HAZARD ASSESSMENT OF GREATER-THAN-CLASS C WASTE STREAMS: INTRUDER AND ACCIDENT SCENARIOS

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ABSTRACT

To support the U.S. Nuclear Regulatory Commission (NRC) evaluations of potential revisions to regulatory requirements following a risk-informed, performance-based approach, technical evaluations involving acute and chronic dose estimates of 17 Greater-Than-Class C (GTCC) waste streams were conducted within the context of the Title of the *Code of Federal Regulations* (10 CFR) 10 CFR Part 61 performance objective on the protection of individuals from inadvertent intrusion into a low-level radioactive waste disposal site after loss of active institutional controls. Additional technical evaluations of the potential hazards to workers and the general population from accidental releases of GTCC waste stream radioactivity during disposal facility operations also were conducted. Overall, the chronic intruder scenario dose estimates were higher relative to the acute intruder dose estimates because of the relatively longer annual exposure duration and the inclusion of additional homegrown food crop exposure pathways. Dose estimates from both scenarios that were above 5 mSv [500 mrem] were considered to present potential challenges for near surface disposal that may warrant additional consideration and perhaps more refined analysis. It is recognized that conservative analysis assumptions were adopted regarding the availability of waste material for inhalation and plant transfer that do not account for individual waste form properties. Those conservative assumptions may cause elevated chronic intruder dose estimates. The inhalation dose estimates for the accidental release acute onsite worker exposure scenario showed generally high doses consistent with expectations for an unmitigated release of GTCC waste stream constituents and close proximity exposure to a worker. The inhalation dose estimates for the accidental release acute offsite public exposure scenario were lower but still elevated public doses. Although conservative methods were used in both worker and public accidental release scenarios, the dose estimates suggest consideration of near surface disposal of GTCC waste streams should take into account the potential worker and public safety hazards associated with credible accidents and consider additional safety measures that might be needed. Overall, these technical analyses provide insights into how the radiological properties of various GTCC waste streams and exposure scenario considerations may affect required compliance demonstrations for disposal of GTCC waste streams.

CONTENTS

APPENDICES

FIGURES

FIGURES (Continued)

Figure | Page

TABLES

Tables

TABLES (Continued)

Tables Page

ABBREVIATIONS/ACRONYMS

AEA	Atomic Energy Act of 1954, as amended
BDOSE™	Biosphere Dose Model
CFR	Title 10 of the *Code of Federal Regulations*
CNWRA®	Center for Nuclear Waste Regulatory Analyses
DOE	U.S. Department of Energy
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
FEIS	Final Environmental Impact Statement
GTCC	Greater-Than-Class C
HLW	High-Level Radioactive Waste
ICRP	International Commission on Radiological Protection
LLRW	Low-Level Radioactive Waste
NRC	U.S. Nuclear Regulatory Commission
TOP	Technical Operating Procedures
TRU	Transuranic
WVDP	West Valley Demonstration Project

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: There are no original CNWRA-generated data in this report. Sources of other data should be consulted for determining the level of quality of those data.

ANALYSES AND CODES: The Biosphere Dose Model (BDOSE™) (Simpkins et al, 2008) software was used to generate results for this report and is controlled in accordance with the CNWRA Technical Operating Procedure (TOP)–018, Development and Control of Scientific and Engineering Software. GoldSim [registered trademark of GoldSim Technology Group, LLC (2017)], and Microsoft® Excel® 2010 (Microsoft Corporation, 2010) were also used but are considered uncontrolled software in accordance with TOP–018.

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1 INTRODUCTION

U.S. Nuclear Regulatory Commission (NRC) licensing requirements for the disposal of commercial low-level radioactive waste (LLRW) in near-surface disposal facilities are in Title 10 of the *Code of Federal Regulations* (10 CFR) Part 61, “Licensing Requirements for Land Disposal of Radioactive Waste.” NRC is considering making revisions to 10 CFR Part 61 that will allow disposal of Greater-Than-Class C (GTCC) and transuranic (TRU) waste (hereafter GTCC waste streams) under 10 CFR Part 61. To support the development of a risk-informed, performance-based approach for revising the regulatory requirements, the Center for Nuclear Waste Regulatory Analyses (CNWRA®) has conducted technical evaluations of GTCC waste streams considering the performance objectives of 10 CFR Part 61 regarding the protection of individuals from inadvertent intrusion into the disposal site after loss of active institutional controls. The CNWRA also conducted technical evaluations of the potential hazards to workers and the general population from accidental releases of GTCC waste stream radioactivity during disposal facility operations. This report presents the results of these technical analyses conducted by CNWRA staff to provide insights into how the radiological properties of various GTCC waste streams and exposure scenario considerations may affect required compliance demonstrations for disposal of GTCC waste streams.

2 BACKGROUND

The NRC has summarized the background of GTCC waste disposal issues In SECY–15–0094 (NRC, 2015a). The following paragraphs incorporate and summarize portions of that background information that provide context for the current NRC efforts to consider revisions to 10 CFR Part 61 and the related technical analyses contained in this report that are intended to support these considerations.

The NRC licensing requirements for the land disposal of LLRW in 10 CFR Part 61 define LLRW as “radioactive waste not classified as high-level radioactive waste (HLRW), TRU waste, spent nuclear fuel, or byproduct material as defined in paragraphs (2), (3), and (4) of the definition of byproduct material set forth in § 20.1003 of this chapter.” In 10 CFR § 61.55, the NRC developed a classification system for LLRW which categorizes waste as Class A, B, C, or GTCC. GTCC waste is LLRW exceeding the limits for Class C prescribed by 10 CFR 61.55 and arising from activities licensed by the NRC.

On May 25, 1989, the Commission amended its regulation at 10 CFR § 61.55 (a)(2)(iv) to require all GTCC waste to be disposed of in a geologic repository unless an alternative proposal is approved by the Commission. In a 1988 proposed rulemaking to amend 10 CFR Part 61, the Commission stated it would develop technical requirements for GTCC waste disposal “after U.S. Department of Energy (DOE) had completed its conceptual design and selected a site for a specific type of facility.” In the DOE’s draft Environmental Impact Statement (EIS) for the Disposal of GTCC LLRW and GTCC-Like Waste, DOE provided conceptual designs for four disposal methods and evaluated the methods of disposal for the possible sites.

If DOE selects the aboveground vaults, trenches or intermediate boreholes methods of disposal, the NRC will need to develop technical requirements consistent with the performance objectives in 10 CFR Part 61 Subpart C. Additional activities that NRC may need to undertake could involve a rulemaking or development of criteria that would be a part of a site-specific license. Additionally, in 2015, the Texas Commission on Environmental Quality’s (Texas) submitted an

inquiry to NRC regarding whether it possesses the authority to license a GTCC waste disposal cell that would receive GTCC, GTCC-like, and TRU waste streams.

Improving the available technical information about the potential hazards associated with GTCC waste and related waste streams will enhance the NRC's capabilities to consider potential changes to the land disposal regulations in 10 CFR Part 61.

3 GREATER-THAN-CLASS C WASTE STREAMS AND ESTIMATED RADIONUCLIDE INVENTORIES

In SECY–15–0094 (NRC, 2015a) the NRC described GTCC waste as being generated by nuclear power reactors and other supporting nuclear fuel cycle facilities and also other facilities and licensees outside of the nuclear fuel cycle including: (i) plutonium-contaminated nuclear fuel cycle wastes; (ii) activated metals; (iii) sealed sources; and (iv) radioisotope product manufacturing wastes (i.e., wastes "occasionally generated as part of manufacture of sealed sources, radiopharmaceutical products and other materials used for industrial, education, and medical applications").

In addition, the DOE has created a term, "GTCC-like waste," which refers to DOE owned and generated LLRW and non-defense-generated TRU waste, which have characteristics similar to GTCC waste. DOE also defines GTCC-like waste to include recovered orphaned sealed sources to which it has taken title, even though those sources were originally licensed under the Atomic Energy Act of 1954, as amended (AEA). DOE has stated that "GTCC-like" was not intended to be a new DOE waste classification of radioactive waste. The majority of the GTCC-like waste is associated with decontamination of the West Valley Demonstration Project (WVDP) site located in Western New York. The WVDP site was the location of a former commercial spent nuclear fuel reprocessing facility (DOE, 2016).

GTCC wastes vary in volume, radionuclide content, and the form of the waste (e.g., activated metal, sealed sources, exhumed waste and soil). The form of the waste can affect the rate at which radioactivity is released to the environment as well as the likelihood of disturbance at some time in the future.

The DOE recently prepared a Final Environmental Impact Statement (FEIS) for the Disposal of GTCC LLRW and GTCC-Like Waste (DOE, 2016) to evaluate the potential environmental impacts associated with the proposed development, operation, and long-term management of a disposal facility or facilities for GTCC LLRW and DOE GTCC-like waste.

DOE's FEIS (DOE, 2016) divided the GTCC waste streams into two groups based on if the waste has been already produced or will be produced in the future from currently operating facilities (Group 1) or if the waste is expected to be generated in the future by facilities that are planned or proposed but not yet operating (Group 2). In this document, Group 1 are referred to as "Expected GTCC" whereas Group 2 are referred to as "Potential GTCC". DOE's FEIS (DOE, 2016) also described three broad categories for GTCC waste: activated metals, sealed sources, and "other waste." The activity levels of these various waste categories range from concentrations well below their respective Class C concentration limits to concentrations significantly above their Class C concentration limits, however, typically at least one radionuclide in a specific waste stream (e.g., activated metals from commercial reactors, sealed sources from Cs-137 irradiators) will exceed the Class C concentration limit. Transuranic radionuclides can be found in each one of these three categories of GTCC waste.

The DOE FEIS provided information from a variety of sources in compiling an inventory of GTCC and GTCC-like waste. The NRC staff used the information in the DOE FEIS and supporting documents to develop inventories for 17 specific GTCC waste streams (e.g., activated metals from commercial waste and activated metals from potential exhumation of the NRC disposal area at West Valley). The resulting inventories are provided in Appendix A. Tables A–1 through A–4 provide the average radionuclide concentration by waste stream. Waste streams are identified by descriptive identifiers as well as a simple numbering system to allow identification in the text, tables, and figures in this report. These inventories for the 17 GTCC waste streams provide the radionuclide concentrations for the individual GTCC waste streams that are used in the dose calculations described in Chapter 4 of this report.

4 DOSE CALCULATIONS

NRC regulations at 10 CFR 61.42 require land disposal LLRW facilities meet a performance objective to protect individuals from inadvertent intrusion. Specifically, the design, operation, and closure of the facility must ensure protection of any individual inadvertently intruding into the disposal site or contacting the waste at any time after active institutional controls over the disposal site are removed. In evaluating potential changes to the types of waste streams that may be allowed to be disposed at a LLRW disposal facility, the NRC staff are interested in assessing the level of hazard posed by the 17 potential waste steams described in Chapter 3 under typical intruder scenarios. NRC has previously described typical intruder scenarios in NUREG–2175 and NUREG–1854 (NRC, 2015b; 2007). The intruder dose calculations conducted for this report are generally consistent with intruder scenarios and analysis methods described by the NRC staff in these NUREGs.

For the GTCC intruder scenarios evaluated in this report, the source of radioactive material is assumed to be the waste inventory. Under this scenario, after the waste has been emplaced and 100 years of institutional control has elapsed, the intruder is assumed to be an individual in a rural residential setting where a residential water well is inadvertently drilled directly into the waste and the contaminated materials are brought to the surface during well construction and distributed over the surface of the land. This type of intruder scenario is comparable to the intruder-resident scenario described in Section 5.1.3.1 of NUREG–1854 (NRC, 2007). Two variants of this scenario considered in the current analysis include an acute intruder and the chronic intruder. Concepts related to acute and chronic intruder exposure scenarios are described further in Section 4.3.1.1 of NUREG–2175 (NRC, 2015b). Details of the acute and chronic intruder dose calculations are provided in Sections 4.1 and 4.2.

For the GTCC accidental release scenarios evaluated in this report, the source of the radioactive material is also assumed to be the waste inventory. Under these scenarios short-term acute doses are calculated from an assumed fractional accidental release of the GTCC waste inventory to air that exposes a disposal facility worker and a member of the public at the facility boundary to the passing plume.

The following Sections 4.1 through 4.4 describe the conceptual and mathematical models, input parameters and assumptions, resulting dose estimates, and discussion for each of the four exposure scenarios evaluated in this report.

4.1 Acute Intruder Drilling Exposure Scenario

The acute intruder exposure scenario evaluates the short-term dose to a construction worker (driller) that inadvertently drills into a subsurface waste disposal facility and is exposed by a limited suite of applicable exposure pathways to waste material from the drill cuttings.

4.1.1 Conceptual and Mathematical Models

The acute intruder is assumed to be the worker involved in the water well drilling (the driller) for the residential dwelling. The drilling activity exhumes a combination of waste material and clean soil based on the diameter and depth of the well and the thickness of the subsurface waste material layer. After waste is exhumed to the ground surface, it is assumed to be deposited on top of the ground surface near the driller for the duration of the drilling time. The driller is then exposed to the waste material (that was spread over the surface) by direct radiation, inhalation, and inadvertent soil ingestion. The exposure pathways applicable to the acute intruder are depicted in Figure 1.

The mathematical model that was selected to implement the conceptual model is BDOSE 2.0 (Simpkins et al., 2008). BDOSE 2.0 is a probabilistic biosphere dose model developed in the GoldSim [registered trademark of GoldSim Technology Group, LLC] probabilistic simulation environment. The model considers acute and chronic intruder scenarios based on inputs of subsurface (e.g., LLRW disposal facility) waste concentrations in units of activity per unit volume. Exposure pathways include external exposure from contaminated ground surface, contaminated air; internal exposure from inhalation of contaminated air; and internal exposure from ingestion of contaminated vegetables, fruits, animal products, and soil. More detailed descriptions of the BDOSE 2.0 methods are documented in the User's Guide (Simpkins et al., 2008).

The BDOSE 2.0 intruder models were developed to support NRC consultations on non-high-level waste and waste-incidental-to-reprocessing determinations. The performance objectives applicable to non-high-level waste and waste-incidental-to-reprocessing determinations are NRC's licensing requirements for land disposal of LLRW in 10 CFR Part 61. Because the hazard assessment was requested by NRC staff to support the NRC staff's development of regulatory analyses in support of potential revisions to 10 CFR Part 61, the intruder scenario models in BDOSE 2.0, developed to be consistent with these 10 CFR Part 61 requirements, are uniquely applicable to supporting the NRC 10 CFR Part 61 regulatory analyses.

The model was run for a 10,000 year timeframe to capture long term evolution of the inventory, accounting for radioactive decay and ingrowth. As executed, at any time the dose calculations consider the entire acute intruder scenario (e.g., exhuming and spreading material causing doses) assuming instantaneous distribution of radionuclides in the modeled biosphere, which was previously uncontaminated. The model was run stochastically for 125 realizations to balance adequate precision and run time efficiency. Tests conducted increasing the number of realizations for the chronic intruder (which has more sampled input parameters than the acute intruder scenario) found this number of realizations to be sufficient to support the current analysis (Section 4.2.1).

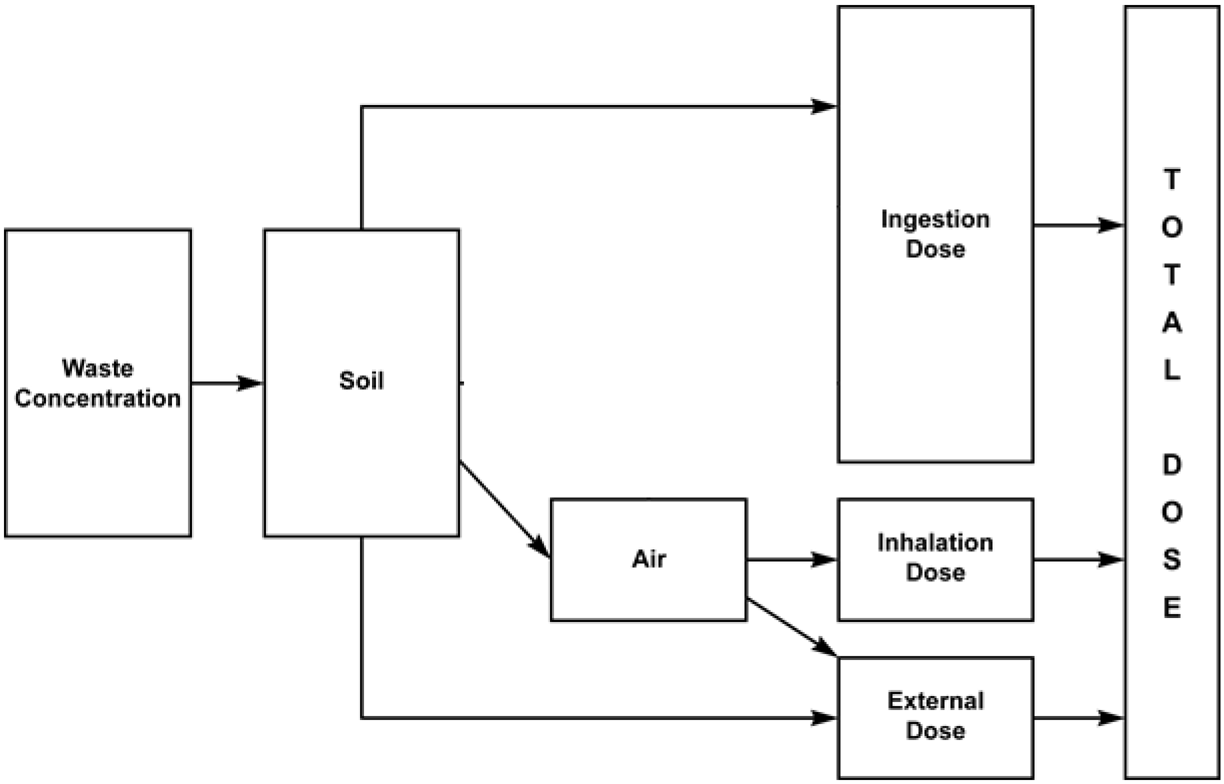

Figure 1. Conceptualization of exposure pathways for acute intruder scenario

4.1.2 Input Parameters

The input parameters used to model the acute intruder scenario in BDOSE 2.0 include waste inventories that were provided by the NRC staff (Appendix A) and parameters related to the disposal facility, well drilling, biosphere characteristics, receptor characteristics, and human dosimetry (Appendix B). Because the dose calculations were not site-specific the parameter values were selected as values expected to be either generally applicable or reasonably conservative for the acute intruder scenario under evaluation. Inhalation and ingestion dose calculations involve International Commission on Radiological Protection (ICRP) ICRP 72 (ICRP, 1996) effective dose coefficients and external dose calculations utilize Federal Guidance No 12 (EPA, 1993) effective dose equivalent dose coefficients (see Appendix B for details). The technical bases and references supporting the selection of input parameters are provided in Appendix B (Tables B–1 through B–12).

4.1.3 Assumptions

Modeling exposure scenarios such as an intruder scenario involve a number of explicit and implicit assumptions. The following assumptions apply to the BDOSE 2.0 acute intruder dose calculations:

- Institutional controls are assumed to be effective at the LLRW site for 100 years, therefore, no intrusion dose calculations are executed prior to 100 years.
- The driller constructing a residential water well is the receptor.

- The receptor is exposed to drill cuttings containing exhumed waste for the duration of the well construction (25 hours).

- The residential water well that is constructed is assumed to be 55 m [180 ft] deep.

- The thickness of the packaged waste is assumed to be 0.5 m [1.6 ft] to account for variability in packing efficiencies among variable waste streams. Results can be scaled proportionately to a change in waste thickness if a need arises to evaluate a different waste thickness for a specific waste stream.

- A waste package is assumed to be directly and completely intercepted by the drilling.

- All intercepted waste material is assumed to be uniformly available for exhumation to the surface at the specified inventory concentration with no credit for waste form resilience. An exception to avoid excessive conservatism involved adjusting two activated metal waste stream inventories (Reactor AM RH, Reactor AM370 RH) to account for the availability of long-term corrosion products that are in a more mobile form and therefore could be released to the environment and contribute to dose, rather than considering the full inventory of the bulk metal that would not be in a mobile form. A DOE (2016) estimated a release rate of 1.19×10^{-5} /yr for an activated metals waste stream based on an evaluation of corrosion rates was applied to a 1,000 year period to derive a release fraction of 1.19×10^{-2} that was used to adjust the two inventories to account for a more realistic available inventory.

- All material exhumed by the well drilling is assumed to be uniformly mixed (in the drill cuttings pile) and spread over the soil at this concentration prior to calculating dose estimates with no further dilution or loss of material.

- External dose calculations assume exposure to a 1 cm [0.39 in] plane of exhumed material at the concentration of the uniformly mixed drill cuttings.

- Inhalation and external exposure durations for the driller are the duration of the well construction activity (25 hours).

- The volume of air inhaled by the driller is determined by a construction worker inhalation rate and the duration of the well construction.

4.1.4 Results

The mean effective dose estimates by GTCC waste stream over time for the acute intruder scenario are provided in Figure 2. Results of particular interest include dose estimates that exceed 5 mSv [500 mrem] at 100 and 500 years. NRC previously considered a 5 mSv [500 mrem] intruder dose as the basis of the waste classification limits in 10 CFR Part 61 (NRC, 1982). Additionally, existing requirements in 10 CFR 61.59(b) limit reliance on institutional controls beyond 100 years and current requirements at 10 CFR Part 61.52(a)(2) for disposal of Class C waste require intrusion barriers to protect against intrusion for 500 years. Beyond 500 years, the dose estimates provide insights into the persistence of elevated doses over time for GTCC waste streams that include radionuclides with relatively longer half-lives.

