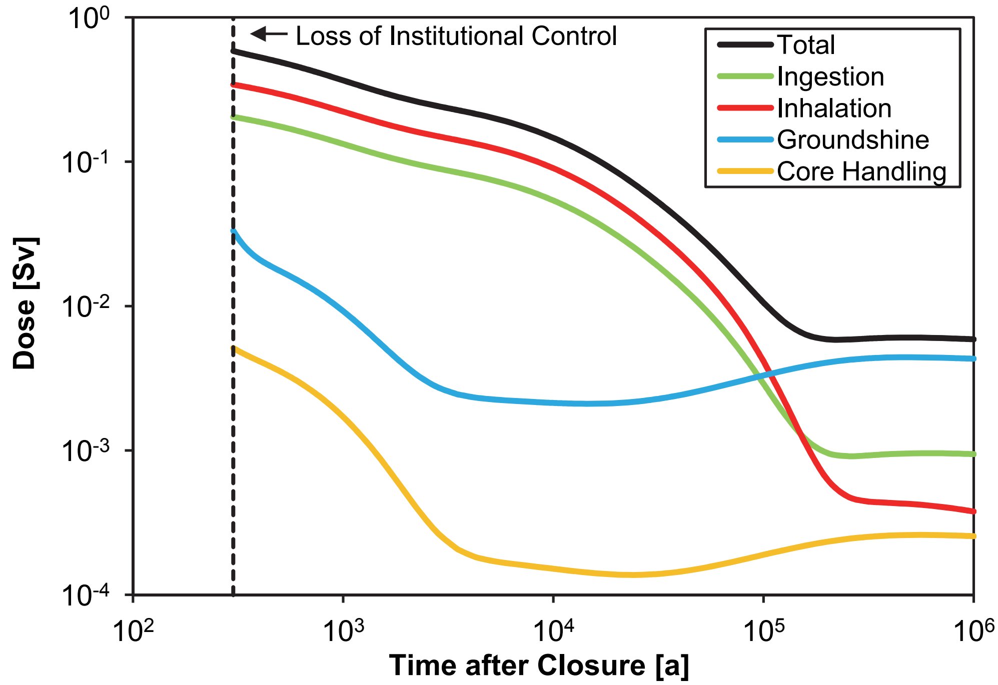
Figure 5-3: Summary of Exposures in Scenario 2

The principal results are that:

- The maximum one-time dose to the drill crew member is 590 mSv.
- The maximum annual chronic dose to the resident is 580 mSv.
- After 100 years of leaching, maximum annual dose to resident decreases to 470 mSv.
- Doses decrease as a function of the assumed time of intrusion, due to radioactive decay. Intrusion doses after about 100 000 years are in the range of 10-20 mSv.

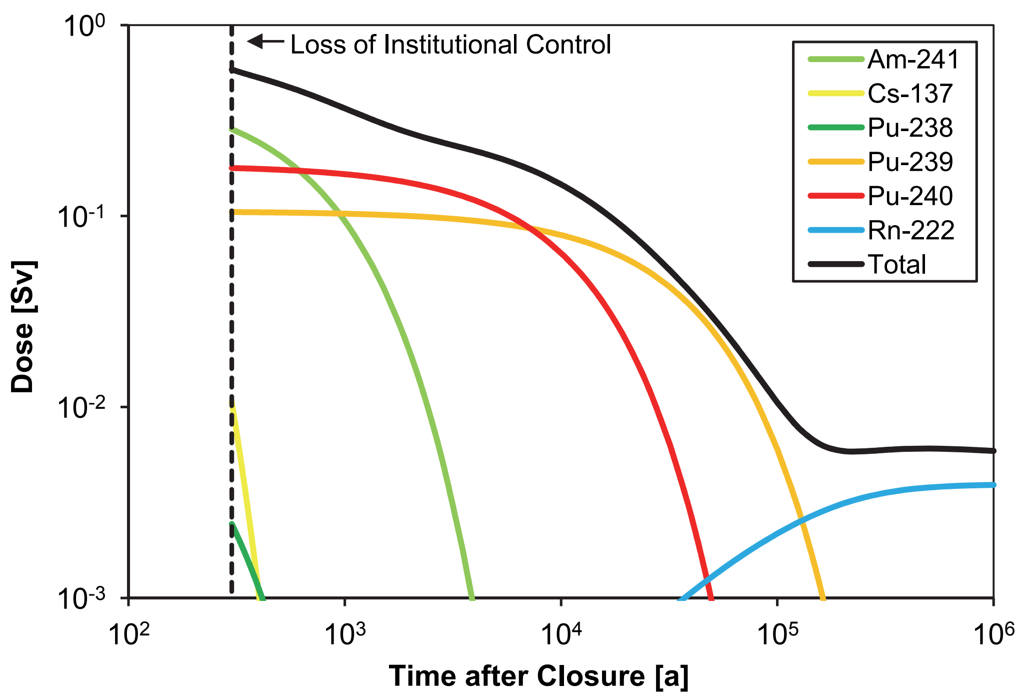
Figure 5-4 and Figure 5-6 show the breakdown of pathways for the drill crew member and the resident. Figure 5-5 and Figure 5-7 show the most significant radionuclides for each exposure case. The total dose for both groups tends to be dominated by Am-241 for the first 300 to 1000 years, by Pu-240 and Pu-239 from 1000 to 100,000 years, and by the U-234, U-238 and Pu-241 decay chains for longer times. Many of the decay products at these longer times contribute on the order to 10^{-4} Sv or 10^{-4} Sv/a, and are therefore not visible in Figure 5-5 and Figure 5-7 given the lower bounds of the vertical axes.

At times beyond about 100,000 years, the consequences are similar to those that might result from similar inadvertent drilling into an equivalent amount of natural uranium.



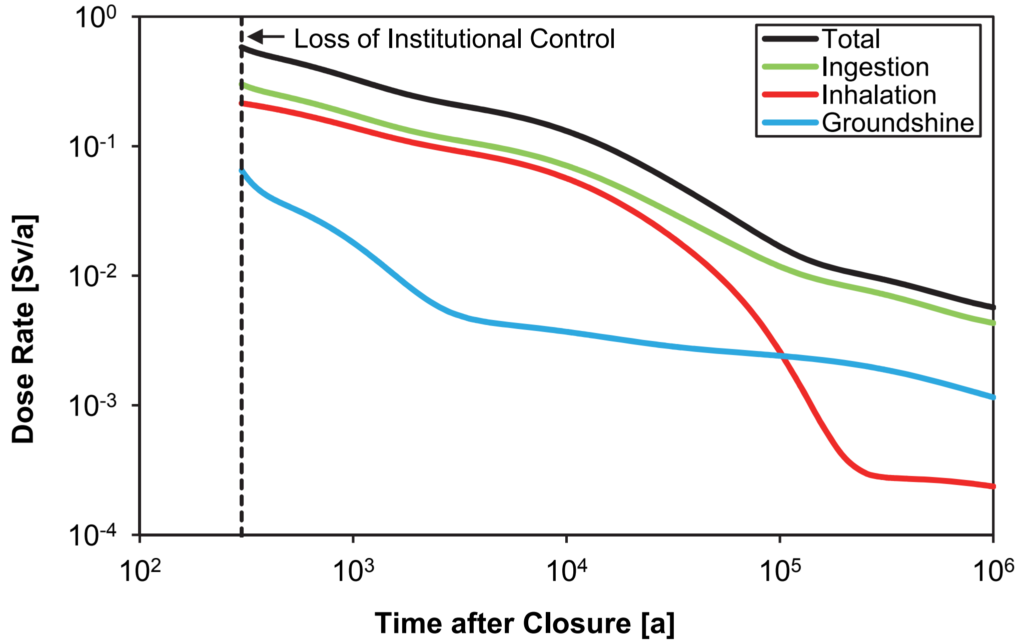
Note: Drill crew receives a one-time (acute) dose.

Figure 5-4: Pathways for Drill Crew Exposure in Scenario 2



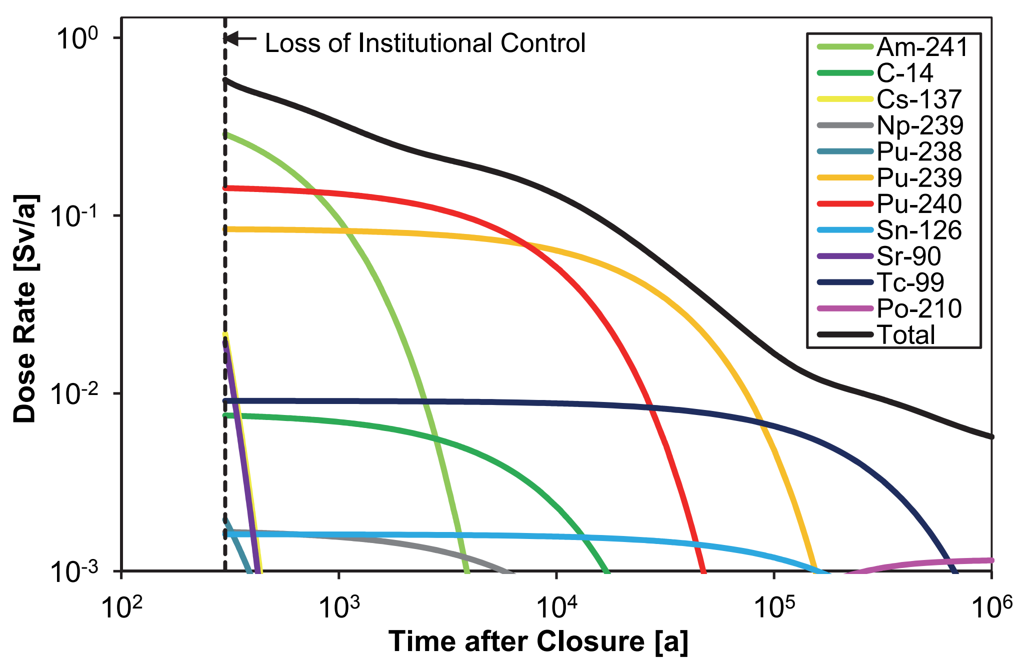
Note: Drill crew receives a one-time (acute) dose.

