OFF-SITE GROUNDWATER PATHWAY HAZARD ASSESSMENT FOR DISPOSAL OF GREATER-THAN-CLASS C AND TRANSURANIC WASTE IN LOW-LEVEL RADIOACTIVE WASTE DISPOSAL FACILITIES

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ACRONYMS/ABBREVIATIONS

10 CFR	Title 10 of the *Code of Federal Regulations*
CNWRA	Center for Nuclear Waste Regulatory Analyses
CONUS	conterminous United States
C-S-H	calcium-silicate-hydrate
DB	Deep Borehole
DOE	U.S. Department of Energy
GTCC	Greater-Than-Class C
HI-SWT	high infiltration-shallow water table
INL	Idaho National Laboratory
LANL	Los Alamos National Laboratory
LHS	Latin Hypercube Sampling
LI-DWT	low infiltration-deep water table
LLW	low level radioactive waste
MDDU	Moderate Depth Disposal Unit
MI	infiltration rates
MI-IDWT	medium infiltration-intermediate depth water table
NRC	U.S. Nuclear Regulatory Commission
NNSS	Nevada Nuclear Security Site
NST	near surface trench
SZ	saturated zone
TRU	transuranic
UZ	unsaturated zone
WIPP	Waste Isolation Pilot Plant

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: None.

ANALYSES AND CODES: GoldSim Version 12 was used to perform the dose assessments described in this report.

OFF-SITE GROUNDWATER PATHWAY HAZARD ASSESSMENT FOR DISPOSAL OF GREATER-THAN-CLASS C AND TRANSURANIC WASTE IN LOW-LEVEL RADIOACTIVE WASTE DISPOSAL FACILITIES

U.S. Nuclear Regulatory Commission (NRC) licensing requirements for the disposal of commercial low-level radioactive waste (LLW) 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 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 stylized dose assessments to estimate the potential hazards posed by different GTCC and TRU waste streams from off-site releases of radioactivity by the groundwater. This report presents the results of technical analyses conducted by CNWRA staff to improve the NRC's understanding of how differences in disposal design and configuration, as well as site climate, hydrology, and geology, may impact required compliance demonstrations for GTCC and TRU waste disposal with respect to the groundwater release pathway.

1 INTRODUCTION

NRC is considering revisions to 10 CFR Part 61 that would (i) require new and revised site-specific technical analyses, (ii) permit the development of site-specific criteria for LLW acceptance based on the results of these analyses, and (iii) facilitate implementation and better align the requirements with updated current health and safety standards. The NRC staff is also evaluating potential revisions for incorporating disposal of GTCC and TRU wastes under 10 CFR Part 61.

To support the development of a risk-informed, performance-based approach for revising the regulatory requirements and developing accompanying guidance, the CNWRA has conducted technical evaluations of compliance with the performance objectives of 10 CFR Part 61, including (i) the protection of the general population from off-site releases of radioactivity by the groundwater and air pathways and (ii) the protection of individuals from inadvertent intrusion into the disposal site after loss of active institutional controls. This report presents the results of technical analyses conducted by CNWRA staff to improve the NRC's understanding of how differences in disposal design and configuration as well as site hydrometeorologic and hydrogeologic conditions may affect compliance demonstrations for GTCC and TRU waste disposal with respect to the groundwater release pathway.

CNWRA developed off-site groundwater-pathway probabilistic dose assessment models for 17 GTCC and TRU waste streams. For each waste stream, six disposal scenarios were evaluated using a GoldSim® Version 12.0-based probabilistic radionuclide release, transport, and uptake model. The scenarios are: (i) disposal in a near surface trench located in an arid to semi-arid region where the depth to the water table is 135 to 200 m [443 to 656 ft]; (ii) disposal in a near surface trench located in a semi-arid to sub-humid region where the depth to the water table is 50 to 135 m [164 to 443 ft]; (iii) disposal in a near surface trench located in a sub-humid to humid region where the depth to the water table is 20 to 50 m [66 to 164 ft]; (iv) disposal in a moderate depth disposal unit located in an arid to semi-arid region where the depth to the water table is 135 to 200 m [443 to 656 ft]; (v) disposal in a moderate depth disposal unit located in a semi-arid to sub-humid region where the depth to the water table is 50 to 135 m [164 to 443 ft];

and (vi) disposal in a deep borehole in an arid to semi-arid region where the depth to the water table is 135 to 200 m [443 to 656 ft]. For each of the 102 scenario evaluations[1], 100 realizations of the infiltration rate, depth to the water table, waste container failure time, waste form dissolution rate, and distribution coefficients for 16 nuclides were generated using Latin Hypercube Sampling (LHS) and each realization was propagated through the radionuclide release, transport, biosphere, and dose assessment sub-models over a simulated post-closure period of 100,000 years.

2 DATA AND ASSUMPTIONS FOR THE GROUNDWATER PATHWAY DOSE ASSESSMENT MODEL

2.1 Disposal Cell Configurations

The data presented in Table 1 for the three disposal cell configurations were taken from the technical analyses conducted by NRC (2018). To ensure that GTCC and TRU wastes are disposed in the unsaturated zone above the zone of water table fluctuation, as required by 10 CFR 61.50(a)(7), a disposal configuration is used only where the water table is at least 5 m 16 ft] below the bottom of the disposal cell[2]. The 5 m [16 ft] zone of water table fluctuation used in this analysis is an assumption, not a quantitative requirement of 10 CFR Part 61. The environmental settings considered in this study are illustrated in Figure 1: (i) a shallow water table typical of humid eastern woodlands where infiltration is relatively high [Figure 1(a)]; (ii) an intermediate depth water table that may be found in the semi-arid to sub-humid prairie and steppe of the Great Plains where infiltration is intermediate [Figure 1(b)]; and (iii) a deep water table that may be found in the valley floors and bajadas of arid to semi-arid deserts where infiltration is low [Figure 1(c)]. The depths for the top and bottom of each of the disposal cell configurations (dark red) are given in meters below ground surface (Figure 1). The minimum depths to the water table are illustrated in Figure 1 by the top of the light blue region. A near surface trench can be sited where the depth to water is 20 m [65 ft] or greater [Figure 1(a)], a moderate depth disposal where the depth to water is a least 50 m [164 ft] [Figure 1(b)], and a deep borehole where the depth to water is at least 135 m [442 ft] [Figure 1(c)].

Each disposal cell configuration is capable of holding 450 m^3 [15,892 ft^3] of waste. If all GTCC and TRU wastes were disposed at a single facility, 45 cells would be required to hold the roughly 38,000 drums of waste. The total surface area of 45 cells is 202 m^2 [2,174 ft^2] for the deep borehole, 2,025 m^2 [21,797 ft^2] for the moderate depth disposal unit, and 4,050 m^2 [43,594ft^2] for the near surface trench. The total land area required for the disposal facility would need to be considerably larger than the total surface areas of all disposal cells to: (i) facilitate constructing the cells; (ii) provide room for receipt, handling, and temporary storage of the waste drums; (iii) provide the waste canister handling and emplacement equipment room to maneuver; and (iv) build temporary facilities used for other pre-closure operations. Additional details on the number of waste drums and number of disposal cells required for each disposal cell configuration are listed for each of the 17 GTCC and TRU waste streams in Table 2.

[1]17 waste streams × 6 scenarios = 102 probabilistic simulations.
[2]Disposal cell is a general term used to refer to either a near surface trench, underground vault, or large-diameter deep borehole considered for permanently disposing GTCC and TRU waste in the subsurface above the water table,

Table 1. Dimensions and positions of disposal cell configurations	
Disposal Configuration	**Dimensions and Position with Respect to the Ground Surface**
Near Surface Trench (NST)	3 m wide × 30 m long × 5 m high. Volume 450 m^3. Buried 10 m below the ground surface. Bottom of trench is 15 m below surface. Used where water table is at least 20 m below surface.
Moderate Depth Disposal Unit (MDDU)	3 m wide × 15 m long × 10 m high. Volume 450 m^3. Buried 35 m below the ground surface. Bottom of MDDU is 45 m below surface. Used where water table is at least 50 m below surface.
Deep Borehole (DB)	Cylindrical volume: 4.5 m^2 cross-sectional area × 100 m in length. Volume 450 m^3. Borehole extends vertically from 30 to 130 m below ground surface. Bottom of DB is 130 m below surface. Volume is 450 m^3. Used where water table is at least 135 m below surface.

2.2 Cover Failure, Waste Container Failure, and Waste Form Release Models

Four types of waste containers are used to package the 17 waste streams: (i) 55-gal drums, (ii) 100-gal drums, (iii) stainless steel "pencils" containing radionuclides that emit high levels of gamma radiation, and (iv) stainless steel sealed sources that contain alpha-emitting radionuclides and low-atomic number target materials, such as beryllium and lithium. Although the stainless steel pencils will be disposed in their shielded irradiator devices, these devices were not assumed to provide any additional isolation and release performance. It is also assumed that the concrete covers placed on top of the disposal cells will prevent infiltrating water from contacting the waste containers for 500 years following closure (DOE, 2016b). After 500 years, infiltration will percolate through fractures and the matrix of the increasingly porous and permeable concrete. The lifetimes of the four metal waste containers depend in part on the chemistry of the percolating concrete pore water that contacts the containers in the disposal cell.

The 55-gal and 100-gal drum containers are constructed of carbon steel, which will begin to corrode after being contacted by infiltration that seeps through the damaged concrete disposal cell covers. Corrosion rates of carbon steel depend on the pH and Eh of the water contacting it. Under oxidizing conditions (positive Eh), corrosion rates for carbon steel at a pH of 13 were reported by Hartt et al. (2004) to be between 16 and 104 mA/m^2, which is equivalent to 1.86×10^{-2} and 1.21×10^{-1} mm/year.[3]

[3] 1 mA/m^2 = 0.00116 mm/year for carbon steel. Personal communication from Xihua He, March 5, 2019.

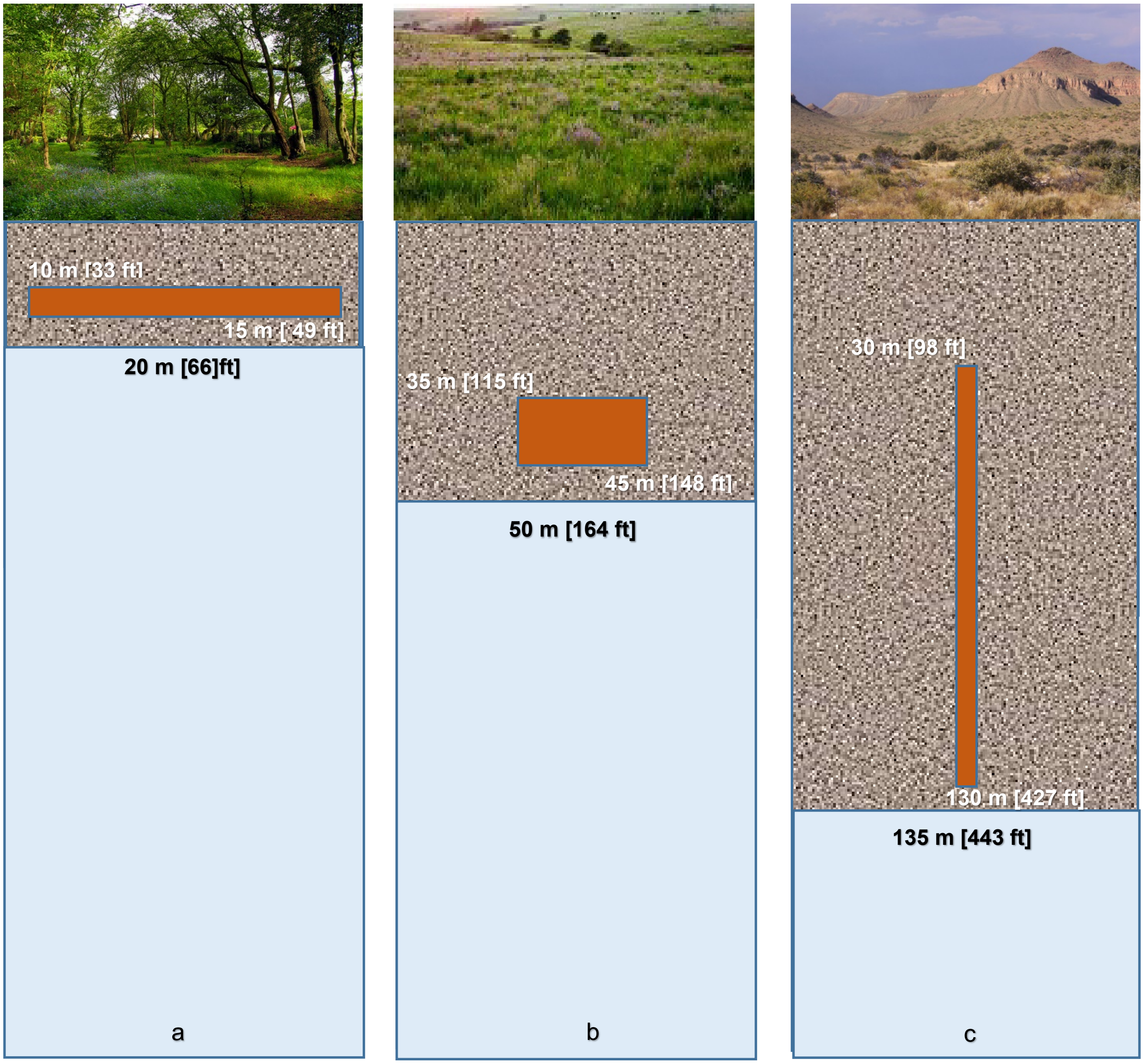

Figure 1. **Disposal configurations and environmental settings, the latter defined on the basis of infiltration and depth to water table. Disposal cells are depicted by dark red rectangles. Infiltration regime illustrated by photographs of vegetation and depth to the water table is depicted by light blue zone below the disposal cell. Figure 1(a) near surface trench (NST) and high infiltration-shallow water table (HI-SWT). Figure 1(b) moderate depth disposal unit (MDDU) and medium infiltration-intermediate depth water table (MI-IDWT). Figure 1(c) deep borehole (DB) and low infiltration-deep water table (LI-DWT).**

Table 2. Waste stream specific disposal cell data

Waste Stream Number	Waste Stream Designation	Total Waste Volume [m³]	Container Type	Volume of Container [m³]	Number of Containers	Number of Cells Required	Total NST Area [m²]	Total MDDU Area [m²]	Total DB Area [m²]	Containers per Cell
1	G1-GTCC-Reactor-AM-RH	880	100-gal drum	0.4	2,200	3	270	135	13.5	734
2	G1-GTCC-Cs-137-SS-CH	1,000	Irradiator	0.7	1,429	4	360	180	18	358
3	G1-GTCC-Neutron-Ir-SS-CH	1,800	55-gal drum	0.2	9,000	6	540	270	27	1,500
4	G1-GTCC-like-WV Decon-O-CH	710	55-gal drum	0.2	3,550	3	270	135	13.5	1,184
5	G1-GTCC-like-WV Decon-O-RH	540	100-gal drum	0.4	1,350	2	180	90	9	675
6	G2a-GTCC-Reactor-AM-RH	370	100-gal drum	0.4	925	2	180	90	9	463
7	G2a-GTCC-Mo99(MURR)-O-RH	355	100-gal drum	0.4	888	2	180	90	9	444
8	G2a-GTCC-Mo99(MIPS)-O-RH	35	100-gal drum	0.4	88	1	90	45	4.5	88
9	G2a-GTCC-WV NDA-AM-RH	210	100-gal drum	0.4	525	1	90	45	4.5	525
10	G2a-GTCC-WV NDA-O-RH	1,900	100-gal drum	0.4	4,750	7	630	315	31.5	679
11	G2b-GTCC-WV SDA-AM-RH	525	100-gal drum	0.4	1,313	2	180	90	9	657
12	G2b-GTCC-WV SDA-O-CH	400	55-gal drum	0.2	2,000	2	180	90	9	1,000
13	G2b-GTCC-WV SNAP-O-CH	1,200	55-gal drum	0.2	6,000	4	360	180	18	1,500
14	G2b-GTCC-like-WV Decom-O-CH	220	55-gal drum	0.2	1,100	1	90	45	4.5	1,100
15	G2b-GTCC-like-WV Decom-O-RH	760	100-gal drum	0.4	1,900	3	270	135	13.5	634
16	G2b-GTCC-like-Pu-238-O-CH	120	55-gal drum	0.2	600	1	90	45	4.5	600
17	G2b-GTCC-like-Pu-238-O-RH	260	100-gal drum	0.4	650	1	90	45	4.5	650
Totals		11,285			38,268	45	4,050	2,025	202.5	

Assuming that the drums are made from 18 gauge steel and have a wall thickness of 0.127 cm [50 mil], the steel drums have a lifetime of only 10 to 70 years at a pH of 13 and positive Eh (oxidizing conditions). However, under anoxic conditions at a pH value of 12.5, He et al. (2017) report corrosion rates for carbon steel as low 0.1 to 0.5 µm/year (0.004 to 0.02 mil/yr), which suggest the steel drums have lifetimes of 2,500 to 12,700 years.