Five waste streams had a calculated acute intruder dose above 5 mSv [500 mrem] after 100 years of institutional control including in descending order Neutron SS CH, CS SS CH,

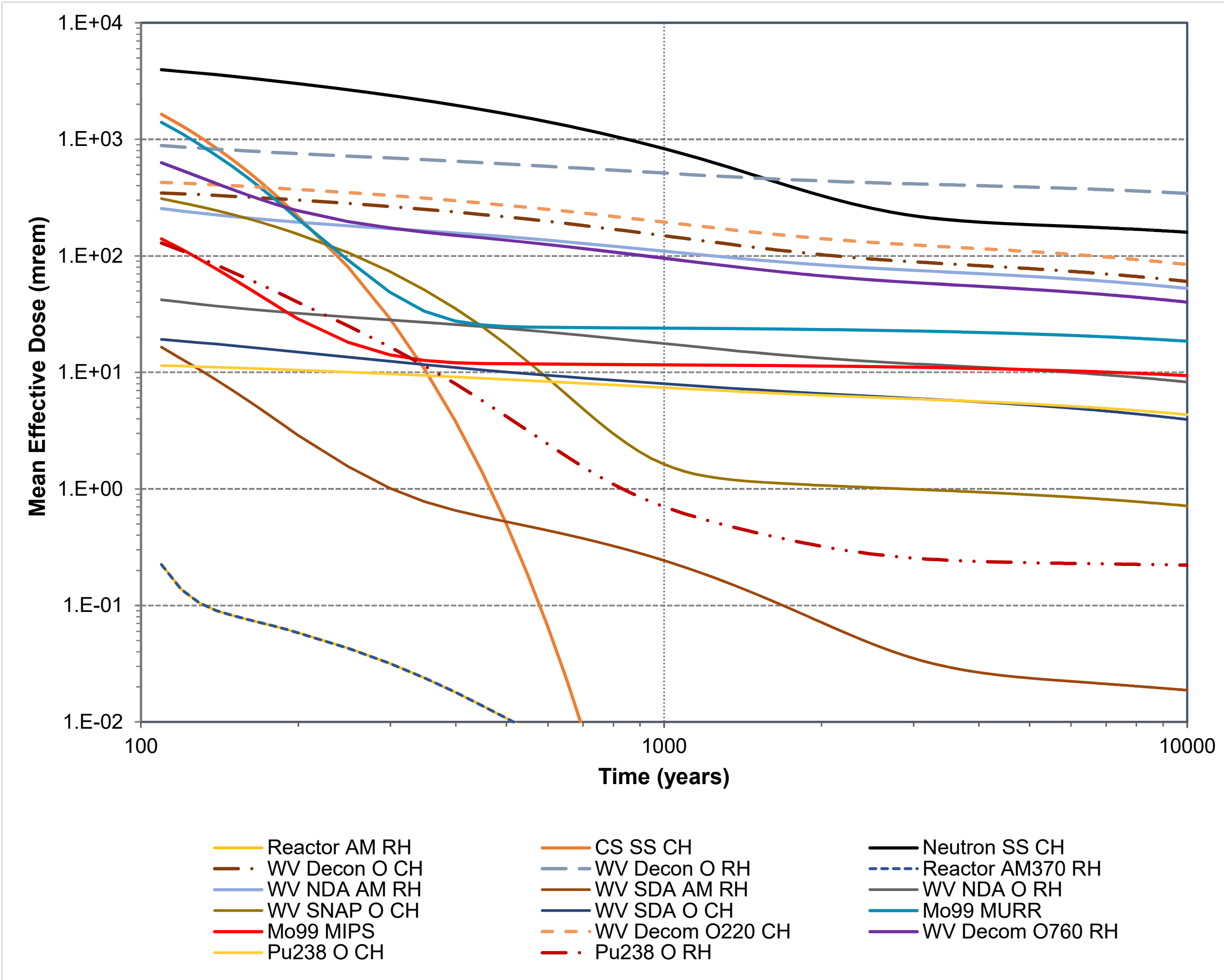

Figure 2. Calculated acute intruder mean total effective dose by GTCC waste stream and time

MO99 MURR, WV DECON O RH, and WV DECOM O760 RH. An additional six waste streams had calculated doses between 1 and 5 mSv [100 and 500 mrem] including WV DECOM O220 CH, WV DECON O CH, WV SNAP O CH, WV NDA AM RH, MO99 MIPS, and PU238 O RH. The remaining six GTCC waste streams (WV NDA O RH, WV SDA O CH, WV SDA AM RH, REACTOR AM RH, PU238 O CH, and REACTOR AM370 RH) had acute intruder doses below [100 mrem] at 100 years. At 500 years of institutional control the additional time for radioactive decay reduced the concentration of some radionuclides within several waste streams such that only two, Neutron SS CH and WV DECON O RH, exceeded 5 mSv [500 mrem]. The acute intruder dose estimates for these two waste streams gradually diminished over time by radioactive decay but remained above 5 mSv [500 mrem] until 1,500 years when all waste were below 5 mSv [500 mrem]. Four other GTCC waste streams had calculated doses between 1 and 5 mSv [100 and 500 mrem] at 500 years including in descending order WV DECOM O220 CH, WV DECON O CH, WV NDA AM RH, and WV DECOM O760 RH and the remaining 11 GTCC waste streams had acute dose estimates below 1 mSv [100 mrem] at 500 years.

The radionuclide-specific mean effective dose estimates by GTCC waste stream over time for the acute intruder scenario are provided in Figures 3 through 8. These figures show the variation in the radionuclide-specific contributions to the calculated acute intruder doses over

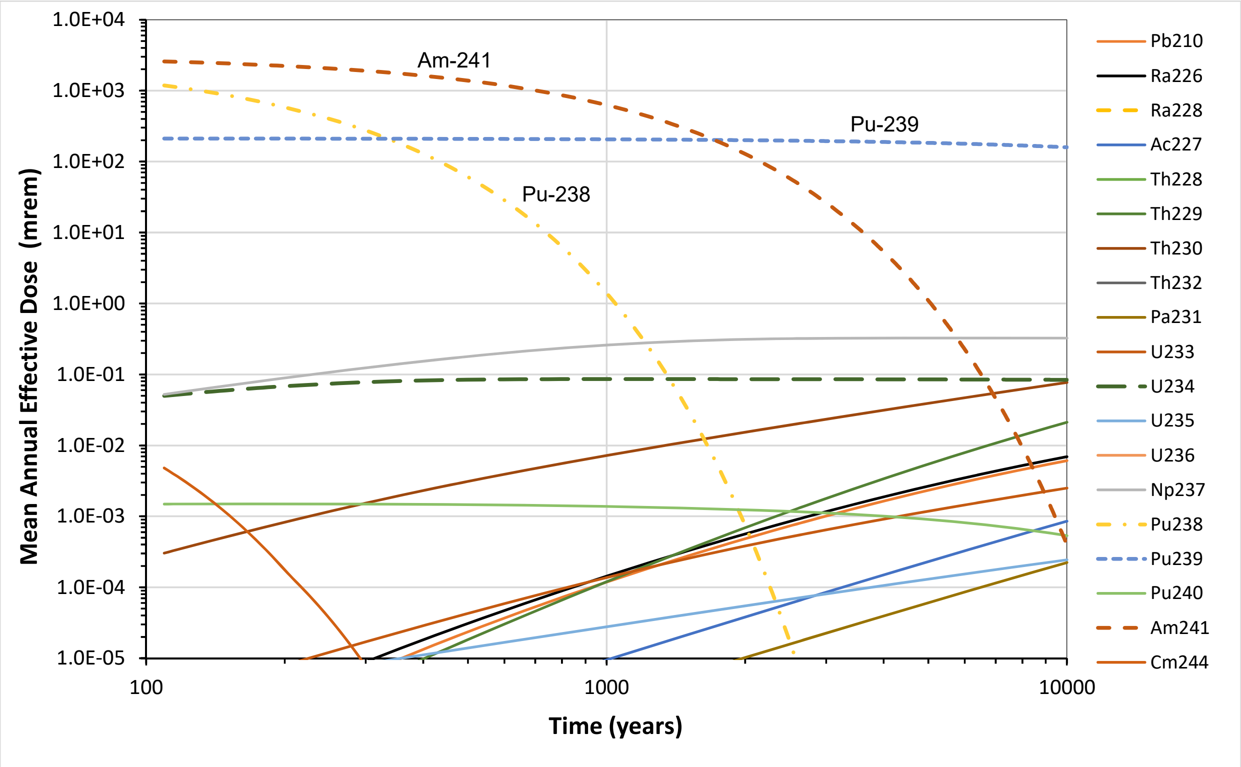

Figure 3. Calculated acute intruder mean radionuclide-specific effective dose with time for the neutron SS CH waste stream

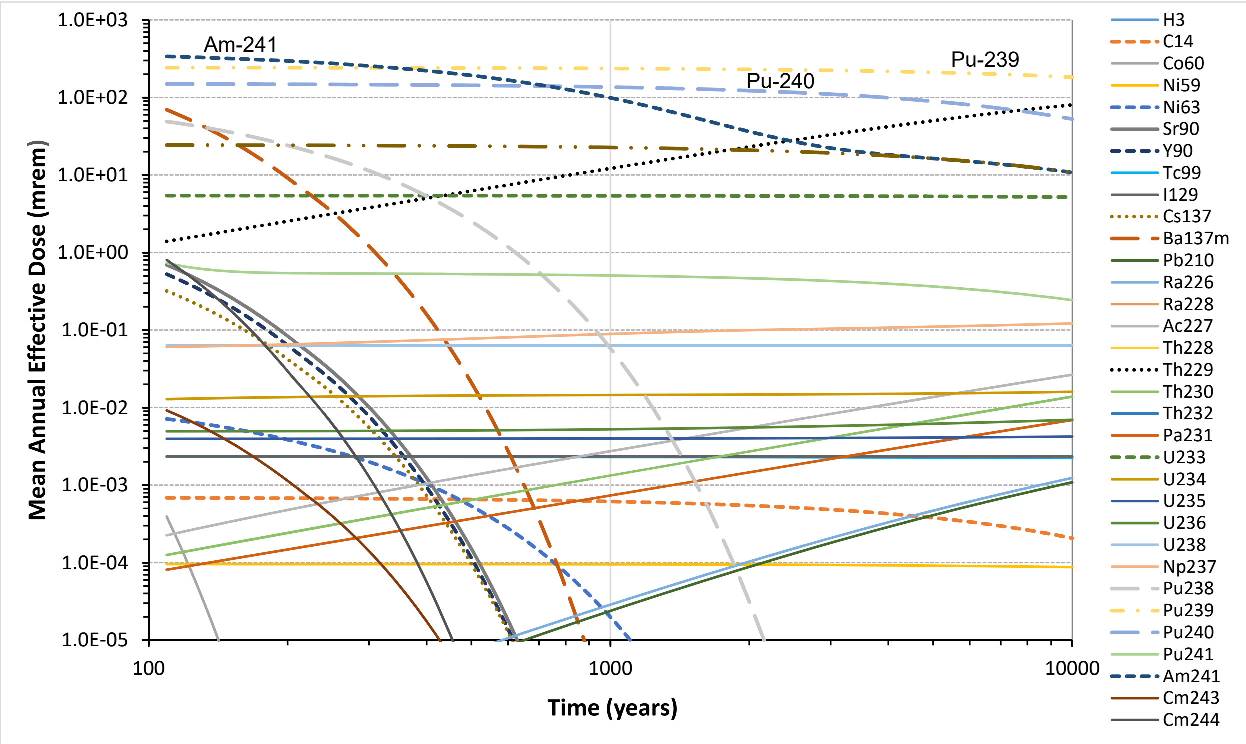

Figure 4. Calculated acute intruder mean radionuclide-specific effective dose with time for the WV DECON O RH waste stream

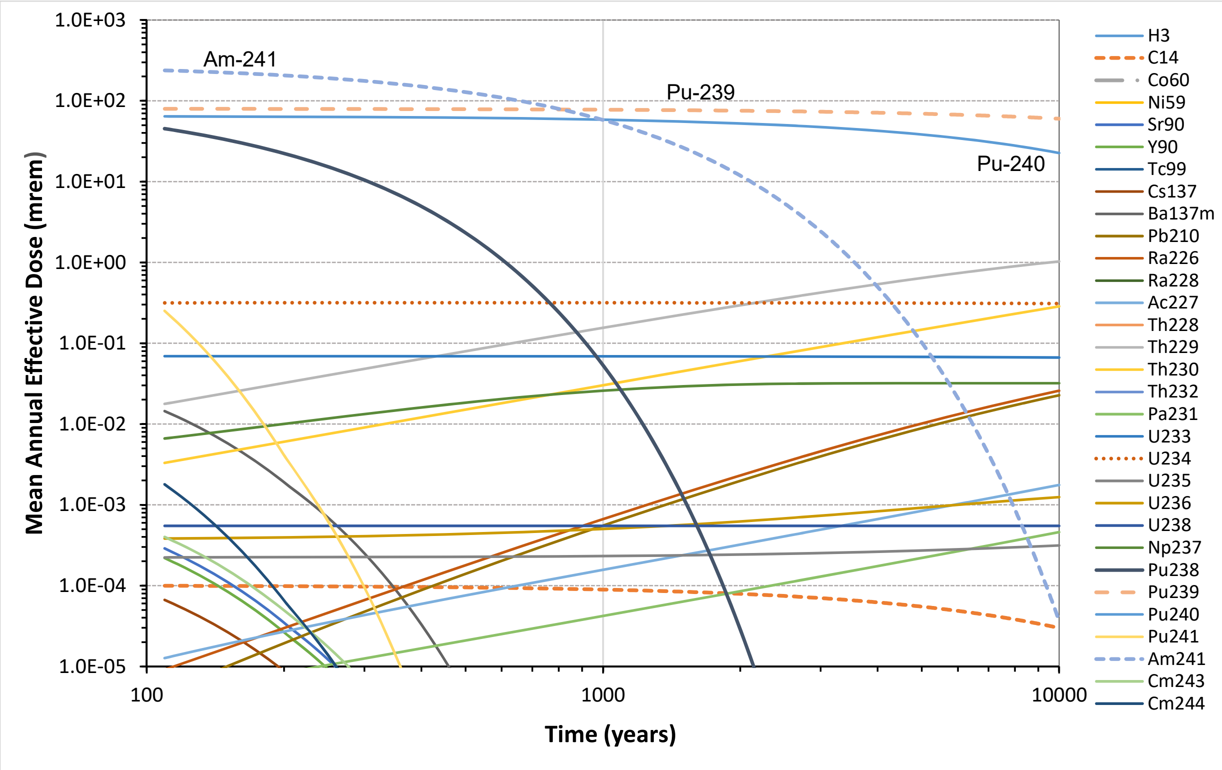

Figure 5. **Calculated acute intruder mean radionuclide-specific effective dose with time for the WV DECOM O220 CH waste stream**

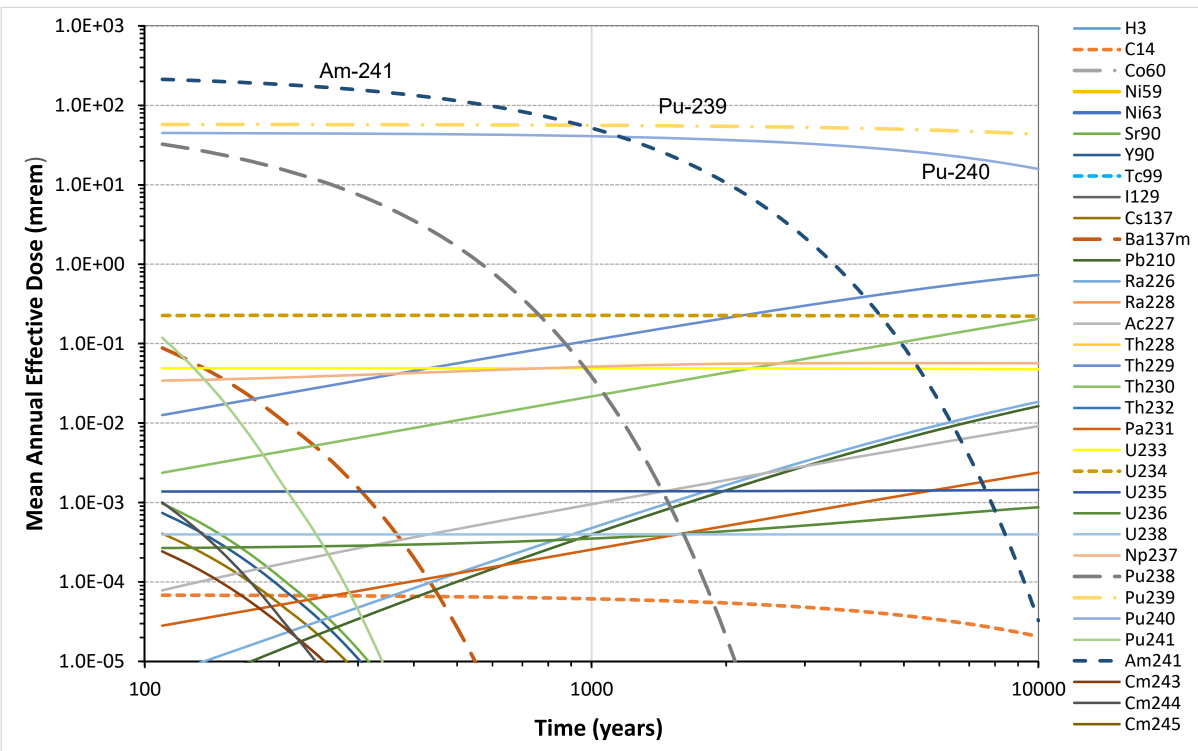

Figure 6. **Calculated acute intruder mean radionuclide-specific effective dose with time for the WV DECON O CH waste stream**

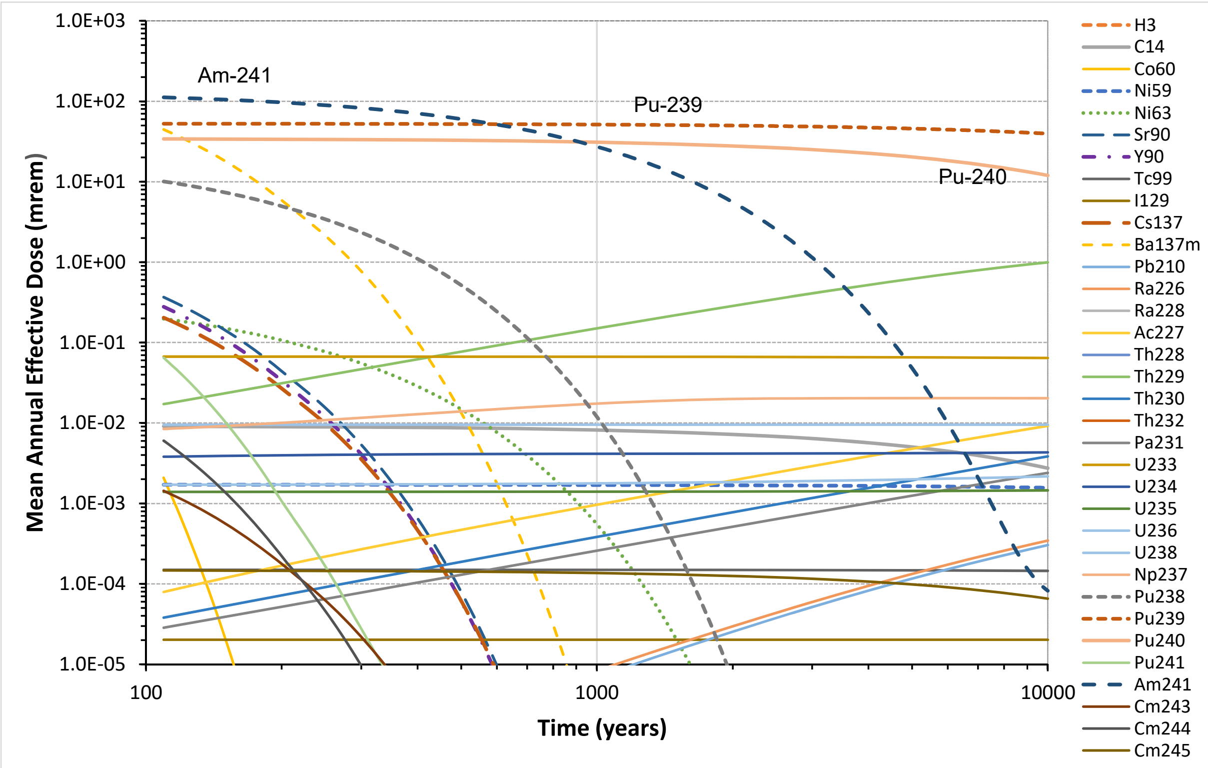

Figure 7. Calculated acute intruder mean radionuclide-specific effective dose with time for the WV NDA AM RH waste stream

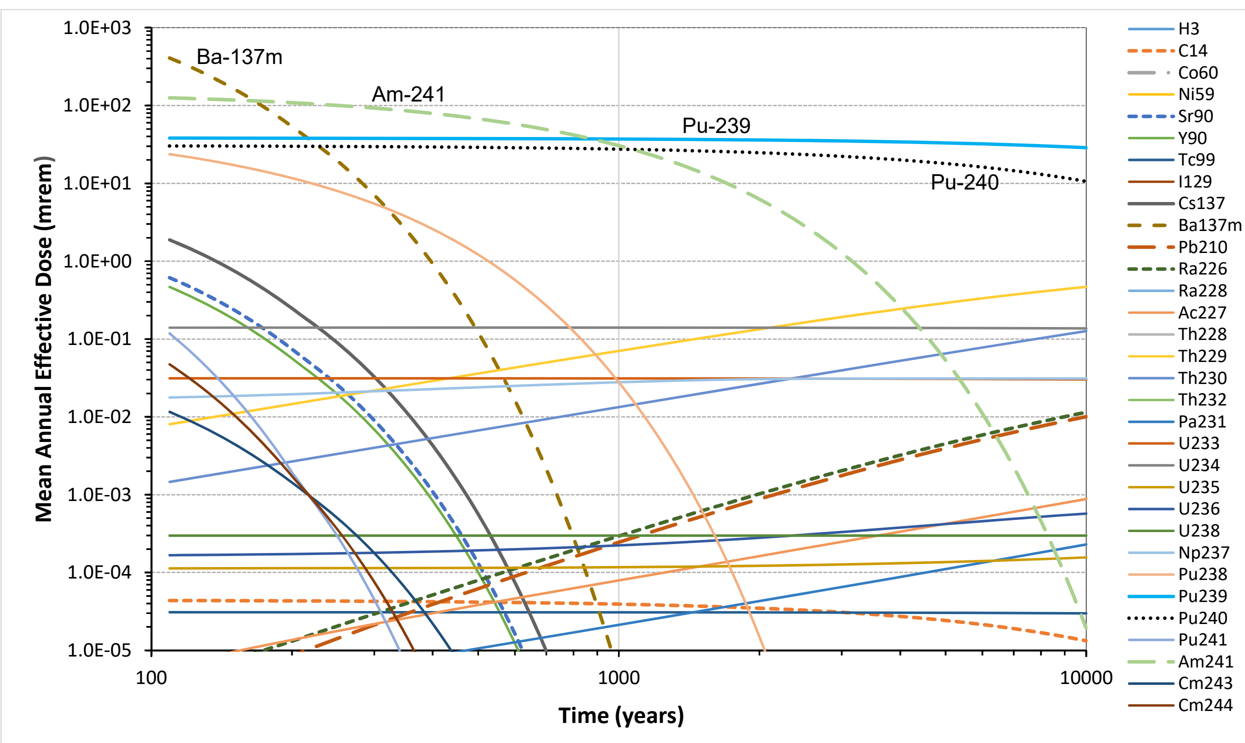

Figure 8. Calculated acute intruder mean radionuclide-specific effective dose with time for the WV Decom O760 RH waste stream

the entire 10,000 year timeline. For all of the waste streams the number of radionuclides that contribute significantly to the calculated dose is small relative to the number of radionuclides in the waste stream.