Figure 5-5: Radionuclides Breakdown for Drill Crew Exposure in Scenario 2



Note: Resident receives a chronic dose rate.

Figure 5-6: Pathways for Resident Exposure in Scenario 2



Note: Resident receives a chronic dose rate.

Figure 5-7: Radionuclides Breakdown for Resident Exposure in Scenario 2

Although the likelihood of these exposures is not estimated in this report, the probability would be small. This is because of the influence of markers, records or societal memory that would preserve knowledge of the site, as well as the absence of resources at the site.

Furthermore, the probability of the resident exposure is even lower than that for the drill crew member since these dose rates assume contaminated material is left on the site surface and the resident starts growing a garden in that area immediately. The resident's exposure could potentially occur much longer after the used fuel was inadvertently brought to surface, assuming that the site was not remediated in the interim. In this case, the exposure would be lower due to radioactive decay and to leaching of contaminants from the near-surface. Figure 5-8 shows the dose rate to residents living near and growing crops on the contaminated site as a function of time following an intrusion that occurs 300 years after repository closure. Leaching is not a significant factor in reducing potential doses until after about 1000 years.

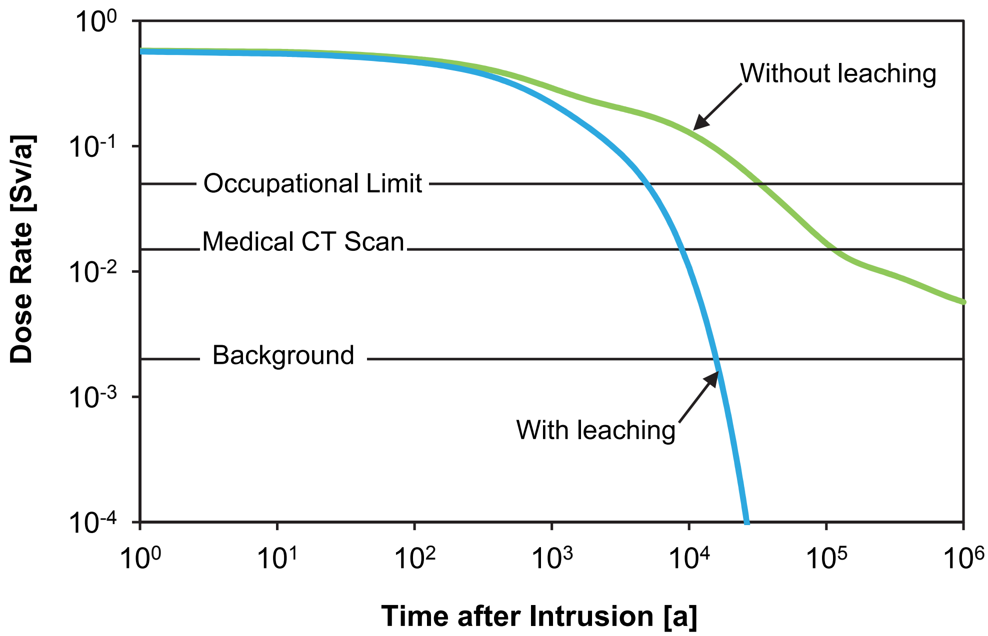
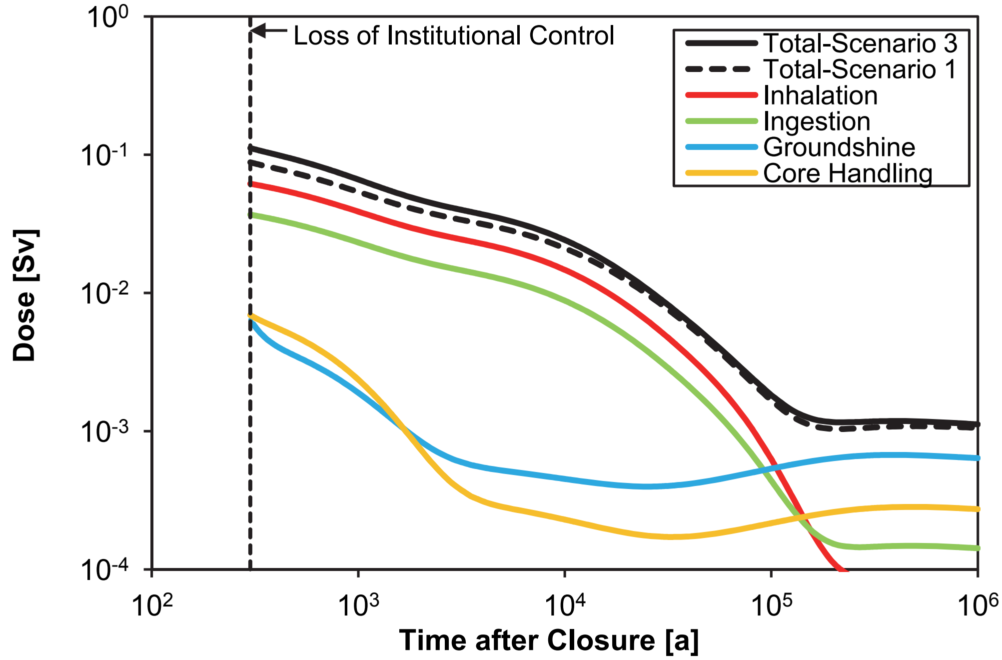


Figure 5-8: Effect of Leaching on Exposure to Resident for Intrusion at 300 years in Scenario 2

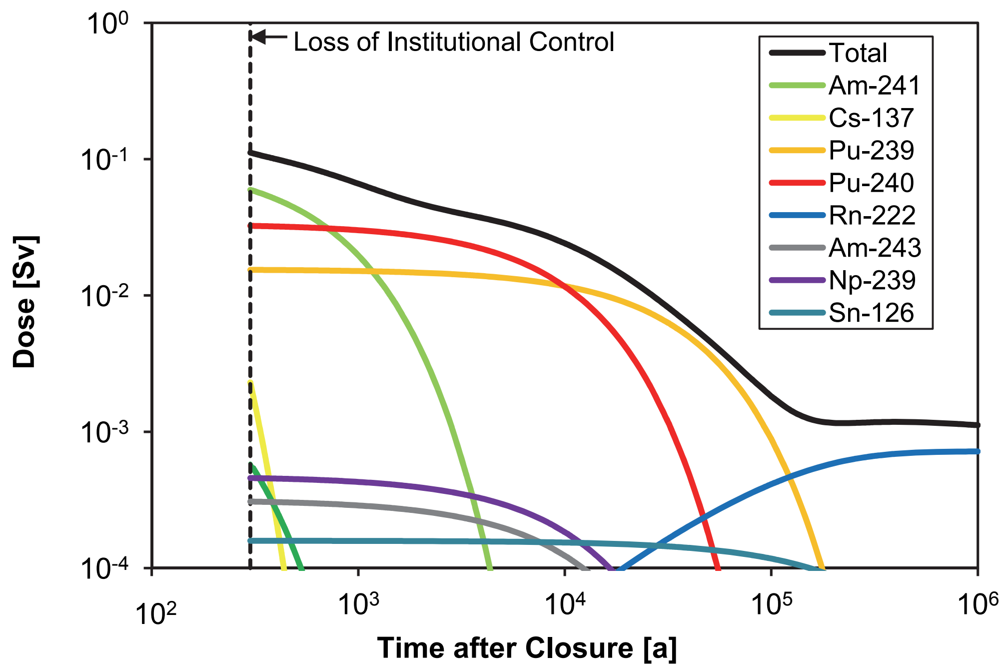
5.3 SCENARIO 3: USED FUEL WITH A HIGHER BURNUP

Scenario 3 is described in Section 3.1.3. It considers the unlikely case that the container is loaded with all 280 MWh/kgU burnup fuel. As shown in Figure 5-9, increasing the burnup increases the maximum one-time acute dose to the Drill Crew member from 90 mSv to 110 mSv. This is because the amount of actinides increases with burnup, due to the increased time for neutron absorption. Figure 5-10 shows the radionuclide breakdown of the exposure to the Drill Crew member. The increase in dose is due mainly to the higher initial inventory of Am-241, Pu-241 (which decays to Am-241) and Pu-240. The total dose rate to the drill crew member in Scenario 1 is included in Figure 5-9 for comparison.



Note: Drill crew receives a one-time (acute) dose.

Figure 5-9: Pathways for Drill Crew Exposure in Scenario 3



Note: Drill crew receives a one-time (acute) dose.