Initially the pH of the water contacting the waste containers is expected to be as high as 13.5. According to Cooper (2011), the pH of water after passing through concrete has a pH of 13.5 to 12.0 when it is fresh (less than 523 pore volumes of infiltration), 12 to 11.2 when mature (523 to 1,097 pore volumes), and 11.2 to 10.3 when mature but transitioning to degraded (1,097 to 4,413 pore volumes). Assuming a porosity of 0.1 for the concrete disposal cell covers, the estimated duration of each pH range is listed in Table 3 for infiltration rates representative of conditions relevant to the current study.

Assuming that the concrete cover prevents infiltration from contacting the drums for 500 years, their minimum lifetime is assigned a value of 500 years. Although the Eh of the disposal cell environment is not known, it was assumed for the base case that the concrete pore water has a pH greater than 12 and a negative Eh (anoxic conditions). Under these conditions the drums were assumed to last as long as 1,000 years. Several simulations were also conducted assuming that the concrete pore water has a pH greater than 12, but a positive Eh (oxidizing conditions). Under these conditions the drums would last only 100 years after being contacted with concrete pore water.

The sealed stainless steel pencils that contain CsCl or another cesium salt in the large Cs-137 irradiators have a wall thickness of 1.25 mm (Patil et al., 2015)[4] that is subject to general corrosion at a mean rate of 0.5 µm/year (0.02 mil/yr). The mean lifetime of a stainless steel pencil is therefore 2,500 years.[5] Because lower rates of general corrosion have also been reported for stainless steel under relevant environmental conditions, a distribution of stainless steel pencil failure times ranging from 2,500 to 5,000 years following exposure to water was used. The stainless steel sealed capsules containing neutron sources, which consist of a source of alpha particles, such as Pu-239, Am-241, and Po-210, and a target material, such as Be or Li, have reported wall thicknesses that range from 2.6 to 3.2 mm [102 to 126 mil] (Byerly et al., 2017). Based on these wall thickness data and an assumed corrosion rate of 0.5 µm/year [0.02 mil/yr], stainless steel sealed gamma sources are assumed to have lifetimes ranging from 5,200 to 6,400 years.

There are four waste forms used for the 17 waste streams: (i) activated stainless steel components from reactors, (ii) a cesium salt, such as CsCl, in large gamma irradiators, (iii) mechanical mixtures of PuO and BeO or alloys of $PuBe_{13}$ in neutron sources, and (iv) grout-stabilized waste from West Valley decontamination and decommissioning, Mo-99 production, Pu-238 production, and waste exhumed from various disposal locations at West Valley. The activated stainless steel waste is assumed to uniformly release radionuclides by corrosion that lasts 100,000 years. The cesium salts in the gamma irradiator pencils are assumed to dissolve as soon as exposed to water. There is little information on the stability of the mechanical mixtures of metal oxides and the metal alloys that are used in the sealed

[4]Patil et al. (2015) report an inner diameter of 23 mm and an outer diameter of 25.5 mm for Cs-137 source pencils.
[5]1.25 mm = 1.25×10^3 µm. 1.25×10^3 µm / 0.5 µm/yr = 2,500 yr.

neutron sources. It is assumed that the material inside the sealed neutron sources is dissolved when exposed to water.

The grout waste form release model attempts to capture the effects of a number of complex physicochemical degradation processes using a simple “lifetime.” Degradation processes include those that change the pH, Eh and ion concentrations of the pore water, and alter the physical structure of the cementitious materials. As the grout waste form is exposed to greater volumes of infiltration, the pH of the pore water decreases from 13.5 to 10, which in turn increases the mobility of dissolved radionuclides. As more water contacts the waste form, more calcium-silicate-hydrate gel (C-S-H) weathers from the cementitious matrix, which increases the porosity and permeability of the waste form. As the porosity and permeability of the waste form increase, the leaching rate of the radionuclides increases. Investigations have found that the useful lifetime of cementitious materials is often correlated with the time required to decrease the pH of the concrete water from 13.5 to around 10. As shown in Table 3, the lifetime of cementitious material can range from as little as 4,000 years when subject to an infiltration rate of 100 mm/year to more than 200,000 years at 2 mm/year. In the base case, the grout used to stabilize the waste is assumed to include sulfur and iron compounds that produce reducing conditions (negative Eh) in the pore water. In the base case, grout waste forms are assumed to release their radionuclide inventory uniformly over 10,000 years. For all waste forms, sorption is assumed to delay the release of radionuclides from the disposal cell to the unsaturated zone. Cover failure, container failure, and waste form failure models are listed by waste stream in Table 4.

Table 3. Duration of concrete dissolution stages. Fresh concrete, 12 < pH < 13.5; mature concrete, 11.2 < pH < 12; mature to degraded concrete, 10.3 < pH < 11.2.

Infiltration Rate (mm/yr)	Fresh Concrete (years)	Mature Concrete (years)	Mature to Degraded Concrete (years)
2	26,000	55,000	220,000
25	2,100	4,400	18,000
100	50	1,100	4,400

Table 4. Cover failure, waste container failure, and waste form release models					
Waste Stream Number	**Waste Stream Designation**	**Cover Failure Model**	**Container Failure Model**	**Waste Form**	**Waste Form Release Model**
1	G1-GTCC-Reactor-AM-RH	Impervious to water between 0 and 500 years. Allows 100% Infiltration after 500 years	No container function after 500 years.	Stainless steel	Uniform corrosion over 100,000 years. RN release controlled by sorption.
2	G1-GTCC-Cs-137-SS-CH	Impervious to water between 0 and 500 years. Allows 100% Infiltration after 500 years	Stainless steel pencil fully corrodes between 3,000 and 5,500 years	Cesium salt (CsCl)	Dissolves in 1 year. RN release controlled by sorption.
3	G1-GTCC-Neutron-Ir-SS-CH	Impervious to water between 0 and 500 years. Allows 100% Infiltration after 500 years	Stainless steel sealed source fully corrodes between 5,200 and 6,400 years.	PuO, BeO, and $PuBe_{13}$	Dissolves in 1 year [conservative]. RN release controlled by sorption.
4	G1-GTCC-like-WV Decon-O-CH	Impervious to water between 0 and 500 years. Allows 100% Infiltration after 500 years	Steel drums fail uniformly between 500 and 1,500 years.	Grout	Uniform dissolution over 10,000 years. RN release controlled by sorption.
5	G1-GTCC-like-WV Decon-O-RH	Impervious to water between 0 and 500 years. Allows 100% Infiltration after 500 years	Steel drums fail uniformly between 500 and 1,500 years.	Grout	Uniform dissolution over 10,000 years. RN release controlled by sorption.
6	G2a-GTCC-Reactor-AM-RH	Impervious to water between 0 and 500 years. Allows 100% Infiltration after 500 years	No container function after 500 years.	Stainless steel	Uniform corrosion over 100,000 years. RN release controlled by sorption.
7	G2a-GTCC-Mo99(murr)-O-RH	Impervious to water between 0 and 500 years. Allows 100% Infiltration after 500 years	Steel drums fail uniformly between 500 and 1,500 years.	Grout	Uniform dissolution over 10,000 years. RN release controlled by sorption.
8	G2a-GTCC-Mo99(mips)-O-RH	Impervious to water between 0 and 500 years. Allows 100% Infiltration after 500 years	Steel drums fail uniformly between 500 and 1,500 years.	Grout	Uniform dissolution over 10,000 years. RN release controlled by sorption.
9	G2a-GTCC-WV NDA-AM-RH	Impervious to water between 0 and 500 years. Allows 100% Infiltration after 500 years	No container function after 500 years.	Stainless steel	Uniform corrosion over 100,000 years. RN release controlled by sorption.
10	G2a-GTCC-WV NDA-O-RH	Impervious to water between 0 and 500 years. Allows 100% Infiltration after 500 years	Steel drums fail uniformly between 500 and 1,500 years.	Grout	Uniform dissolution over 10,000 years. RN release controlled by sorption.
11	G2b-GTCC-WV SDA-AM-RH	Impervious to water between 0 and 500 years. Allows 100% Infiltration after 500 years	No container function after 500 years.	Stainless Steel	Uniform corrosion over 100,000 years. RN release controlled by sorption.

Table 4.	Cover failure, waste container failure, and waste form release models				
12	G2b-GTCC-WV SDA-O-CH	Impervious to water between 0 and 500 years. Allows 100% Infiltration after 500 years	Steel drums fail uniformly between 500 and 1,500 years.	Grout	Uniform dissolution over 10,000 years. RN release controlled by sorption.
13	G2b-GTCC-WV SNAP-O-CH	Impervious to water between 0 and 500 years. Allows 100% Infiltration after 500 years	Steel drums fail uniformly between 500 and 1,500 years.	Grout	Uniform dissolution over 10,000 years. RN release controlled by sorption.
14	G2b-GTCC-like-WV Decom-O-CH	Impervious to water between 0 and 500 years. Allows 100% Infiltration after 500 years	Steel drums fail uniformly between 500 and 1,500 years.	Grout	Uniform dissolution over 10,000 years. RN release controlled by sorption.
15	G2b-GTCC-like-WV Decom-O-RH	Impervious to water between 0 and 500 years. Allows 100% Infiltration after 500 years	Steel drums fail uniformly between 500 and 1,500 years.	Grout	Uniform dissolution over 10,000 years. RN release controlled by sorption.
16	G2b-GTCC-like-Pu-238-O-CH	Impervious to water between 0 and 500 years. Allows 100% Infiltration after 500 years	Steel drums fail uniformly between 500 and 1,500 years.	Grout	Uniform dissolution over 10,000 years. RN release controlled by sorption.
17	G2b-GTCC-like-Pu-238-O-RH	Impervious to water between 0 and 500 years. Allows 100% Infiltration after 500 years	Steel drums fail uniformly between 500 and 1,500 years.	Grout	Uniform dissolution over 10,000 years. RN release controlled by sorption.

A GoldSim Pipe Element is used to simulate the rate and timing of radionuclide release from the bottom of each disposal cell configuration. Pipe Element dimensions (Table 5) depend on the type of disposal cell used and the number of disposal cells required for a given waste stream (Column 7 of Table 2). The water velocity through the Pipe Element is equal to the infiltration rate divided by the effective porosity of the waste form and backfill material contained in the disposal cell. For all waste forms, the porosity of the mix inside the disposal cells is assumed to be 0.3. The longitudinal dispersity within the Pipe Element is assumed to be 10 percent of the length of the Pipe Element.

After the waste form releases its inventory of radionuclides within the disposal cell, the rate of transport of the radionuclides through the disposal cell to the interface at the bottom of the disposal cell and the unsaturated zone is controlled by the infiltration rate and the effects of sorption, which are modeled using a distribution coefficient or K_d [cm^3/g]. The lower and upper values for the distribution coefficient log-uniform density functions for the elements assumed to sorb on the surface of waste form dissolution products, corrosion products, and backfill materials are listed in Table 6. Except where indicated, all distribution coefficient upper and lower values listed in Table 6 come from Table E–20 in DOE (2016b).

Table 5. Pipe element dimensions		
Configuration	**Length [m]**	**Cross-sectional Area [m^2]**
Near Surface Trench (NST)	5	90 × Number of Cells Required
Moderate Depth Disposal Unit (MDDU)	10	45 × Number of Cells Required
Deep Borehole (DB)	100	4.5 × Number of Cells Required

Table 6. Lower and upper values for log-uniform probability density functions used to account for uncertainty in distribution coefficients by element		
Element	**Lower Value [cm^3/g]**	**Upper Value [cm^3/g]**
Actinium (Ac)	228	538
Americium (Am)	82	200
Curium (Cm)	82	200
Cesium (Cs)	51	250 [a]
Cobalt (Co)	2	9
Nickel (Ni)	12	59
Neptunium (Np) [b]	1	5
Protactinium (Pa) [c]	1×10^{-4}	2
Lead (Pb)	234	597
Polonium (Po)	234	597
Plutonium (Pu)	10	100
Radium (Ra)	24	100
Strontium (Sr)	24	100
Technetium (Tc)[d]	2	4
Thorium (Th)[e]	90	110
Uranium (U)	1[f]	50

[a]Maximum value of 249 in DOE (2016b), Table E–20.
[b]Single value of 3 in DOE (2016b), Table E–20. Used range [1,5] mean = 2.49
[c]Range of [0,50] in DOE (2016b), Table E–20. Range based on discussion with David Pickett
[d]Single value of 3 in DOE (2016b), Table E–20. Used range [1,5] mean = 2.49
[e]Single value of 100 in DOE (2016b), Table E–20. Used range [90,110] mean = 99.7
[f]Minimum value of 0 in DOE (2016b), Table E–20.

2.3 Environmental Settings and Unsaturated Zone Transport Parameters

Environmental settings for possible GTCC and TRU waste disposal locations in the conterminous U.S. are distinguished by specific combinations of mean annual infiltration rate and depth to water table, as illustrated in Figure 1. Environmental settings include: (i) LI-DWT, (ii) MI-IDWT, and (iii) HI-SWT.

The LI-DWT setting represents conditions likely to be found in arid to semi-arid regions of the western U.S. underlain by groundwater systems such as the basin-fill aquifers of the Great Basin and Columbia Plateau, the Rio Grande aquifer system, the Colorado Plateau aquifers, the Pecos River Basin alluvial aquifer, and the southern High Plains aquifer (the location of these groundwater systems is outlined in gold in Figure 2, labelled “Western”).

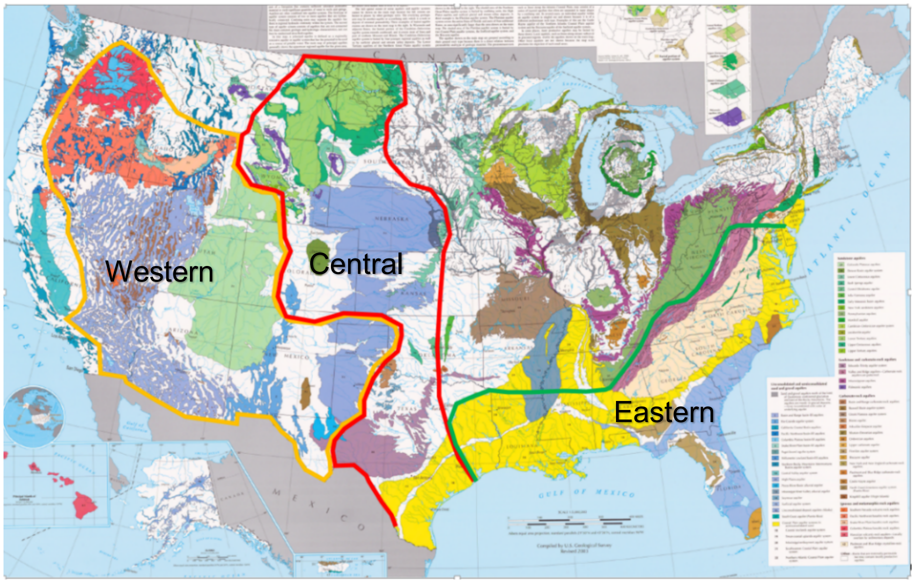

Figure 2. Principal aquifers of the United States from Reilly et al. (2008).