Table 1 summarizes the acute intruder mean annual dose estimates at 500 years by waste stream and provides the contributions of specific radionuclides and exposure pathways to the calculated dose. The dose estimates show the acute intruder dose is dominated by the inhalation pathway and that the isotopes of americium and plutonium are the predominant contributors to the calculated doses.

4.1.5 Discussion

The acute intruder dose estimates indicated that 12 waste streams had doses below 5 mSv [500 mrem] after 100 years of institutional control and this increased to 15 waste streams below 5 mSv [500 mrem] at 500 years as some of the radionuclides with shorter half-lives had been significantly reduced by radioactive decay.

Conversely, the acute intruder dose analysis also indicated that five waste streams had dose estimates above 5 mSv [500 mrem] after 100 years of institutional control and this reduced (due to radioactive decay) to two waste streams (NEUTRON SS CH and WV DECON O RH) above 5 mSv [500 mrem] at 500 years. At approximately 1,500 years all waste streams were below 5 mSv [500 mrem]. The NEUTRON SS CH waste stream consists of sealed sources containing long-lived isotopes of plutonium and americium (Appendix A, Table A–1) that upon release would result in a 500-year acute intruder dose estimate of 1.7 rem—over 3 times above the 5 mSv [500 mrem] intruder objective. Analysis of the pathway-specific dose estimates showed inhalation contributed 98 percent of the calculated mean dose at 500 years consistent with expectations for these predominantly alpha radiation emitting radionuclides.

The high dose for the NEUTRON SS CH waste stream at 500 years suggests that there could be challenges for shallow land burial of this waste stream, however, simplifying assumptions were implemented that tend to overestimate doses for the acute intruder scenario. For example, the dose estimates were based on an assumption that the waste form would be readily available for exhumation and resuspension to air. Incorporating more realism about the waste form availability in the current calculations would help to discern the level of conservatism in dose estimates and help improve the evaluation of the potential hazard. While also elevated at 500 years, the WV DECON O RH acute intruder dose is much closer to the 5 mSv [500 mrem] objective at 6.2 mSv [620 mrem]. Therefore the WV DECON O RH waste stream may present challenges for near surface disposal but remains much closer to the objective than the NEUTRON SS CH waste stream.

4.2 Chronic Intruder Drilling Exposure Scenario

The chronic intruder exposure scenario evaluates the annual dose to a resident that inadvertently builds a house above a waste disposal facility. The chronic intruder is exposed for a longer duration to a broader suite of exposure pathways applicable to residential exposure to radioactive material in drill cuttings brought to the surface during the installation of a residential water well that intercepted buried waste material.

Table 1. Calculated acute intruder mean dose at 500 years by waste stream with radionuclide and exposure pathway fractions			
Waste Stream	**Mean Annual Dose at 500 Years in mSv [mrem]**	**Key Radionuclides (Fraction of Mean Annual Dose)**	**Exposure Pathways (Fraction of the Mean Annual Dose)**
NEUTRON SS	17 [1,700]	Am-241 (84%)	Inhalation (98%) Soil Ingestion (1%) Groundshine (1%)
		Pu-239 (13%)	
		Pu-238 (4%)	
WV DECON O RH	6.2 [620]	Pu-239 (39%)	Inhalation (98%) Soil Ingestion (1%) Groundshine (1%)
		Am-241 (31%)	
		Pu-240 (23%)	
		Cm-245 (4%)	
		U-233 (1%)	
		Th-229 (1%)	
WV DECOM O220 CH	2.7 [270]	Am-241 (47%)	Inhalation (98%) Soil Ingestion (1%) Groundshine (<1%)
		Pu-239 (29%)	
		Pu-240 (23%)	
		Pu-238 (1%)	
WV DECON O CH	2.2 [220]	Am-241 (53%)	Inhalation (98%) Soil Ingestion (1%) Groundshine (1%)
		Pu-239 (26%)	
		Pu-240 (20%)	
		Pu-238 (1%)	
WV NDA AM RH	1.5 [150]	Am-241 (41%)	Inhalation (98%) Soil Ingestion (1%) Groundshine (<1%)
		Pu-239 (36%)	
		Pu-240 (22%)	
WV DECOM O760 RH	1.4 [140]	Am-241 (50%)	Inhalation (98%) Soil Ingestion (1%) Groundshine (1%)
		Pu-239 (28%)	
		Pu-240 (21%)	
		Pu-238 (1%)	

4.2.1 Conceptual and Mathematical Models

The chronic intruder is assumed to be an individual that builds a residence above the waste facility and is exposed to the drill cuttings that have been uniformly distributed over the soil to a depth of 2.54 cm [1 in] and then tilled into the top 15 cm [5.9 in] of soil to allow for residential gardening of edible crops including leafy vegetables, other vegetables, grain, and fruit. The exposure pathways applicable to the chronic intruder are depicted in Figure 9.

The mathematical model that was selected to implement the conceptual model is BDOSE 2.0 (Simpkins et al., 2008). Additional details about the models in BDOSE 2.0 and their applicability to 10 CFR Part 61 intruder dose estimates is provided in Section 4.1.1. The model was run for a 10,000 year timeframe to capture long term evolution of the inventory, accounting for decay and ingrowth. As executed, at any given time greater than 100 years (the institutional control period), the dose estimates correspond to the entire chronic intruder scenario (e.g., exhuming and spreading material) occurring at that time, in a previously uncontaminated biosphere. It is assumed that radionuclides are instantaneously distributed in the modeled biosphere. The model was run stochastically for 125 realizations to balance adequate precision and run time efficiency. Tests conducted for increasing the number of realizations up to 5,000 increased mean dose estimates for some radionuclides by a factor of 1.11 or less while a small subset of

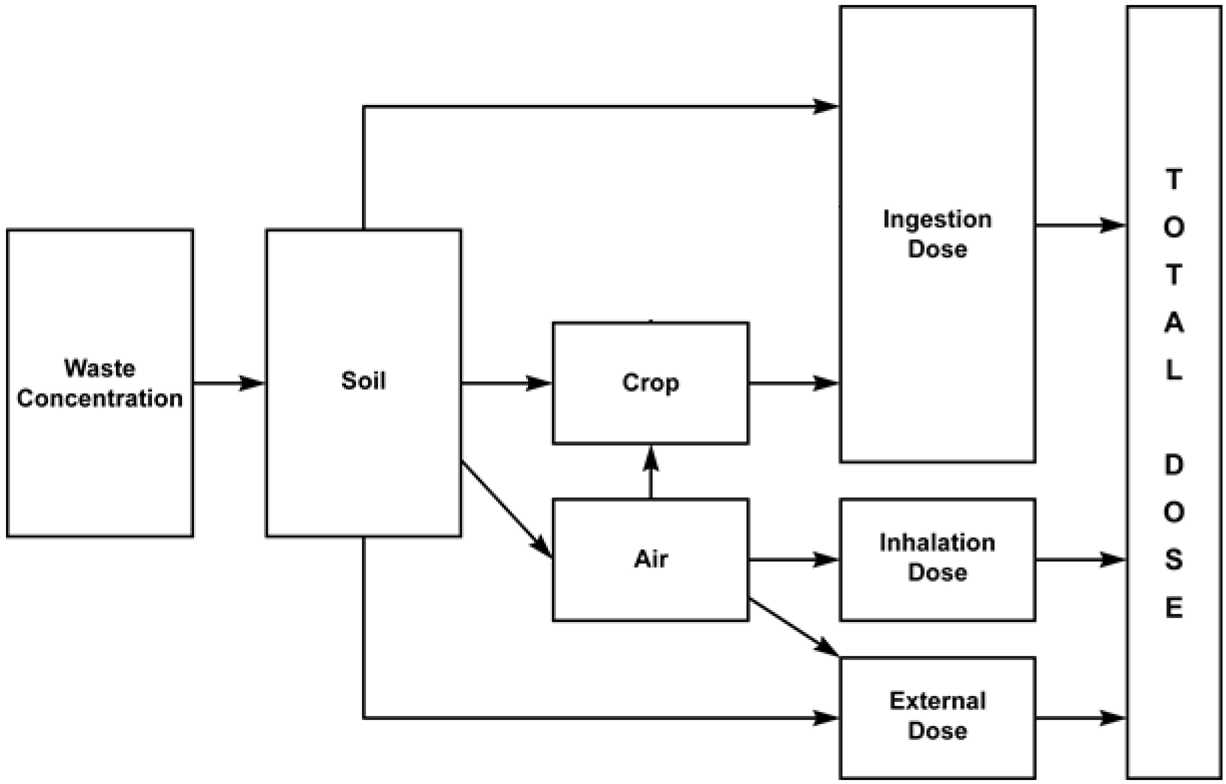

Figure 9. Conceptualization of exposure pathways for chronic intruder scenario

radionuclides (isotopes of uranium and radium) that were not important contributors to waste stream mean dose estimates increased by a factor of 1.37 or less. Based on this information, the number of realizations was determined to be sufficient to support the current analysis.

4.2.2 Input Parameters

The input parameters used to model the chronic intruder scenario in BDOSE 2.0 include waste inventories that were provided by the NRC staff (Appendix A) and parameters related to the disposal facility, well drilling, biosphere characteristics, receptor characteristics, and human dosimetry (Appendix B). Because the dose calculations were not site-specific the parameter values were selected as values expected to be either generally applicable or reasonably conservative for the chronic intruder scenario under evaluation. Inhalation and ingestion dose calculations involve ICRP 72 (ICRP, 1996) effective dose coefficients and external dose calculations utilize Federal Guidance No 12 (EPA, 1993) effective dose equivalent dose coefficients (see Appendix B for details). The technical bases and references supporting the selection of input parameters for the intruder scenario dose calculations are provided in Tables B–1 through B–12 in Appendix B.

4.2.3 Assumptions

Modeling exposure scenarios such as an intruder scenario involve a number of explicit and implicit assumptions. The following assumptions apply to the BDOSE 2.0 chronic intruder dose calculations:

- The receptor is an individual who builds a house on top of a LLRW disposal cell after institutional controls are lost.

- Institutional controls are assumed to be effective at the LLRW site for 100 years, therefore, no intrusion dose calculations are conducted prior to 100 years.

- Like the acute intruder scenario, drill cuttings from constructing a residential water well containing exhumed waste are brought to the uncontaminated ground surface and spread over the land resulting in contaminated soil.

- A waste package is assumed to be directly and completely intercepted by the drilling.

- All intercepted waste material is assumed to be uniformly available for exhumation to the surface at the specified inventory concentration with no credit for waste form resilience. An exception to avoid excessive conservatism involved adjusting two activated metal waste stream inventories (Reactor AM RH, Reactor AM370 RH) by assuming that only long-term contaminated corrosion products would be mobilized and released in the environment and contribute to dose, rather than considering the full inventory of the bulk metal that would not be in a mobile form. A DOE (2016) estimated a release rate of 1.19×10^{-5} /yr for an activated metals waste stream (based on an evaluation of corrosion rates) was applied to a 1,000 year period to derive a release fraction of 1.19×10^{-2} that was used to adjust the two inventories to account for a more realistic available inventory.

- The chronic intruder receptor is assumed to have a garden where food is grown (garden crops) in soil contaminated with exhumed waste material.

- The garden crops include leafy green vegetables, root vegetables, fruit, and grain.

- The residential water well that is constructed is assumed to be 55 m [180 ft] deep.

- The thickness of the packaged waste is assumed to be 0.5 m [1.6 ft] to account for variability in packing efficiencies among variable waste streams. Results can be scaled proportionately to a change in waste thickness if a need arises to evaluate a different waste thickness for a specific waste stream.

- All material exhumed by the well drilling activity is assumed to be uniformly mixed (in the drill cuttings pile) and instantly spread over and plowed into the top 15 cm [5.91 in] of soil prior to the assumed gardening and dose calculations.

- External dose calculations assume exposure to a 15 cm [5.91 in] plane of exhumed material at the concentration of the uniformly mixed drill cuttings that have been uniformly plowed into the top 15 cm [5.91 in] of garden soil.

- Inhalation and external exposure durations for the chronic intruder (resident) are based on indoor and outdoor activity pattern assumptions and attenuation of both external radiation levels and air concentrations when the chronic intruder is indoors.

- The volume of air inhaled by the chronic intruder is determined by human activity-specific inhalation rates and the duration of indoor, outdoor, and offsite activities.

4.2.4 Results

The mean effective dose estimates for GTCC waste stream over time for the chronic intruder scenario are provided in Figure 10. Results of particular interest include doses that exceed 5 mSv [500 mrem] at 100 and 500 years. NRC previously considered a 5 mSv [500 mrem] intruder dose as the basis of the waste classification limits in 10 CFR Part 61 (NRC, 1982). Additionally, existing requirements in 10 CFR 61.59(b) limit reliance on institutional controls beyond 100 years and current requirements at 10 CFR 61.52(a)(2) for disposal of Class C waste require intrusion barriers to protect against intrusion for 500 years. Beyond 500 years, dose estimates provide insights into the persistence of elevated doses over time for GTCC waste streams that include radionuclides with relatively longer half-lives.

Thirteen of the waste streams had a calculated chronic intruder dose above 5 mSv [500 mrem] after 100 years of institutional control including in descending order MO99 MURR, CS SS CH, WV DECOM O760 RH, MO99 MIPS, WV DECON O RH, WV NDA AM RH, PU238 O RH, Neutron SS CH, WV SDA O CH, WV NDA O RH, WV DECOM O220 CH, WV DECON O CH, and WV SNAP O CH. Two other waste streams had calculated doses at 100 years between 1 and 5 mSv [100 and 500 mrem] including in descending Reactor AM RH and Reactor AM370 RH. The remaining two waste streams had chronic intruder doses at 100 years below 1 mSv [100 mrem] including WV SDA O CH and PU238 O CH. At 500 years of institutional control the additional time for radioactive decay reduced the concentration of some radionuclides within the waste streams such that six waste streams had calculated chronic intruder doses above 5 mSv [500 mrem] including in descending order NEUTRON SS CH, WV DECON O RH, WV NDA AM RH, MO99 MURR, WV DECOM O220 CH, and WV NDA AM RH. Four other waste streams had calculated chronic intruder doses at 500 years between 1 and 5 mSv [100 and 500 mrem] including in descending order WV DECOM O760 RH, MO99 MIPS, REACTOR AM RH and REACTOR AM370 RH. The remaining seven waste streams had calculated chronic intruder doses at 500 years below 1 mSv [100 mrem] including in descending order CS SS CH, WV NDA O CH, WV SNAP O CH, WV SDA AM RH, WV SDA O CH, PU238 O CH, and PU238 O RH.

The radionuclide-specific mean effective dose estimates by GTCC waste stream over time for the chronic intruder scenario are provided in Figures 11 through 18. These figures show the radionuclide-specific contributions to the calculated chronic intruder doses over the entire 10,000 year timeline. These dose estimates show dose contributions from each radionuclide vary considerably throughout the simulation period. For all of the waste streams the number of radionuclides that contribute significantly to the calculated dose is small relative to the number of radionuclides in the waste stream.

Table 2 summarizes the chronic intruder mean annual dose estimates at 500 years by waste stream and shows the contributions of specific radionuclides and exposure pathways to the calculated dose. The dose estimates show the chronic intruder dose for NEUTRON SS, WV DECOM O220 CH, WV DECON O CH, and WV DECOM O760 RH is dominated by the inhalation pathway and isotopes of americium and plutonium are the predominant contributors to the calculated dose. Other waste streams including WV DECON O RH, WV NDA AM RH, MO99 MURR, and MO99 MIPS show a predominant contribution of the crop ingestion pathway and include a different mix of contributing radionuclides such as Tc-99 and C-14 in addition to the isotopes of americium and plutonium.

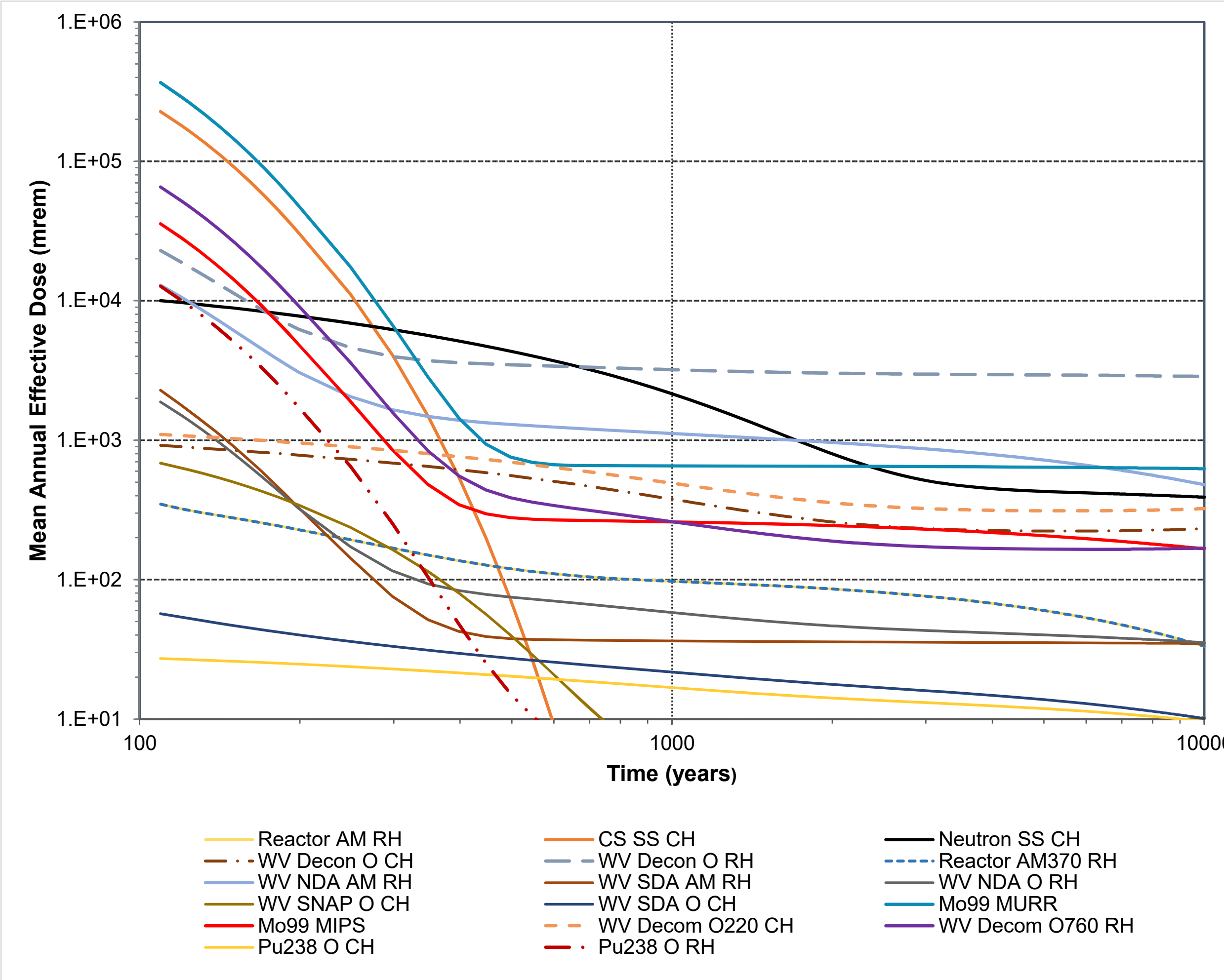

Figure 10. Calculated chronic intruder mean annual total effective dose by GTCC waste stream and time

4.2.5 Discussion

The chronic intruder dose estimates indicated that four waste streams had doses below 5 mSv [500 mrem] after 100 years of institutional control and this increased to 11 waste stream chronic doses below 5 mSv [500 mrem] at 500 years as radionuclides with shorter half-lives were significantly reduced by radioactive decay. Overall, the chronic intruder scenario dose estimates were higher relative to the acute intruder dose estimates (Section 4.1) because of the relatively longer annual exposure duration and the inclusion of additional homegrown food crop exposure pathways.