Figure 5-10: Radionuclide Breakdown of Drill Crew Exposure in Scenario 3

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APPENDIX A: MODEL DETAILS

CONTENTS

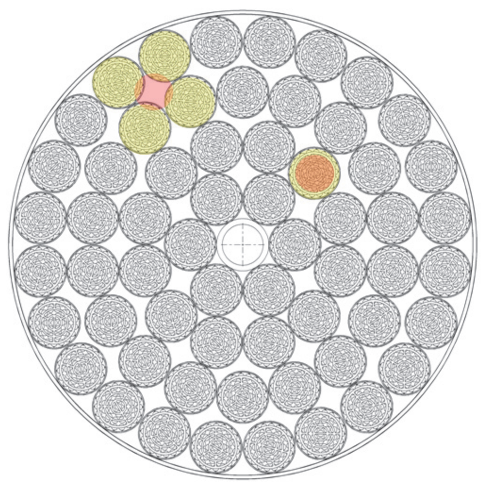
A.1 MODEL DIFFERENCES BETWEEN HIMv2.0 and HIMv2.1

A.1.1 Mass of Used Fuel in the Container

The Mark II used fuel containers have 48 fuel bundles, whereas the IV-25 used fuel containers assumed in HIMv2.0 have 360 fuel bundles (Medri 2012). As such, the mass of used fuel in each type of container is different. Given that there is 24 kg of used fuel per bundle, the mass of used fuel in the container (M_{UF}) is 1150 kg (instead of 8650 kg).

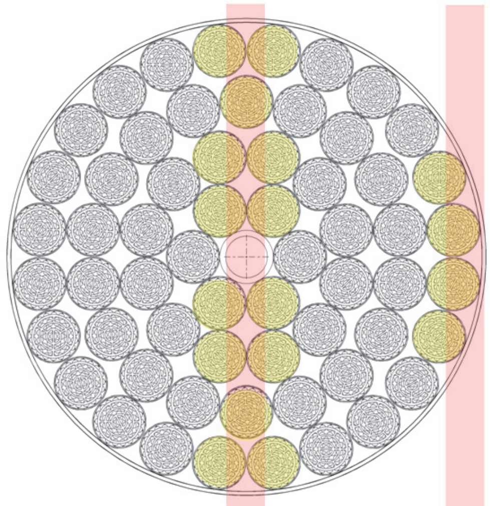
A.1.2 Fraction of Used Fuel Damaged by Borehole and Brought to Surface

In HIMv2.0, it is assumed that all the used fuel in the bundles that are even partially intercepted by the borehole is damaged. As shown in Appendix A of Medri (2012), the fraction of used fuel per container that is intercepted and damaged is assumed to be 0.04, which is the midrange value for both the horizontally and vertically placed IV-25 containers. Figure A.1 and Figure A.2 illustrate the maximum and minimum amount of fuel that is damaged for IV-25 containers assuming a completely vertical 7.6 cm borehole.



Note: The red represents the borehole and the yellow represents the damaged used fuel.

Figure A.1: Intercepted and Damaged Portions of a Vertically Placed IV-25 Used Fuel Container

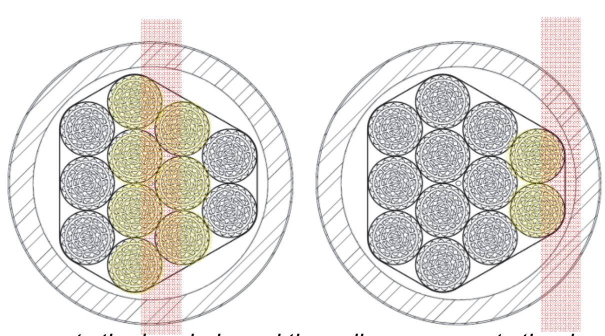


Note: The red represents the borehole and the yellow represents the damaged used fuel.

Figure A.2: Intercepted and Damaged Portions of a Horizontally Placed IV-25 Used Fuel Container

In the current assessment, the Mark II containers are placed horizontally. However, because of the difference in container size, their configuration in the placement room is different than for the horizontally placed IV-25 containers. There are two layers of containers in each placement room, and they are staggered with bentonite blocks in such a way that the containers are not stacked one above the other. Therefore, a perfectly vertical 7.6 cm borehole would only intercept one Mark II container perpendicularly to its side.

Approximately two fuel bundles would be damaged if the borehole were to intercept the container at its side. If the borehole were to intercept the container down the middle, seven fuel bundles would be damaged. Furthermore, if the borehole were to intercept the container between two layers of bundles, 14 bundles would be damaged. Figure A.3 illustrates the two interception scenarios. Because there are 48 bundles per container, the fraction of intercepted and damaged fuel bundles ranges from 0.04 (2/48) to 0.29 (14/48), with a midrange value of 0.17.



Note: The red represents the borehole and the yellow represents the damaged used fuel.

Figure A.3: Intercepted and Damaged Portions of the Horizontally Place Mark II Used Fuel Container

For HIMv2.1, the fraction of used fuel per container that is intercepted and damaged (f_I) is assumed to be 0.17.

A.1.3 Additional Scenarios

HIMv2.1 considers three different exposure scenarios.

Scenario 1 evaluates the dose consequence to the drill crew member when the hazard is identified within 2 working days, at which point the drill crew vacates the site instead of staying at the site for 14 working days (as assumed in Scenario 2, where there hazard is not identified). As such, the inadvertent soil ingestion amount ($Usoil_{DC}$) is reduced to 6.6×10^{-4} kg and the inhalation duration (T_{DC}) in reduced to 2.47×10^{-3} a (see Table A.4). Furthermore, because the site is assumed to be completely remediated, the resident's soil is assumed to be uncontaminated. Therefore, the soil concentration for the resident ($Csoil_j^i$) is set to 0.

Scenario 2 is very similar to the scenario modelled in HIMv2.0, except that the contribution of Rn-222 in the soil to the resident's exposure is not included. This is because radon is a gas, and it can be assumed that within a few hours of mixing the fuel into the resident soil, Rn-222 will have been released into the atmosphere and its short-lived daughters will have decayed. Therefore, the soil concentration ($Csoil_j^i$) of Rn-222 for the resident exposure in Scenario 2 is set to 0.

Scenario 3 is similar to Scenario 1, except the dose consequences are calculated for used fuel with a burnup of 280 MWh/kgU instead of 220 MWh/kgU. Therefore, changes to the drill crew inadvertent soil ingestion amount ($Usoil_{DC}$), the drill crew inhalation duration (T_{DC}) and the resident's soil concentration ($Csoil_j^i$) are the same as the changes described for Scenario 1. In addition, the radionuclide inventory of Uranium (I_U^i) and of Zircaloy (I_{ZIR}^i) are changed to the 280 MWh/kgU burnup values instead of the 220 MWh/kgU burnup values (See Table A.6).

For ease of use of HIMv2.1 and for data quality control, the following scenario–specific parameters are added to HIMv2.1:

Scenario 1: $Usoil_{DC}\_S1$, $Csoil_j^i\_S1$, T_{DC}_S1, $I_U^i\_S1$, and $I_{ZIR}^i\_S1$
Scenario 2: $Usoil_{DC}\_S2$, $Csoil_j^i\_S2$, T_{DC}_S2, $I_U^i\_S2$, and $I_{ZIR}^i\_S2$
Scenario 3: $Usoil_{DC}\_S3$, $Csoil_j^i\_S3$, T_{DC}_S3, $I_U^i\_S3$, and $I_{ZIR}^i\_S3$

Each of these new scenario-specific parameters correspond to the values described above. To run each scenario, the User of HIMv2.1 replaces the parameters of $Usoil_{DC}$, $Csoil_j^i$, T_{DC}, I_U^i, and I_{ZIR}^i with the scenario-specific parameters.

A.1.4 Branching Ratios

Branching ratios and decay constants were corrected to ensure the sum of all branching ratios in HIMv2.1 for each radionuclide is equal to 1. This specifically affects Ac-227, Am-242m, Pu-241, Sb-125 and Sn-126 (see Table A-7). These changes have no significant impact on the model results.

A.1.5 Screening Methodology

The screening methodology for HIMv2.1 (described in Appendix A.3) resulted in the addition of Bi-210 and the exclusion of Bi-208, Ca-41, Cm-246, Fe-55, Mo-93, Nb-91, Ni-59, Pm-145, Pm-146, Pt-193, Pu-236, Rh-102, Se-79, Sm-147, Sn-121, Sn-121m, Tl-204 and Tm-171, as compared to the radionuclides that were used in HIMv2.0. These changes have no significant impact on the model results.

A.2 PARAMETER INPUT VALUES

The tables in this appendix contain values for all parameters in HIMv2.1. Differences between HIMv2.0 and HIMv2.1 are highlighted.

Table A.1: Parameter Values Related to Used Fuel Quantities

Symbol	Parameter	Value	Reference
M_{UF}	Mass of used fuel in each container [kgUF]	1150*	48 bundles per container and 24.04 kg used fuel per bundle (Garisto et al. 2012). Includes UO_2 and Zircaloy cladding.
F_U	Mass fraction of uranium to used fuel per bundle [kgU/kgUF]	0.801	Garisto *et al.* (2012); 19.25 kg uranium, 2.59 kg oxygen and 2.2 kg zircaloy per bundle.
F_{ZIR}	Mass fraction of zircaloy to used fuel per bundle [kgZir/kgUF]	0.0915	Garisto *et al.* (2012); 19.25 kg uranium, 2.59 kg oxygen and 2.2 kg zircaloy per bundle.
f_I	Fraction of used fuel in container that is damaged by borehole [-]	0.17*	See Appendix A.1.2 for calculation.
f_C	Fraction of damaged used fuel brought to surface as core [-]	0.4	Estimated from a typical coring drill bit with an outer diameter of 7.6 cm and an inner diameter of 4.8 cm.
f_S	Fraction of damaged used fuel brought to surface as slurry [-]	0.3	Estimated, assuming half of the remaining damaged used fuel stays behind in borehole and half is brought to surface with slurry.