The MI-IDWT setting represents conditions that can be found in the semi-arid to sub-humid southern Coastal Plain, the Great Plains, and Missouri River Valley. Major aquifer systems in these regions include, the coastal lowlands aquifer systems, the Texas coastal uplands aquifer system, the Edwards-Trinity aquifer system, the central and northern High Plains aquifer, and the Lower Tertiary and Upper Cretaceous sandstone aquifers of the western Dakotas and eastern Montana and Wyoming (partly outlined in red in Figure 2, labeled “Central”). Finally, the HI-SWT environmental setting represents conditions that can be found in the humid eastern woodlands of the North Atlantic Coastal Plain, the Appalachian Mountains, the eastern Gulf Coastal Plain and the Eastern Coastal Plain. Major aquifer systems in these regions include unconsolidated and semi-consolidated sand and gravel surficial aquifers of the Eastern Coastal Plain, the Southeastern Coastal Plain aquifer system, the North Atlantic Costal Plain aquifer system, and the Piedmont and Blue Ridge crystalline-rock aquifers (partly outlined in green in Figure 2, labelled “Eastern”). The HI-SWT environmental setting may also be found between the Great Plains and Appalachian Mountains in the area drained by the Ohio and Mississippi rivers (the Midwest). Although the Midwest was not included in this study, it is likely that there are locations in this region where one or more of the environmental settings can be found. The depth to the water table can vary over time because of pumping, prolonged drought, and sustained precipitation surfeit, and over space due to topographic relief, faults that compartmentalize aquifer systems, and the presence of focused recharge and discharge features. Therefore, the environmental settings defined here are not restricted to a single region.

Lower and upper limits for the log-uniform probability density functions for the annual infiltration rates for each region were assigned using: (i) the infiltration ranges used in NRC (2018); (ii) groundwater region recharge estimates from Back et al. (1988), (iii) infiltration estimates in DOE (2016a,b); and (iv) the average annual total recharge map from Reitz et al. (2017) for the conterminous United States (CONUS) [Figure 7(A), p. 975]. The map from Reitz et al. (2017) is reproduced here as Figure 3 with colored lines to delineate the regions where the three environmental settings occur.

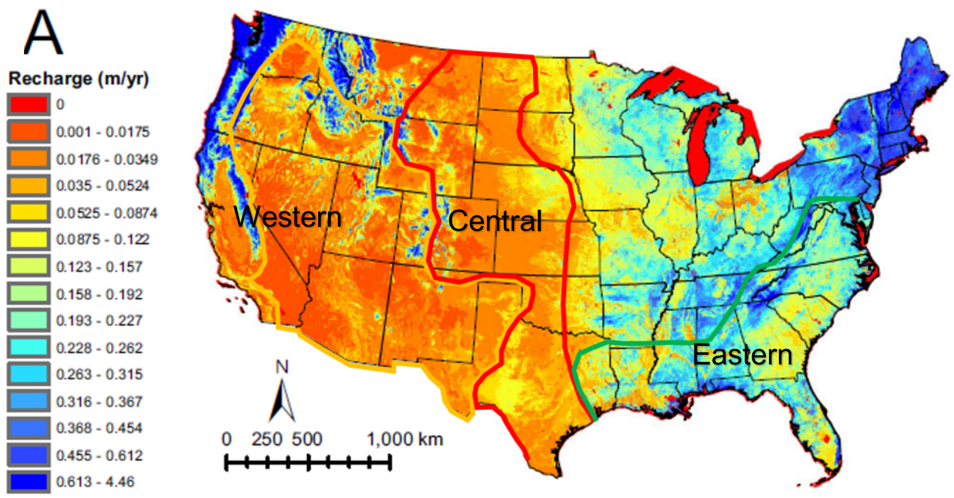

Figure 3. Map of estimated total recharge for the conterminous U.S. from Reitz et al. (2017).

NRC (2018) defined three infiltration ranges: (i) low 0.1 to 3 mm/year;[6] (ii) intermediate 5 to 30 mm/year; and (iii) high 50 to 200 mm/year. For groundwater regions in the western U.S. where the LI-DWT setting may be found, Back et al. (1988) list recharge ranges of 5 to 250 mm/year on the Columbia Plateau, 3 to 50 mm/year for the Colorado Plateau and Wyoming Basin, 5 to 50 mm/year for the Great Basin, 5 to 50 mm/year for Basin and Range alluvial basins, and 1 to 150 mm/year on the High Plains [Back et al. (1988), Table 2, pp. 21-23]. For groundwater regions in the central U.S. where the MI-IDWT setting can be found, Back et al. (1988) list recharge estimates of 5 to 300 mm/year in the central non-glaciated plains, 3 to 50 mm/year for the Rocky Mountains, and 50 to 500 mm/year in the Gulf of Mexico Coastal Plain. For groundwater regions in the Atlantic and Gulf States, where the HI-SWT setting occurs, Back et al. (1988) identify recharge rates of 50 to 500 mm/year for the Gulf of Mexico coastal plain, 50 to 500 mm/year for the Atlantic and Eastern Gulf coastal plains, and 30 to 300 mm/year for the Piedmont and Blue Ridge. DOE (2016a,b) used infiltration rates for sites in the arid to semi-arid western U.S. that include 0.03 mm/year at the Nevada Nuclear Security Site (NNSS) located in the Basin and Range, 2 mm/year in the vicinity of the Waste Isolation Pilot Plant (WIPP) located at the western margin of the Great Plains, 3.5 mm/year at the Hanford Reservation located on the Columbia Plateau, 5 mm/year at Los Alamos National Laboratory (LANL) located in the Basin and Range, and 50 mm/year at Idaho National Laboratory (INL) in the eastern portion of the Columbia Plateau. Figure 3 shows there are large areas of the western region where recharge is between 0 to 17.5 mm/year. In the central region there are areas with recharge rates of 17.6 to 52.4 mm/year. In the eastern region the lowest recharge rates range from 52.5 to 157 mm/year. All estimates of infiltration and recharge discussed above are summarized in Table 7.

Infiltration ranges used in the groundwater dose assessment are presented in Column 6 of Table 7. These infiltration ranges were selected to reflect favorable, but reasonably likely

[6]To convert to inches per year, divide by 25.4 mm/inch.

Table 7. Estimates of infiltration and groundwater recharge (mm/year)*					
Region	**Infiltration NRC (2018)**	**Recharge Back et al. (1988)**	**Infiltration DOE (2016a,b)**	**Recharge Reitz et al. (2017)**	**Infiltration Range**
Western	0.1 to 3	1 to 150 3 to 50 5 to 50 5 to 250	0.03 2 3.5 5 50	0 to 17.5	0.1 to 10
Central	5 to 30	3 to 50 5 to 300 50 to 500	18	17.6 to 52.4	10 to 50
Eastern	50 to 200	30 to 300 50 to 500	38	52.5 to 157	50 to 200
*To convert to inches per year, divide by 25.4 mm/inch.					

environmental conditions that can be expected when a disposal facility is sited in a region using a carefully executed site evaluation process.

The lower and upper limits for the uniform probability density functions for the depth to groundwater for each region were assigned using: (i) a map of depth to water table estimated for CONUS using the MODFLOW groundwater flow model,[7] which is reproduced here as Figure 4; and (ii) values used by DOE (2016a,b) in the FEIS. From Figure 4, reasonable and favorable depth to water ranges are 30 to greater than 122 m [100 to greater than 400 ft] in the western region, 9 to 61 m [30 to 200 ft] in the central region, and 1 to 30 m [3 to 98 ft] in the eastern region. DOE (2016a,b) used water table depths for sites in the arid to semi-arid western U.S. that include 246 m [807 ft] at NNSS, 153 m [502] in the vicinity of WIPP, 88 m [289 ft] at the Hanford Reservation, 269 m [883 ft] at LANL, and 137 m [449 ft] at INL. Figure 3 shows there are large areas of the western region where recharge rates are between 0 and 17.5 mm/year. In the central region there are large areas characterized by recharge rates of 17.6 to 52.4 mm/year. In the eastern region the lowest recharge rates range from 52.5 to 157 mm/year. These estimates of depths to the water table are summarized in Table 8. The depth to the water table ranges used in the groundwater dose assessments are listed in Column 4.

The probability density functions used in the GoldSim-based groundwater dose assessment model for infiltration rate and depth to water for the three environmental settings are listed in Table 9.

A GoldSim Aquifer Element is used to simulate the transport of radionuclides released from the bottom of the disposal cells through the underlying unsaturated zone (UZ). The transport velocity is given by the sampled infiltration rate divided by the effective porosity of the material in the UZ, which is assumed to be 0.3. The length of the downward vertical transport pathway is equal to the difference of the sampled depth to the water table minus the depth to the bottom of the disposal cell (Table 1). To facilitate further discussion of the modeling approach as well as the presentation of results from the probabilistic dose

[7]http://www.gwpc.org/sites/default/files/event-sessions/Cunningham_GWPC_Forum_091118.pdf, slide 28. (accessed 4/3/3019)

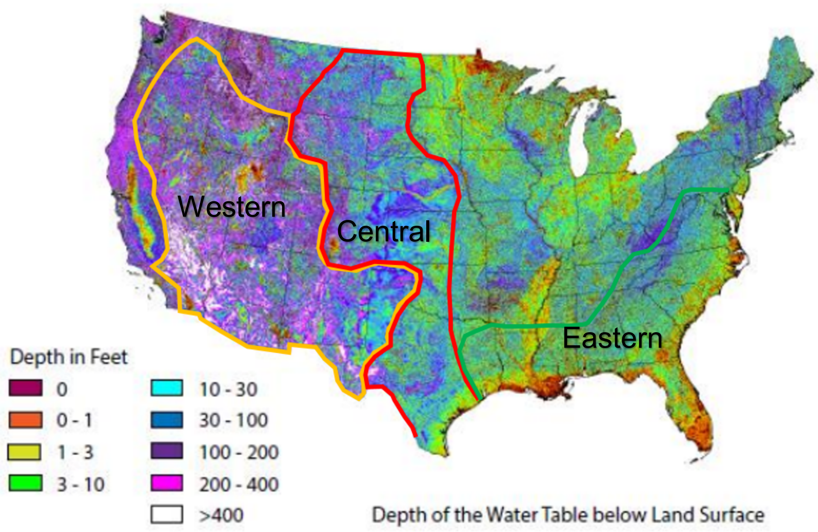

Figure 4. Map of depth to water estimated for the conterminous U.S. using a large-scale MODFLOW model for the shallow groundwater system.[8]

Table 8. Depth to water table ranges (m)

Region	Water Table Depth[9]	Water Table Depth DOE (2016a,b)	Depth to Water Table Range
Western	30 to 122	88 119 137 153 246 269	135 to 200
Central	9 to 61	13	50 to 135
Eastern	1 to 30	17 23 29	20 to 50

Table 9. Infiltration rate and water table depth probability density functions

Environmental Setting	Infiltration Rate [mm/yr]	Depth to Water Table [m]
Low Infiltration-Deep Water Table	Log-Uniform [0.1, 10][10] Mean = 2.15	Uniform [135, 200] Mean = 167.5
Medium Infiltration-Intermediate Depth Water Table	Log-Uniform [10, 50] Mean = 24.85	Uniform [50, 135] Mean = 92.5
High Infiltration-Shallow Water Table	Log-Uniform [50, 200] Mean = 108.2	Uniform [20, 50] Mean = 35

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[8]http://www.gwpc.org/sites/default/files/event-sessions/Cunningham_GWPC_Forum_091118.pdf, slide 28. (Accessed 4/3/3019).

[9]Ibid.

[10]Mean of Log-Uniform[A, B] = (B – A)/[Ln(B) – Ln(A)]

assessment, the possible combinations of disposal cell configuration and environmental setting are called “scenarios,” as shown in Table 10.

The mean disposal cell residence times for each scenario are listed in Table 11. The disposal cell mean residence time is computed by Monte Carlo methods (10 realizations of 1,000 samples per scenario) by dividing the length of the disposal cell (5, 10, and 100 m for the NST, MDDU, and DB, respectively) by the sampled transport velocity for that scenario.

The distributions of UZ transport pathway lengths are shown in Table 12 for the six scenarios. Longitudinal dispersivity in the Aquifer Element is assumed to be one-tenth the length of the transport pathway. The cross-sectional area of each Aquifer Element depends on the disposal cell configuration and number of required disposal cells and is calculated using the formulae shown in Column 3 of Table 5. Minimum and maximum advective transport times for radionuclides that are not sorbed by materials and minerals in the disposal cell and porous media in the unsaturated zone transport pathway are listed in Table 12 for each scenario. The mean unretarded transport time in the UZ is computed by Monte Carlo methods (10 realizations of 1,000 samples per scenario) by dividing the sampled length of the UZ transport pathway (Table 13) by the sampled transport velocity for that scenario.

2.4 Biosphere and Dose Conversion Factor Information

Radionuclides that reach the saturated zone (SZ) are assumed to be captured by a municipal water supply well that serves a population of 25 persons and pumps 2,000 m^3 70,630 ft^3] annually. Transport in the SZ between the locations where the radionuclides enter the water table and where they are captured by the municipal well is assumed to be instantaneous. No credit is taken for decay, delay, and dispersion within the SZ. Exposure of the persons living in the community is assumed to be by drinking 2 L (0.5 gal) of well water per day. The dose conversion factors used for the drinking water dose pathways come from ICRP 60 and are listed in Column 4 of Table 14.

Table 10. Definition of simulation scenarios

Scenario	Disposal Cell Configuration	Environmental Setting
1	Near Surface Trench	Low Infiltration−Deep Water Table
2	Near Surface Trench	Medium Infiltration−Intermediate Depth Water Table
3	Near Surface Trench	High Infiltration−Shallow Water Table
4	Moderate Depth Disposal Unit	Low Infiltration−Deep Water Table
5	Moderate Depth Disposal Unit	Medium Infiltration−Intermediate Depth Water Table
6	Deep Borehole	Low Infiltration−Deep Water Table

Table 11. Disposal cell residence times for non-sorbed nuclides [yr]

Scenario	Bounds on Residence Time	Estimated Mean
1	150 to 15,000	3,250
2	30 to 150	74
3	7.5 to 30	16
4	300 to 30,000	6,330
5	60 to 300	149
6	3,000 to 300,000	65,300

Table 12. Unsaturated zone transport pathway length density function (m)		
Scenario	**Distribution**	**Mean**
1	Uniform [120, 185]	152.5
2	Uniform [35, 120]	77.5
3	Uniform [5, 35]	20.0
4	Uniform [90, 155]	122.5
5	Uniform [5, 90]	47.5
6	Uniform [5, 70]	37.5

Table 13. UZ transport times for non-sorbed nuclides [yr]		
Scenario	**Bounds on Distribution**	**Estimated Mean**
1	3,600 to 555,000	98,400
2	210 to 3,600	1,150
3	7.5 to 210	65
4	2,700 to 465,000	77,300
5	30 to 2,700	711
6	150 to 210,000	24,400

Table 14. Radionuclides and daughters tracked in the model and their drinking water dose conversion factors						
Species ID	**Atomic Weight**	**Half-life [year]**	**Drinking Water Dose Conversion Factor [mrem/Ci]**	**Daughter1**	**Daughter2**	**Description**
Ac227	227.028	21.772	4.7×10^{9}			Actinium 227
Am241	241.057	432.2	7.4×10^{8}	Np237		Americium 241
Am243	243.061	7370	7.4×10^{8}	Pu239		Americium 243
C14	14.0032	5700	2.15×10^{6}			Carbon 14
Cm243	243.061	29.1	5.55×10^{8}	Pu239	Am243	Curium 243
Cm244	244.063	18.1	4.44×10^{8}	Pu240		Curium 244
Cm245	245.065	8500	7.77×10^{8}	Pu241		Curium 245
Co60	59.9338	5.2713	1.26×10^{7}			Cobalt 60
Cs137	136.907	30.167	4.81×10^{7}			Cesium 137
H3	3.01605	12.32	6.66×10^{4}			Hydrogen 3
I129	128.905	1.57×10^{7}	4.07×10^{8}			Iodine 129
Ni59	58.9343	1.01×10^{5}	2.33×10^{5}			Nickel 59
Ni63	62.9297	100.1	5.55×10^{5}			Nickel 63
Np237	237.048	2.144×10^{6}	4.07×10^{8}	U233		Neptunium 237
Pa231	231.036	32760	2.63×10^{9}	Ac227		Protactinium 231
Pb210	209.984	22.2	2.55×10^{9}			Lead 210
Pu238	238.05	87.7	8.51×10^{8}	U234		Plutonium 238
Pu239	239.052	24110	9.25×10^{8}	U235		Plutonium 239
Pu240	240.054	6564	9.25×10^{8}	U236		Plutonium 240