Conversely, the chronic intruder dose estimates also indicated that 13 waste streams had doses above 5 mSv [500 mrem] after 100 years of institutional control and this reduced to 6 waste streams (NEUTRON SS CH, WV DECON O RH, WV NDA AM RH, MO99 MURR, WV DECOM O220 CH, and WV NDA AM RH) above 5 mSv [500 mrem] at 500 years as radionuclides with shorter half-lives were significantly reduced by radioactive decay. Several of the waste streams continued to be elevated in the chronic dose estimates until at approximately 3,100 years all but 3 waste streams (WV DECON O RH, WV NDA AM RH, MO99 MURR) were below 5 mSv [500 mrem].

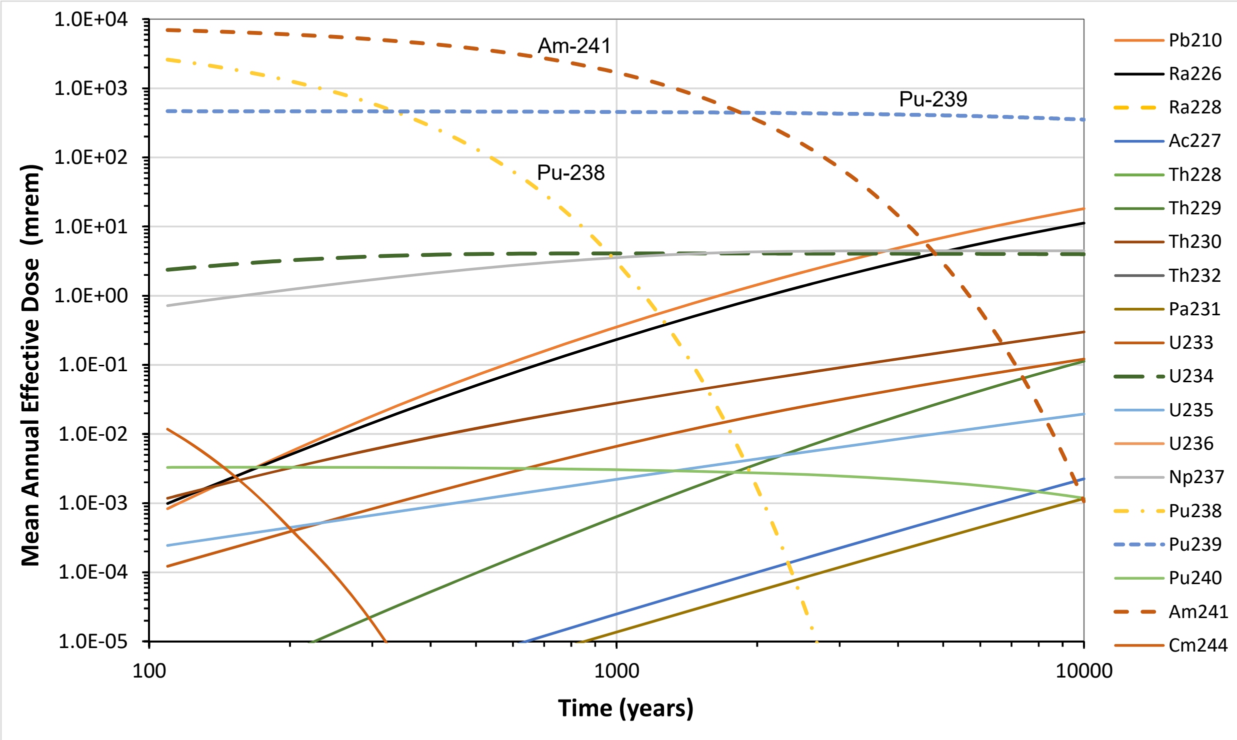

Figure 11. **Calculated chronic intruder mean annual radionuclide-specific effective dose with time for the neutron SS CH waste stream**

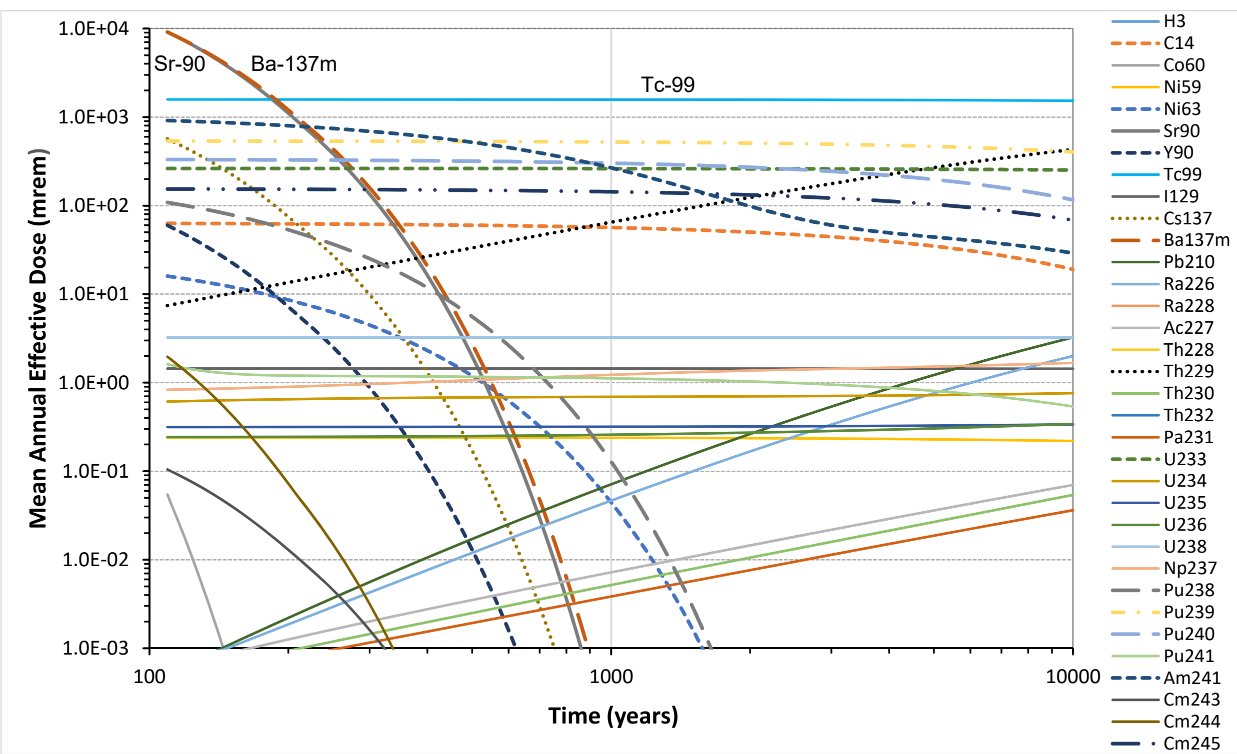

Figure 12. **Calculated chronic intruder mean annual radionuclide-specific effective dose with time for the WV Decom O RH waste stream**

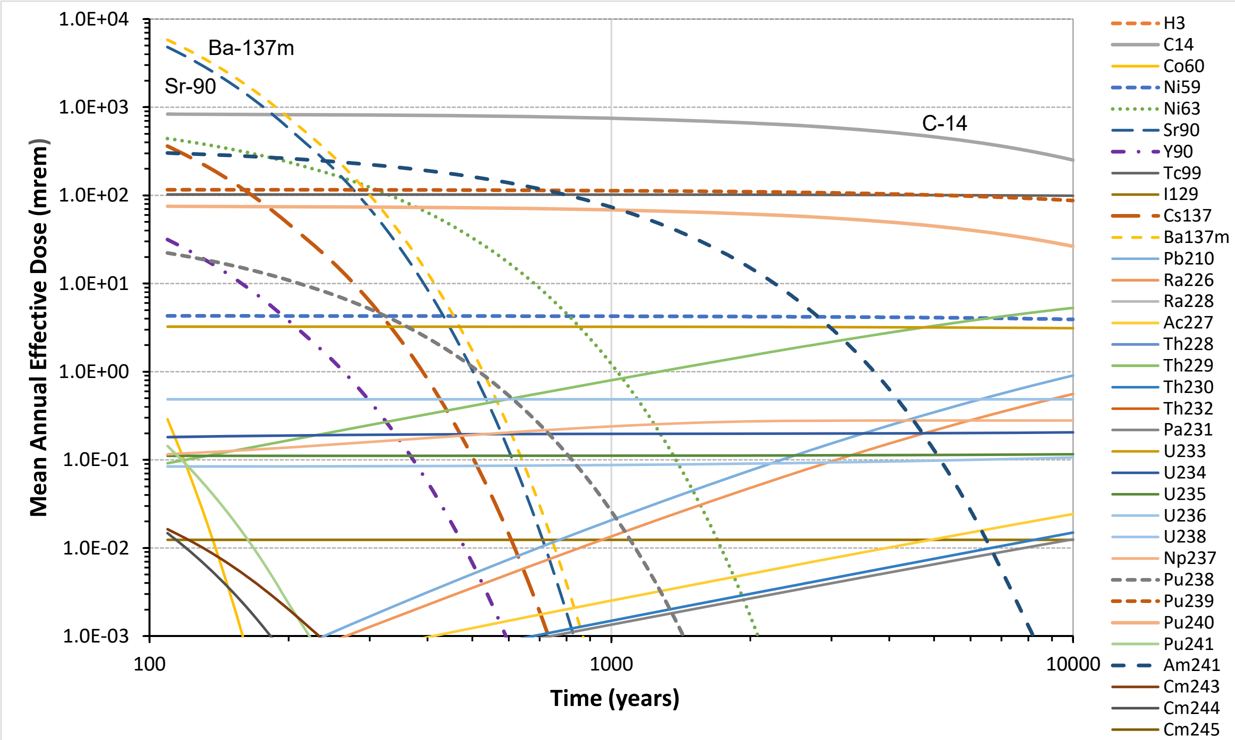

Figure 13. **Calculated chronic intruder mean annual radionuclide-specific effective dose with time for the WV NDA AM RH waste stream**

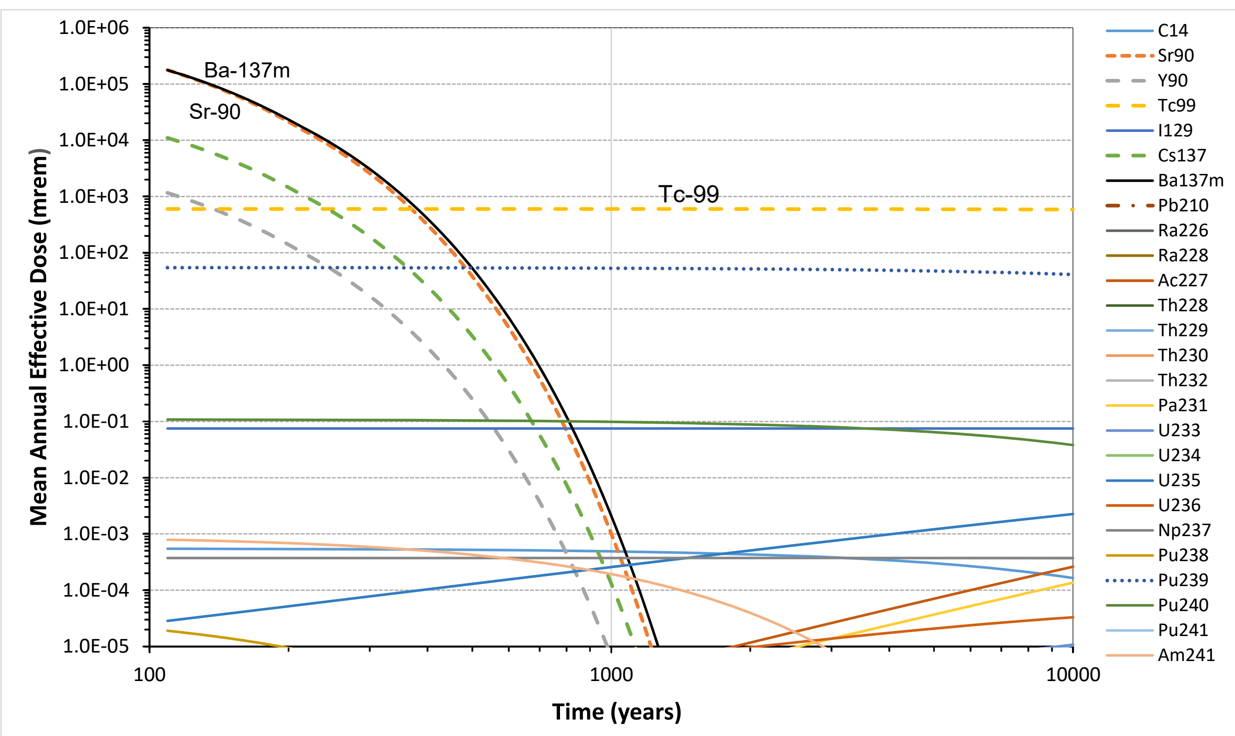

Figure 14. **Calculated chronic intruder mean annual radionuclide-specific effective dose with time for the MO99 MURR waste stream**

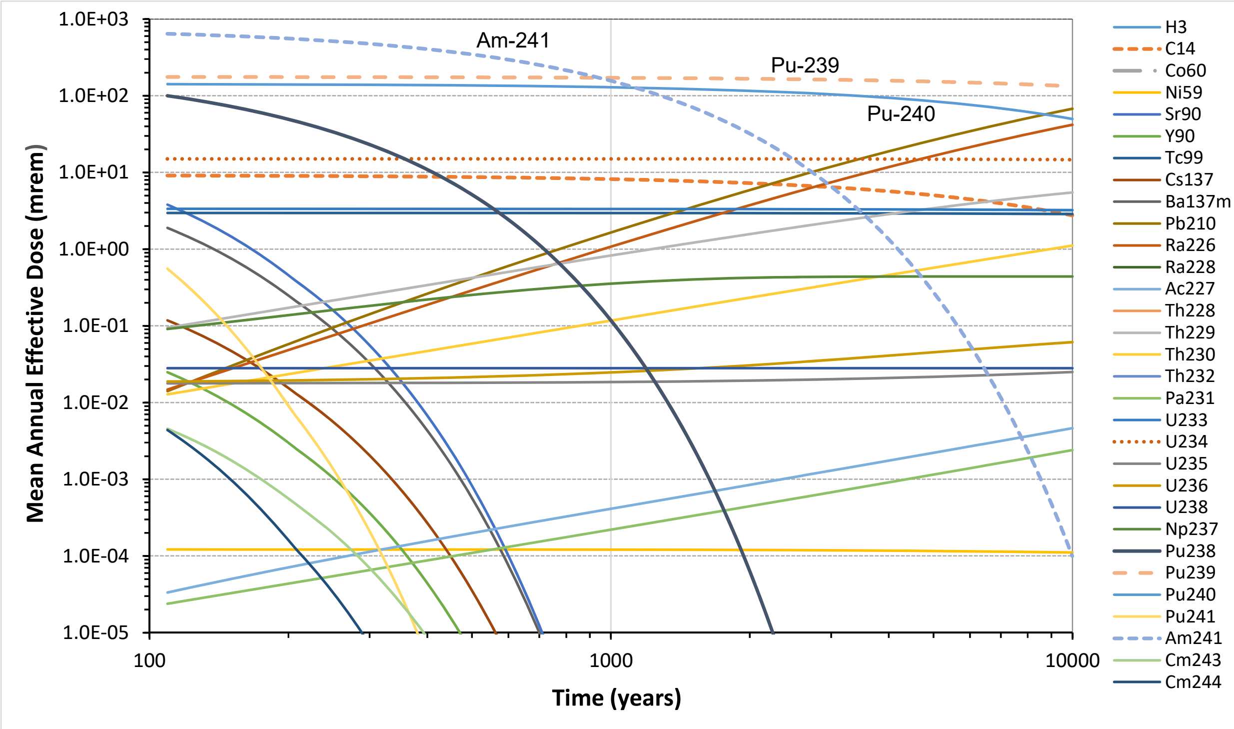

Figure 15. Calculated chronic intruder mean annual radionuclide-specific effective dose with time for the WV Decom O220 CH waste stream

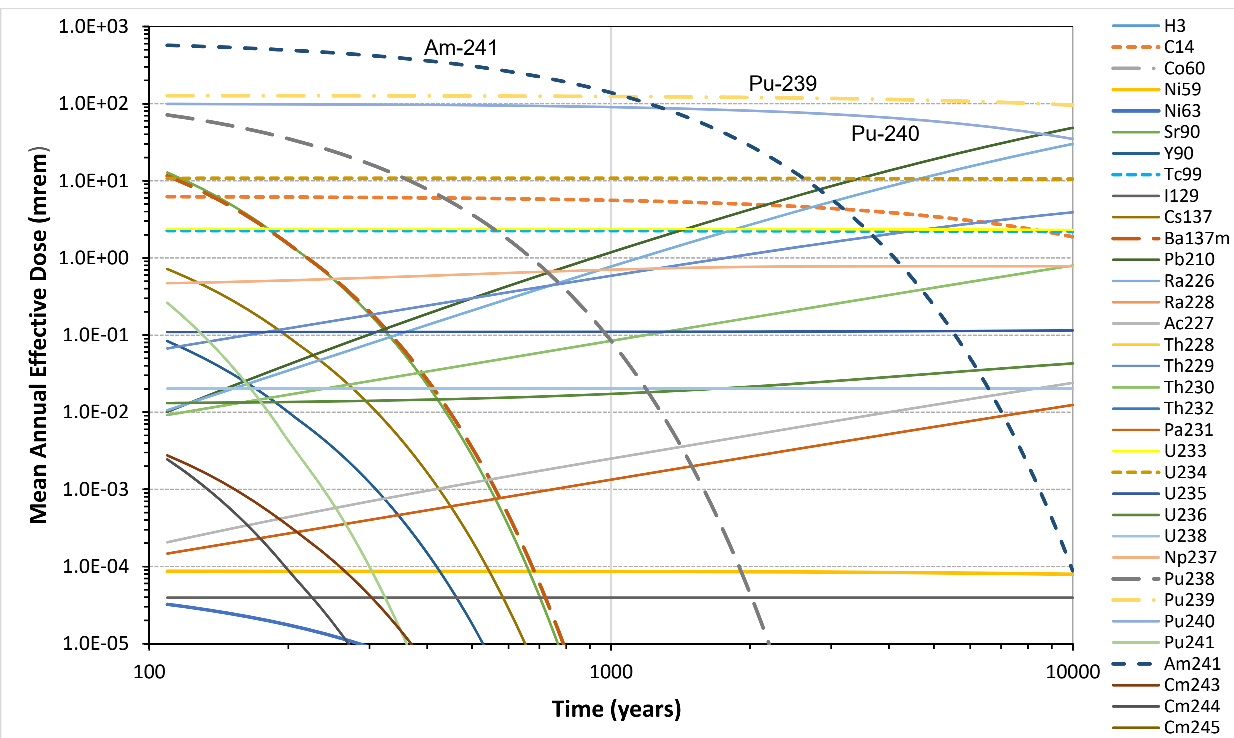

Figure 16. Calculated chronic intruder mean annual radionuclide-specific effective dose with time for the WV Decom O CH waste stream

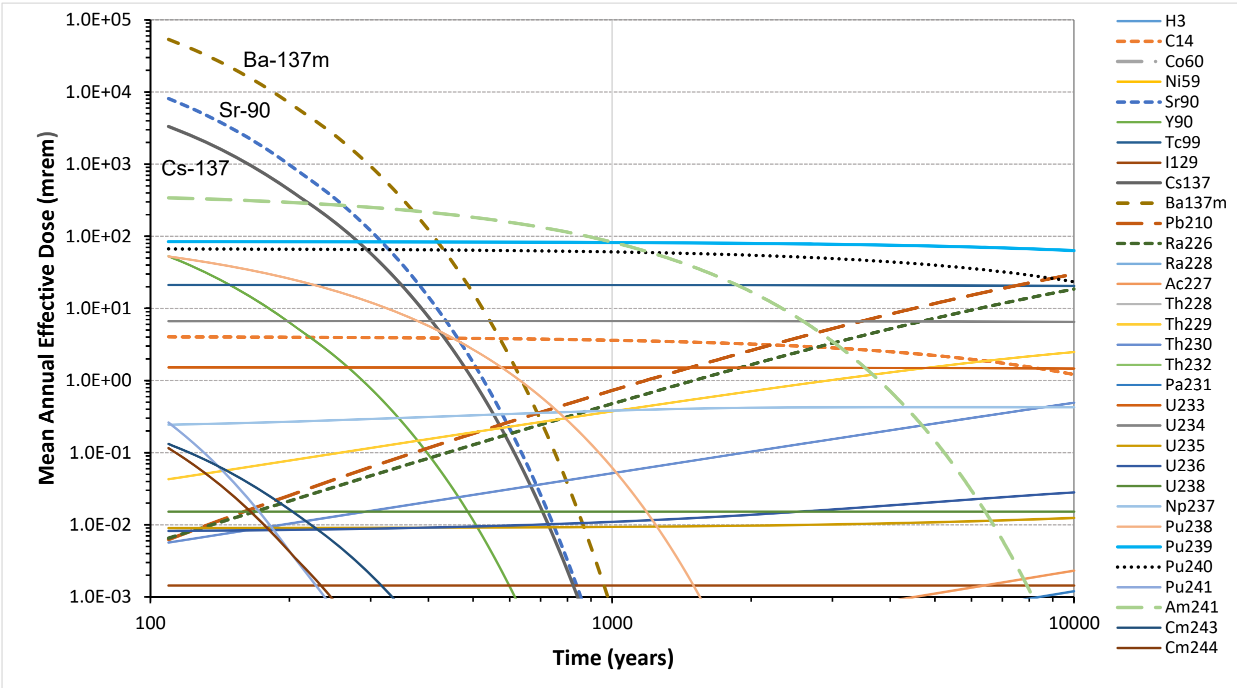

Figure 17. Calculated chronic intruder mean annual radionuclide-specific effective dose with time for the WV Decom O760 RH waste stream