*HIMv2.1 values different from HIMv2.0 values.

Table A.2: Parameter Values Related to the Leaching Transfer

Symbol	Parameter	Value	Reference
Q_{infl}	Net infiltration rate of water through the soil [m/a]	0.325	CSA (2008); average of Canadian Shield locations.
WCs	Water content of soil [m^3/m^3]	0.3	CSA (2008); value for clay.*
ρ_s	Surface soil bulk density [kg_{soil}/m^3]	1400	CSA (2008); value for clay.*
$f(t_{intr})$	Enables leaching to begin at time of intrusion for resident case [-]	$t \geq t_{leach}$	A Boolean function in AMBER which returns 1 if true 0 if false.
t_{leach}	Time of start of leaching [a]	1000500	Default set to 1000500 years, such that no leaching occurs until after the last result time in the model. The User may switch this value to an earlier time to activate leaching.

* Clay assumed for surface soil properties as this results in highest retention of radionuclides.

Table A.3: Parameter Values Related Soil and Air Concentration

Symbol	Parameter	Value	Reference
A_{DC}	Area of slurry for drill crew [m^2]	30	Estimated as a 6 m diameter area.
A_R	Area of slurry for resident [m^2]	80	Estimated as a 10 m diameter area.
Z_{DC}	Depth of contaminated soil for drill crew [m]	0.2	CSA (2008)
Z_R	Depth of contaminated soil for resident [m]	0.2	CSA (2008)
ADL_{DC}	Atmospheric dust loading for drill crew [kg_{soil}/m^3]	1×10^{-7}	Wuschke (1996). According to Smith *et al*. (2013), dust loadings range from 10^{-9} to 10^{-5}. Value selected represents the midrange. Note also that because contaminated soil area is relatively small, contaminated dust loading would be diluted with uncontaminated dust loading.
ADL_R	Atmospheric dust loading for resident [kg_{soil}/m^3]	3.2×10^{-8}	Geometric mean of suspended particle matter concentrations in ON, NB, QC and SK during years 1996 to 2002 (NAPS 1996 to 2002).

Table A.4: Parameter Values Related to Dose Calculations

Symbol	Parameter	Value	Reference
INH	Adult inhalation rate [m^3/a]	8400	CSA (2008)
T_{CS}	Exposure time of drill crew to core sample [a]	1.14×10^{-4}	Estimate for time to retrieve and log core from core barrel (1 hour)
T_{DC}	Exposure time for drill crew to contaminated site [a]	S1: 0.00274* S2: 0.0192* S3: 0.00274*	12 hours/day for 2 days (24 hours) 12 hours/day for 14 days (168 hours) 12 hours/day for 2 days (24 hours)
T_R	Annual exposure time for resident [a]	0.1	Assumes resident spends 10% of a year near contaminated soil; proportional to the ratio of the contaminated area to total farmland area (see below).
$Usoil_R$	Adult annual soil ingestion amount (resident) [kg_{soil}]	0.12	CSA (2008)
$Uplant$	Annual plant ingestion amount (resident) [kg_{plant}]	291	CSA (2008), Table G.9a. Includes all plants ingested by adults with the exception of dulse and honey.
$Usoil_{DC}$	Soil ingestion amount per intrusion event (drill crew) [kg_{soil}]	S1: 0.00066* S2: 0.00462* S3: 0.00066*	CSA (2008)-0.33 g/d for 2 days. CSA (2008) - 0.33 g/d for 14 days. CSA (2008)-0.33 g/d for 2 days.
f_R	Contaminated soil fraction [-]	0.1	Ratio of the contaminated soil area (A_R) to the total farmland of 1100 m^2 # required to support a family of 3
f_{Lf}	Contaminated food fraction[-]	0.1	

#Calculated from the annual plant ingestion amount ($Uplant$) and a plant yield of 0.8kg/m^2 (Garisto et al. 2012).
*HIMv2.1 values different from HIMv2.0 values.

The ingestion, inhalation and groundshine dose coefficients are presented in Table A.5 (Gobien and Garisto 2012). The inhalation and ingestion dose coefficients are based on the values in ICRP 72 (ICRP 1996), which are consistent with the recommendations of ICRP 60 (1991). The groundshine dose coefficients are based on values from Eckerman and Leggett (1996), which are also consistent with ICRP 60 (ICRP 1991). The dose coefficients of parent nuclides include contributions from daughters with half-lives less than one day, so that doses from these short-lived nuclides are included in any dose calculations involving their parent.

The external dose coefficients in Table A.5 were calculated from the mean gamma energies per decay, which are taken from ICRP 107 (ICRP 2008). Where ICRP 107 does not record photon energies above 50 keV, low intensity Internal Bremsstrahlung (IB) emissions from Browne and Firestone (1986) were used. ICRP does not account for IB emissions. Photons with individual energies below 50 keV have not been included because the equation used to calculate the dose coefficient from a dose point source substantially over-estimates the dose for energies below this value. Dose coefficients for objects at a distance of 1 m away from the point source are obtained by multiplying the mean gamma energy in MeV by the factor 1.4×10^{-13} (Sv/(Bq·MeV·h)) (Smith *et al.* 1988). This calculation method does not consider any self-shielding.

The used fuel radionuclide inventories 30 years after removal from the reactor shown in Table A-6 were obtained from Tait and Hanna (2001). Table A.7 shows the effective half-lives used in HIMv2.1 to take into account the decay branches (see Section 3.3.2). The radionuclide half-lives and branching ratios in Table A.7 were taken from the ENDF/B-VII.1 Library (Chadwick et al. 2011) and ICRP (2008), respectively.

Table A.8 lists the plant/soil concentration ratios, the soil distribution coefficients and the instant release fractions.

Table A.5: Dose Coefficients

Radionuclide	Ingestion Dose Coefficient [Sv/Bq]	Inhalation Dose Coefficient [Sv/Bq]	Groundshine Dose Coefficient [(Sv/a)/(Bq/kg)]	External Dose Coefficient [(Sv/a)/Bq]
Symbol	DF_{ing}^{i}	DF_{inh}^{i}	DF_{grd}^{i}	DF_{ext}^{i}
Ac-225	2.43×10^{-8}	8.53×10^{-6}	3.20×10^{-7}	3.05×10^{-10}
Ac-227	1.10×10^{-6}	5.50×10^{-4}	7.97×10^{-10}	1.05×10^{-12}
Ag-108m	2.30×10^{-9}	3.70×10^{-8}	2.44×10^{-6}	1.98×10^{-9}
Am-241	2.00×10^{-7}	9.60×10^{-5}	1.00×10^{-8}	3.40×10^{-11}
Am-242m	1.90×10^{-7}	9.20×10^{-5}	1.24×10^{-8}	1.60×10^{-11}
Am-243	2.00×10^{-7}	9.60×10^{-5}	3.36×10^{-8}	7.79×10^{-11}
Ar-39	0.00×10^{0}	0.00×10^{0}	2.17×10^{-10}	1.31×10^{-13}*
Ba-133	1.50×10^{-9}	1.00×10^{-8}	4.92×10^{-7}	4.67×10^{-10}
Bi-210#	1.30×10^{-9}	9.30×10^{-8}	1.47×10^{-9}	3.78×10^{-16}
C-14	5.80×10^{-10}	5.80×10^{-9}	2.97×10^{-12}	2.28×10^{-15} *
Cd-113m	2.30×10^{-8}	1.10×10^{-7}	1.63×10^{-10}	1.87×10^{-13}
Cl-36	9.30×10^{-10}	7.30×10^{-9}	6.72×10^{-10}	7.42×10^{-14} *
Cm-242	1.20×10^{-8}	5.90×10^{-6}	3.47×10^{-11}	2.22×10^{-14}
Cm-243	1.50×10^{-7}	6.90×10^{-5}	1.44×10^{-7}	2.70×10^{-10}
Cm-244	1.20×10^{-7}	5.70×10^{-5}	2.42×10^{-11}	3.04×10^{-14}
Cm-245	2.10×10^{-7}	9.90×10^{-5}	8.28×10^{-8}	1.83×10^{-10}
Co-60	3.40×10^{-9}	3.10×10^{-8}	4.17×10^{-6}	3.07×10^{-9}
Cs-134	1.90×10^{-8}	2.00×10^{-8}	2.41×10^{-6}	1.92×10^{-9}
Cs-135	2.00×10^{-9}	8.60×10^{-9}	8.68×10^{-12}	2.00×10^{-9}
Cs-137	1.30×10^{-8}	3.90×10^{-8}	8.65×10^{-7}	7.65×10^{-10}
Eu-152	1.40×10^{-9}	4.20×10^{-8}	1.79×10^{-6}	1.43×10^{-9}
Eu-154	2.00×10^{-9}	5.30×10^{-8}	1.96×10^{-6}	1.56×10^{-9}
Eu-155	3.20×10^{-10}	6.90×10^{-9}	4.37×10^{-8}	7.76×10^{-11}
H-3	1.80×10^{-11}	3.60×10^{-11}	0.00×10^{0}	0.00×10^{0}
Ho-163	1.20×10^{-6}	5.50×10^{-4}	6.06×10^{-6}	0.00×10^{0}
Ho-166m	2.00×10^{-9}	1.20×10^{-7}	2.61×10^{-6}	2.08×10^{-9}
I-129	1.10×10^{-7}	3.60×10^{-8}	2.58×10^{-9}	1.56×10^{-15} *
Ir-192	1.40×10^{-9}	6.60×10^{-9}	1.16×10^{-6}	1.05×10^{-9}
Ir-192m	3.10×10^{-10}	3.90×10^{-8}	1.86×10^{-7}	1.85×10^{-11}
Kr- 85	0.00×10^{0}	0.00×10^{0}	3.65×10^{-9}	2.74×10^{-12}
Nb-93m	1.20×10^{-10}	1.80×10^{-9}	1.99×10^{-11}	0.00×10^{0}
Nb- 94	1.70×10^{-9}	4.90×10^{-8}	2.46×10^{-6}	1.92×10^{-9}
Ni-63	1.50×10^{-10}	1.30×10^{-9}	0.00×10^{0}	8.84×10^{-18} *
Np-237	1.10×10^{-7}	5.00×10^{-5}	1.88×10^{-8}	5.61×10^{-11}
Np-238	9.10×10^{-10}	3.50×10^{-9}	8.79×10^{-7}	7.19×10^{-10}
Np-239	8.00×10^{-10}	1.00×10^{-9}	1.86×10^{-7}	2.34×10^{-10}
Os-194	3.70×10^{-9}	8.56×10^{-8}	1.42×10^{-7}	1.12×10^{-10}
Pa-231	7.10×10^{-7}	1.40×10^{-4}	4.77×10^{-8}	5.14×10^{-11}
Pa-233	8.70×10^{-10}	3.90×10^{-9}	2.54×10^{-7}	4.16×10^{-10}
Pb-210	6.90×10^{-7}	5.60×10^{-6}	5.35×10^{-10}	1.04×10^{-18} *
Pd-107	3.70×10^{-11}	5.90×10^{-10}	0.00×10^{0}	0.00×10^{0}
Pm-147	2.60×10^{-10}	5.00×10^{-9}	1.16×10^{-11}	4.23×10^{-15}
Po-210	1.20×10^{-6}	4.30×10^{-6}	1.33×10^{-11}	1.20×10^{-14}
Pu-238	2.30×10^{-7}	1.10×10^{-4}	3.15×10^{-11}	1.03×10^{-13}
Pu-239	2.50×10^{-7}	1.20×10^{-4}	7.12×10^{-11}	4.55×10^{-13}