Table 14. Radionuclides and daughters tracked in the model and their drinking water dose conversion factors

Pu241	241.057	14.35	1.78×10^{7}	Am241	Np237	Plutonium 241
Ra226	226.025	1600	1.04×10^{9}	Pb210		Radium 226
Ra228	228.031	5.75	2.55×10^{9}	Th228		Radium 228
Sr90	89.9077	28.79	1.04×10^{8}			Strontium 90
Tc99	98.9063	2.111×10^{5}	2.37×10^{6}			Technetium 99
Th228	228.029	1.9116	2.66×10^{8}			Thorium 228
Th229	229.032	7340	1.81×10^{9}			Thorium 229
Th230	230.033	75380	7.77×10^{8}	Ra226		Thorium 230
Th232	232.038	1.405×10^{1}	8.81×10^{8}	Ra228		Thorium 232
U233	233.04	1.592×10^{5}	1.89×10^{8}	Th229		Uranium 233
U234	234.041	2.455×10^{5}	1.81×10^{8}	Th230		Uranium 234
U235	235.044	7.04×10^{8}	1.74×10^{8}	Pa231		Uranium 235
U236	236.046	2.342×10^{7}	1.74×10^{8}	Th232		Uranium 236
U238	238.051	4.468×10^{9}	1.67×10^{8}	U234		Uranium 238

3 PEAK EXPECTED DOSE ESTIMATES

Peak expected annual dose estimates (mrem/yr) during the first 10,000 years following closure of the disposal facility calculated by the GoldSim off-site groundwater dose assessment models are listed in Table 15 by waste stream number, environmental setting, disposal configuration, and scenario. Bar charts of peak dose before 10,000 years versus disposal configuration and environmental setting are shown in Appendix A for each waste stream except Waste Stream 2, which produces no dose.[11] Plots of the expected annual dose versus time out to 100,000 years for each scenario are presented in Appendix B for all waste streams, except Waste Stream 2. Figure 5 shows the expected annual dose from all waste streams disposed in a single facility as a function of the time for each of the six scenarios.

Table 15. Peak expected annual dose in 10,000 years sorted by waste stream producing largest dose and scenario producing largest total dose for all waste streams (mrem/year)

Waste Stream	HI-SWT	MI-IDWT		LI-DWT		
	NST Scenario 3	NST Scenario 2	MDDU Scenario 5	NST Scenario 1	MDDU Scenario 4	DB Scenario 6
WS5 G1-GTCC-like-WV Decon-O-RH	1,300.00	140.00	58.00	4.70	3.80	0.00
WS3 G1-GTCC-Neutron-Ir-SS-CH	390.00	20.00	8.80	0.02	0.01	0.00
WS1 G1-GTCC-Reactor-AM-RH	62.00	54.00	32.00	7.80	6.80	0.00
WS4 G1-GTCC-like-WV Decon-O-CH	130.00	14.00	4.70	0.16	0.15	0.00
WS15 G2b-GTCC-like-WV Decom-O-RH	110.00	6.40	2.00	0.04	0.03	0.00
WS6 G2a-GTCC-Reactor-AM-RH	26.00	22.00	13.00	3.00	2.50	0.00
WS14 G2b-GTCC-like-WV Decom-O-CH	59.00	3.90	1.10	0.03	0.02	0.00
WS10 G2a-GTCC-WV NDA-O-RH	43.00	3.30	2.00	0.12	0.11	0.00
WS8 G2a-GTCC-Mo99(mips)-O-RH	8.90	4.50	3.20	0.39	0.33	0.00
WS17 G2b-GTCC-like-Pu-238-O-RH	11.00	1.80	0.61	0.00	0.00	0.00
WS13 G2b-GTCC-WV SNAP-O-CH	7.70	1.00	0.43	0.00	0.00	0.00
WS11 G2b-GTCC-WV SDA-AM-RH	1.50	1.40	0.96	0.25	0.20	0.00
WS9 G2a-GTCC-WV NDA-AM-RH	1.40	1.20	0.71	0.16	0.13	0.00
WS12 G2b-GTCC-WV SDA-O-CH	3.00	0.16	0.12	0.02	0.01	0.00
WS7 G2a-GTCC-Mo99(murr)-O-RH	2.50	0.13	0.11	0.02	0.01	0.00
WS16 G2b-GTCC-like-Pu-238-O-CH	0.89	0.00	0.00	0.00	0.00	0.00
WS2 G1-GTCC-Cs-137-SS-CH	0.00	0.00	0.00	0.00	0.00	0.00
Peak Dose All Waste Streams*	**2,100**	**260**	**120**	**17**	**14**	**0**

*From Figure 5 at 10,000 years. Not equal to the column sum. Peak doses for different waste streams occur at different times.

[11]Estimated doses for Waste Stream 2 (Group 1 GTCC Large Contact-Handled Neutron Irradiator Sealed Sources) are zero for all scenarios. The stainless steel pencils containing the Cs-137 gamma source are assumed to remain intact for 3,000 to 5,500 years following failure of the concrete disposal cell cover. This is equivalent to 99 to 182 Cs-137 half-lives. Over a time period of ten half-lives, radioactivity is reduced by a factor of 1,000.

3.1 Discussion of Results

When all of the waste streams are disposed in a single facility, the largest peak expected dose in 10,000 years occurs for the scenario where the waste is disposed in an NST in an HI-SWT environmental setting (Scenario 3, Column 2 of Table 15). This result is reasonable based on the short mean delay time for Scenario 3 (81 years, Column 4 of Table 16). Regardless of waste stream and disposal configuration, peak expected doses do not exceed 10 mrem/year when the disposal facility is located in an LI-DWT environmental setting (fifth through seventh Columns of Table 15). For the LI-DWT environmental setting the mean delay times through the disposal cell and UZ are 84,000, 89,000 and 101,000 years (Table 16) for the MDDU, DB, and NST, respectively. The total annual expected dose when all waste streams are disposed in the LI-DWT environmental setting does not exceed 17 mrem/year for any of the disposal configurations. In the LI-DWT environmental setting the deep borehole (green line, Figure 5) produces the lowest doses for all waste streams (less than 0.01 mrem/year).

The waste streams that produce some of the largest peak estimated doses come from decontaminating (Waste Streams 4 and 5) and decommissioning (Waste Streams 14 and 15) of the West Valley site. Other waste streams that produce relatively large peak expected doses under Scenario 3 include Waste Stream 3, sealed neutron sources, Waste Streams 1 and 6, activated metals from commercial reactor pressure vessel internal components, and Waste Stream 10, remote-handled other waste from the disposal facility at West Valley regulated by New York State. The top two radionuclides, the dose due to the radionuclide, and the initial inventory of the radionuclide or the initial inventory of parent radionuclides, are listed below for each of these waste streams.

Waste Stream 5: ^{233}U (892 mrem/yr, 740 Ci) and ^{239}Pu (195 mrem/yr, 2,900 Ci).

Waste Stream 4: ^{234}U (48 mrem/yr, 1,300 Ci $^{238}Pu \rightarrow {}^{234}U$) and ^{239}Pu (41 mrem/yr, 900 Ci)

Waste Stream 15: ^{239}Pu (44 mrem/yr, 638 Ci) and ^{234}U (31 mrem/yr, 1,000 Ci $^{238}Pu \rightarrow {}^{234}U$)

Waste Stream 14: ^{239}Pu (22 mrem/yr, 387 Ci) and ^{234}U (21 mrem/yr, 560 Ci $^{238}Pu \rightarrow {}^{234}U$)

Waste Stream 3: ^{237}Np (290 mrem/yr, 150,000 Ci $^{241}Am \rightarrow {}^{237}Np$) and ^{234}U (122 mrem/yr, 120,000 Ci $^{238}Pu \rightarrow {}^{234}U$)

Waste Stream 1: ^{14}C (60 mrem/year, 22,900 Ci) and ^{129}I (2 mrem/yr, 4.8 Ci)

Waste Stream 6: ^{14}C (25 mrem/year, 9,600 Ci) and ^{129}I (0.9 mrem/yr, 0.8 Ci)

Waste Stream 10: ^{239}Pu (21 mrem/yr, 340 Ci) and ^{233}U (8.1 mrem/yr, 1,000 Ci $^{241}Am \rightarrow {}^{237}Np \rightarrow {}^{233}U$ and 3,900 Ci $^{241}Pu \rightarrow {}^{241}Am \rightarrow {}^{237}Np \rightarrow {}^{233}U$)

In Table 17, waste stream−scenario combinations shaded in peach are for peak expected doses resulting from radioactive elements that are substantially retarded (uranium, plutonium, thorium, actinium: $100 < R < 3000$), those in buff are for peak expected doses resulting from a mix of moderately-retarded (neptunium, uranium, plutonium, thorium: $20 < R < 350$) to poorly-retarded (iodine, carbon, protactinium: $1 < R < 3$) elements, and those shaded green are for peak expected doses resulting solely from poorly-retarded elements**.** The retardation coefficient is

Table 16.	Mean delay time for non-sorbed radionuclides (years)		
Scenario	Mean Residence Time Disposal Cell (yr)	Mean Travel Time Unsaturated Zone (yr)	Mean Delay Time (yr)
1	3,300	98,000	101,000
2	74	1,200	1,300
3	16	65	81
4	6,300	77,000	84,000
5	150	710	860
6	65,000	24,000	89,000

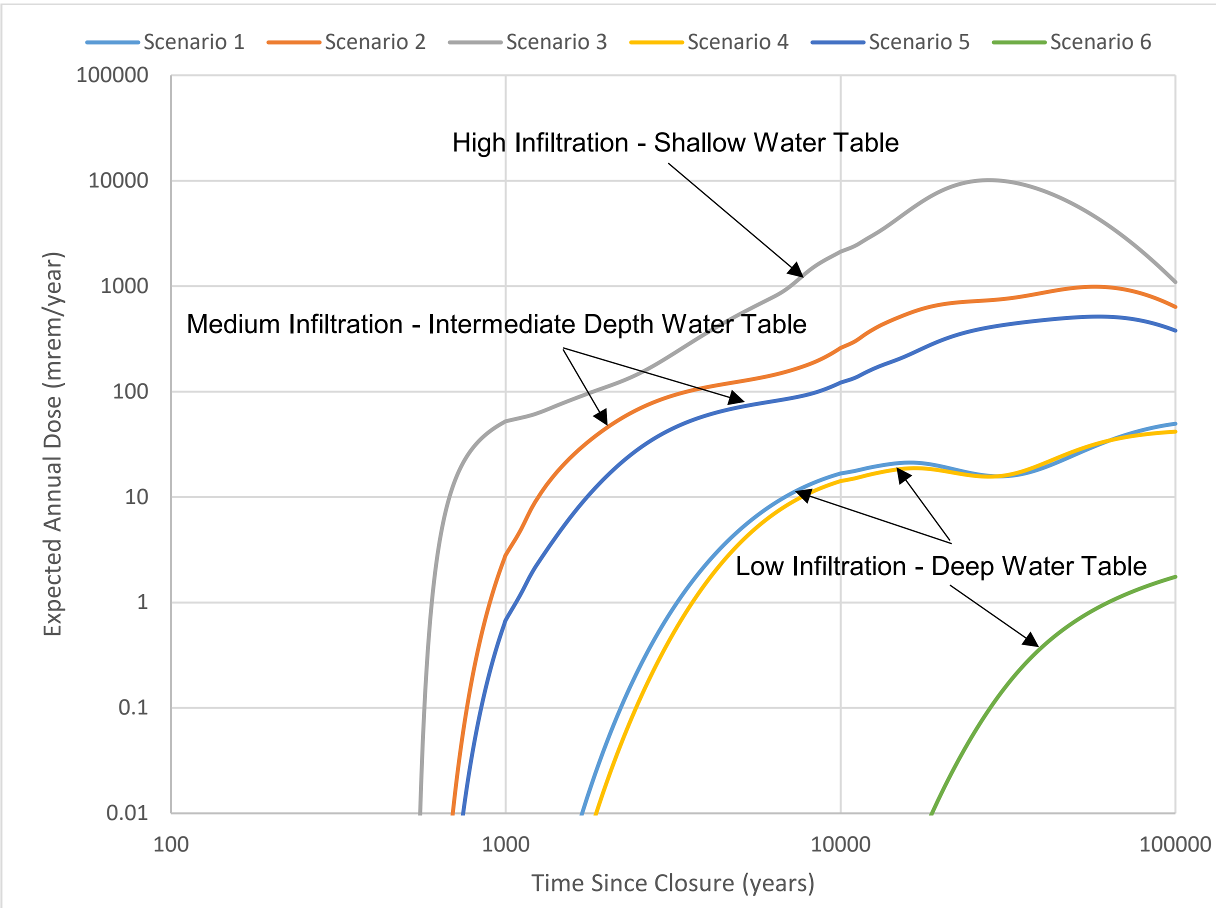

Figure 5. Expected annual dose versus time from all waste streams being disposed in a single disposal facility.

$$R = 1 + \frac{\rho}{\theta} K_d \qquad (1)$$

where ρ is the bulk density of the porous medium (in the disposal cell and in the UZ), θ is the porosity of the porous medium, and K_d is the distribution coefficient for the chemical element.

As noted at the beginning of this section, the largest peak expected doses occur under Scenario 3, which has a relatively high infiltration rate (HI), a thin disposal cell (5m-thick NST), and a short mean transport distance from the base of the disposal cell to the water table (20 m), for waste streams (5, 3, 4, 15, 14, and 10) that have relatively large inventories of substantially-

Table 17. Primary contributors to peak expected annual dose at 10,000 years by waste stream and scenario, sorted top to bottom by waste stream and left to right by scenario producing the largest doses. Explanation of cell colors is in the text.

Waste Stream	HI-SWT	MI-IDWT		LI-DWT		
	NST	NST	MDDU	NST	MDDU	DB
	Scenario 3	Scenario 2	Scenario 5	Scenario 1	Scenario 4	Scenario 6
5	^{233}U ^{239}Pu ^{229}Th	^{233}U ^{129}I ^{231}Pa	^{233}U ^{239}Pu ^{129}I	^{129}I ^{231}Pa ^{14}C	^{129}I ^{14}C ^{231}Pa	^{129}I ^{14}C
3	^{237}Np ^{234}U ^{233}U	^{227}Ac ^{237}Np ^{231}Pa	^{231}Pa ^{227}Ac	^{231}Pa	^{231}Pa	^{231}Pa
1	^{14}C ^{129}I	^{14}C ^{129}I	^{14}C ^{129}I	^{14}C ^{129}I	^{14}C ^{129}I	^{14}C ^{129}I
4	^{239}Pu ^{234}U ^{240}Pu ^{233}U	^{234}U ^{231}Pa ^{237}Np	^{234}U ^{231}Pa ^{237}Np	^{231}Pa ^{14}C	^{231}Pa ^{14}C	^{231}Pa ^{14}C
15	^{239}Pu ^{240}Pu ^{234}U	$^{234}U$$^{237}Np$ ^{233}U	^{234}U ^{237}Np ^{233}U	^{14}C ^{231}Pa ^{129}I	^{14}C ^{231}Pa ^{129}I	^{14}C ^{231}Pa ^{129}I
6	^{14}C ^{129}I	^{14}C ^{129}I	^{14}C ^{129}I	^{14}C ^{129}I	^{14}C ^{129}I	^{14}C ^{129}I
14	^{239}Pu ^{240}Pu ^{234}U	^{234}U ^{233}U ^{237}Np	^{234}U ^{14}C ^{233}U ^{231}Pa ^{237}Np	^{14}C ^{231}Pa	^{14}C ^{231}Pa	^{14}C ^{231}Pa
10	^{239}Pu ^{240}Pu ^{233}U	^{233}U ^{231}Pa ^{129}I	^{129}I ^{233}U ^{231}Pa	$^{231}Pa$$^{129}I$	$^{231}Pa$$^{129}I$	^{129}I ^{231}Pa
8	^{239}Pu ^{14}C	^{14}C ^{129}I	^{14}C ^{129}I	^{14}C ^{129}I	^{14}C ^{129}I	^{14}C ^{129}I
17	^{237}Np ^{234}U	^{237}Np ^{234}U	^{237}Np ^{234}U	^{237}Np ^{231}Pa	^{237}Np ^{231}Pa	^{237}Np
13	^{234}U ^{239}Pu	^{234}U	^{234}U ^{239}Pu	^{231}Pa	^{231}Pa	^{231}Pa
11	^{129}I	^{129}I	^{129}I	^{129}I	^{129}I	^{129}I
9	^{14}C ^{231}Pa ^{233}U ^{239}Pu	^{14}C ^{231}Pa	^{14}C ^{231}Pa	^{14}C ^{231}Pa	^{14}C ^{231}Pa	^{14}C
12	^{239}Pu ^{240}Pu	^{14}C ^{129}I	^{14}C ^{129}I	^{14}C ^{129}I	^{14}C ^{129}I	^{14}C ^{129}I
7	^{239}Pu ^{99}Tc ^{129}I	^{129}I	^{129}I	^{129}I	^{129}I	^{129}I
16	^{239}Pu ^{240}Pu	^{237}Np ^{231}Pa	^{237}Np ^{231}Pa	^{231}Pa	^{231}Pa	^{231}Pa
2						

to moderately-retarded radionuclides. Waste streams 1 and 6 contain large inventories of activated metals (^{60}Co and ^{63}Ni) with half-lives (5.3 and 96 years) that are short compared to their mean total delay times (3,500 and 22,000 years) taking into account the effects of retardation ($R_{Co} = 43$ and $R_{Ni} = 267$). Thus, doses from waste streams 1 and 6 result primarily from ^{14}C and ^{129}I, which, although present in smaller quantities, not only have longer half-lives (5,700 and 1,570,000 years) but also are unaffected by retardation.