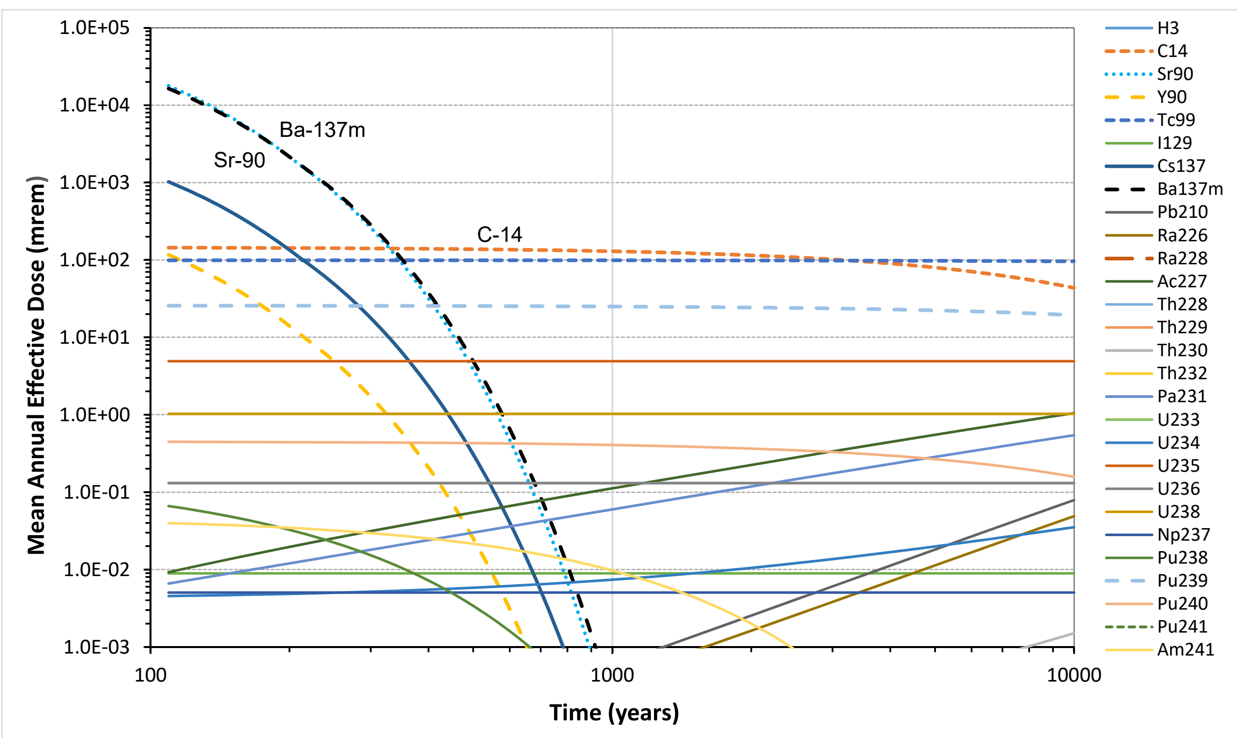

Figure 18. Calculated chronic intruder mean annual radionuclide-specific effective dose with time for the Mo99 MIPS waste stream

Table 2. Calculated chronic intruder mean annual dose at 500 years by waste stream with radionuclide and exposure pathway fractions			
Waste Stream	**Mean Annual Dose at 500 Years in mSv [mrem]**	**Key Radionuclides (Fraction of the Mean Annual Dose)**	**Exposure Pathways (Fraction of the Mean Annual Dose)**
NEUTRON SS CH	43 [4,300]	Am-241 (86%) Pu-239 (11%) Pu-238 (3%)	Inhalation (58%) Groundshine (17%) Soil Ingestion (15%) Crop Ingestion (10%)
WV DECON O RH	35 [3,500]	Tc-99 (45%) Am-241 (15%) Pu-239 (15%) Pu-240 (9%) U-233 (8%) Cm-245 (4%) C-14 (2%)	Crop Ingestion (60%) Inhalation (27%) Soil Ingestion (7%) Groundshine (6%)
WV NDA AM RH	13 [1,300]	C-14 (61%) Am-241 (13%) Pu-239 (9%) Tc-99 (8%) Pu-240 (6%) Ni-63 (3%)	Crop Ingestion (76%) Inhalation (17%) Soil Ingestion (4%) Groundshine (3%)
MO99 MURR	7.6 [760]	Tc-99 (80%) Pu-239 (7%) Ba-137m (7%) Sr-90 (5%)	Crop Ingestion (86%) Groundshine (7%) Inhalation (5%) Soil Ingestion (1%)
WV DECOM O220 CH	7.0 [700]	Am-241 (50%) Pu-239 (25%) Pu-240 (20%) Pu-238 (1%) C-14 (1%)	Inhalation (60%) Crop Ingestion (15%) Soil Ingestion (15%) Groundshine (10%)
WV DECON O CH	5.0 [560]	Am-241 (56%) Pu-239 (23%) Pu-240 (17%) U-234 (2%)	Inhalation (59%) Soil Ingestion (15%) Crop Ingestion (14%) Groundshine (11%)
WV DECOM O760 RH	3.9 [390]	Am-241 (47%) Pu-239 (21%) Pu-240 (16%) Tc-99 (5%) Ba-137m (4%) U-234 (2%)	Inhalation (54%) Crop Ingestion (18%) Soil Ingestion (14%) Groundshine (14%)
MO99 MIPS (13)	2.8 [280]	C-14 (49%) Tc-99 (36%) Pu-239 (9%) Ba-137m (2%) U-235 (2%)	Crop Ingestion (89%) Inhalation (6%) Groundshine (3%) Soil Ingestion (2%)

The NEUTRON SS CH waste stream consists of sealed sources containing long-lived isotopes of plutonium and americium (Appendix A, Table A–1) that upon release result in a 500 year chronic intruder dose of 4,300 mrem was over 8.6 times above the 5 mSv [500 mrem] intruder objective. The WV DECOM O220 CH waste stream had a 500 year chronic intruder dose of 7 mSv [700 mrem] that is dominated by similar radionuclides as NEUTRON SS CH. The pathway-specific dose estimates for these waste streams were similar showing inhalation contributing approximately 60 percent of the calculated mean dose with the remainder from ground shine, soil ingestion, and crop ingestion. The large contribution of the inhalation pathway is consistent with expectations for these predominantly alpha radiation emitting radionuclides.

Three other elevated waste streams (WV DECON O RH, WV NDA AM RH, MO99 MURR) had 500 year chronic intruder doses ranging from 13 to 7 mSv [1,300 to 700 mrem] but included a different mix of radionuclides in their inventories that consisted of more biologically mobile elements (technetium and carbon) that resulted in an increased contribution from the homegrown crop pathway. For these waste streams the crop pathway contributed from 60 to 86 percent of the calculated chronic intruder dose with technetium or carbon contributing the most to the calculated chronic intruder dose at 500 years. This behavior in the dose estimates is consistent with the presence of these radionuclides in these waste streams (Appendix A) and their expected biological mobility as indicated by elevated plant transfer factors for technetium as shown in Appendix B (Tables B–4 through B–7) or in the underlying bases and assumptions of the specific activity model used to model carbon uptake in plants in BDOSE 2.0 (Simpkins et al., 2008).

The high chronic doses for several waste streams including NEUTRON SS CH NEUTRON SS CH, WV DECON O RH, WV NDA AM RH, MO99 MURR, WV DECOM O220 CH at 500 years suggests that there could be challenges for shallow land burial for these waste streams if a similar chronic intruder calculation with the adopted assumptions is used, but recognizing that some assumptions tend to overestimate the doses. For example, the current dose calculations conservatively assume the waste form would be readily available for exhumation and would be in a readily dispersible form for inhalation, groundshine, and soil ingestion and in a soluble form for plant uptake. These assumptions are expected to be reasonable for waste forms such as contaminated soil and waste with removable contamination but would be more conservative for more solid better contained waste forms such as metals and possibly sealed sources. Incorporating more realism about the waste form availability in the current dose calculations would help to discern the level of conservatism and help improve the evaluation of the potential hazard.

4.3 Accidental Release: Acute Onsite Worker Exposure Scenario

The acute onsite worker exposure scenario evaluates the short-term dose to a disposal facility worker in close proximity to an accidental release of waste material. The acute onsite worker is exposed by inhalation to the passage of a plume of released GTCC waste material.

4.3.1 Conceptual and Mathematical Models

The acute onsite worker exposure scenario assumes a worker is in close proximity to a drop or depressurization type accident at a LLRW facility where a waste drum is ruptured and a fraction of the contents (0.1 percent) is assumed to be uniformly dispersed into a small assumed volume of air {a half sphere with diameter of 10 m [33 ft]}. The worker is assumed to be exposed to the plume concentration for 20 seconds as it passes. The calculation can be characterized as a

conservative screening style calculation to gain insights into the level of hazard presented by the materials in different waste streams. The following equation (Eq. 1) describes the mathematical model for the acute onsite worker dose calculation.

$$\mathrm{Dose_w} = \sum_i \frac{\mathrm{C_i\ V_{pkg}\ F_{rel}}}{\mathrm{V_{air}}}\ \mathrm{B_{rate}\ E_{time}\ DC_{inh,i}\ U_{conv}} \quad (1)$$

$\mathrm{Dose_w}$ = acute total onsite worker dose for an accidental release by GTCC waste stream (mrem)
$\mathrm{C_i}$ = inventory concentration for a GTCC waste stream for radionuclide i (Ci/m^3)
$\mathrm{V_{pkg}}$ = package volume (m^3)
$\mathrm{F_{rel}}$ = release fraction (unitless)
$\mathrm{T_{rel}}$ = release duration (sec)
$\mathrm{V_{air}}$ = volume of air containing the plume of released waste material (uniformly dispersed) (m^3)
$\mathrm{B_{rate}}$ = inhalation rate (m^3/sec)
$\mathrm{E_{time}}$ = exposure duration (sec)
$\mathrm{DC_{inh,i}}$ = inhalation dose coefficient for radionuclide i (Sv/Bq)
$\mathrm{U_{conv}}$ = unit conversions for mrem/Sv and Bq/Ci

4.3.2 Input Parameters

The input parameters used to calculate the dose for the acute onsite worker exposure scenario are provided in Table 3.

4.3.3 Assumptions

Modeling exposure scenarios like the accidental release acute onsite worker exposure scenario involve a number of explicit and implicit assumptions. The following assumptions apply to the calculations conducted for this report:

- The waste material is assumed to have a uniform concentration and is readily dispersible. The calculations do not account for waste form mitigating release although the inventories of 2 activated metal waste streams (Reactor AM RH, Reactor AM370 RH) were developed accounting for the available surface contamination that could contribute to release to air rather than the bulk metal which would not be available for release to air).

- The worker breathing rate is assumed to be elevated consistent with elevated activity during an accident response scenario.

- The movement of the plume is based on an assumed low velocity wind {1 m/s [3.3 ft/s]}.

- No deposition or settling of material from the plume is considered.

4.3.4 Results

The total effective inhalation dose for the acute onsite worker exposure scenario by waste stream is provided in Figure 19. The highest calculated worker dose for this scenario was for the Neutron SS CH waste stream at over 10 Sv [1,000 rem] followed by three waste streams that were above 1 Sv [100 rem] including in descending order WV DECON O RH, WV SNAP O CH, and WV DECOM O220 CH. Between 0.25 and 1 Sv [25 and 100 rem] were 5 other

Table 3.	**Input parameters for the accidental release acute onsite worker exposure scenario**		
Input parameters	**Value**	**Units**	**Remarks**
Release Height	10	m	The assumed height of an accidental puff release from a single package (e.g., package drop or reactive de-pressurization). Used to calculate the volume of air for plume dispersion.
Release Width (total lateral dispersion on both sides of plume centerline)	20	m	The assumed width of an accidental puff release from a single package (e.g., package drop or reactive de-pressurization). Used to calculate the volume of air for plume dispersion.
Release Air Volume (calculated)	157	m^3	The volume of air the release is dispersed into {i.e., volume of 1/2 of a sphere with radius of 10 m [33 ft]}.
Release Fraction	0.001	unitless	The assumed fractional release from the waste package of 0.1 percent. Allows for simple proportional scaling of dose estimates for different release fractions if necessary.
Inhalation Rate	7.20×10^{-2}	m^3/min	EPA exposure factors handbook (2011) Table 6-49. Inhalation Rates for Short-Term Exposures; heavy activity, ages 18 to <30 years.
Exposure Duration	0.33	min	An assumed 20 second exposure time {for a 20 m [66 ft] wide plume with 1m/s wind, the centerline passes the receptor in 20 seconds}.
Package Volume	0.15	m^3	Volume of cylinder assuming 55 gal drum of 0.61 m [2.0 ft] diameter filled to a depth of 0.5 m [1.6 ft] with waste material.

waste streams including in descending order WV DECON O CH, WV DECOM O760 RH, WV NDA AM RH, and Pu-238 O RH and MO99 MURR. Conversely, 8 waste streams produced inhalation doses that were less than 0.25 Sv [25 rem]. The U.S. Environmental Protection Agency (EPA) Protective Action Guideline for a lifesaving emergency worker of 0.25 Sv [25 rem] is provided as a reference point for context. This guideline was established as a level of radiation exposure during an emergency that the EPA has determined would not be expected to result in early onset health effects to the worker.

The radionuclide-specific effective inhalation doses that are above 0.01 Sv [1 rem] for the acute onsite worker exposure scenario by waste stream is provided in Figure 20. This figure shows the relatively small number of radionuclides that contribute to the calculated doses including Co-60, Sr-90, Cs-137, and isotopes of plutonium, americium, and curium. The highest onsite

worker accidental release doses from any of the radionuclides evaluated were from Pu-238 and Am-241 in the NEUTRON SS CH waste stream.

4.3.5 Discussion

The total effective inhalation dose estimates for the acute onsite worker exposure scenario for an accidental release show generally high doses with a majority of waste stream doses exceeding 0.1 Sv [10 rem] which is consistent with expectations for an unmitigated release of GTCC waste stream constituents and close proximity exposure to a worker. While generally simple and conservative methods have been applied to these dose calculations, the dose estimates suggest consideration of near surface disposal of GTCC waste streams should take into account the potential worker safety hazards associated with credible accidents and consider additional safety measures that might be needed to provide assurance that accident prevention and mitigation would be considered in evaluating any future proposals or changes to requirements.

4.4 Accidental Release: Acute Offsite Public Exposure Scenario

The acute offsite public exposure scenario evaluates the short-term dose to a member of the public at the facility boundary during an accidental release of GTCC waste material. The acute offsite public individual is exposed by inhalation to the passage of a plume of released GTCC waste material.

4.4.1 Conceptual and Mathematical Models

The acute offsite public exposure scenario assumes a member of the public is 100 m [328 ft] downwind from a 30 minute fire that releases 0.1 percent of a waste package contents into the air. The downwind concentration is estimated based on applying an available DOE χ/Q value from a Gaussian plume calculation that involves conservative dispersion assumptions. The χ/Q value is based on NUREG–1140 and is used by DOE to estimate accident consequences from DOE facilities. The public receptor is assumed to be exposed to the full duration of the plume passage (30 minutes). The calculation can be characterized as a conservative screening style calculation to gain insights into the level of hazard presented by the materials in different waste streams. The following equation (Eq. 2) describes the mathematical model for the acute offsite public exposure scenario.

$$\mathrm{Dose_p} = \sum_i \frac{\mathrm{C_i\ V_{pkg}\ F_{rel}}}{\mathrm{T_{rel}}}\ \chi/\mathrm{Q_{acc}}\ \mathrm{B_{rate}}\ \mathrm{E_{time}}\ \mathrm{DC_{inh,i}}\ \mathrm{U_{conv}} \qquad (2)$$

where

$\mathrm{Dose_p}$ = acute total offsite public dose for an accidental release by GTCC waste stream (mrem)
$\mathrm{C_i}$ = inventory concentration for a GTCC waste stream for radionuclide i (Ci/m^3)
$\mathrm{V_{pkg}}$ = package volume (m^3)
$\mathrm{F_{rel}}$ = release fraction (unitless)
$\mathrm{T_{rel}}$ = release duration (sec)
$\chi/\mathrm{Q_{acc}}$ = downwind centerline ground-level time-integrated air concentration at 100 m [sec/m^3]
$\mathrm{B_{rate}}$ = inhalation rate (m^3/sec)
$\mathrm{E_{time}}$ = exposure duration (sec)
$\mathrm{DC_{inh,i}}$ = inhalation dose coefficient for radionuclide i (Sv/Bq)
$\mathrm{U_{conv}}$ = unit conversions for mrem/Sv and Bq/Ci

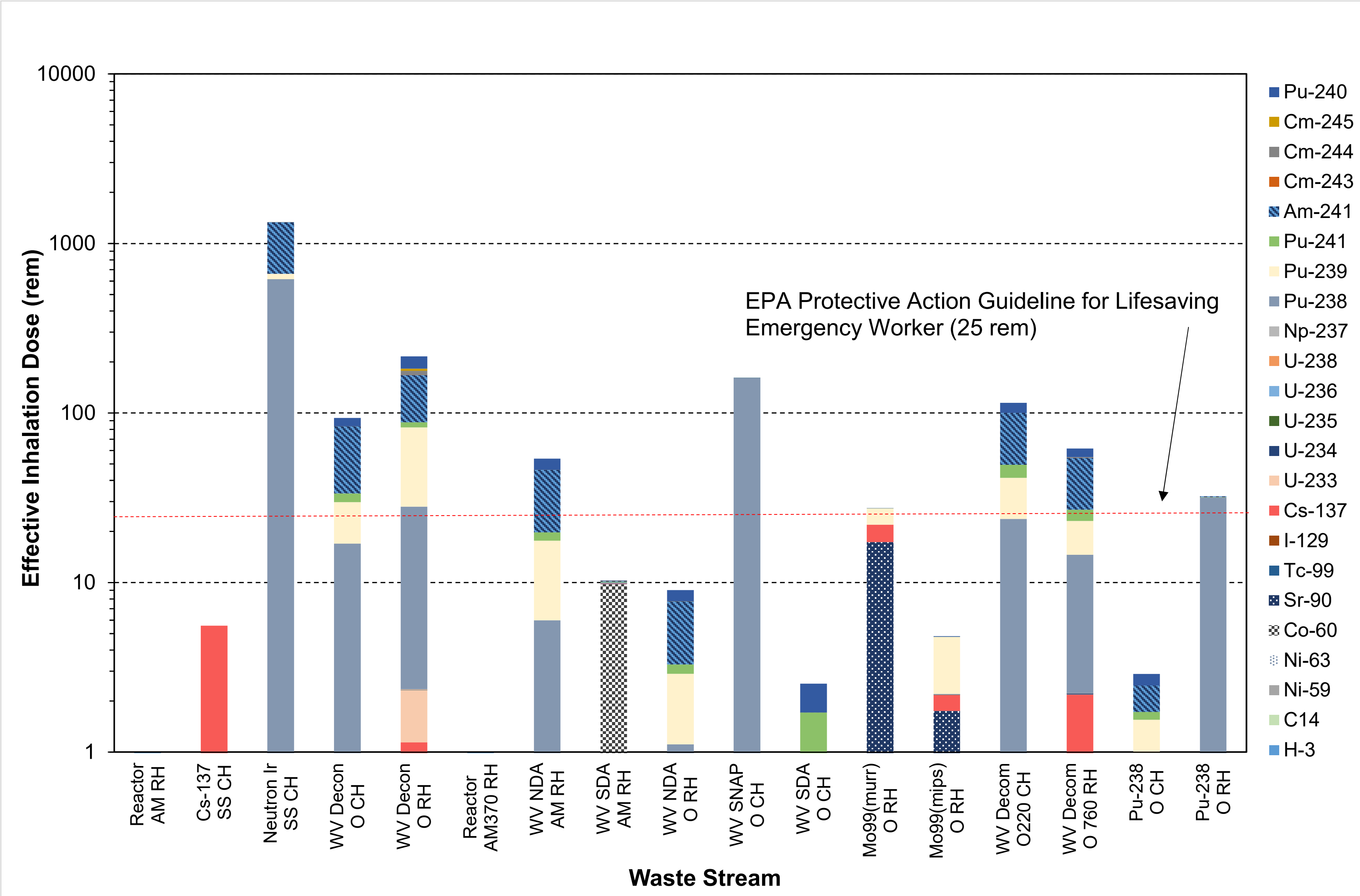

Figure 19. Calculated acute onsite worker total effective inhalation dose by waste stream for the accidental release scenario