Radionuclide	Ingestion Dose Coefficient [Sv/Bq]	Inhalation Dose Coefficient [Sv/Bq]	Groundshine Dose Coefficient [(Sv/a)/(Bq/kg)]	External Dose Coefficient [(Sv/a)/Bq]
Symbol	DF_{ing}^{i}	DF_{inh}^{i}	DF_{grd}^{i}	DF_{ext}^{i}
Pu-240	2.50×10^{-7}	1.20×10^{-4}	3.04×10^{-11}	8.80×10^{-14}
Pu-241	4.80×10^{-9}	2.30×10^{-6}	1.43×10^{-12}	1.86×10^{-15}
Pu-242	2.40×10^{-7}	1.10×10^{-4}	2.68×10^{-11}	1.12×10^{-13}
Ra-223	1.00×10^{-7}	8.71×10^{-6}	3.76×10^{-7}	4.67×10^{-10}
Ra-224	7.13×10^{-8}	3.62×10^{-6}	2.62×10^{-6}	1.89×10^{-9}
Ra-225	9.90×10^{-8}	7.70×10^{-6}	2.33×10^{-9}	8.37×10^{-14} *
Ra-226	2.80×10^{-7}	9.50×10^{-6}	7.88×10^{-9}	1.34×10^{-11}
Ra-228	6.90×10^{-7}	1.60×10^{-5}	1.53×10^{-6}	1.04×10^{-9}
Rn-222	2.50×10^{-10}	3.50×10^{-9}	2.86×10^{-6}	2.16×10^{-9}
Ru-106	7.00×10^{-9}	6.60×10^{-8}	3.37×10^{-7}	2.49×10^{-10}
Sb-125	1.10×10^{-9}	1.20×10^{-8}	6.16×10^{-7}	5.22×10^{-10}
Sb-126	2.40×10^{-9}	3.20×10^{-9}	4.34×10^{-6}	3.24×10^{-9}
Sm-151	9.80×10^{-11}	4.00×10^{-9}	1.83×10^{-13}	3.93×10^{-14} *
Sn-126	4.74×10^{-9}	2.80×10^{-8}	2.39×10^{-6}	3.51×10^{-10}
Sr-90	2.80×10^{-8}	1.60×10^{-7}	1.75×10^{-10}	1.09×10^{-13} *
Ta-182	1.50×10^{-9}	1.00×10^{-8}	2.03×10^{-6}	1.65×10^{-9}
Tc-99	6.40×10^{-10}	1.30×10^{-8}	2.93×10^{-11}	7.14×10^{-16}
Te-125m	8.70×10^{-10}	4.20×10^{-9}	3.00×10^{-9}	1.12×10^{-10}
Th-227	8.80×10^{-9}	1.00×10^{-5}	1.30×10^{-7}	1.71×10^{-10}
Th-228	7.20×10^{-8}	4.00×10^{-5}	1.94×10^{-9}	2.57×10^{-11}
Th-229	4.90×10^{-7}	2.40×10^{-4}	7.83×10^{-8}	1.78×10^{-10}
Th-230	2.10×10^{-7}	1.00×10^{-4}	2.89×10^{-10}	1.01×10^{-11}
Th-231	3.40×10^{-10}	3.30×10^{-10}	8.68×10^{-9}	5.00×10^{-11}
Th-232	2.30×10^{-7}	1.10×10^{-4}	1.23×10^{-10}	4.61×10^{-12}
Th-234	3.40×10^{-9}	7.70×10^{-9}	4.21×10^{-8}	4.83×10^{-11}
U -232	3.30×10^{-7}	3.70×10^{-5}	2.14×10^{-10}	6.30×10^{-12}
U -233	5.10×10^{-8}	9.60×10^{-6}	3.42×10^{-10}	8.05×10^{-13}
U-234	4.90×10^{-8}	9.40×10^{-6}	9.29×10^{-11}	1.69×10^{-12}
U-235	4.70×10^{-8}	8.50×10^{-6}	1.78×10^{-7}	2.17×10^{-10}
U-236	4.70×10^{-8}	8.70×10^{-6}	4.80×10^{-11}	1.65×10^{-13}
U-237	7.60×10^{-10}	1.90×10^{-9}	1.30×10^{-7}	2.66×10^{-10}
U-238	4.50×10^{-8}	8.00×10^{-6}	2.15×10^{-11}	9.60×10^{-14}
Y -90	2.70×10^{-9}	1.50×10^{-9}	1.09×10^{-8}	3.76×10^{-17}
Zr-93	1.10×10^{-9}	2.50×10^{-8}	0.00×10^{0}	0.00×10^{0}

* Low intensity Internal Bremsstrahlung emissions from Browne and Firestone (1986)

[#] Added in HIMv2.1.