More moderate peak expected doses occur for waste streams 5, 3, and 4 under Scenarios 2 and 5, because these scenarios have medium infiltration rates (MI), thin to slightly thicker disposal cells (5m-thick NST and 10m-thick MDDU), and somewhat greater mean transport distances to the water table (77.5 m for Scenario 2 and 47.5 m for Scenario 5) with longer mean delay times (1,300 years for Scenario 2 and 860 years for Scenario 5). As in the case of Scenario 3, doses from waste streams 1 and 6 result primarily from radioelements ^{14}C and ^{129}I, which are unaffected by retardation.

Relatively small doses occur for waste streams 5, 1, and 6 under Scenarios 1, 4, and 5, because these scenarios have relatively low infiltration rates (LI), greater mean transport distances from the base of the disposal cell to the water table (152.5, 122.5, and 37.5 m) and longer total delay times through the disposal cell and the UZ (101,000, 84,000, and 89,000 years) for non-retarded radioelements.

3.2 Tests of Two Model Assumptions

Four additional dose assessment simulations were conducted to examine the effect of changes to the assumed 1,000-year lifetime of the carbon steel waste drums and the 10,000-year release period for the grout waste form, the bases for which are described in Section 2.2. Table 18 lists the peak dose over 10,000 years for Waste Streams 5 and 15 when the lifetime of the carbon steel drums is reduced from 1,000 to 100 years. Table 18 also lists the peak dose over 10,000 years for Waste Streams 5 and 15 when the release period for the grout waste form is reduced from 10,000 to 1,000 years.

The effect of reducing the lifetime of the steel drum from 1,000 to 100 years on peak dose is minimal for these waste streams. However, the effect of reducing the release period for the grout waste form from 10,000 to 1,000 years is more significant. In these cases, the peak dose for Waste Streams 5 and 15 for all scenarios except Scenario 6 is at least double that of the nominal case. As described in Section 2.2, the grout waste form release model is an attempt to capture the effects of a number of complex physicochemical degradation processes using a simple “lifetime.” In the base case it is assumed that the grout waste form includes materials that will maintain reducing conditions (negative Eh) and retard the release of radionuclides. The retarded release of radionuclides is simulated using the longer 10,000-year release period. If the grout waste form does not include materials that will maintain reducing conditions, the shorter 1,000-year release period is appropriate.

Because of the pronounced effect that changes to assumptions may have on the results of a dose assessment, sensitivity analyses should be conducted to identify important assumptions and parameters. Models, assumptions, and parameters that significantly affect safety assessment results should have a well-supported technical basis.

3.3 Conclusions and Suggestions

Waste stream—disposal scenario combinations that do not meet the 25 mrem/year whole body dose performance standard at 10 CFR 61.41 based on results from this simple dose assessment model are shaded light red in Table 15. Disposal scenarios that do not meet the 25 mrem/year standard when all waste streams are disposed in a single facility are shaded bright red in the last row of Table 15. The latter results suggest that disposal in (i) regions with infiltration rates that vary from 50 to 200 mm/yr and where the water table lies between 20 and 50 m below ground surface or (ii) regions with infiltration rates that vary between 10 and 50 mm/year where the water table lies 50 to 135 m below ground surface, would require more

Table 18. Effect of (i) reducing carbon steel drum maximum lifetime from 1,000 to 100 years and (ii) reducing the release period for grout waste form from 10,000 to 1,000 years for Waste Streams 5 and 15 (mrem/yr).						
	Scenario					
Waste Stream	***3***	***2***	***5***	***1***	***4***	***6***
WS5	1,300	140	58	4.70	3.90	0.00
WS5 100-Year Drum	1,300	150	98	5.20	4.20	0.00
WS5 1,000-Year Grout	2,600	290	140	9.60	8.30	0.00
WS15	110	6.40	2.00	0.04	0.03	0.00
WS15 100-Year Drum	120	6.20	2.90	0.05	0.03	0.00
WS15 1,000-Year Grout	340	18	5.20	0.08	0.07	0.00

effective natural and engineered barriers to meet the standard. Improvements to natural barriers in HI-SWT and MI-IDWT settings could include identifying a location where the mineral assemblage of the unsaturated zone provides demonstrably greater sorptive capacity for uranium, plutonium, thorium, neptunium, and protactinium than assumed here (see Table 6). For activated metals waste streams, such as Waste Streams 1 and 6, whose doses are dominated by the unretarded transport of ^{14}C and ^{129}I, improving natural barrier performance may require HI-SWT and MI-IDWT settings that have the lowest infiltration rate and deepest water table. Improvements to engineered barriers in HI-SWT and MI-IDWT settings could include: (i) longer-lived grout waste forms, (ii) thicker and more corrosion-resistant metal drums, (iii) backfilling disposal cells with materials that increase pH, lower Eh, and reduce radionuclide leach rates; (iv) disposal cell covers that prolong the period before water seeps into the disposal cells; and (v) cell covers with compositions that raise the pH of percolating water.

The last row of Table 15 indicates that all waste streams can be disposed using any one of the three disposal cell configurations if located in a region with an infiltration rate that ranges from 0.1 to 10 mm/year where the water table lies between 135 and 200 m below ground surface (LI-DWT setting). All peak expected doses in 10,000 years for the 17 waste streams are 0.00 mrem/year (doses less than 0.01 are reported as 0.00) when using a deep borehole disposal configuration in the LI-DWT setting (last column of Table 15). However, the way the GoldSim Pipe Element was used to simulate releases from the deep borehole may overstate the deep borehole's ability to limit release. To accurately evaluate the potential performance benefits of filling a deep borehole from bottom to top with GTCC and TRU wastes in a thick UZ, a conceptual model of deep borehole leaching should be constructed using first principles. The conceptual model can then be used to determine what combination of GoldSim radionuclide transport elements appropriately captures the physics.

The primary takeaway from these analyses is that it appears all of the waste streams can be disposed individually or collectively in the LI-DWT environmental setting in either an NST or an MDDU. Although a formal sensitivity analysis has not been conducted, it appears that the environmental setting is a significant factor affecting the safety of disposing GTCC and TRU waste streams in a LLW facility. This finding is also illustrated in Figure 5 by the relative positions of the peak expected dose versus time curves for the HI-SWT, MI-IDWT, and LI-DWT settings.

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APPENDIX A

PEAK EXPECTED ANNUAL DOSE IN 10,000 YEARS

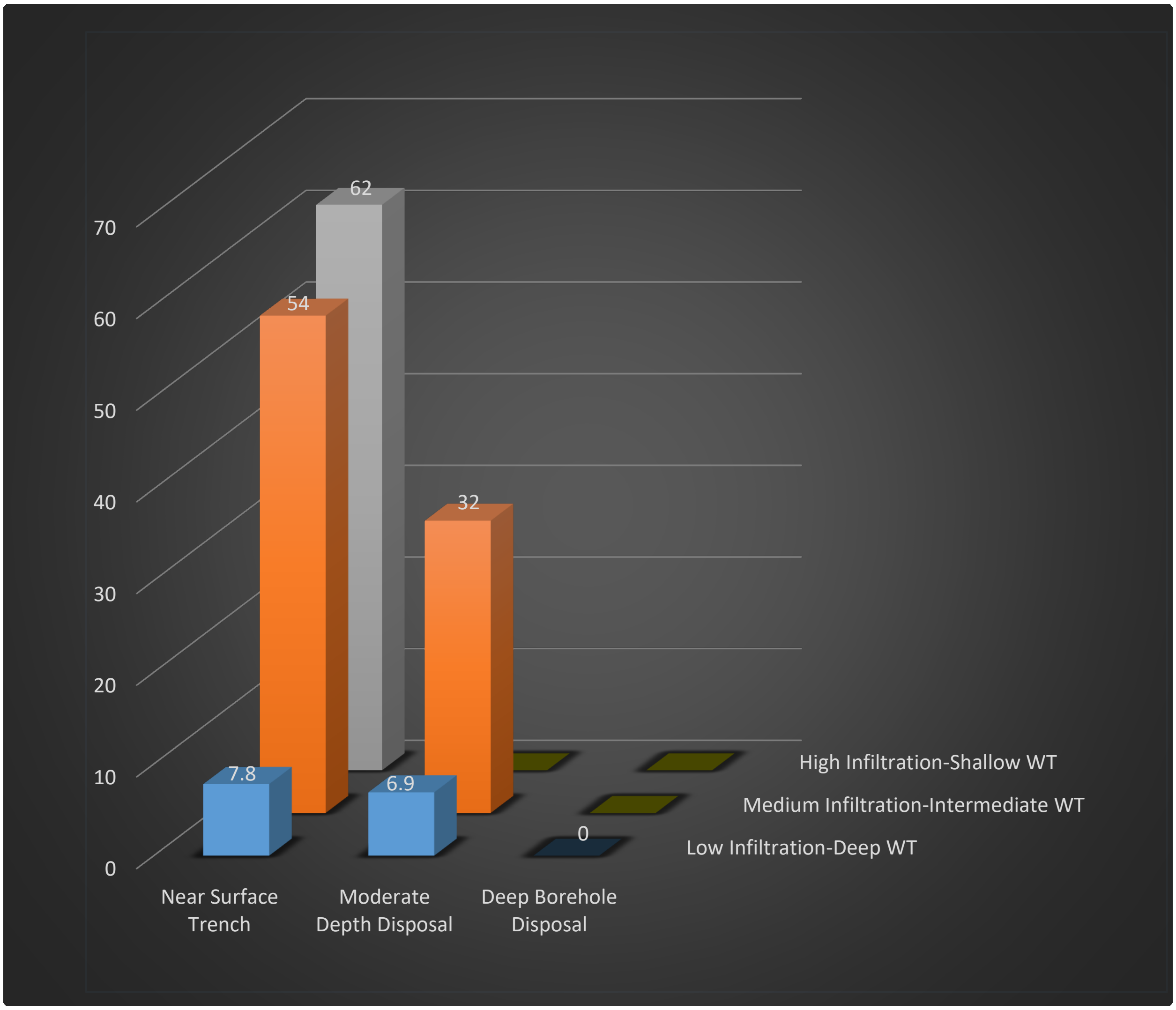

Figure A–1. Peak expected dose [mrem/yr] before 10,000 years versus disposal cell configuration {near surface trench [5m-thick], moderate depth disposal unit [10m-thick], deep borehole disposal [100m-thick]} and disposal environment (low infiltration-deep WT [mean annual infiltration (MAI) 0.1 to 10mm/yr] with deep water table (WT) [135 to 200 m], medium infiltration-intermediate depth WT [MAI 10 to 50 mm/yr] with intermediate depth water table [50 to 135 m], high infiltration-shallow WT [MAI 50 to 200 mm/yr] with shallow water table [20 to 50 m]) for Group 1 GTCC remote-handled activated metals from commercial reactors (Waste Stream 1). Yellow shaded columns without number labels are for configuration-environment combinations that were not evaluated because they would require disposal in the saturated zone. Primary dose contributors are C-14 and I-129.

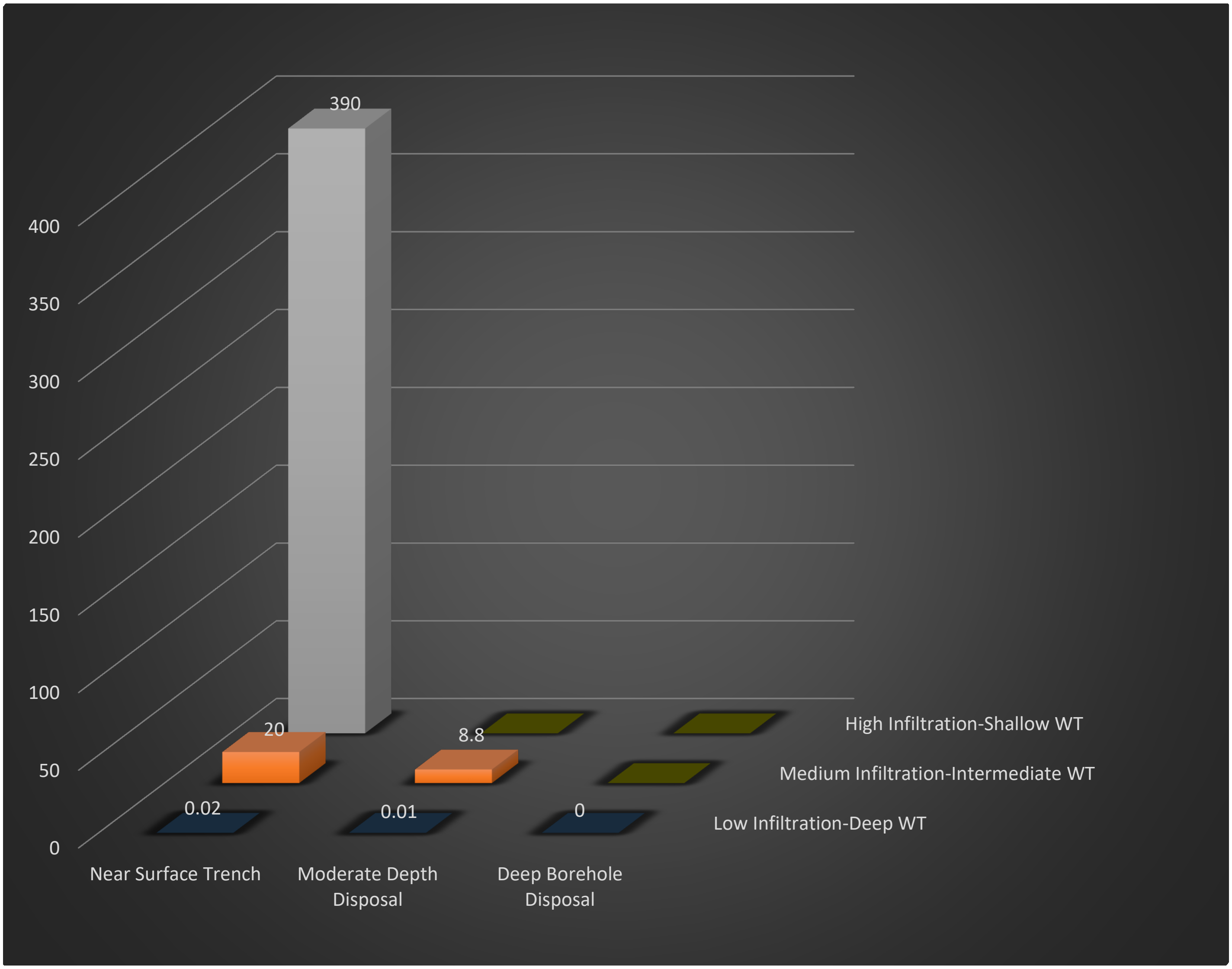

Figure A–2. Peak expected dose [mrem/yr] before 10,000 years versus disposal cell configuration (near surface trench [5m-thick], moderate depth disposal unit [10m-thick], deep borehole disposal [100m-thick]) and disposal environment (low infiltration-deep WT [mean annual infiltration (MAI) 0.1 to 10mm/yr] with deep water table (WT) [135 to 200 m], medium infiltration-intermediate depth WT [MAI 10 to 50 mm/yr] with intermediate depth water table [50 to 135 m], high infiltration-shallow WT [MAI 50 to 200 mm/yr] with shallow water table [20 to 50 m]) for Group 1 GTCC contact-handled small sealed neutron sources (waste stream 3). Yellow shaded columns without number labels are for configuration-environment combinations that were not evaluated because they would require disposal in the saturated zone. For larger doses, the primary contributor is Np-237. For smaller doses, the primary contributor is Pa-231.