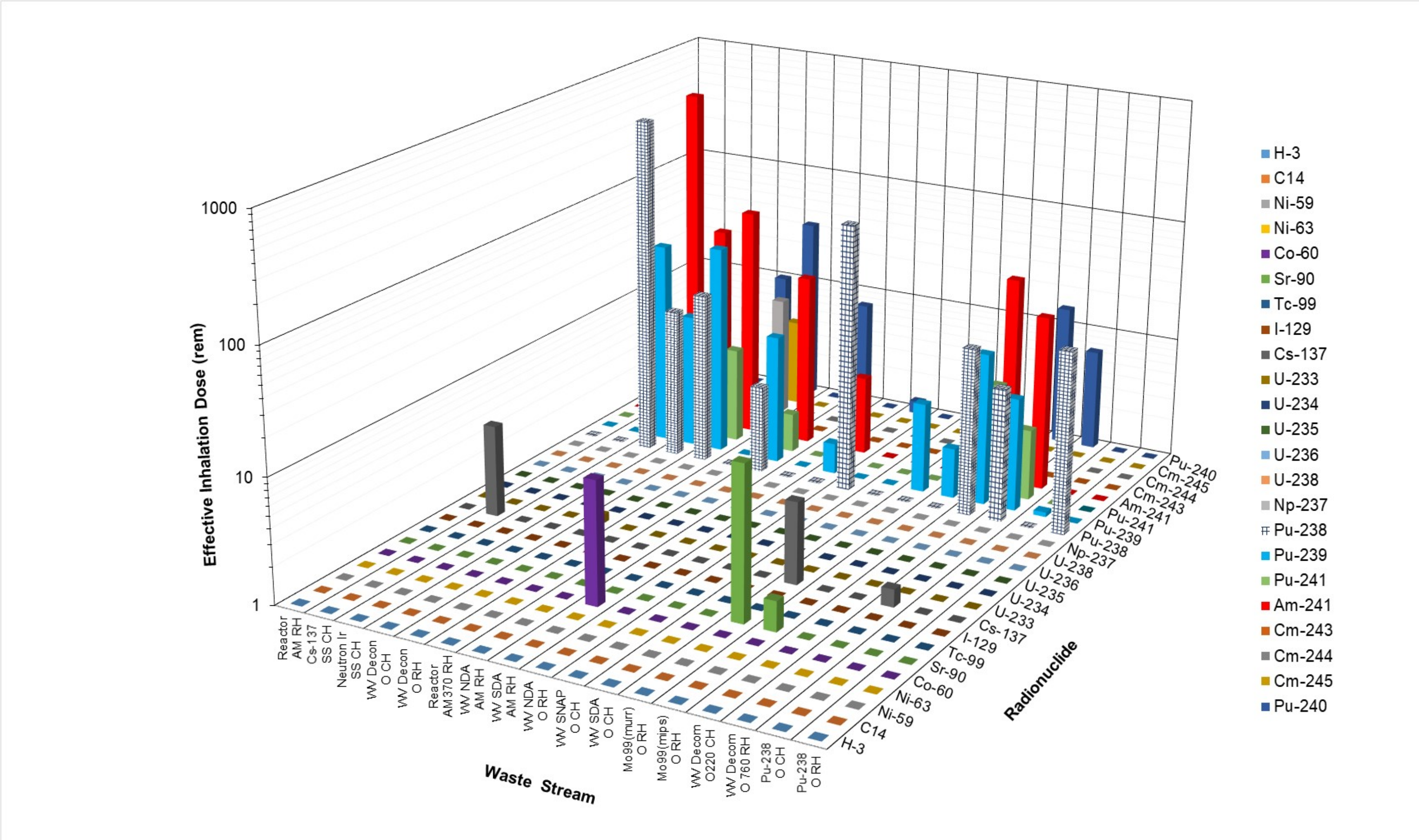

Figure 20. Calculated acute onsite worker effective radionuclide-specific inhalation dose by waste stream for the accidental release scenario

4.4.2 Input Parameters

The input parameters used to calculate the dose for the acute offsite public exposure scenario are provided in Table 4.

Table 4. Input parameters for the accidental release acute offsite public exposure scenario

Input parameters	Value	Units	Remarks
Downwind Air Concentration (χ/Q)	3.50×10^{-3}	s/m^3	The relative downwind centerline ground level air concentration (χ/Q) at 100 m [328 ft] from DOE (2015)
Release Fraction	0.001		The assumed fractional release from the waste package of 0.1 percent, allows scaling of dose estimates for different release fractions if necessary
Inhalation Rate	3.89×10^{-4}	m^3/sec	The inhalation rate for general outdoor activities of 1.4 m^3/hr (Beyeler et al., 1999)
Exposure Duration	1,800	sec	The assumed exposure to the plume for a 30 minute duration fire consistent with DOE (2015)
Waste Package Volume	0.15	m^3	The volume of a 55 gal drum of 0.61 m [2.0 ft] diameter filled to a depth of 0.5 m [1.6 ft] with waste material
Release Duration	1,800	sec	A 30 minute fire duration is assumed with continuous release

4.4.3 Assumptions

Modeling exposure scenarios like the accidental release acute offsite public exposure scenario involve a number of explicit and implicit assumptions. The following assumptions apply to the dose calculations conducted for this report:

- The waste material is assumed to have a uniform concentration and is readily dispersible. There is no consideration in the dose calculation that waste form would mitigate the release, although the inventories of 2 activated metal waste streams (REACTOR AM RH, REACTOR AM370 RH) were developed accounting for the available surface contamination that could contribute to release to air rather than the bulk metal which would not be available for release to air).

- The χ/Q value for dispersion modeling conservatively assumes F stability, 1 m/s wind, flat terrain, and a continuous 30 minute release.

- A building wake effect is assumed. This is not conservative because it enhances plume dispersion but LLRW facilities include buildings so it is considered applicable and reasonable.

4.4.4 Results

The total effective inhalation dose for the acute offsite public exposure scenario by waste stream is provided in Figure 21. The highest calculated public dose for this scenario was for the Neutron SS CH waste stream at over 0.1 Sv [10 rem] followed by three waste streams that were above within the range of 0.01 to 0.05 Sv [1 to 5 rem] including in descending order WV DECON O RH, WV SNAP O CH, and WV DECOM O220 CH. Between 1 and 10 mSv [100 mrem and 1,000 mrem] were 5 other waste streams including in descending order WV DECON O CH, WV DECOM O760 RH, WV NDA AM RH, and Pu-238 O RH and MO99 MURR. Eight waste stream public doses for the accidental release were below 1 mSv [100 mrem]. The EPA Protective Action Guideline for public evacuation or sheltering-in-place of 0.01 to 0.05 Sv [1 to 5 rem] is provided as a reference point for context. This guideline was established as a level of radiation exposure during an emergency that the EPA has determined would be protective of public health and safety during a radiological emergency.

The radionuclide-specific effective inhalation doses that are above 0.1 mrem for the acute offsite public exposure scenario by waste stream is provided in Figure 22. This figure shows the relatively small number of radionuclides that contribute to the calculated doses including Co-60, Sr-90, Cs-137, and isotopes of plutonium, americium, and curium. The highest offsite public accidental release doses from any of the radionuclides evaluated were from Pu-238 and Am-241 in the NEUTRON SS CH waste stream.

4.4.5 Discussion

The total effective inhalation dose estimates for the acute offsite public exposure scenario for an accidental release show elevated public doses with slightly more than half of the waste streams showing doses above 1 mSv [100 mrem] up to approximately 0.1 Sv [10 rem] which is consistent with expectations for an unmitigated release of GTCC waste stream constituents and exposure to a member of the public at the facility boundary. Conversely, all but three waste streams produced public doses that were below the EPA protective action guideline for members of the public evacuating or sheltering in place during a radiological accident. While generally simple and conservative methods have been applied to these dose calculations, the results of this analysis suggests consideration of near surface disposal of GTCC waste streams should take into account the potential public safety hazards associated with credible accidents and consider additional safety measures that might be needed to provide assurance that accident prevention and mitigation would be considered in evaluating any future proposals or changes to requirements.

5 CONCLUSIONS

To support NRC evaluations of potential revisions to regulatory requirements following a risk-informed, performance-based approach, technical evaluations involving acute and chronic dose estimates of 17 GTCC waste streams were conducted within the context of the 10 CFR Part 61 performance objective on the protection of individuals from inadvertent intrusion into a LLRW disposal site after loss of active institutional controls. Additional technical evaluations of the potential hazards to workers and the general population from accidental releases of GTCC waste stream radioactivity during disposal facility operations were also conducted.

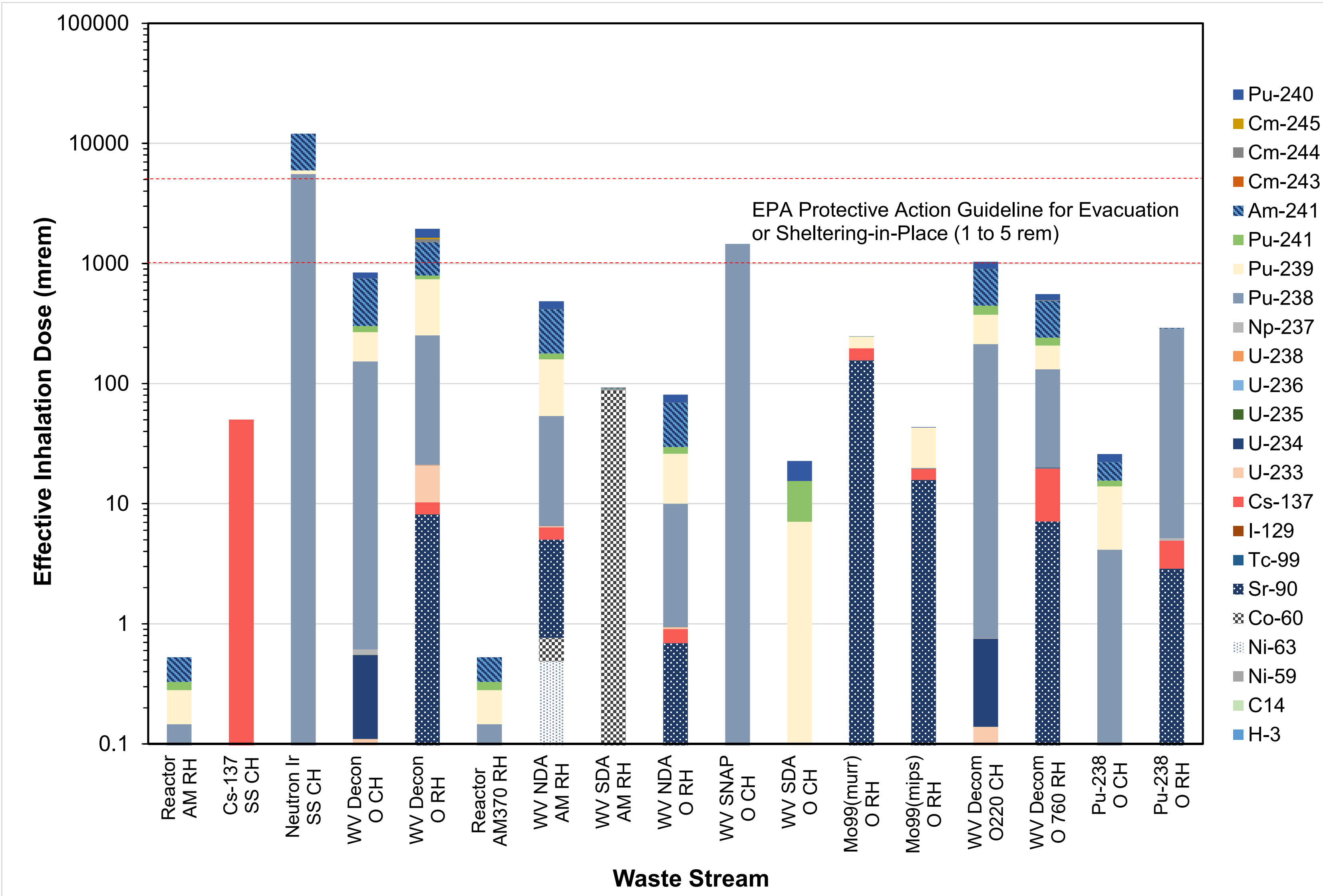

Figure 21. Calculated acute offsite public total effective inhalation dose by waste stream for the accidental release scenario

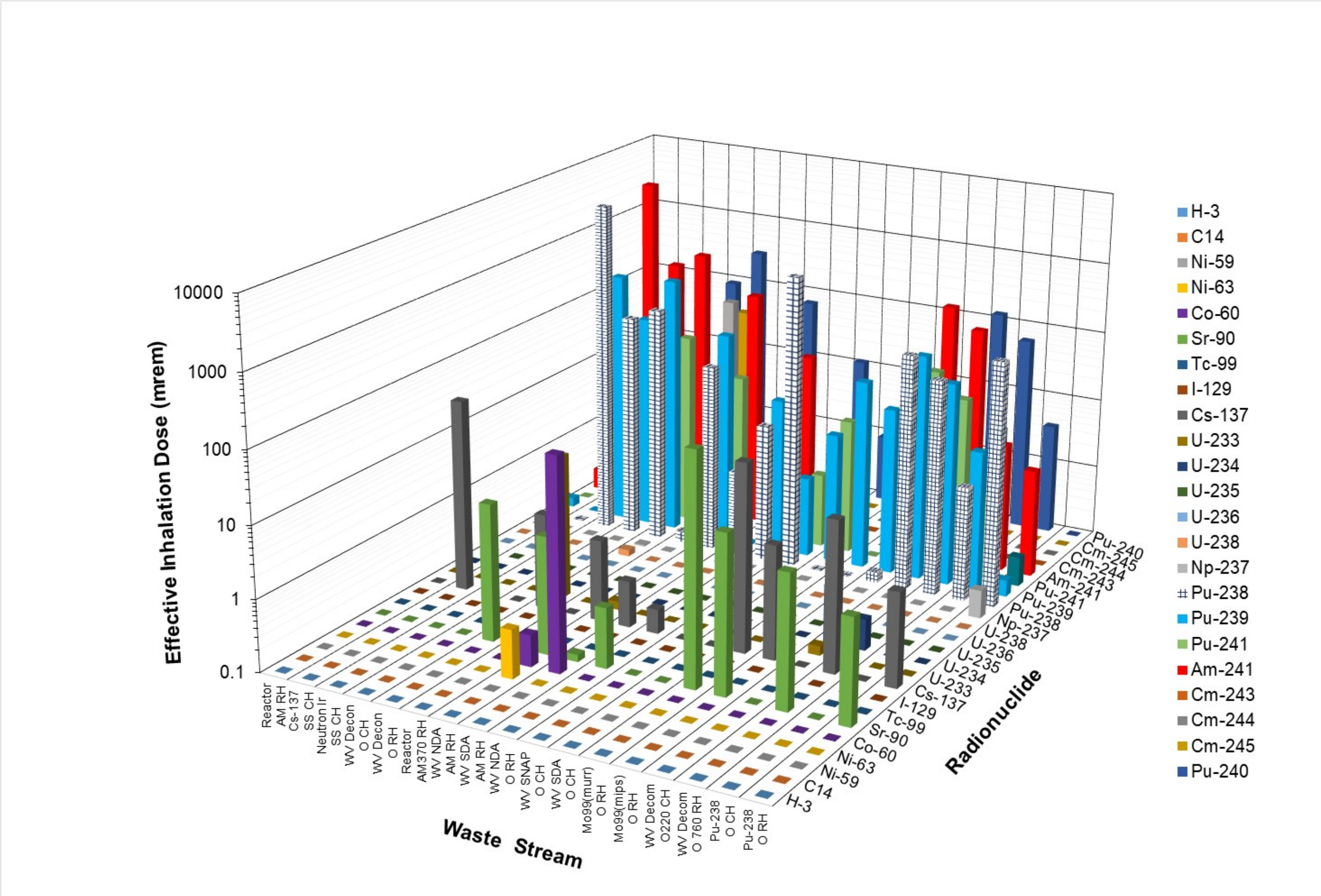

Figure 22. **Calculated acute offsite public radionuclide-specific effective inhalation dose by waste stream for the accidental release scenario**

Analysis of the acute intruder dose estimates indicated that 12 potential GTCC waste streams had doses below 5 mSv [500 mrem] after 100 years of institutional control and this increased to 15 waste streams below 5 mSv [500 mrem] at 500 years as radionuclides with shorter half-lives were significantly reduced by radioactive decay. Therefore, under the acute intruder scenario, a majority of the waste streams met the 5 mSv [500 mrem] objective. The acute intruder dose estimates included 5 waste streams with doses above 5 mSv [500 mrem] after 100 years of institutional control. This group of waste streams with elevated dose estimates reduced to 2 waste streams above 5 mSv [500 mrem] at 500 years as radionuclides with shorter half-lives were significantly reduced by radioactive decay. At approximately 1,500 years all waste stream dose estimates were below 5 mSv [500 mrem]. These waste streams that exceeded the 5 mSv [500 mrem] objective may present additional challenges for near surface disposal and therefore may require additional attention and analysis. The analysis showed the acute intruder dose was dominated by the inhalation pathway and that the isotopes of americium and plutonium were the predominant contributors to the calculated doses.

The chronic intruder scenario dose estimates were higher relative to the acute intruder dose estimates because of the relatively longer annual exposure duration and the inclusion of additional homegrown food crop exposure pathways. The chronic intruder dose estimates included only 4 waste streams with doses below 5 mSv [500 mrem] after 100 years of institutional control and this increased to 11 waste streams below 5 mSv [500 mrem] at 500 years as radionuclides with shorter half-lives were significantly reduced by radioactive decay. Therefore, under the chronic intruder scenario, a minority of the waste streams met the 5 mSv [500 mrem] objective at 100 years and a majority met the objective at 500 years. This analysis indicates the importance of assumptions about the duration of institutional controls.

The chronic intruder dose estimates also indicated that 13 waste streams had doses above 5 mSv [500 mrem] after 100 years of institutional control and this reduced to 6 waste streams above 5 mSv [500 mrem] at 500 years as radionuclides with shorter half-lives were significantly reduced by radioactive decay. Several of the waste streams continued to be elevated in the chronic dose estimates until at approximately 3,100 years all but 3 waste streams were below 5 mSv [500 mrem]. These waste streams that exceeded the 5 mSv [500 mrem] objective may present additional challenges for near surface disposal and therefore may require additional attention and analysis.

The pathway-specific dose estimates for the elevated chronic intruder doses at 500 years included a group of waste streams that showed predominant radionuclides and pathways similar to what was found with the acute intruder. Here, inhalation of isotopes of plutonium and americium contributed approximately 60 percent of the calculated mean dose with the remainder from groundshine, soil ingestion, and crop ingestion pathways. Another group of waste streams with elevated chronic intruder doses at 500 years included more biologically mobile elements (technetium and carbon) that resulted in an increased contribution from the homegrown crop pathway. For these waste streams the crop pathway contributed from 60 to 86 percent of the calculated chronic intruder dose with technetium or carbon contributing the most to the calculated chronic intruder dose at 500 years. Elevated chronic intruder dose estimates focused attention on conservative assumptions regarding the availability of waste material for inhalation and plant transfer that do not account for individual waste form properties. Improved understanding and accounting for the effect of waste form on the potential for release and transport in intruder and accident scenarios could improve the realism of estimated doses.

The inhalation dose estimates for the accidental release acute onsite worker exposure scenario showed generally high doses with a majority of waste stream doses exceeding 0.1 Sv [10 rem]

which was consistent with expectations for an unmitigated release of GTCC waste stream constituents and close proximity exposure to a worker. The inhalation dose estimates for the accidental release acute offsite public exposure scenario showed elevated public doses with slightly more than half of the waste streams with doses above 1 mSv [100 mrem] up to approximately 0.1 Sv [10 rem]. The dose estimates were lower than the onsite worker dose estimates which is consistent with a more distant exposure to a member of the public at the facility boundary that accounts for plume dispersion. Conversely, all but 3 waste streams produced public doses that were below the EPA protective action guideline for members of the public evacuating or sheltering in place during a radiological accident. Although conservative methods were used in both worker and public accidental release scenarios, this analysis suggests consideration of near surface disposal of GTCC waste streams should take into account the potential worker and public safety hazards associated with credible accidents and consider additional safety measures that might be needed to provide assurance that accident prevention and mitigation would be considered in evaluating any future proposals or changes to requirements.

Overall, the results of these technical analyses are expected to provide insights into how the radiological properties of various GTCC waste streams and exposure scenario considerations may impact required compliance demonstrations for disposal of GTCC waste streams.