Table A.6: Radionuclide Inventory at 30 years

Component	Uranium [mol/kgU]	Zircaloy [mol/kgZir]	Uranium [mol/kgU]	Zircaloy [mol/kgZir]
Scenarios	**S1 & S2 (220 MWh/kgU)**		**S3 (280 MWh/kgU)**	
Symbol	I_U^i	I_{ZIR}^i	I_U^i	I_{ZIR}^i
Ac-225	1.66×10^{-14}	-	1.86×10^{-14}	-
Ac-227	$1.57\times10^{-11\#}$	-	$1.87\times10^{-11\#}$	-
Ag-108m	$3.13\times10^{-8\#}$	$3.10\times10^{-7\#}$	$3.98\times10^{-8\#}$	$3.95\times10^{-7\#}$
Am-241	8.81×10^{-4}	-	1.18×10^{-3}	-
Am-242m	1.81×10^{-7}	-	2.98×10^{-7}	-
Am-243	2.46×10^{-5}	-	5.85×10^{-5}	-
Ar-39	6.28×10^{-8}	3.139×10^{-9}	6.97×10^{-8}	3.50×10^{-9}
Ba-133	1.91×10^{-9}	1.90×10^{-12}	2.45×10^{-9}	2.43×10^{-12}
Bi-210*	5.30×10^{-18}	-	5.23×10^{-18}	-
C-14	6.13×10^{-6}	1.90×10^{-5}	7.91×10^{-6}	2.46×10^{-5}
Cd-113m	7.09×10^{-8}	7.89×10^{-10}	1.01×10^{-7}	1.02×10^{-9}
Cl-36	9.86×10^{-6}	1.34×10^{-6}	1.25×10^{-5}	1.49×10^{-5}
Cm-242	4.70×10^{-10}	-	7.75×10^{-10}	-
Cm-243	$2.52\times10^{-8\#}$	-	$6.37\times10^{-8\#}$	-
Cm-244	6.66×10^{-7}	-	2.11×10^{-6}	-
Cm-245	$1.60\times10^{-8\#}$	-	$5.74\times10^{-8\#}$	-
Co-60	5.33×10^{-7}	5.30×10^{-7}	6.67×10^{-7}	6.63×10^{-7}
Cs-134	4.50×10^{-9}	2.20×10^{-11}	6.98×10^{-9}	2.56×10^{-11}
Cs-135	2.68×10^{-4}	9.85×10^{-8}	3.46×10^{-4}	1.53×10^{-7}
Cs-137	1.29×10^{-3}	1.89×10^{-13}	1.64×10^{-3}	4.04×10^{-13}
Eu-152	8.39×10^{-10}	7.63×10^{-14}	8.95×10^{-10}	5.81×10^{-14}
Eu-154	1.83×10^{-6}	5.43×10^{-9}	2.77×10^{-6}	4.81×10^{-9}
Eu-155	1.20×10^{-7}	2.65×10^{-10}	1.67×10^{-7}	2.38×10^{-10}
H-3	2.67×10^{-6}	2.46×10^{-7}	3.04×10^{-6}	2.89×10^{-7}
Ho-163	4.05×10^{-10}	1.34×10^{-10}	5.08×10^{-10}	1.68×10^{-10}
Ho-166m	$2.20\times10^{-8\#}$	$7.24\times10^{-9\#}$	$2.83\times10^{-8\#}$	$9.23\times10^{-9\#}$
I-129	4.23×10^{-4}	2.55×10^{-9}	5.49×10^{-4}	3.26×10^{-9}
Ir-192	5.93×10^{-13}	5.93×10^{-13}	6.15×10^{-13}	6.14×10^{-13}
Ir-192m	7.06×10^{-10}	7.05×10^{-10}	7.32×10^{-10}	7.31×10^{-10}
Kr- 85	1.07×10^{-5}	8.06×10^{-15}	1.28×10^{-5}	2.13×10^{-14}
Nb-93m	1.28×10^{-8}	3.29×10^{-8}	1.58×10^{-8}	4.21×10^{-8}
Nb- 94	4.85×10^{-7}	4.80×10^{-6}	6.21×10^{-7}	6.14×10^{-6}
Ni-63	9.33×10^{-7}	1.08×10^{-6}	1.19×10^{-6}	1.38×10^{-6}
Np-237	1.71×10^{-04}	-	2.22×10^{-4}	-
Np-238	3.34×10^{-14}	-	5.50×10^{-14}	-
Np-239	2.05×10^{-11}	-	4.87×10^{-11}	-
Os-194	5.78×10^{-12}	5.69×10^{-12}	7.49×10^{-12}	7.37×10^{-12}
Pa-231	$3.78\times10^{-8\#}$	-	$4.53\times10^{-8\#}$	-
Pa-233	5.90×10^{-12}	-	7.66×10^{-12}	-
Pb-210	8.60×10^{-15}	-	8.49×10^{-15}	-
Pd-107	6.90×10^{-4}	6.22×10^{-4}	9.87×10^{-4}	8.03×10^{-8}
Pm-147	2.08×10^{-7}	1.09×10^{-13}	2.36×10^{-7}	1.29×10^{-13}
Po-210	1.46×10^{-16}	-	1.44×10^{-16}	-
Pu-238	2.26×10^{-5}	-	3.79×10^{-5}	-
Pu-239	1.12×10^{-2}	-	1.15×10^{-2}	-

Component	Uranium [mol/kgU]	Zircaloy [mol/kgZir]	Uranium [mol/kgU]	Zircaloy [mol/kgZir]
Scenarios	**S1 & S2 (220 MWh/kgU)**		**S3 (280 MWh/kgU)**	
Symbol	I_U^i	I_{ZIR}^i	I_U^i	I_{ZIR}^i
Pu-240	5.34×10^{-3}	-	6.79×10^{-3}	-
Pu-241	2.74×10^{-4}	-	3.65×10^{-4}	-
Pu-242	$4.18\times10^{-4\#}$	-	$7.77\times10^{-4\#}$	-
Ra-223	2.24×10^{-14}	-	2.67×10^{-14}	-
Ra-224	1.10×10^{-12}	-	1.66×10^{-12}	-
Ra-225	2.46×10^{-14}	-	2.75×10^{-14}	-
Ra-226	2.35×10^{-12}	-	2.28×10^{-12}	-
Ra-228	8.37×10^{-13}	-	8.31×10^{-13}	-
Rn-222	1.54×10^{-17}	-	1.49×10^{-17}	-
Ru-106	9.52×10^{-13}	3.00×10^{-23}	1.25×10^{-12}	3.63×10^{-23}
Sb-125	1.16×10^{-8}	4.65×10^{-9}	1.51×10^{-8}	5.79×10^{-9}
Sb-126	2.46×10^{-12}	-	3.36×10^{-12}	-
Sm-151	1.46×10^{-5}	1.00×10^{-9}	1.60×10^{-5}	9.32×10^{-10}
Sn-126	5.18×10^{-5}	-	7.06×10^{-5}	-
Sr-90	7.56×10^{-4}	4.78×10^{-11}	8.97×10^{-4}	7.36×10^{-11}
Ta-182	3.21×10^{-16}	3.16×10^{-15}	4.47×10^{-16}	4.40×10^{-15}
Tc-99	2.41×10^{-3}	2.27×10^{-8}	3.02×10^{-3}	2.90×10^{-8}
Te-125m	1.64×10^{-10}	6.60×10^{-11}	2.14×10^{-10}	8.23×10^{-11}
Th-227	3.62×10^{-14}	-	4.31×10^{-14}	-
Th-228	2.10×10^{-10}	-	3.16×10^{-10}	-
Th-229	4.78×10^{-9}	-	5.34×10^{-9}	-
Th-230	1.64×10^{-8}	-	1.57×10^{-8}	-
Th-231	2.94×10^{-14}	-	1.93×10^{-14}	-
Th-232	2.10×10^{-3}	-	2.08×10^{-3}	-
Th-234	6.09×10^{-11}	-	6.07×10^{-11}	-
U -232	7.43×10^{-9}	-	1.12×10^{-8}	-
U -233	3.61×10^{-5}	-	4.00×10^{-5}	-
U-234	1.86×10^{-4}	-	1.79×10^{-4}	-
U-235	$7.24\times10^{-3\#}$	-	$4.75\times10^{-3\#}$	-
U-236	3.50×10^{-3}	-	3.85×10^{-3}	-
U-237	8.44×10^{-12}	-	1.13×10^{-11}	-
U-238	4.13×10^{0}	-	4.11×10^{0}	-
Y -90	1.97×10^{-7}	1.24×10^{-14}	2.33×10^{-7}	1.91×10^{-14}
Zr-93	1.37×10^{-3}	1.40×10^{-3}	1.67×10^{-3}	1.80×10^{-3}

[#]Median value from Tait et al. increased to account for “ring sum” correction: Ac-227 (1%), Ag-108m (2.3%), Am-243 (5%), Cm-243 (3.2%), Cm-245 (11.6%), Cm-246 (17.6%), Ho-166m (3.4%), Pa-231 (1.2%), Pu-242 (1.9%) and U-235 (1.7%) (Appendix B, Tait et al. 2000)
*Added in HIMv2.1.

Table A.7: Radionuclide Half-Lives and Branching Ratios

Nuclide	Daughter[a]	Half-Life [a]	Branching Ratio	Effective Half-Life [a]
Ac-225	*Null*[b]	2.738×10^{-2}	1	2.738×10^{-2}
Ac-227	Th-227	2.177×10^{1}	0.9862	2.208×10^{1}
Ac-227[c]	*Null*	2.177×10^{1}	0.0138	1.578×10^{3}
Ag-108m	*Null*	4.180×10^{2}	1	4.180×10^{2}
Am-241	Np-237	4.380×10^{2}	1	4.380×10^{2}
Am-242m	Cm-242	1.410×10^{2}	0.8233[c]	1.713×10^{2}
Am-242m	Pu-242	1.410×10^{2}	0.1722[c]	8.188×10^{2}[c]
Am-242m	Np-238	1.410×10^{2}	0.0045	3.133×10^{4}
Am-243	Np-239	7.370×10^{3}	1	7.370×10^{3}
Ar-39	*Null*	2.690×10^{2}	1	2.690×10^{2}
Ba-133	*Null*	1.052×10^{1}	1	1.052×10^{1}
Bi-210[c]	Po-210	1.372×10^{-2}	1	1.372×10^{-2}
C-14	*Null*	5.700×10^{3}	1	5.700×10^{3}
Cd-113m	*Null*	1.410×10^{1}	1	1.410×10^{1}
Cl-36	*Null*	3.010×10^{5}	1	3.010×10^{5}
Cm-242	Pu-238	4.461×10^{-1}	1	4.461×10^{-1}
Cm-243	Am-243	2.910×10^{1}	0.0024	1.213×10^{4}
Cm-243	Pu-239	2.910×10^{1}	0.9976	2.917×10^{1}
Cm-244	Pu-240	1.811×10^{1}	1	1.811×10^{1}
Cm-245	Pu-241	8.500×10^{3}	1	8.500×10^{3}
Co-60	*Null*	5.271×10^{0}	1	5.271×10^{0}
Cs-134	*Null*	2.065×10^{0}	1	2.065×10^{0}
Cs-135	*Null*	2.300×10^{6}	1	2.300×10^{6}
Cs-137	*Null*	3.008×10^{1}	1	3.008×10^{1}
Eu-152	*Null*	1.354×10^{1}	1	1.354×10^{1}
Eu-154	*Null*	8.601×10^{0}	1	8.601×10^{0}
Eu-155	*Null*	4.753×10^{0}	1	4.753×10^{0}
H-3	*Null*	1.232×10^{1}	1	1.232×10^{1}
Ho-163	*Null*	4.570×10^{3}	1	4.570×10^{3}
Ho-166m	*Null*	1.200×10^{3}	1	1.200×10^{3}
I-129	*Null*	1.570×10^{7}	1	1.570×10^{7}
Ir-192	*Null*	2.021×10^{-1}	1	2.021×10^{-1}
Ir-192m	*Null*	2.410×10^{2}	1	2.410×10^{2}
Kr-85	*Null*	1.076×10^{1}	1	1.076×10^{1}
Nb-93m	*Null*	1.613×10^{1}	1	1.613×10^{1}
Nb-94	*Null*	2.030×10^{4}	1	2.030×10^{4}
Ni-63	*Null*	1.012×10^{2}	1	1.012×10^{2}
Np-237	Pa-233	2.144×10^{6}	1	2.144×10^{6}
Np-238	Pu-238	5.796×10^{-3}	1	5.796×10^{-3}
Np-239	Pu-239	6.450×10^{-3}	1	6.450×10^{-3}
Os-194	*Null*	6.000×10^{0}	1	6.000×10^{0}
Pa-231	Ac-227	3.276×10^{4}	1	3.276×10^{4}
Pa-233	U-233	7.385×10^{-2}	1	7.385×10^{-2}
Pb-210	Bi-210[c]	2.220×10^{1}	1	2.220×10^{1}
Pd-107	*Null*	6.500×10^{6}	1	6.500×10^{6}
Pm-147	*Null*[c]	2.623×10^{0}	1	2.623×10^{0}
Po-210	*Null*	3.789×10^{-1}	1	3.789×10^{-1}
Pu-238	U-234	8.770×10^{1}	1	8.770×10^{1}