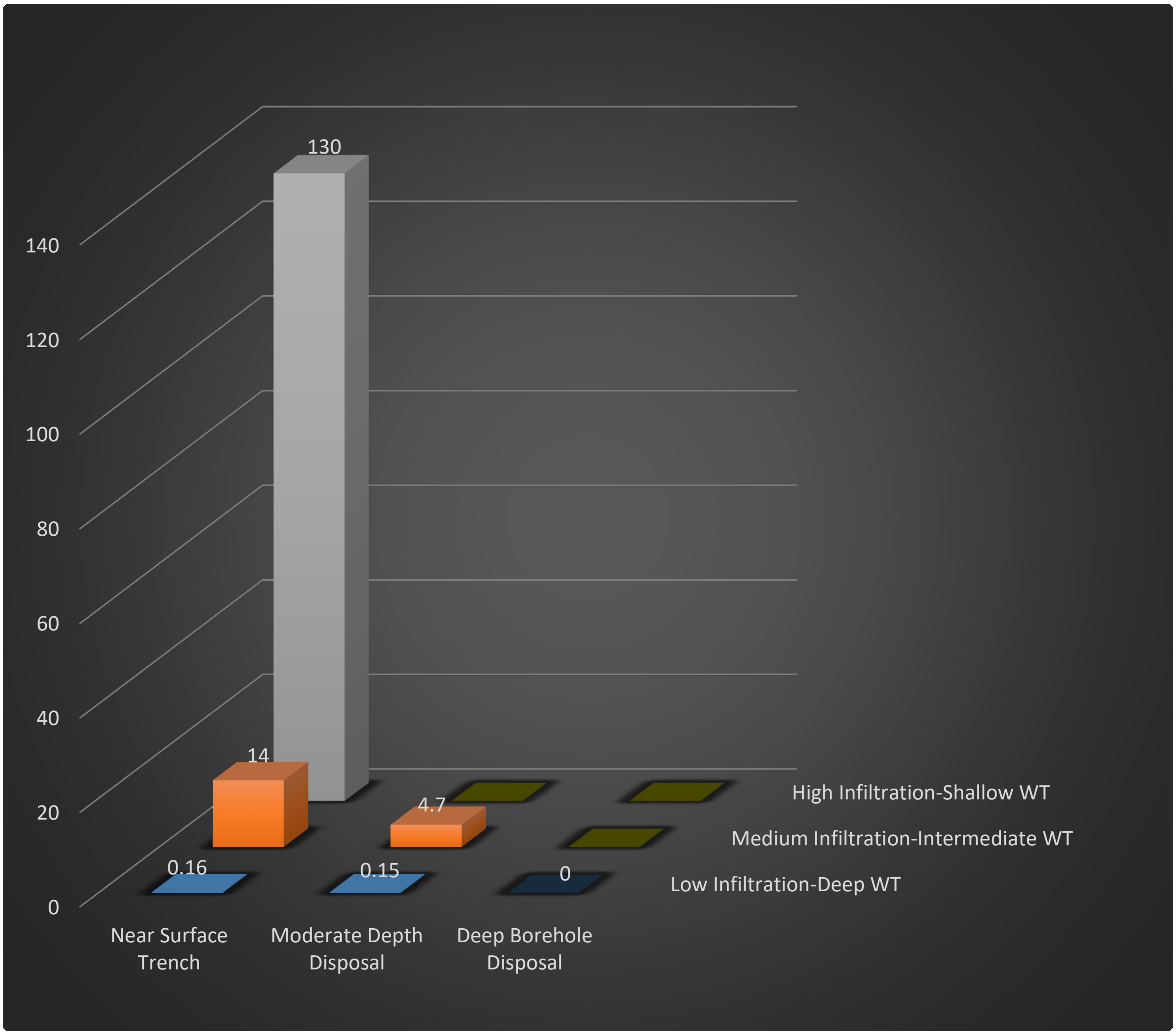

Figure A–3. Peak expected dose [mrem/yr] before 10,000 years versus disposal cell configuration {near surface trench [5m-thick], moderate depth disposal unit [10m-thick], deep borehole disposal [100m-thick]} and disposal environment {low infiltration-deep WT [mean annual infiltration (MAI) 0.1 to 10mm/yr]} with deep water table (WT) [135 to 200 m], medium infiltration-intermediate depth WT [MAI 10 to 50 mm/yr] with intermediate depth water table [50 to 135 m], high infiltration-shallow WT [MAI 50 to 200 mm/yr] with shallow water table [20 to 50 m]) for Group 1 GTCC-like contact-handled other waste from decontaminating West Valley (Waste Stream 4). Yellow shaded columns without number labels are for configuration-environment combinations that were not evaluated because they would require disposal in the saturated zone. For larger doses, the primary dose contributors are Pu-239, U-234, Pu-240, and U-234.

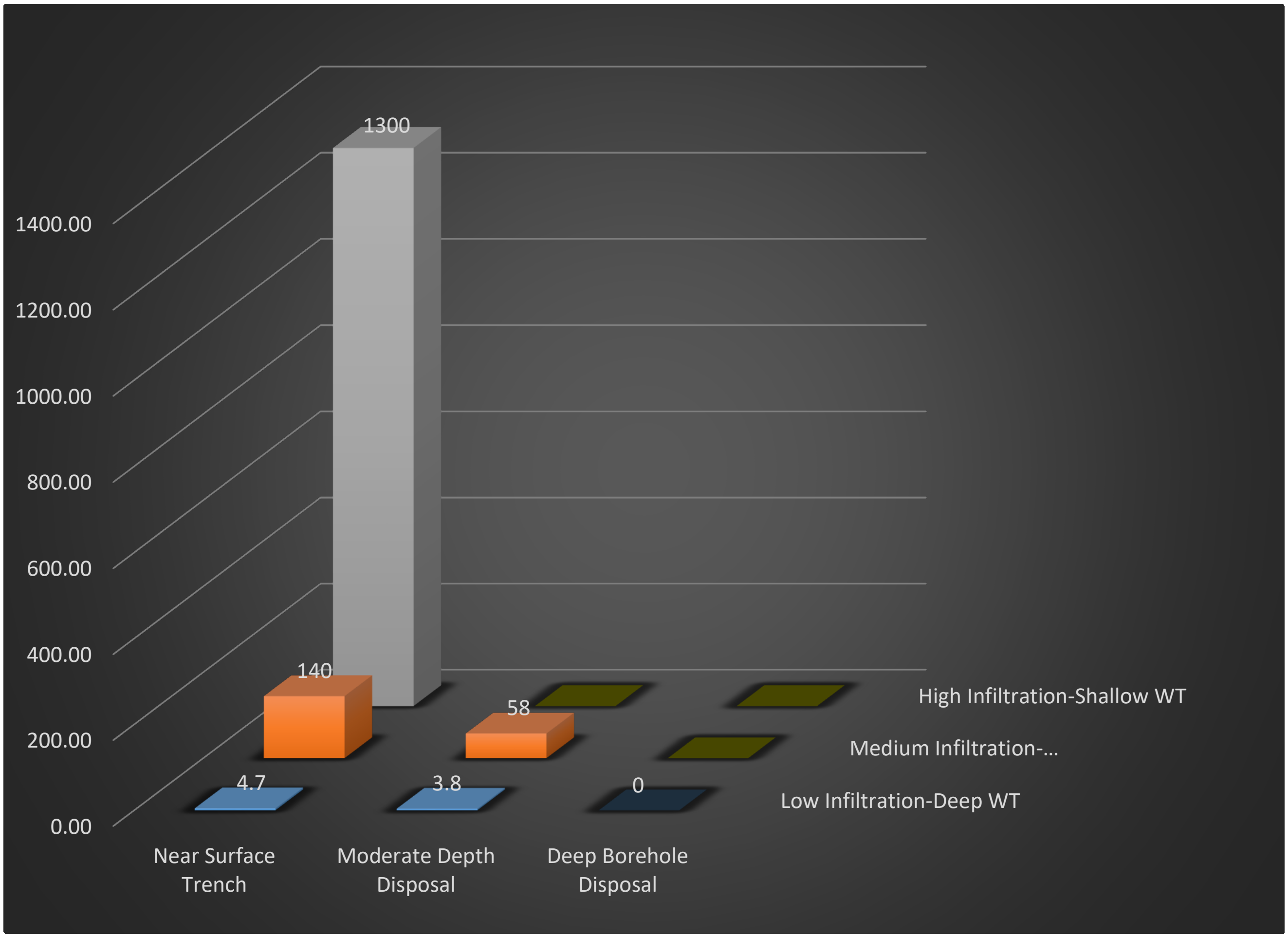

Figure A–4. Peak expected dose [mrem/yr] before 10,000 years versus disposal cell configuration {near surface trench [5m-thick], moderate depth disposal unit [10m-thick], deep borehole disposal [100m-thick]} and disposal environment (low infiltration-deep WT {[mean annual infiltration (MAI) 0.1 to 10mm/yr] with deep water table (WT) [135 to 200 m], medium infiltration-intermediate depth WT [MAI 10 to 50 mm/yr] with intermediate depth water table [50 to 135 m], high infiltration-shallow WT [MAI 50 to 200 mm/yr] with shallow water table [20 to 50 m]) for Group 1 GTCC-Like West Valley remote-handled other waste from decontaminating (Waste Stream 5). Yellow shaded columns without number labels are for configuration-environment combinations that were not evaluated because they would require disposal in the saturated zone. For larger doses, the primary contributors are Pu-239, Pu-240, U-233, and Th-229. For smaller doses, the primary contributors are I-129 and Pa-231.

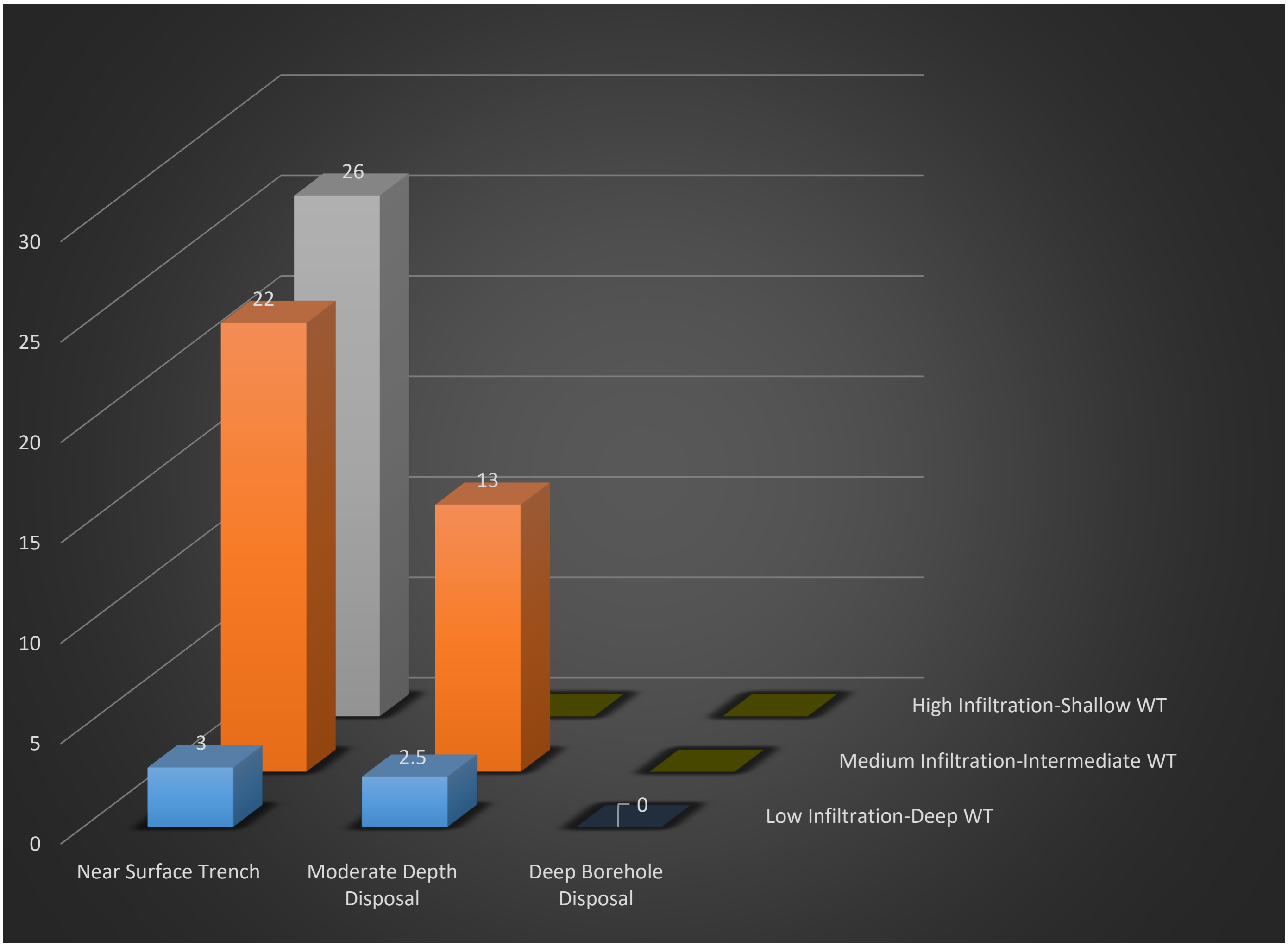

Figure A–5. Peak expected dose [mrem/yr] before 10,000 years versus disposal cell configuration {near surface trench [5m-thick], moderate depth disposal unit [10m-thick], deep borehole disposal [100m-thick]} and disposal environment (low infiltration-deep WT [mean annual infiltration (MAI) 0.1 to 10mm/yr] with deep water table (WT) [135 to 200 m], medium infiltration-intermediate depth WT [MAI 10 to 50 mm/yr] with intermediate depth water table [50 to 135 m], high infiltration-shallow WT [MAI 50 to 200 mm/yr] with shallow water table [20 to 50 m]) for Group 2a GTCC remote-handled activated metals from commercial reactors (Waste Stream 6). Yellow shaded columns without number labels are for configuration-environment combinations that were not evaluated because they would require disposal in the saturated zone. Primary dose contributors are C-14 and I-129.