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APPENDIX A

GREATER-THAN-CLASS C WASTE STREAM INVENTORIES

Table A–1. Radionuclide inventories for Group 1 GTCC and GTCC-like waste streams (Ci/m^3)						
Waste Stream # ----->		**1**	**2**	**3**	**4**	**5**
Nuclide	**Half Life (years)**	**REACTOR AM RH**	**Cs-137 SS CH**	**NEUTRON SS CH**	**WV DECON O CH**	**WV DECON O RH**
H-3	1.2E+01	7.73E+00	0.00E+00	0.00E+00	2.39E-04	2.96E-02
C14	5.7E+03	2.61E+01	0.00E+00	0.00E+00	1.83E-02	1.85E-01
Co-60	5.3E+00	5.68E+04	0.00E+00	0.00E+00	5.77E-06	2.22E+00
Ni-59	7.5E+04	1.48E+02	0.00E+00	0.00E+00	1.07E-04	2.96E-01
Ni-63	9.6E+01	2.05E+04	0.00E+00	0.00E+00	3.52E-05	1.74E+01
Sr-90	2.9E+01	4.89E-03	0.00E+00	0.00E+00	9.30E-02	6.67E+01
Tc-99	2.1E+05	2.27E-04	0.00E+00	0.00E+00	4.51E-04	3.15E-01
I-129	1.6E+07	2.11E-06	0.00E+00	0.00E+00	1.37E-07	5.00E-03
Cs-137	3.0E+01	8.64E-02	1.70E+03	0.00E+00	9.15E-02	7.22E+01
U-233	1.6E+05	0.00E+00	0.00E+00	0.00E+00	1.32E-02	1.46E+00
U-234	2.4E+05	0.00E+00	0.00E+00	0.00E+00	6.20E-02	2.96E-03
U-235	7.0E+08	0.00E+00	0.00E+00	0.00E+00	2.25E-04	6.48E-04
U-236	2.3E+07	0.00E+00	0.00E+00	0.00E+00	7.61E-05	1.46E-03
U-238	4.5E+09	0.00E+00	0.00E+00	0.00E+00	1.28E-04	2.04E-02
Np-237	2.1E+06	0.00E+00	0.00E+00	0.00E+00	1.55E-03	2.78E-03
Pu-238	8.8E+01	1.70E-03	0.00E+00	6.67E+01	1.83E+00	2.78E+00
Pu-239	2.4E+04	1.48E-03	0.00E+00	4.67E+00	1.27E+00	5.37E+00
Pu-240	6.5E+03	0.00E+00	0.00E+00	0.00E+00	1.00E+00	3.33E+00
Pu-241	1.4E+01	2.84E-02	0.00E+00	0.00E+00	1.97E+01	3.15E+01
Am-241	4.3E+02	2.73E-03	0.00E+00	8.33E+01	6.20E+00	9.81E+00
Cm-243	2.9E+01	0.00E+00	0.00E+00	0.00E+00	1.07E-04	4.07E-03
Cm-244	1.8E+01	0.00E+00	0.00E+00	1.22E-02	2.54E-03	2.04E+00
Cm-245	8.5E+03	0.00E+00	0.00E+00	0.00E+00	2.82E-12	6.30E-01
Note: Waste streams 1 through 3 are GTCC; Waste streams 4 and 5 are DOE GTCC-Like Source: Inventories developed by NRC staff considering information in the DOE FEIS (DOE, 2016)						

Table A–2. Radionuclide inventories for Group 2 GTCC activated metal waste streams (Ci/m^3)				
Waste Stream #----->		**6**	**7**	**8**
Nuclide	**Half Life (years)**	**REACTOR AM RH**	**WV NDA AM RH**	**WV SDA AM RH**
H-3	1.2E+01	7.73E+00	4.16E-02	1.39E+00
C14	5.7E+03	2.61E+01	2.45E+00	0.00E+00
Co-60	5.3E+00	5.68E+04	1.18E+01	3.76E+03
Ni-59	7.5E+04	1.48E+02	5.28E+00	0.00E+00
Ni-63	9.6E+01	2.05E+04	4.82E+02	0.00E+00
Sr-90	2.9E+01	4.89E-03	3.52E+01	1.04E+00
Tc-99	2.1E+05	2.27E-04	2.04E-02	6.97E-03
I-129	1.6E+07	2.11E-06	4.30E-05	2.46E-03
Cs-137	3.0E+01	8.64E-02	4.61E+01	1.50E+01
U-233	1.6E+05	0.00E+00	1.80E-02	5.80E-05
U-234	2.4E+05	0.00E+00	9.30E-04	9.50E-06
U-235	7.0E+08	0.00E+00	2.28E-04	4.59E-05
U-236	2.3E+07	0.00E+00	5.05E-04	7.60E-06
U-238	4.5E+09	0.00E+00	3.07E-03	3.73E-04
Np-237	2.1E+06	0.00E+00	3.20E-04	0.00E+00
Pu-238	8.8E+01	1.70E-03	5.69E-01	1.93E-02
Pu-239	2.4E+04	1.48E-03	1.16E+00	0.00E+00
Pu-240	6.5E+03	0.00E+00	7.58E-01	6.13E-04
Pu-241	1.4E+01	2.84E-02	1.08E+01	4.20E-01
Am-241	4.3E+02	2.73E-03	3.27E+00	1.39E-02
Cm-243	2.9E+01	0.00E+00	6.35E-04	1.23E-05
Cm-244	1.8E+01	0.00E+00	1.53E-02	9.13E-03
Cm-245	8.5E+03	0.00E+00	3.79E-06	8.06E-09
Source: Inventories developed by NRC staff considering information in the DOE FEIS (DOE, 2016)				

Table A–3. Radionuclide inventories for Group 2 GTCC other waste streams (Ci/m^3)						
Waste Stream #----->		**9**	**10**	**11**	**12**	**13**
Nuclide	**Half Life (years)**	**WV NDA O RH**	**WV SNAP O CH**	**WV SDA O CH**	**MO99 MURR O RH**	**MO99 MIPS O RH**
H-3	1.2E+01	7.13E-03	0.00E+00	5.00E-01	0.00E+00	4.79E-01
C14	5.7E+03	4.57E-04	0.00E+00	1.10E-02	1.60E-06	4.23E-01
Co-60	5.3E+00	2.54E-02	0.00E+00	1.63E-02	0.00E+00	0.00E+00
Ni-59	7.5E+04	9.68E-04	0.00E+00	8.25E-05	0.00E+00	0.00E+00
Ni-63	9.6E+01	8.95E-02	0.00E+00	9.25E-03	0.00E+00	0.00E+00
Sr-90	2.9E+01	5.70E+00	0.00E+00	7.00E-03	1.29E+03	1.30E+02
Tc-99	2.1E+05	3.13E-03	0.00E+00	2.50E-06	1.20E-01	1.97E-02
I-129	1.6E+07	6.50E-06	0.00E+00	7.25E-06	2.60E-04	3.10E-05
Cs-137	3.0E+01	7.40E+00	0.00E+00	5.50E-02	1.40E+03	1.30E+02
U-233	1.6E+05	3.94E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
U-234	2.4E+05	2.01E-04	0.00E+00	2.43E-05	0.00E+00	2.39E-05
U-235	7.0E+08	3.82E-05	0.00E+00	1.20E-06	0.00E+00	1.01E-02
U-236	2.3E+07	8.95E-05	0.00E+00	0.00E+00	0.00E+00	7.89E-04
U-238	4.5E+09	4.30E-04	0.00E+00	2.50E-05	0.00E+00	6.48E-03
Np-237	2.1E+06	4.90E-05	0.00E+00	8.50E-12	1.40E-06	1.89E-05
Pu-238	8.8E+01	1.09E-01	1.74E+01	3.90E-01	4.86E-07	1.69E-03
Pu-239	2.4E+04	1.77E-01	1.50E-02	7.80E-02	5.43E-01	2.56E-01
Pu-240	6.5E+03	1.26E-01	1.00E-02	8.10E-02	1.09E-03	4.51E-03
Pu-241	1.4E+01	2.05E+00	6.50E-01	4.80E+00	2.77E-04	1.38E-02
Am-241	4.3E+02	5.51E-01	0.00E+00	3.00E-05	1.86E-09	6.20E-06
Cm-243	2.9E+01	1.25E-04	0.00E+00	1.85E-08	0.00E+00	0.00E+00
Cm-244	1.8E+01	2.64E-03	0.00E+00	1.23E-05	0.00E+00	0.00E+00
Cm-245	8.5E+03	6.73E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Source: Inventories developed by NRC staff considering information in the DOE FEIS (DOE, 2016)						

Table A–4. Radionuclide inventories for Group 2 GTCC-like waste streams (Ci/m^3)					
Waste Stream #----->		**14**	**15**	**16**	**17**
Nuclide	**Half Life (years)**	**WV DECOM O 220 CH**	**WV DECOM O 760 RH**	**PU238 O CH**	**PU238 O RH**
H-3	1.2E+01	5.00E-04	2.24E-04	0.00E+00	0.00E+00
C14	5.7E+03	2.68E-02	1.18E-02	0.00E+00	0.00E+00
Co-60	5.3E+00	9.09E-07	3.95E-07	0.00E+00	0.00E+00
Ni-59	7.5E+04	1.50E-04	6.71E-05	0.00E+00	0.00E+00
Ni-63	9.6E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sr-90	2.9E+01	2.77E-02	5.89E+01	0.00E+00	2.38E+01
Tc-99	2.1E+05	5.91E-04	4.21E-03	0.00E+00	0.00E+00
I-129	1.6E+07	0.00E+00	5.00E-06	0.00E+00	0.00E+00
Cs-137	3.0E+01	1.50E-02	4.24E+02	1.00E-09	6.92E+01
U-233	1.6E+05	1.86E-02	8.42E-03	0.00E+00	0.00E+00
U-234	2.4E+05	8.64E-02	3.82E-02	0.00E+00	0.00E+00
U-235	7.0E+08	3.64E-05	1.84E-05	0.00E+00	0.00E+00
U-236	2.3E+07	1.09E-04	4.74E-05	0.00E+00	0.00E+00
U-238	4.5E+09	1.77E-04	9.61E-05	0.00E+00	0.00E+00
Np-237	2.1E+06	1.00E-04	7.89E-04	0.00E+00	6.54E-03
Pu-238	8.8E+01	2.56E+00	1.34E+00	5.00E-02	3.38E+00
Pu-239	2.4E+04	1.76E+00	8.41E-01	1.08E-01	1.88E-03
Pu-240	6.5E+03	1.43E+00	6.71E-01	4.17E-02	8.08E-04
Pu-241	1.4E+01	4.18E+01	1.97E+01	9.17E-01	1.50E-01
Am-241	4.3E+02	6.31E+00	3.41E+00	9.17E-02	4.62E-02
Cm-243	2.9E+01	1.77E-04	5.13E-03	0.00E+00	0.00E+00
Cm-244	1.8E+01	4.55E-03	1.20E-01	0.00E+00	0.00E+00
Cm-245	8.5E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Source: Inventories developed by NRC staff considering information in the DOE FEIS (DOE, 2016)					

APPENDIX B

INPUT PARAMETERS FOR ACUTE AND CHRONIC INTRUDER EXPOSURE SCENARIOS

Table B–1. Input parameter values for BDOSE 2.0 GTCC hazard analysis intruder calculations: Source parameters			
Parameter Name	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
Bore_hole_depth	m	constant 55	Depth of acute and chronic intruder well. Value provided by NRC staff. Considered to be applicable to a residential water well.
Intruder_manual_input	pCi/m^3	constant various	Radionuclide-specific inventories for each of 17 GTCC waste streams were provided by NRC staff.
RF	m^{-1}	constant 3.0E−10	Soil resuspension factor for acute and chronic intruder calculations. Value provided by NRC staff. Considered to be applicable to a residential chronic exposure scenario. Value is within the range of values applicable to lower surface disturbing activities and lower wind conditions documented in IAEA 1616 (2009) and Sehmel (1980) and nominal ambient conditions documented by DOE (BSC, 2006).
Waste_thickness	m	constant 0.508	Thickness of waste within package for acute and chronic intruder calculations. Value provided by NRC staff.
Well_diameter		constant 0.15	Diameter of well drilled for chronic intruder calculations. Default value from U.S. Department of Energy (DOE)–Idaho (2003, Section 5.2) assuming a 6-in-diameter residential water well.
Well_diameter_Acute	m	constant 0.15	Diameter of well drilled for acute intruder calculations. Default value from U.S. Department of Energy (DOE)–Idaho (2003, Section 5.2) assuming a 6-in-diameter residential water well.
Institution_control_period*	yr	constant 100	Period where institutional controls are assumed to remain effective and prevent intrusion. Value from 10 CFR 61.59(b)
*Institutional control period is located in the Controls input container in BDOSE 2.0			

Table B–2. Input parameter values for BDOSE 2.0 GTCC hazard analysis intruder calculations: Soil model parameters			
Parameter Name	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
Intruder_spread_area	m^2	constant 40	Surface area for spreading of intruder drilling spoils. Estimated land area that would be covered by the volume of excavated material (from a residential well drilled to a depth of 55 m [180 ft] with a bore diameter of 15 cm [6 in] spread to a depth of 2.54 cm [1 in]
Soil_density	kg/m^3	constant 1510	Computed value of soil density based on sandy soil porosity (0.43), practical mean particle density (2.65 g/cm^3), and Eq. 6.57 from Beyeler et al. (1999).
Soil_Plow_depth	m	constant 0.15	Depth of soil mixed by plowing used to calculate chronic intruder soil concentration. Commonly assumed value for plow depth.

Table B–3. Input parameter values for BDOSE 2.0 GTCC hazard analysis intruder calculations: Crop parameter inputs			
Parameter Name	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
FoodProduct_TF_sampling_switch (where FoodProduct is Grain, Fruit, LGV, Veg)	unitless	1=constant values used 2= stochastic values used	Toggle for selection of soil-to-plant transfer factors used in chronic intruder calculations. The switch is set to sample transfer factor distributions (2=stochastic selected).
Stoch_Grain_TF Constant_Grain_TF Stoch_Fruit_TF Constant_Fruit_TF Stoch_LGV_TF Constant_LGV_TF Stoch_Veg_TF Constant_Veg_TF	unitless	stochastic values (see Tables A–4 through A–7)	Soil-to-plant transfer factor distributions by radionuclide and food product type for chronic intruder calculations. Stochastic plant transfer factors and distribution information were selected and derived (as needed to address data gaps) based on a review of existing transfer factor compilations (IAEA, 2010; 1994) (Kennedy and Strenge, 1992). Emphasis was placed on the most recent compilations with complete data. A lognormal distribution was assumed based on IAEA (2010) unless the reported statistical information was inconsistent with a lognormal distribution then an applicable alternate distribution was selected (triangular, uniform) in a minority of instances. Truncated lognormal distributions were derived based on geometric mean, geometric standard deviation, and the range of data values reported in the source documents. Where no geometric standard deviation was available for a specific transfer factor value, a generic value (of 2.47) was used based on an analysis of transfer factor data reported by Sheppard and Evenden (1990). If no data range was reported, the range was calculated as the limits that bound 95 percent of the values in the probability distribution using normal distribution confidence interval methods (that apply to log-transformed lognormal data which is normally distributed).
Grain_air_deposition_fract Fruit_air_deposition_fract LGV_air_deposition_fract Veg_air_deposition_fraction	unitless	uniform 0.10, 0.60	Fraction of airborne dust deposited on crops for chronic intruder. Values from Beyeler et al. (1999) based on consideration of experimentally derived values by Hoffman et al. (1992). Range encompasses value from NRC (1977) of 0.25. The same distribution is applied to all types of crops.
Grain_Growth_Duration Fruit_Growth_Duration	days	constant 90	Minimum growing periods for various crop groups obtained from Beyeler et al. (1999, Table 6.30).
LGV_Growth_Duration		constant 45	
Veg_Growth_Duration		constant 90	

Table B–3. Input parameter values for BDOSE 2.0 GTCC hazard analysis intruder calculations: Crop parameter inputs			
Parameter Name	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
Grain_root_fraction Fruit_root_fraction LGV_root_fraction Veg_root_fraction	unitless	constant 1.0	Fraction of crop roots that are within the contaminated plow layer of soil for chronic intruder calculations. All roots are assumed to be within the contaminated plow layer.
Grain_translocation_factor Fruit_translocation_factor		constant 0.1	Values from Beyeler et al. (1999) represent the fraction of activity deposited on plant surface that is transferred to edible portions.
LGV_translocation_factor		constant 1.0	
Veg_translocation_factor		constant 0.1	
Grain_yield	kg/m^2	triangular 0.28, 0.40, 0.52	Crop yield (biomass) for edible crops from Beyeler et al. (1999, Vol. 3, Table 6.55).
Fruit_yield		triangular 2.2, 2.4, 2.6	
Fruit_yield		triangular 2.2, 2.4, 2.6	
LGV_yield		triangular 2.7, 2.9, 3.2	
Veg_yield		triangular 2.3, 2.4, 2.5	
Grain_dry_to_wet	unitless	constant 0.91	Wet-to-dry-weight conversion factors are used in chronic intruder calculations to allow use of typical (dry weight based) soil to plant uptake factors. Values are from Beyeler et al. (1999, Vol. 3, Table 6.77).
Fruit_dry_to_wet		constant 0.18	
LGV_dry_to_wet		constant 0.2	
Veg_dry_to_wet		constant 0.25	

Table B–4. Plant transfer factor distribution statistics: Grain*

Element	Geometric Mean	Geometric Standard Deviation	Minimum	Maximum
H	0.0†	0.0†	0.0†	0.0†
C	0.0†	0.0†	0.0†	0.0†
Co	8.5E−03	5.5	4.0E−04	6.0E−02
Ni	2.7E−02	2.7	3.1E−03	1.7E−01
Se	2.5E−02	2.47	4.2E−03	1.5E−01
Sr	1.1E−01	2.7	3.6E−03	1.0E+00
Y	5.0E−04	2.47	8.5E−05	2.9E−03
Nb	1.4E−02	1.34	2.0E−03	2.5E−02
Tc	1.3E+00	1.35	1.8E−01	2.4E+00
I	2.0E−02	2.47	3.4E−03	1.2E−01
Cs	2.9E−02	4.1	2.0E−04	9.0E−01
Ba	1.0E−03	2.47	1.7E−04	5.9E−03
Eu	4.0E−03	2.47	6.8E−04	2.4E−02
Pb	1.1E−02	3.6	1.9E−03	4.8E−02
Ra	1.7E−02	12	8.0E−05	6.7E−01
Ac	3.5E−04	2.47	6.0E−05	2.1E−03
Th	2.1E−03	3.4	1.6E−04	2.2E−02
Pa	2.5E−04	2.47	4.2E−05	1.5E−03
U	6.2E−03	7.7	1.6E−04	8.2E−01
Np	2.9E−03	5	2.3E−05	7.1E−02
Pu	9.5E−06	6.7	2.0E−07	1.1E−03
Am	2.2E−05	11	7.4E−07	3.4E−02
Cm	2.3E−05	3.3	1.4E−06	2.0E−04
Cf	1.0E−02	2.47	1.7E−03	5.8E−02

Sources:
IAEA (2010) for Co, Ni, Sr, Y, Nb, Tc, Cs, Ba, Pb, Ra, Th, U, Np, Pu, Am, Cm
IAEA (1994) for I
Kennedy and Strenge (1992) for Se, Eu, Ac, Pa, Cf

Notes: Where source documents provided a single value constant or mean value it was assumed to be a geometric mean. Elements shown with a geometric standard deviation of 2.47 had incomplete distribution data in the source documents. For these elements, the geometric standard deviation was assumed to be 2.47 based on a review of transfer factor distributions in Beyeler et al. 1999. Ranges for these elements were estimated as a 95 percent confidence interval about the geometric mean. For Nb and Tc, a range but no geometric standard deviation was provided in the source documents so the geometric standard deviation was estimated from the range and geometric mean assuming the range was a 95 percent confidence interval.

*Values based on dry weight

†BDOSE 2.0 carbon and tritium models do not use transfer factor inputs although the model includes these elements in transfer factor input tables. Values of 0.0 are entered in the model to avoid double counting plant uptake.

Table B–5. Plant transfer factor distribution statistics: Fruit*

Element	Geometric Mean	Geometric Standard Deviation	Minimum	Maximum
H	0.0†	0.0†	0.0†	0.0†
C	0.0†	0.0†	0.0†	0.0†
Co	4.8E−03	2.47	8.2E−04	2.8E−02
Ni	6.0E−02	2.47	1.0E−02	3.5E−01
Se	2.5E−02	2.47	4.2E−03	1.5E−01
Sr	1.7E−02	0.97	1.2E−03	7.0E−02
Y	6.0E−03	2.47	1.0E−03	3.5E−02
Nb	5.0E−03	2.47	8.5E−04	2.9E−02
Tc	1.5E+00	2.47	2.5E−01	8.8E+00
I	6.3E−03	1.6	4.1E−04	3.1E−02
Cs	5.8E−03	1.5	8.6E−04	8.0E−02
Ba	1.5E−02	2.47	2.5E−03	8.8E−02
Eu	4.0E−03	2.47	6.8E−04	2.4E−02
Pb	9.0E−03	2.47	1.5E−03	5.3E−02
Ra	6.1E−03	2.47	1.0E−03	3.6E−02
Ac	3.5E−04	2.47	5.9E−05	2.1E−03
Th	8.5E−05	2.47	1.4E−05	5.0E−04
Pa	2.5E−04	2.47	4.2E−05	1.5E−03
U	4.0E−03	2.47	6.8E−04	2.4E−02
Np	1.0E−02	2.47	1.7E−03	5.9E−02
Pu	1.4E−04	2.9	1.3E−06	2.1E−02
Am	3.1E−05	2.4	1.3E−06	6.2E−04
Cm	5.3E−04	1.3E−04	4.4E−04	6.2E−04
Cf	1.0E−02	2.47	1.7E−03	5.9E−02

Sources:
IAEA (2010) for Co, Sr, I, Cs, Pu, Am, Cm
IAEA (1994) for Y, Ra
Kennedy and Strenge (1992) for Ni, Se, Nb, Tc, Ba, Eu, Pb, Ac, Th, Pa, U, Np, Cf
Notes: Where source documents provided a single value constant or mean value it was assumed to be a geometric mean. Elements shown with a geometric standard deviation of 2.47 had incomplete distribution data in the source documents. For these elements, the geometric standard deviation was assumed to be 2.47 based on a review of transfer factor distributions in Beyeler et al. 1999. Ranges for these elements were estimated as a 95 percent confidence interval about the geometric mean.
*Values based on dry weight
†BDOSE 2.0 carbon and tritium models do not use transfer factor inputs although the model includes these elements in transfer factor input tables. Values of 0.0 are entered in the model to avoid double counting plant uptake.