Nuclide	**Daughter[a]**	**Half-Life [a]**	**Branching Ratio**	**Effective Half-Life [a]**
Pu-239	U-235	2.411×10^{4}	1	2.411×10^{4}
Pu-240	U-236	6.561×10^{3}	1	6.561×10^{3}
Pu-241	Am-241	1.429×10^{1}	0.999976[c]	1.429×10^{1}[c]
Pu-241	U-237	1.429×10^{1}	0.000024[c]	5.954×10^{5}[c]
Pu-242	U-238	3.735×10^{5}	1	3.735×10^{5}
Ra-223	*Null*	3.129×10^{-2}	1	3.129×10^{-2}
Ra-224	*Null*	1.002×10^{-2}	1	1.002×10^{-2}
Ra-225	Ac-225	4.079×10^{-2}	1	4.079×10^{-2}
Ra-226	Rn-222	1.600×10^{3}	1	1.600×10^{3}
Ra-228	Th-228	5.750×10^{0}	1	5.750×10^{0}
Rn-222	Pb-210	1.047×10^{-2}	1	1.047×10^{-2}
Ru-106	*Null*	1.018×10^{0}	1	1.018×10^{0}
Sb-125	Te-125m	2.759×10^{0}	0.231	1.194×10^{1}
Sb-125[c]	*Null*	2.759×10^{0}	0.769	3.466×10^{0}
Sb-126	*Null*	3.381×10^{-2}	1	3.381×10^{-2}
Sm-151	*Null*	9.000×10^{1}	1	9.000×10^{1}
Sn-126	Sb-126	2.300×10^{5}	0.14	1.643×10^{6}
Sn-126[c]	*Null*	2.300×10^{5}	0.86	2.674×10^{5}
Sr-90	Y-90	2.879×10^{1}	1	2.879×10^{1}
Ta-182	*Null*	3.141×10^{-1}	1	3.141×10^{-1}
Tc-99	*Null*	2.111×10^{5}	1	2.111×10^{5}
Te-125m	*Null*	1.572×10^{-1}	1	1.572×10^{-1}
Th-227	Ra-223	5.114×10^{-2}	1	5.114×10^{-2}
Th-228	Ra-224	1.912×10^{0}	1	1.912×10^{0}
Th-229	Ra-225	7.340×10^{3}	1	7.340×10^{3}
Th-230	Ra-226	7.538×10^{4}	1	7.538×10^{4}
Th-231	Pa-231	2.911×10^{-3}	1	2.911×10^{-3}
Th-232	Ra-228	1.405×10^{10}	1	1.405×10^{10}
Th-234	U-234	6.598×10^{-2}	1	6.598×10^{-2}
U-232	Th-228	6.890×10^{1}	1	6.890×10^{1}
U-233	Th-229	1.592×10^{5}	1	1.592×10^{5}
U-234	Th-230	2.455×10^{5}	1	2.455×10^{5}
U-235	Th-231	7.038×10^{8}	1	7.038×10^{8}
U-236	Th-232	2.342×10^{7}	1	2.342×10^{7}
U-237	Np-237	1.848×10^{-2}	1	1.848×10^{-2}
U-238	Th-234	4.468×10^{9}	1	4.468×10^{9}
Y-90	*Null*	7.301×10^{-3}	1	7.301×10^{-3}
Zr-93	Nb-93m	1.530×10^{6}	0.975	1.569×10^{6}
Zr-93	Null	1.530×10^{6}	0.025	6.120×10^{7}

a Daughters with half-lives shorter than 1 day accounted for in dose coefficients.

b *Null* indicates that the daughter nuclide is not included in the dose calculations because it is either stable or was screened out.

c HIMv2.1 values different from HIMv2.0 values.

Table A.8: Element-Specific Parameters

Element	Soil Distribution Coefficient for clay [m^3/kg]	Ref	Plant/Soil Concentration Ratio [$kg_{drysoil}/kg_{wetplant}$]	Ref	Instant Release Fraction [-][m]
Symbol	KD_S		BV^i		IRF^i
Ac	2.4	i	0.0012	i*	0
Ag	0.18	a	0.088	a*	0
Am	8.1	a	0.00022	a*	0
Ar	0	k	0	i*	0.04
Ba	0.52	a	0.0098	a*	0.025
Bi	0.6	g	0.0046	g	0.006
C	0.001	a	7.7	a*	0.027
Cd	0.56	i	0.20	i*	0.006
Cl	0.0001	b	3.7	b	0.06
Cm	5.4	a	0.000074	a*	0
Co	0.54	a	0.016	a*	0
Cs	1.8	a	0.018	a*	0.04
Eu	0.65	a	0.0063	a*	0
H	0	a	0	a*	0.00001
Ho	1.3	j	0.0035	i*	0
I	0.012	c	0.005	c	0.04
Ir	0.48	j	0.019	i*	0
Kr	0	k	0	i*	0.04
Nb	0.9	a	0.010	a*	0
Ni	0.67	a	0.17	a*	0
Np	0.021	d	0.00060	d	0
Os	1	j	0.0053	i*	0
Pa	2.7	a	0.013	a*	0
Pb	0.55	h	0.00084	h	0.006
Pd	0.27	i	0.053	i*	0.01
Pm	0.65	a	0.0063	a*	0
Po	3	i	0.00088	i*	0.06
Pu	4.9	a	0.000049	a*	0
Ra	0.047	e	0.0041	e	0.025
Rn	0	k	0	i*	0.04
Ru	0.4	a	0.034	a*	0.01
Sb	0.24	a	0.00053	a*	0.006
Sm	1.3	i	0.0035	i*	0
Sn	0.67	a	0.14	a*	0
Sr	0.11	a	0.30	a*	0.025
Ta	1.2	i	0.0035	i*	0
Tc	0.0012	a	1.3	a*	0.01
Te	0.72	a	0.022	a*	0.006
Th	5.4	a	0.0012	a*	0
U	0.18	f	0.00079	f	0
Y	1	a	0.0077	a*	0
Zr	3.3	a	0.0011	a*	0.025

a. CSA (2008), b. Sheppard et al. (2002), c. Sheppard et al. (2004a), d. Sheppard et al. (2004b), e. Sheppard et al. (2005a), f. Sheppard et al. (2005b), g. Sheppard et al. (2012), h. Sheppard et al. (2010), i. Davis et al. (1993), j. Garisto (2002), k. assumed 0 for noble gases, l. BEAK International et al. (2002) and m. Gobien and Garisto (2012).
*Converted to wet weight basis using a dry/wet weight ratio of 0.35, which was calculated assuming a diet of 2/3 fruits and vegetables and 1/3 grains from CSA (2008).

A.3 RADIONUCLIDE SCREENING

A simple screening approach was adopted to identify the subset of radionuclides that is potentially important to the human intrusion model. In this approach, hypothetical doses were calculated for the ingestion and inhalation of the radionuclides in an entire used fuel bundle, and for a one-year groundshine exposure to the contents of a fuel bundle mixed into 1 kg of soil. For each type of exposure, all radionuclides whose dose contribution is within six orders of magnitude of the maximum dose contributor are screened in. These calculations were done for 30, 500 and 1,000 000 year old fuels with discharge burnups of 220 MWh/kgU.

HIMv2.1 runs with 79 radionuclides that were obtained from this screening assessment. These radionuclides are also shown in Tables A.5, A.6 and A.7.

APPENDIX B: SOFTWARE QUALITY ASSURANCE

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B.1 REQUIREMENTS SPECIFICATIONS

B.1.1 Functional Specifications

HIMv2.1 assesses dose consequences to humans as a result of inadvertent human intrusion into an otherwise functional deep geologic repository for used CANDU fuel. The results of the model are dose estimates to humans. The functional specifications of the programs are provided here:

1) Determine common information:

- Radionuclide inventory in fuel, including ingrowth and decay;
- Soil concentration after intrusion;
- Air concentration after intrusion; and
- Plant concentration after intrusion.

2) Model human intrusion scenarios:

- Scenario 1: Recognition of Used Fuel Hazard
    - Exposure to a drill crew member from contaminated drill slurry and contaminated core sample (Inhalation, ingestion, groundshine and external irradiation) until the used fuel hazard is recognized.

- Scenario 2: No Recognition of Used Fuel Hazard
    - Exposure to a drill crew member from contaminated drill slurry and contaminated core sample (Inhalation, ingestion, groundshine and external irradiation) until work at the site is complete; and
    - Exposure to a resident living in a house on contaminated soil (groundshine, inhalation, soil and plant ingestion).