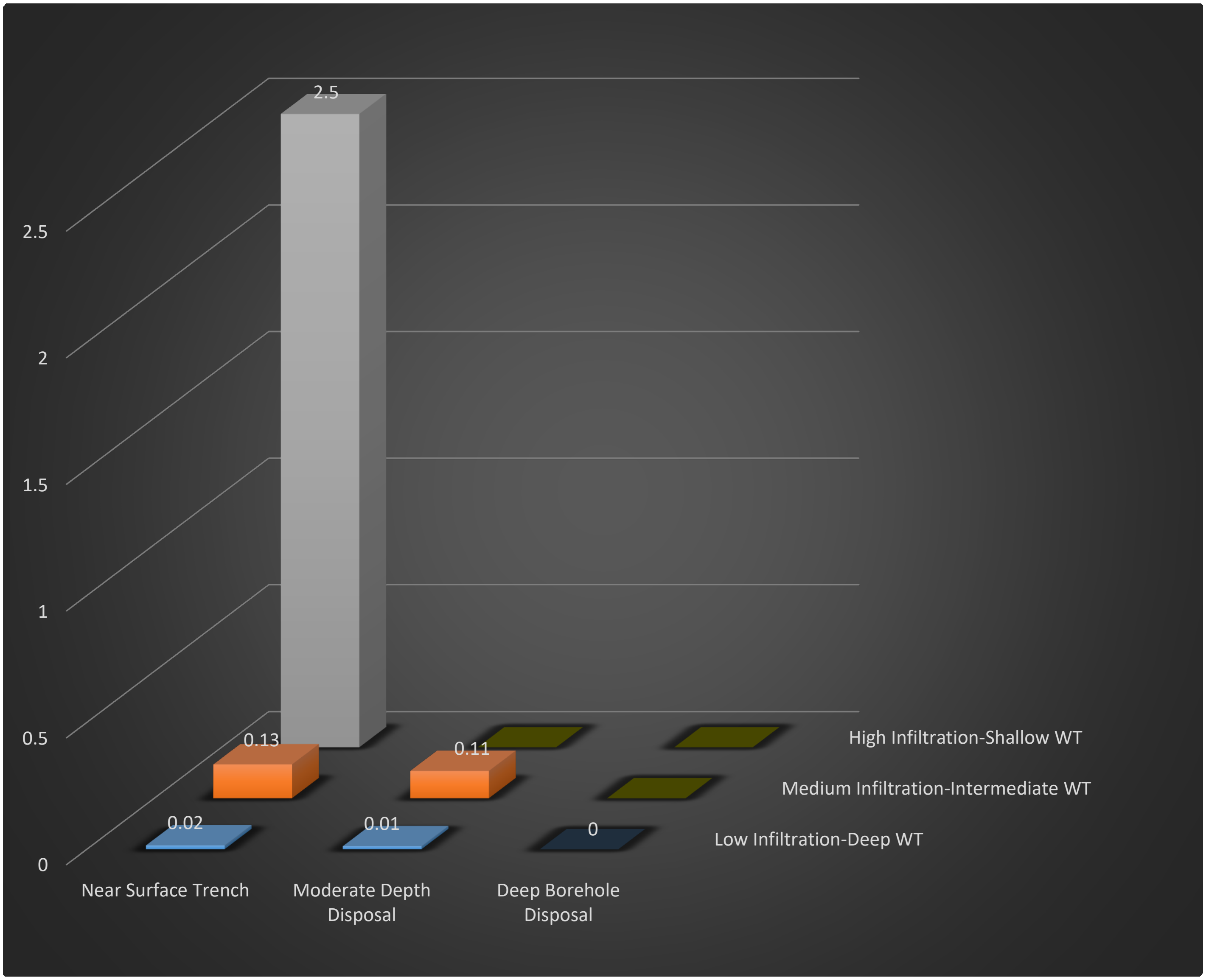

Figure A–6. Peak expected dose [mrem/yr] before 10,000 years versus disposal cell configuration {near surface trench [5m-thick], moderate depth disposal unit [10m-thick], deep borehole disposal [100m-thick]) and disposal environment (low infiltration-deep WT {mean annual infiltration (MAI) 0.1 to 10mm/yr} with deep water table (WT) [135 to 200 m], medium infiltration-intermediate depth WT [MAI 10 to 50 mm/yr] with intermediate depth water table [50 to 135 m], high infiltration-shallow WT [MAI 50 to 200 mm/yr] with shallow water table [20 to 50 m]) for Group 2a GTCC remote-handled waste from the production of Mo-99 at the MURR facility (Waste Stream 7). Yellow shaded columns without number labels are for configuration-environment combinations that were not evaluated because they would require disposal in the saturated zone. For larger doses, the primary contributor is Pu-239. For smaller doses, the primary contributors are I-129 and Tc-99.

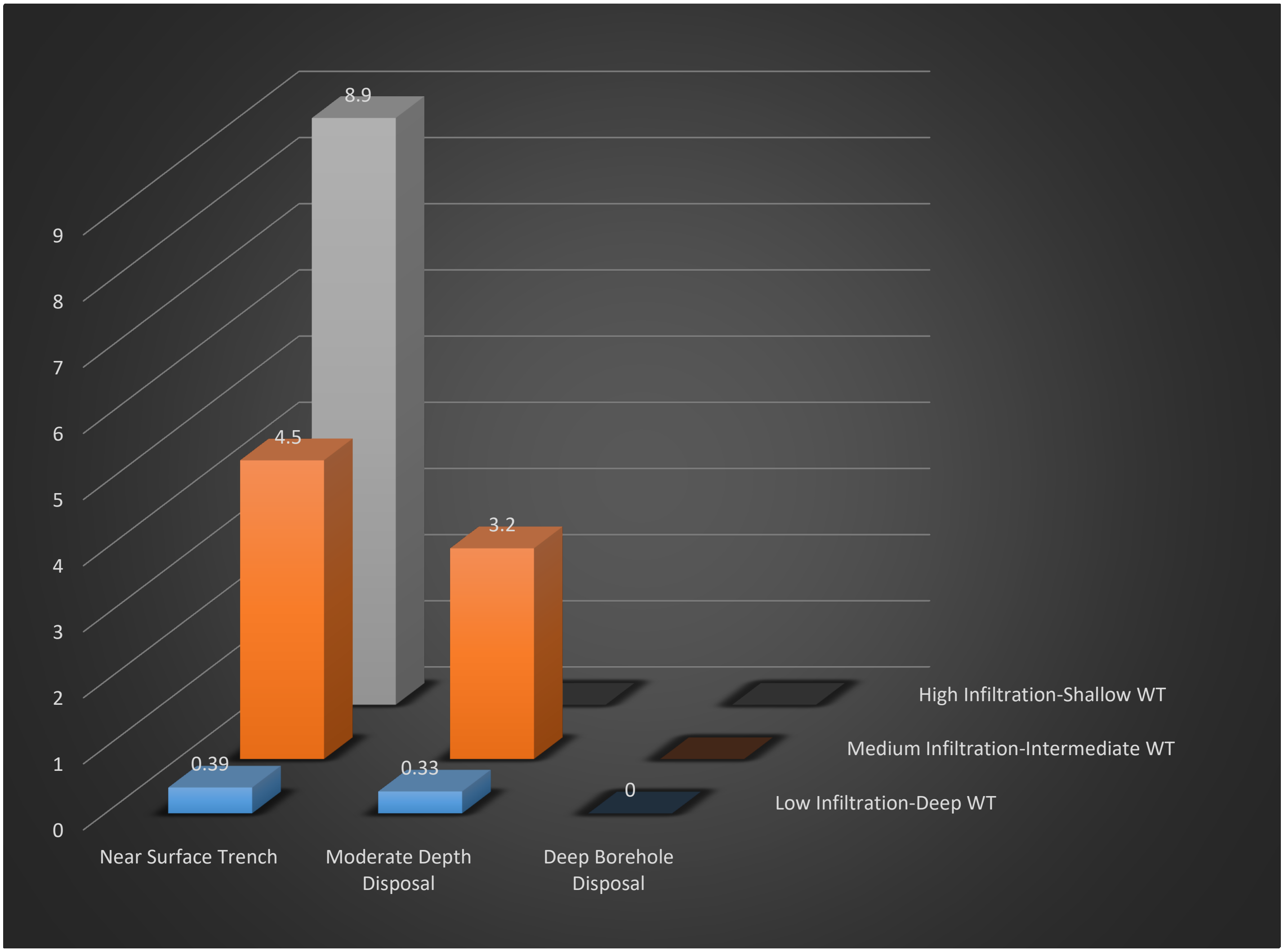

Figure A–7. Peak expected dose [mrem/yr] before 10,000 years versus disposal cell configuration {near surface trench [5m-thick], moderate depth disposal unit [10m-thick], deep borehole disposal [100m-thick]} and disposal environment (low infiltration-deep WT [mean annual infiltration (MAI) 0.1 to 10mm/yr] with deep water table (WT) [135 to 200 m], medium infiltration-intermediate depth WT [MAI 10 to 50 mm/yr] with intermediate depth water table [50 to 135 m], high infiltration-shallow WT [MAI 50 to 200 mm/yr] with shallow water table [20 to 50 m] for Group 2a GTCC remote-handled waste from the production of Mo-99 at the MIPS facility (Waste Stream 8). Yellow shaded columns without number labels are for configuration-environment combinations that were not evaluated because they would require disposal in the saturated zone. For larger doses, the primary contributor is Pu-239. For smaller doses, the primary dose contributor is C-14.

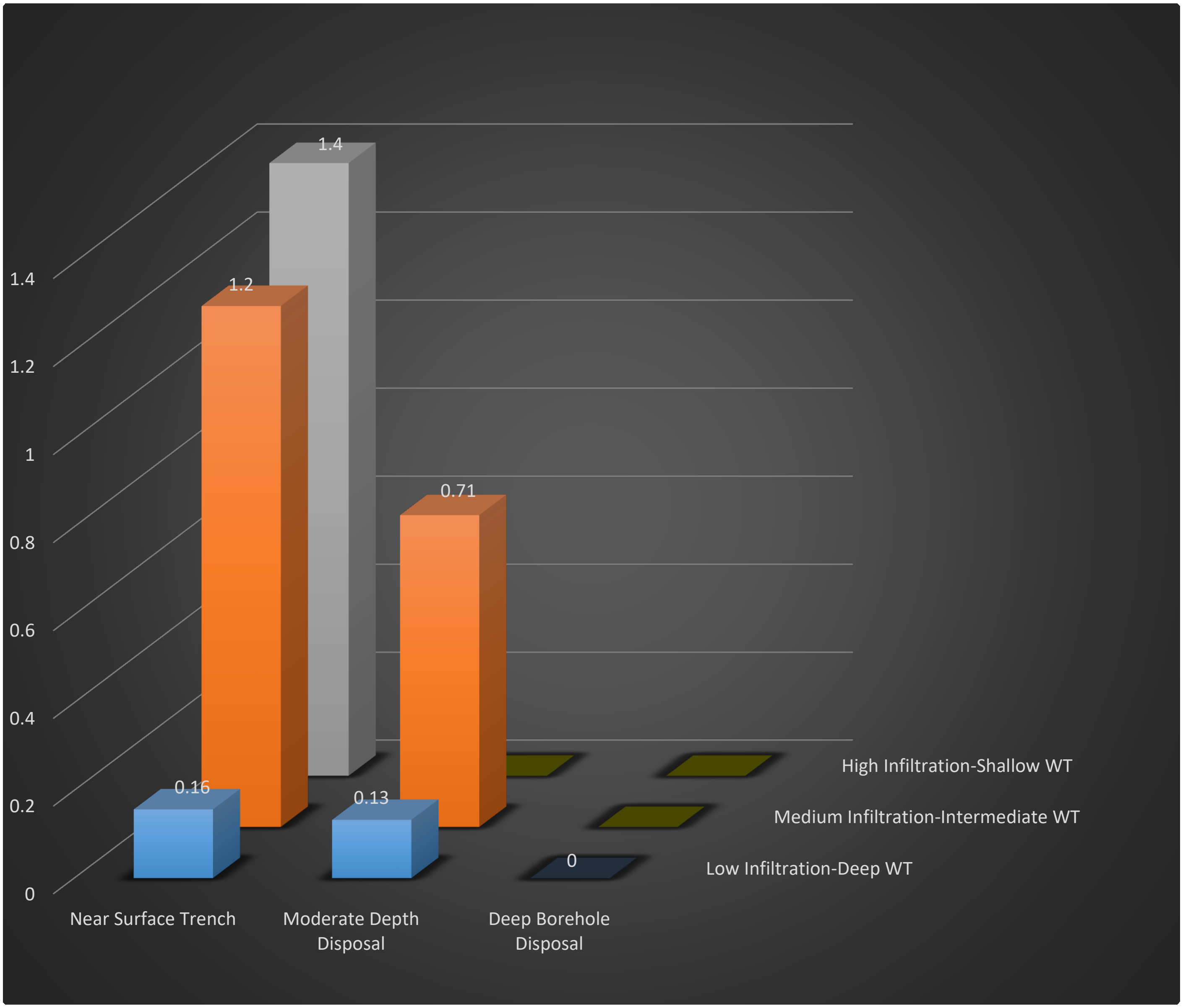

Figure A–8. Peak expected dose [mrem/yr] before 10,000 years versus disposal cell configuration {near surface trench [5m-thick], moderate depth disposal unit [10m-thick], deep borehole disposal [100m-thick]} and disposal environment (low infiltration-deep WT [mean annual infiltration (MAI) 0.1 to 10mm/yr] with deep water table (WT) [135 to 200 m], medium infiltration-intermediate depth WT [MAI 10 to 50 mm/yr] with intermediate depth water table [50 to 135 m], high infiltration-shallow WT [MAI 50 to 200 mm/yr] with shallow water table [20 to 50 m]) for Group 2a GTCC remote-handled activated metals from the NRC-regulated disposal facility at West Valley (Waste Stream 9). Yellow shaded columns without number labels are for configuration-environment combinations that were not evaluated because they would require disposal in the saturated zone. For larger doses, the primary dose contributors are Pu-239 and Pu-240. For smaller doses, the primary dose contributor is C-14.

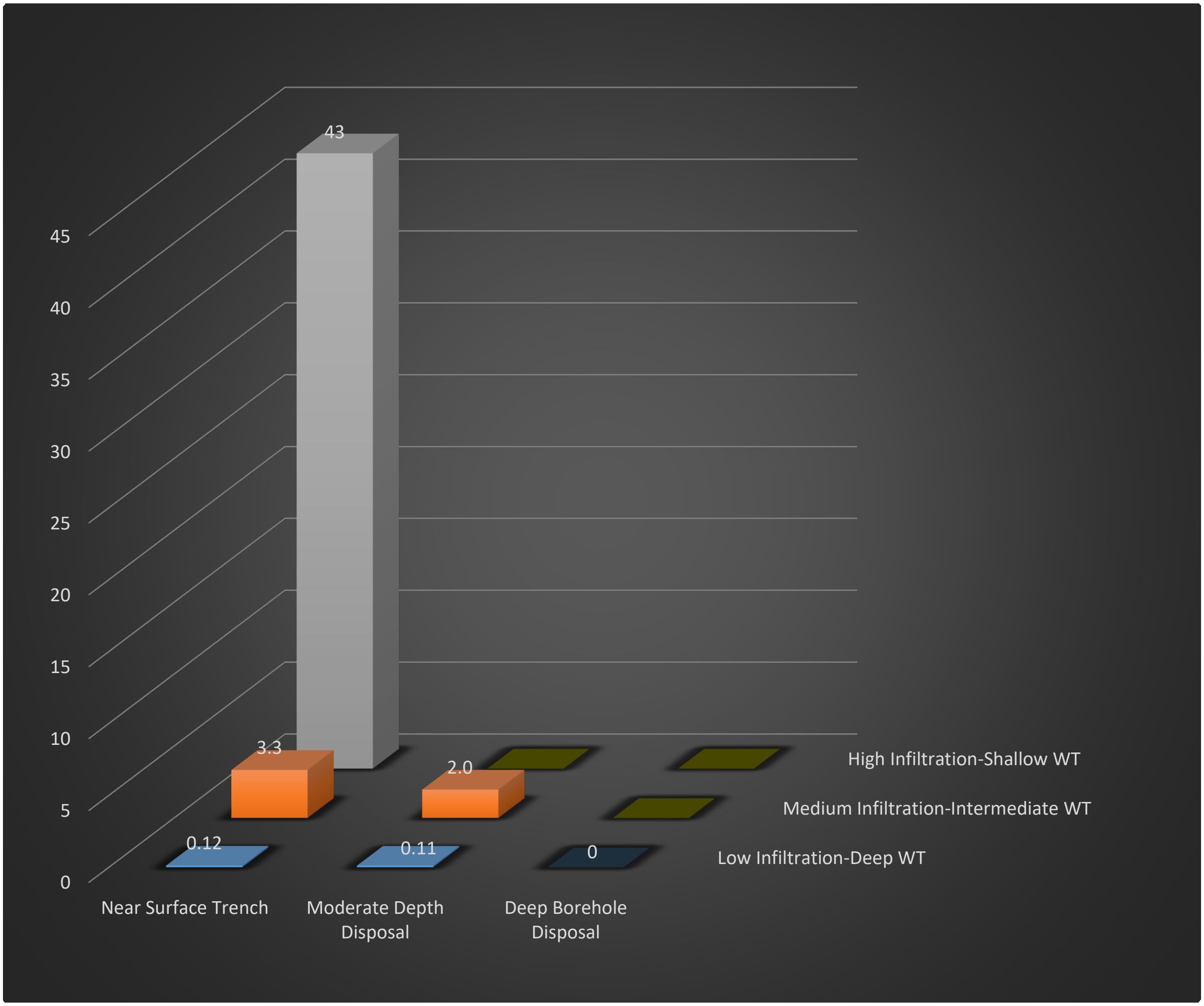

Figure A–9. Peak expected dose [mrem/yr] before 10,000 years versus disposal cell configuration {near surface trench [5m-thick], moderate depth disposal unit [10m-thick], deep borehole disposal [100m-thick]} and disposal environment (low infiltration-deep WT [mean annual infiltration (MAI) 0.1 to 10mm/yr] with deep water table (WT) [135 to 200 m], medium infiltration-intermediate depth WT [MAI 10 to 50 mm/yr] with intermediate depth water table [50 to 135 m], high infiltration-shallow WT [MAI 50 to 200 mm/yr] with shallow water table [20 to 50 m]) for Group 2a GTCC remote-handled Other waste from the NRC-regulated disposal facility at West Valley (Waste Stream 10). Yellow shaded columns without number labels are for configuration-environment combinations that were not evaluated because they would require disposal in the saturated zone. For larger doses, the primary contributors are Pu-239, Pu-240, and U-233. For smaller doses, the primary contributors are Pa-231 and I-129.