Table B–6. Plant transfer factor distribution statistics: Leafy green vegetables*

Element	Geometric Mean	Geometric Standard Deviation	Minimum	Maximum
H	0.0†	0.0†	0.0†	0.0†
C	0.0†	0.0†	0.0†	0.0†
Co	1.7E−01	2.7	1.3E−02	1.0E+00
Ni	2.6E−01	2.47	4.4E−02	1.5E+00
Se	2.5E−02	2.47	4.2E−03	1.5E−01
Sr	7.6E−01	6	3.9E−03	7.8E+00
Y	2.0E−03	2.47	3.4E−04	1.2E−02
Nb	1.7E−02	2.47	8.0E−03	2.5E−02
Tc	1.8E+02	13.5	4.5E+00	3.4E+03
I	3.4E−03	2.47	5.8E−04	2.0E−02
Cs	6.0E−02	6	3.0E−04	9.8E−01
Ba	5.0E−03	2.47	8.5E−04	2.9E−02
Eu	1.1E−02	2.47	1.9E−03	6.5E−02
Pb	8.0E−02	13	3.2E−03	2.5E+01
Ra	9.1E−02	6.7	1.8E−03	1.3E+02
Ac	3.5E−03	2.47	5.9E−04	2.1E−02
Th	1.2E−03	6	9.4E−05	2.1E−01
Pa	2.5E−03	2.47	4.2E−04	1.5E−02
U	2.0E−02	7.3	7.8E−05	8.8E+00
Np	2.7E−02	3	5.0E−03	8.0E−02
Pu	8.3E−05	2.7	1.0E−05	2.9E−04
Am	2.7E−04	3.3	4.0E−05	1.5E−03
Cm	1.4E−03	4.5	2.0E−04	8.1E−03
Cf	1.0E−02	2.47	1.7E−03	5.9E−02

Sources:
IAEA (2010) for Co, Sr, Y, Nb, Tc, Cs, Ba, Pb, Ra, Th, U, Np, Pu, Am, Cm
Kennedy and Strenge (1992) for Ni, Se, I, Eu, Ac, Pa, U, Np, Cf
Notes: Where source documents provided a single value constant or mean value it was assumed to be a geometric mean. Elements shown with a geometric standard deviation of 2.47 had incomplete distribution data in the source documents. For these elements, the geometric standard deviation was assumed to be 2.47 based on a review of transfer factor distributions in Beyeler et al. 1999. Ranges for these elements were estimated as a 95 percent confidence interval about the geometric mean.
*Values based on dry weight
†BDOSE 2.0 carbon and tritium models do not use transfer factor inputs although the model includes these elements in transfer factor input tables. Values of 0.0 are entered in the model to avoid double counting plant uptake.

Table B–7. Plant transfer factor distribution statistics: Root vegetables*				
Element	Geometric Mean	Geometric Standard Deviation	Minimum	Maximum
H	0.0†	0.0†	0.0†	0.0†
C	0.0†	0.0†	0.0†	0.0†
Co	1.1E−01	2.2	4.7E−02	7.2E−01
Ni	6.0E−02	2.47	1.0E−02	3.5E−01
Se	2.5E−02	2.47	4.2E−03	1.5E−01
Sr	7.2E−01	4.1	3.0E−02	4.8E+00
Y	2.0E−03	2.47	3.4E−04	1.2E−02
Nb	1.7E−02	1.2	8.0E−03	2.5E−02
Tc	4.6E+01	1.32	1.4E+01	7.9E+01
I	2.0E−02	2.47	3.4E−03	1.2E−01
Cs	4.2E−02	3.0	1.0E−03	8.8E−01
Ba	5.0E−03	2.47	8.5E−04	2.9E−02
Eu	4.0E−03	2.47	6.8E−04	2.4E−02
Pb	1.5E−02	16	2.4E−04	3.3E+00
Ra	7.0E−02	9.2	2.0E−03	5.6E+01
Ac	3.5E−04	2.47	6.0E−05	2.1E−03
Th	8.0E−04	13	8.2E−06	9.5E−02
Pa	2.5E−04	2.47	4.2E−05	1.5E−03
U	8.4E−03	6.2	4.9E−04	2.6E−01
Np	2.2E−02	2.0	5.0E−03	3.6E−02
Pu	3.9E−04	10	7.0E−05	5.8E−03
Am	6.7E−04	2.4	2.0E−04	1.7E−03
Cm	8.5E−04	3.0	2.0E−04	3.9E−03
Cf	1.0E−02	2.47	1.7E−03	5.88E−02

Sources:
IAEA (2010) for Co, Sr, Y, Nb, Tc, Cs, Ba, Pb, Ra, Th, U, Np, Pu, Am, Cm
IAEA (1994) for I
Kennedy and Strenge (1992) for Ni, Se, Eu, Ac, Pa, Cf

Notes: Where source documents provided a single value constant or mean value it was assumed to be a geometric mean. Elements shown with a geometric standard deviation of 2.47 had incomplete distribution data in the source documents. For these elements, the geometric standard deviation was assumed to be 2.47 based on a review of transfer factor distributions in Beyeler et al. 1999. Ranges for these elements were estimated as a 95 percent confidence interval about the geometric mean. For Nb, a range but no geometric standard deviation was provided in the source documents so the geometric standard deviation was estimated from the range and geometric mean assuming the range was a 95 percent confidence interval.

*Values based on dry weight

†BDOSE 2.0 carbon and tritium models do not use transfer factor inputs although the model includes these elements in transfer factor input tables. Values of 0.0 are entered in the model to avoid double counting plant uptake.

Table B–8. Input parameter values for BDOSE 2.0 GTCC hazard analysis intruder calculations: Receptor inputs			
Parameter Name	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
Driller_Acute_occupancy_time	yr	constant 0.0028	Duration of the acute drilling activity. Value provided by NRC staff based on an informed assumption that it would take approximately 25 hours or 0.0028 years to drill a 6 inch diameter residential well to a depth of 55 m [180 ft].
Driller_INT_Acute_INH_vol	m^3	constant 30	The volume of air inhaled by driller during the acute drilling activity. Estimated value for driller based on a breathing rate of 1.20 m^3/hr (EPA, 2011) applicable to a construction worker/laborer engaging in slow level of activity and the 25 hour assumed drill time to complete a 15.24 cm [6 in] diameter residential well to a depth of 55 m [180 ft].
Driller_INT_Acute_SF_AS Driller_INT_Acute_SF_GS	unitless	constant 1	Outdoor shielding factors for acute intruder cloudshine (AS) and groundshine (GS) are based on Beyeler et al., 1999, Section 6.4.1, Table 6.30. These values represents no shielding when the acute intruder driller is outdoors.
Driller_INT_Acute_soil_ING	kg	constant 1.14E−04	Mass of soil inadvertently ingested by acute intruder driller. Value from DOE–Idaho (2003, Section 5.2) assuming 40 g/yr ingestion rate while working and 25 hours to drill and develop or excavate the residential well.
RF_acute_Drilling	m^{-1}	constant 2.5E−09	Soil to air resuspension factor for acute intruder. NRC staff provided a mass loading value of 5.65E–4 g/m^3 considered to be applicable to short-term acute residential construction exposure scenario. The NRC mass loading value was converted to a resuspension factor using a method documented by Napier et al. (1988). The conversion involves dividing the mass load by the areal surface soil density (a value of 224 kg/m^2 was assumed). The resulting resuspension factor value is within the range of values for lower wind and surface disturbance reported in IAEA 1616 (2009) and Sehmel (1980).
INT_air_exp_time INT_surface_exp_time	hr	constant 4,380	Effective exposure times for the chronic intruder cloudshine (air) and groundshine (surface) calculations were derived as weighted sums of the product of time spent indoors and the shielding factor of 0.7 (Yu et al., 2001) and the total time spent outdoors. The intruder was assumed to sleep 8 hr/day, spend 2.6 hr/day outdoors, 8 hr/day at offsite employment, and spend the remainder of time indoors.

Table B–8. Input parameter values for BDOSE 2.0 GTCC hazard analysis intruder calculations: Receptor inputs			
Parameter Name	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks`**
SF_air_INT SF_gs_INT	unitless	constant 1	Shielding factor inputs for chronic intruder cloudshine (air) and groundshine (gs) calculations were set to 1.0 (no shielding) because a shielding factor of 0.7 based on the value in RESRAD (Yu et al., 2001) was already incorporated into the applicable external exposure time input parameters (e.g., see INT_air_exp_time).
INT_INH_rate_air	m^3/yr	constant 2840	Chronic intruder inhalation rate. An annual effective inhalation rate was derived to address indoor and outdoor exposure time, indoor attenuation of inhalation dose, and human activity level-specific breathing rates. These details are not accounted for in other input parameters. The annual effective inhalation rate was calculated as a weighted sum of the annual volume of air inhaled during different activities including indoor sleeping, indoor general level of activity, and outdoor general level of activity. An attenuation factor for indoor inhalation of 0.5 was used based on Kennedy and Strenge (1992). Time-spent indoors and outdoors and applicable average breathing rates for sleep (0.4 m^3/hr), general outdoor activities (1.4 m^3/hr and 1.7 m^3/hr while gardening), and general indoor activities (0.9 m^3/hr) were from Tables 6.22 and 6.29 Beyeler et al. (1999). Receptors were assumed to sleep 8 hr/day, spend 2.6 hr/day outdoors (including 0.192 hr/day gardening), 8 hr/day offsite, and spend the remainder of time indoors.

Table B–8. Input parameter values for BDOSE 2.0 GTCC hazard analysis intruder calculations: Receptor inputs			
Parameter Name	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
INT_Grain_consum_rate	kg/yr	cumulative 0.00, 0.00 0.01, 1.41 0.05, 2.22 0.10, 3.22 0.25, 4.83 0.50, 8.20 0.75, 15.8 0.90, 31.8 0.95, 44.0 0.99, 84.8 1.00, 99.5	Chronic intruder ingestion rate of grain. Ingestion rates of homegrown foods reported by Beyeler et al. (1999) based on an analysis of USDA national survey data that was previously summarized by EPA (1996). A subsequent EPA summary of available consumption rate data confirmed the USDA had not produced more recent surveys that provided information on home-produced foods (EPA, 2011).
INT_Fruit_consum_rate	kg/yr	cumulative 0.00, 0.00 0.01, 1.93 0.05, 3.64 0.10, 5.08 0.25, 9.48 0.50, 20.5 0.75, 45.4 0.90, 126 0.95, 190 0.99, 461 1.00, 674	Chronic intruder ingestion rate of fruit. Ingestion rates of homegrown foods reported by Beyeler et al. (1999) based on an analysis of USDA national survey data that was previously summarized by EPA (1996). A subsequent EPA summary of available consumption rate data confirmed the USDA had not produced more recent surveys that provided information on home-produced foods (EPA, 2011).
INT_LGV_consum_rate	kg/yr	cumulative 0.00, 0.00 0.01, 1.04 0.05, 1.04 0.10, 2.40 0.25, 5.90 0.50, 11.7 0.75, 24.6 0.90, 46.3 0.95, 66.0 0.99, 136 1.00, 223	Chronic intruder ingestion rate of leafy green vegetables. Ingestion rates of homegrown foods reported by Beyeler et al. (1999) based on an analysis of USDA national survey data that was previously summarized by EPA (1996). A subsequent EPA summary of available consumption rate data confirmed the USDA had not produced more recent surveys that provided information on home-produced foods (EPA, 2011). Note that the reported value for the 1th percentile (1.71 kg/yr) (which was described as an estimated value in the referenced report) was set to a value of 1.04 kg/yr (same as the 5th percentile value) to satisfy the monotonic requirement for a cumulative distribution in the Goldsim software.

Table B–8. Input parameter values for BDOSE 2.0 GTCC hazard analysis intruder calculations: Receptor inputs			
Parameter Name	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
INT_Veg_consum_rate	kg/yr	cumulative 0.00, 0.00 0.01, 2.23 0.05, 4.15 0.10, 5.95 0.25, 11.3 0.50, 26.6 0.75, 55.6 0.90, 77.1 0.95, 146 0.99, 301 1.00, 384	Chronic intruder ingestion rate of root vegetables. Ingestion rates of homegrown foods reported by Beyeler et al. (1999) based on an analysis of USDA national survey data that was previously summarized by EPA (1996). A subsequent EPA summary of available consumption rate data confirmed the USDA had not produced more recent surveys that provided information on home-produced foods (EPA, 2011).
INT_Grain_Fract_Local INT_Fruit_Fract_Local INT_LGV_Fract_Local INT_Veg_Fract_Local	unitless	constant 1.0	Fraction of chronic intruder food products obtained locally. Set to 1.0 because the consumption rates are already applicable to homegrown foods. Local fractions only apply when food consumption rates are based on all food intake regardless of origin.
INT_Soil_consum_rate	kg/yr	triangular 0 1.83E−2 4.16E−2	Inadvertent soil ingestion rate for the chronic intruder. The expected value of 50 mg/d [1.83E−2 kg/yr] is the recommended value from EPA (2011). The maximum value equates to 114 mg/d [4.16E−2 kg/yr] from Beyeler, et al. (1999). Lower value is an assumption that bounds the range.

Table B–9. Input parameter values for BDOSE 2.0 GTCC hazard analysis intruder calculations: Carbon and tritium model inputs			
Parameter Name	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
Relative_Humidity	kg/m^3	constant 0.008	Relative humidity from Beyeler et al. (1999, Vol. 3, Table 6.30) value for absolute humidity.
Milk_density		constant 1032	The density of milk from CRC (1980, p. F–3).
Carbon_emission_constant	yr^{-1}	constant 12	Volatilization rate (evasion rate) of carbon from soil to air. Yu et al. (2001, Appendix L, Table L.2).
Grain_reduction_factor Fruit_reduction_factor	unitless	constant 0.8	Crop-specific factors used to estimate tritium concentrations in crops that account for relative moisture differences in soil and air. Napier et al. (2004, Table 9.3).
LGV_reduction_factor		constant 0.9	
Veg_reduction_factor		constant 0.8	
Air_carbon_content	kg/m^3	constant 1.8E−4	The carbon content in air is used to calculate the C-14 concentration in crops for the chronic intruder scenario. Values from Yu et al. (2001, Appendix L).
Soil_carbon_content	unitless	constant 0.03	The fraction of soil that is carbon is used to calculate C-14 concentrations in air and crops. Value from Beyeler et al. (1999, Vol. 3, Table 6.30).
Grain_fract_carbon	unitless	constant 0.4	The carbon fractions for crops are used to calculate C-14 concentrations in crops for the chronic intruder scenario. Beyeler et al. (1999, Vol. 3, Table 6.34).
Fruit_fract_carbon LGV_fract_carbon Veg_fract_carbon		constant 0.09	
Grain_frac_fresh_matter	unitless	constant 0.117	Crop-specific fractions of fresh matter describe the fraction of the plant matter that contains water for use in estimating tritium concentrations. Values from Napier et al. (2004, Table 9.3).
Fruit_frac_fresh_matter		constant 0.853	
LGV_frac_fresh_matter		constant 0.906	
Veg_frac_fresh_matter		constant 0.824	

Table B–10. Input parameter values for BDOSE 2.0 GTCC hazard analysis intruder calculations: Miscellaneous*			
Parameter Name	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
deposition_velocity	m/s	constant 0.001	Value applicable to foliar deposition of most elements for the chronic intruder crop calculations. Value from the RESRAD 6.0 User Manual (Yu et al., 2001)
Weathering_Constant	yr^{-1}	18.07	Rate of weathering losses of resuspended soil on plant surfaces used in chronic intruder crop calculations. Value from NRC (1977) equates to a 14-day weathering half-life.
Leaf_surface_RF	m^{-1}	constant 1E−09	Soil resuspension factor applicable to crop concentration calculations that consider resuspended soil deposition on plant surfaces. Value from Napier et al. (2004, Table F.1).
*Note: Additional inputs located in the Miscellaneous input container are tabulated as Carbon and Tritium Inputs in Table A–9			

Table B–11. ICRP* Publication 72† ingestion and inhalation dose coefficients (Sv/Bq)		
Radionuclide	**Ingestion**	**Inhalation**
H3	1.80E−11	2.60E−10
C14	5.80E−10	5.80E−09
Ni59	6.30E−11	4.40E−10
Co60	3.40E−09	3.10E−08
Ni63	1.50E−10	1.30E−09
Se79	2.90E−09	6.80E−09
Sr90	2.80E−08	1.60E−07
Y90	2.70E−09	1.50E−09
Nb94	1.70E−09	4.90E−08
Tc99	6.40E−10	1.30E−08
I129	1.10E−07	3.60E−08
Cs137	1.30E−08	3.90E−08
Ba137m	nd	nd
Eu152	1.40E−09	nd
Eu154	2.00E−09	nd
Eu155	3.20E−10	nd
Pb210	6.90E−07	5.60E−06
Ra226	2.80E−07	9.50E−06
Ra228	6.90E−07	1.60E−05
Ac227	1.10E−06	5.50E−04
Th228	7.20E−08	4.00E−05
Th229	4.90E−07	2.40E−04
Th230	2.10E−07	1.00E−04
Th232	2.30E−07	1.10E−04
Pa231	7.10E−07	1.40E−04
U232	3.30E−07	3.70E−05
U233	5.10E−08	9.60E−06
U234	4.90E−08	9.40E−06
U235	4.70E−08	8.50E−06
U236	4.70E−08	8.70E−06
U238	4.50E−08	8.00E−06
Np237	1.10E−07	5.00E−05
Pu238	2.30E−07	1.10E−04
Pu239	2.50E−07	1.20E−04
Pu240	2.50E−07	1.20E−04
Pu241	4.80E−09	2.30E−06
Pu242	2.40E−07	1.10E−04
Pu244	2.40E−07	1.10E−04

Table B–11. ICRP* Publication 72† ingestion and inhalation dose coefficients (Sv/Bq)		
Radionuclide	**Ingestion**	**Inhalation**
Am241	2.00E−07	9.60E−05
Am242m	1.90E−09	9.20E−05
Am243	2.00E−07	9.60E−05
Cm242	1.20E−08	5.90E−06
Cm243	1.50E−07	6.90E−05
Cm244	1.20E−07	5.70E−05
Cm245	2.10E−07	9.90E−05
Cm246	2.10E−07	9.80E−05
Cm247	1.90E−07	9.00E−05
Cm248	7.70E−07	3.60E−04
Cf249	3.50E−07	7.00E−05

*ICRP = International Commission on Radiological Protection
†International Commission on Radiological Protection (1996)

Table B–12. Dose coefficients for external exposure to radionuclides in air, water, and soil from Federal Guidance Report No. 12*			
Radionuclide	**Air Submersion (Sv m^3/Bq yr)**	**Soil Contaminated to Depth of 1 cm (Sv m^3/Bq yr)**	**Soil Contaminated to Depth of 15 cm (Sv m^3/Bq yr)**
H3	1.04E−11	0.00E+00	0.00E+00
C14	7.06E−12	1.36E−15	2.27E−15
Ni59	0.00E+00	0.00E+00	0.00E+00
Co60	3.97E−06	4.79E−10	2.29E−09
Ni63	0.00E+00	0.00E+00	0.00E+00
Se79	9.56E−12	1.82E−15	3.14E−15
Sr90	2.38E−10	4.13E−14	1.17E−13
Y90	6.00E−09	1.01E−12	3.78E−12
Nb94	2.43E−06	3.11E−10	1.43E−09
Tc99	5.11E−11	9.21E−15	2.11E−14
I129	1.20E−08	1.88E−12	2.19E−12
Cs137	2.44E−10	4.23E−14	1.24E−13
Ba137m	9.08E−07	1.19E−10	5.39E−10
Eu152	1.78E−06	2.22E−10	1.02E−09
Eu154	1.94E−06	2.40E−10	1.11E−09
Eu155	2.13E−06	1.06E−11	3.07E−11
Pb210	1.78E−09	2.61E−13	4.13E−13
Ra226	9.94E−09	1.31E−12	5.20E−12
Ra228	0.00E+00	0.00E+00	0.00E+00
Ac227	1.84E−10	2.43E−14	8.26E−14
Th228	2.90E−09	3.85E−13	1.32E−12
Th229	1.21E−07	1.61E−11	5.36E−11
Th230	5.49E−10	7.35E−14	2.02E−13
Th232	2.75E−10	7.25E−12	8.77E−14
Pa231	5.43E−08	5.93E−14	3.03E−11
U232	4.48E−10	5.93E−14	1.50E−13
U233	5.14E−10	6.81E−14	2.28E−13
U234	2.41E−10	3.19E−14	6.75E−14
U235	2.27E−07	2.99E−11	1.18E−10
U236	1.58E−10	2.06E−14	3.60E−14
U238	1.08E−10	1.39E−14	1.74E−14
Np237	3.25E−08	4.35E−12	1.31E−11
Pu238	1.54E−10	2.00E−14	2.54E−14
Pu239	1.34E−10	1.77E−14	4.79E−14
Pu240	1.50E−10	1.96E−14	2.47E−14

Table B–12. Dose coefficients for external exposure to radionuclides in air, water, and soil from Federal Guidance Report No. 12*			
Radionuclide	Air Submersion (Sv m^3/Bq yr)	Soil Contaminated to Depth of 1 cm (Sv m^3/Bq yr)	Soil Contaminated to Depth of 15 cm (Sv m^3/Bq yr)
Pu241	2.29E−12	3.03E−16	9.93E−16
Pu242	1.27E−10	1.65E−14	2.16E−14
Pu244	9.37E−11	1.21E−14	1.27E−14
Am241	2.58E−08	3.63E−12	7.38E−12
Am242m	1.94E−08	1.35E−13	2.84E−13
Am243	6.87E−08	9.33E−12	2.40E−11
Cm242	1.80E−10	2.39E−14	2.86E−14
Cm243	1.79E−10	2.46E−11	9.52E−11
Cm244	1.55E−10	2.06E−14	2.13E−14
Cm245	1.25E−07	1.65E−11	5.68E−11
Cm246	1.41E−10	1.88E−14	1.96E−14
Cm247	4.73E−07	6.31E−11	2.78E−10
Cm248	1.07E−10	1.43E−14	1.48E−14
Cf249	4.98E−07	3.91E−12	1.74E−11

*U.S. Environmental Protection Agency (EPA) (1993)

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