- Scenario 3: Scenario 1 with Used Fuel having a Higher Burnup
    - Exposure to a drill crew member from contaminated drill slurry and contaminated core sample (Inhalation, ingestion, groundshine and external irradiation) until the used fuel hazard is recognized. Used fuel burnup is 280 MWh/kgU instead of 220 MWh/kgU.

3) Sort and display results.

B.1.2 Hardware and Operating System Specifications

HIMV2.1 runs under the AMBERv5.7.1 software platform. The recommended systems required to run AMBERv5.7.1 are a personal computer with a Pentium processor or equivalent with at least 126 MB of RAM installed, running under the Windows 7 operating system. AMBER will run on lower specification machines but its performance will be reduced (i.e. calculations will run more slowly). At least 105 MB of hard disk space should be available.

AMBER licences are controlled via USB hardware security keys.

B.1.3 Additional Requirement Specifications

Additional requirements are shown in Table B.1.

Table B.1: Additional Requirements Specifications

Requirement	Specifications
Computational Speed	None.
Portability	HIMv2.1 runs under AMBERv5.7.1 or compatible versions.
File size and Type	None.
Input and Output	HIMv2.1 case files only. HIMv2.1 and the case information are fully specified through the reference case file.
Data Structure and Flow	All parameters values were input into HIMv2.1 via the case file.
Programming Language	HIMv2.1 is created in the AMBERv5.7.1 user interface.
Mathematical Models	Mathematical models are outlined in the Theory (Section 3).
Error Detection and Handling	None beyond standard AMBERv5.7.1 error checks. For further information on this function, see the AMBER Reference Guide (Quintessa 2014a).
Accuracy Targets	Two significant figures out to 10^6 years.
Programming Practices	HIMv2.1 programmed via the AMBERv5.7.1 user interface.

B.2 DESIGN DESCRIPTION

HIMv2.1 is modeled based on the tracking of radionuclide decay in two main compartments as a function of time per unit initial mass of used fuel. All other parameters are obtained as simple functions of the above. The equations of HIMv2.1 are implemented directly into the AMBERv5.7.1 software interface.

B.3 USER GUIDE

For instructions on installing and running the HIMv2.1 case files (HIMv21.cse) see the AMBER Reference Guide (Quintessa 2014a). Default data values are shown in this section. Capabilities and limitations are given in Section 3.

The AMBERv5.7.1 Reference Guide (Quintessa Ltd. 2014a) gives further information about embedded values (i.e. unit conversion parameters) and error messages with AMBER. The AMBERv5.7.1 Starting Guide (Quintessa Ltd. 2014b) provides a tutorial with a sample case that illustrates the use of components and modules.

B.3.1 User Requirements

The User is expected to be technically knowledgeable regarding the deep geologic repository concept to be analysed. The User should be generally familiar with the capabilities and limitations of HIMv2.1 as described in this report. The User of HIMv2.1 is not required to know how to create models with AMBER, only how to view results in the AMBER Graphical User Interface (GUI). Instructions on this are given in Section B.3.2.

B.3.2 Run Model

The HIMv2.1 Graphical User Interface is shown in Figure B.1.

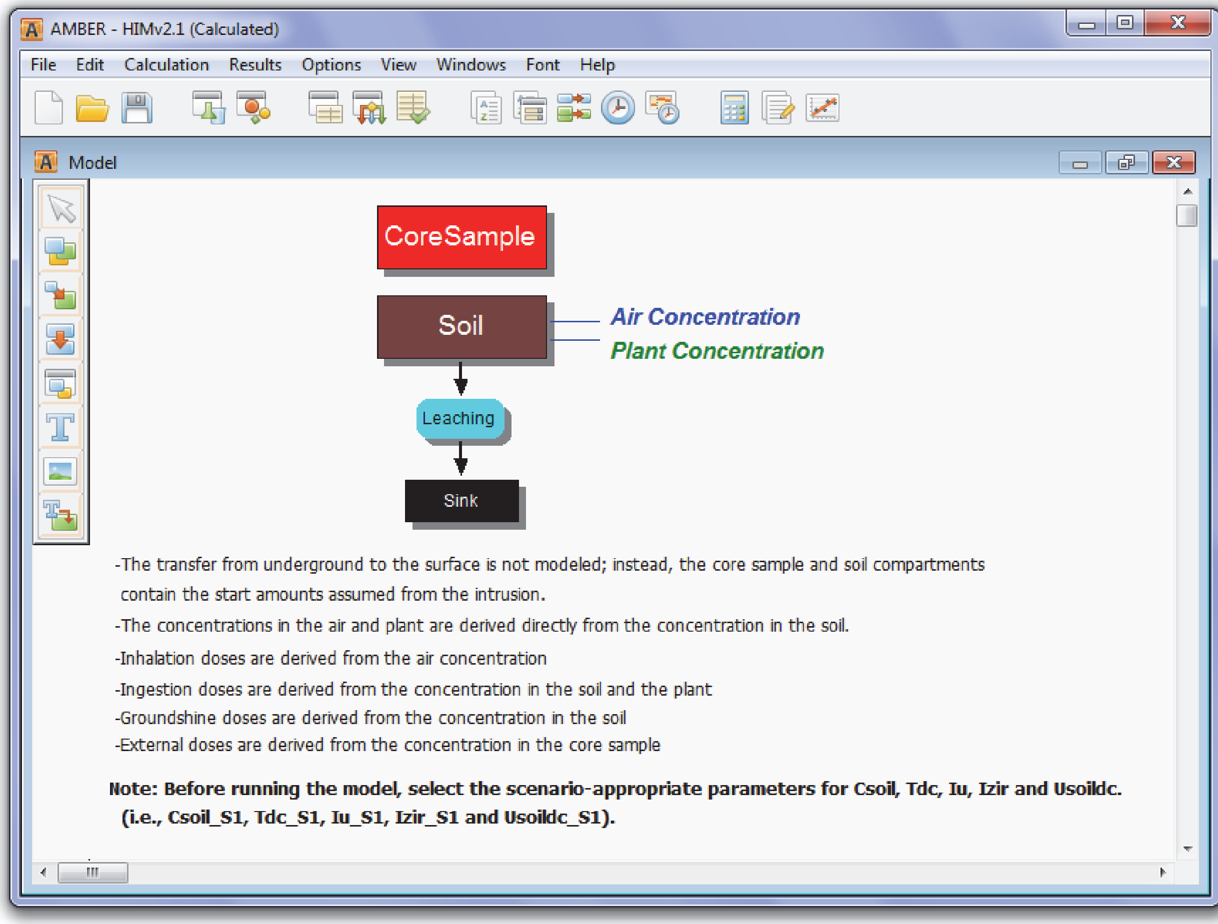

Figure B.1: Graphic User Interface for HIMv2.1

To select a scenario, click  in the top menu bar and change the values for Csoil, Tdc, Iu, Izir and Usoildc to scenario appropriate parameters. For example, to run Scenario 1, set Csoil_S1 as the default equation for Csoil, Tdc_S1 as the default equation for Tdc, etc.)

To run the model without leaching, click  in the top menu bar. When the “Calculate” dial box pops up, click “OK”.

To view the results, once a case has been calculated, there are two options:

1. **Graph:**
   a. Click .
   b. Click “OK” in “Graph Type” dial box.
   c. Select the parameters required for graphing in the “Y axis” drop down menu in the “Graph plots” dial box. To graph the total doses, TDdc (total annual dose to a drill crew member) or TDr (total annual dose to resident).
   d. The graph will automatically be generated and displayed in a separate Window.

e. The information displayed on the graph may be saved as a .csv file by clicking “File” then “Export to CSV” on the graph window.

2. Report:

a. Click  and follow the prompts to produce a .txt file with the desired parameters.
b. Click “Choose Parameters…” in the “Report Information” dial box.
c. Select all desired parameters by using the arrows between the “Chosen” and “Not Chosen” boxes in the “Choose Parameters” dial box. To report the total doses, chose TDdc (total annual dose to drill crew member) and TDr (total annual dose to resident). This gives the total doses as a function of intrusion time.
d. Click “OK” to close the “Choose Parameters” dial box.
e. Click “OK” in the “Report Information” dial box.
f. Save as “.txt” file in desired computer drive.

To run the model with leaching, click  and click on tleach, which is the leaching start time. The default for this parameter is set to 1 000 500 years, such that the model runs without leaching for all result times. Change this parameter value to the desired leaching start time, keeping in mind that the earliest possible leaching start time is 395 years (300 years institutional control + 95 years operation, extended monitoring and closure). In this case, the result should be interpreted as the total annual dose to the resident as a function of time since intrusion.

More detailed instructions on the use of AMBER are available in the AMBERv5.7.1 Reference Guide (Quintessa Ltd. 2014a).

B.3.3 Data Files Types

HIMv2.1 does not require input files. All parameters have already been input into the model through the AMBER GUI. These parameters are shown in Appendix A. Table B.2 shows the data files that are relevant to HIMv2.1.

Table B.2: Data File Types

Type	Format	Contents
Main Case File (*.cse)	AMBER Case File	- All information needed to run the case in AMBER.
Backup Case File(.cbk)	AMBER Back-up Case File	- This file is a backup version of the previous version of the cse file.
Output File (*.txt)	Text File	- Results of the AMBER Model. The User defines file name and the parameters to be printed in these files. - Run date & time. - AMBER version. - Parameter units.