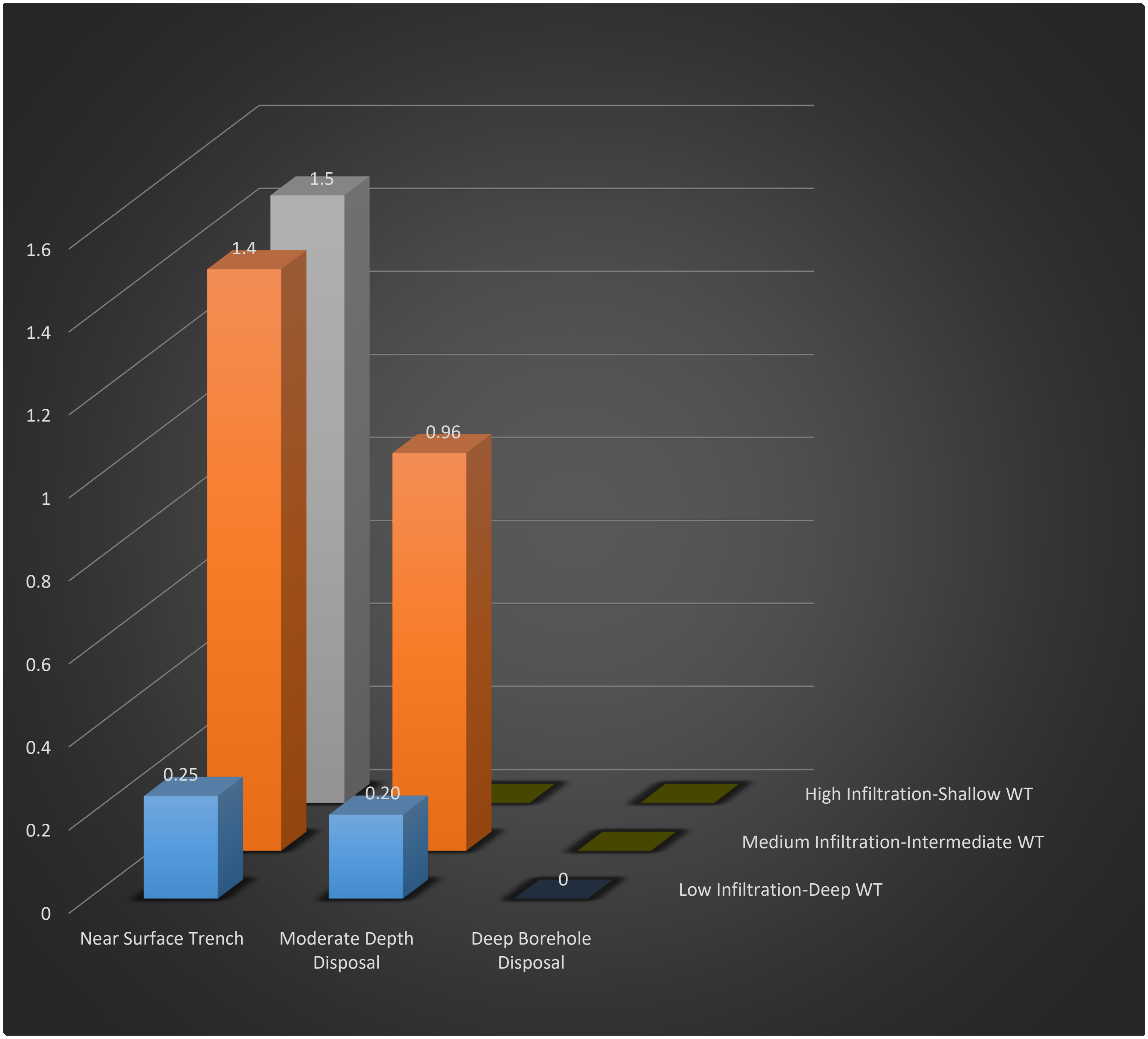

Figure A–10. Peak expected dose [mrem/yr] before 10,000 years versus disposal cell configuration {near surface trench [5m-thick], moderate depth disposal unit [10m-thick], deep borehole disposal [100m-thick]} and disposal environment (low infiltration-deep WT [mean annual infiltration (MAI) 0.1 to 10mm/yr] with deep water table (WT) [135 to 200 m], medium infiltration-intermediate depth WT [MAI 10 to 50 mm/yr] with intermediate depth water table [50 to 135 m], high infiltration-shallow WT [MAI 50 to 200 mm/yr] with shallow water table [20 to 50 m]) for Group 2b GTCC remote-handled activated metals from the New York State-regulated disposal facility at West Valley (Waste Stream 11). Yellow shaded columns without number labels are for configuration-environment combinations that were not evaluated because they would require disposal in the saturated zone. The primary dose contributor is I-129.

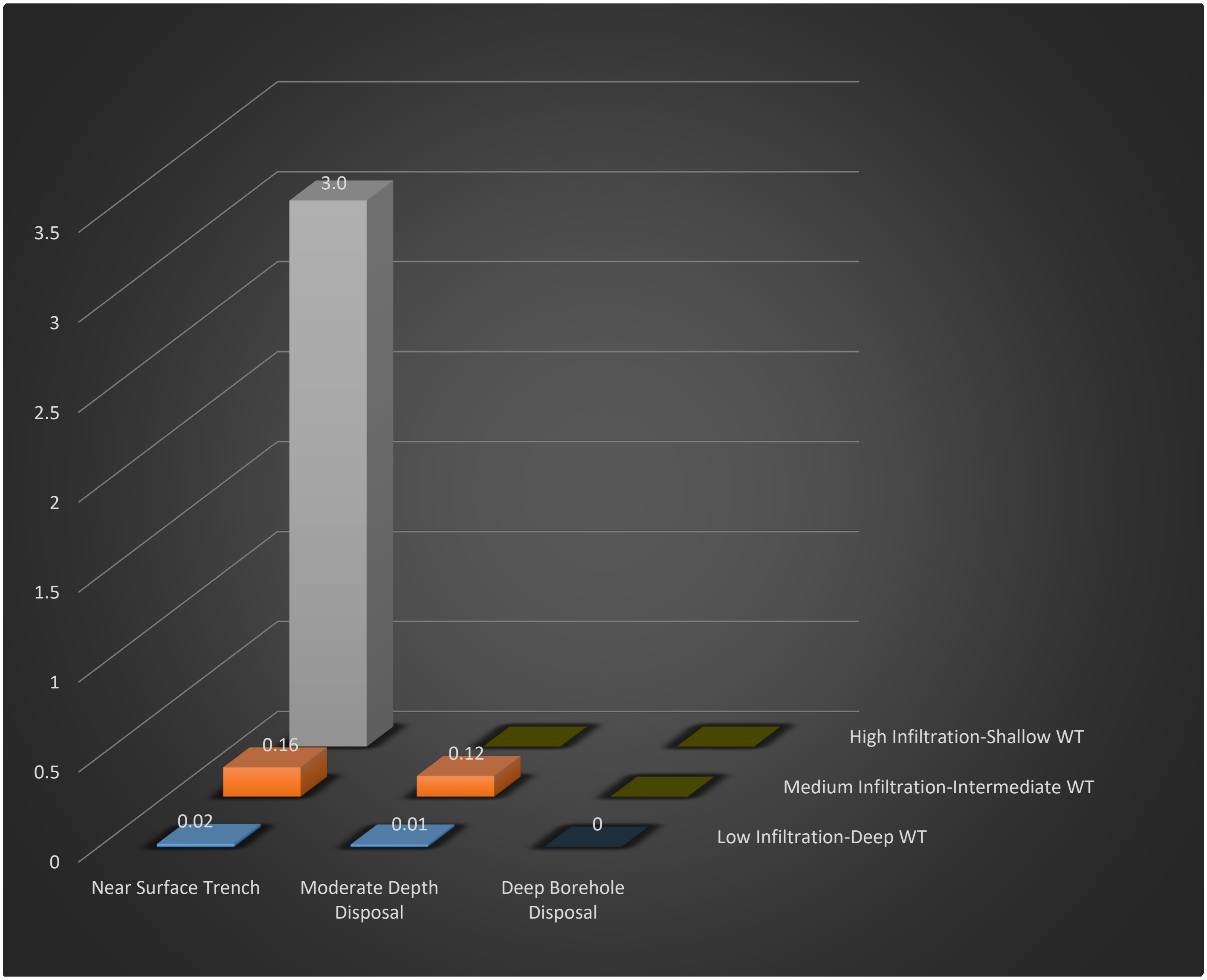

Figure A–11. Peak expected dose [mrem/yr] before 10,000 years versus disposal cell configuration {near surface trench [5m-thick], moderate depth disposal unit [10m-thick], deep borehole disposal [100m-thick]} and disposal environment (low infiltration-deep WT [mean annual infiltration (MAI) 0.1 to 10mm/yr] with deep water table (WT) [135 to 200 m], medium infiltration-intermediate depth WT [MAI 10 to 50 mm/yr] with intermediate depth water table [50 to 135 m], high infiltration-shallow WT [MAI 50 to 200 mm/yr] with shallow water table [20 to 50 m]) for Group 2b GTCC Contact-handled other waste from the New York State-regulated disposal facility at West Valley (Waste Stream 12). Yellow shaded columns without number labels are for configuration-environment combinations that were not evaluated because they would require disposal in the saturated zone. For larger doses, the primary dose contributors are Pu-239 and Pu-240. For smaller doses, the primary contributors are C-14 and I-129.

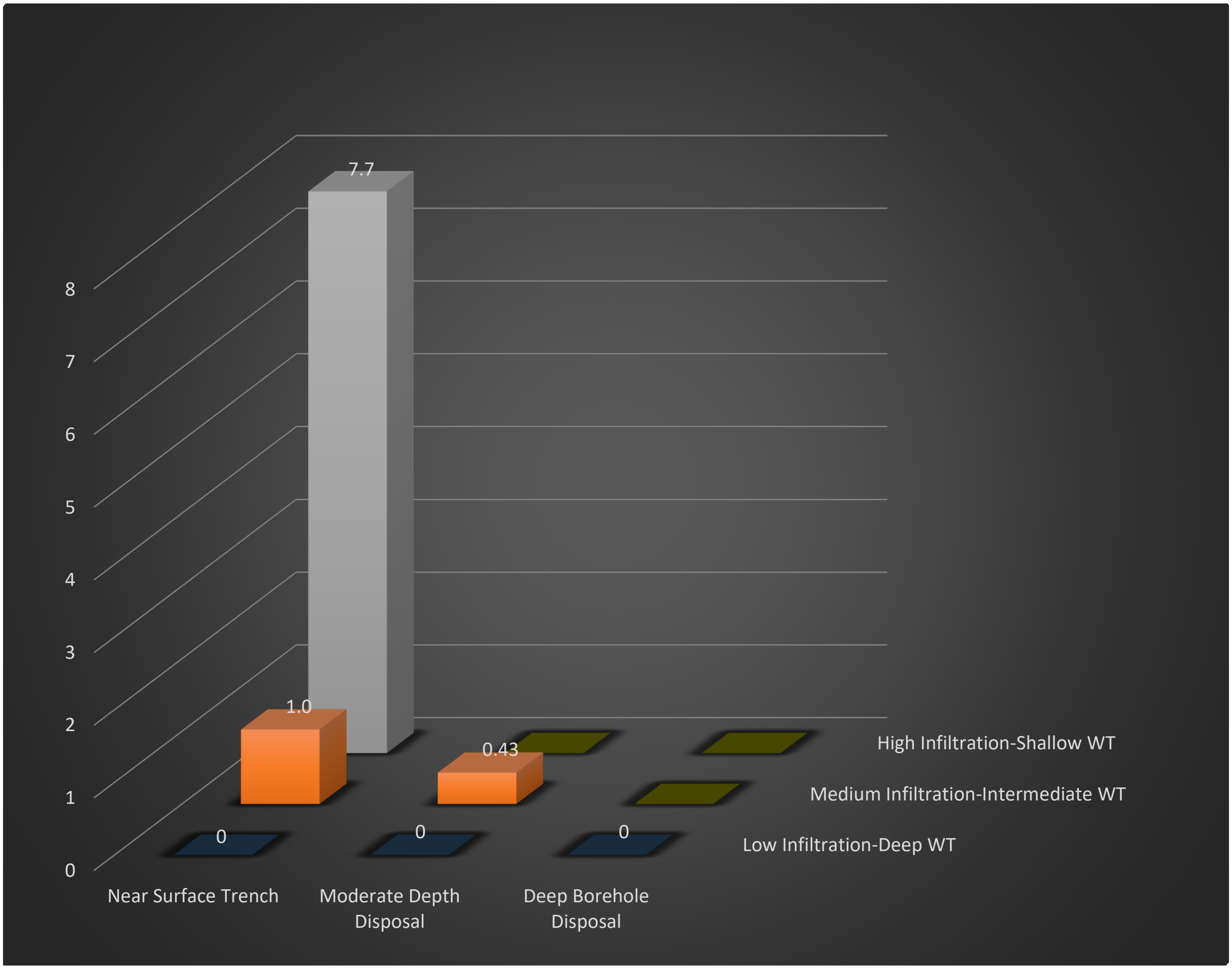

Figure A–12. Peak expected dose [mrem/yr] before 10,000 years versus disposal cell configuration {Near Surface Trench [5m-thick], moderate depth disposal unit [10m-thick], deep borehole disposal [100m-thick]} and disposal environment (low infiltration-deep WT [mean annual infiltration (MAI) 0.1 to 10mm/yr] with deep water table (WT) [135 to 200 m], medium infiltration-intermediate depth WT [MAI 10 to 50 mm/yr] with intermediate depth water table [50 to 135 m], high infiltration-shallow WT [MAI 50 to 200 mm/yr] with shallow water table [20 to 50 m]) for Group 2b GTCC contact-handled special nuclear auxiliary power other waste from the New York State-regulated disposal facility at West Valley (Waste Stream 13). Yellow shaded columns without number labels are for configuration-environment combinations that were not evaluated because they would require disposal in the saturated zone. For larger doses, the primary dose contributors are Pu-239, Pu-240, and U-234. For smaller doses, the primary dose contributor is Pa-231.

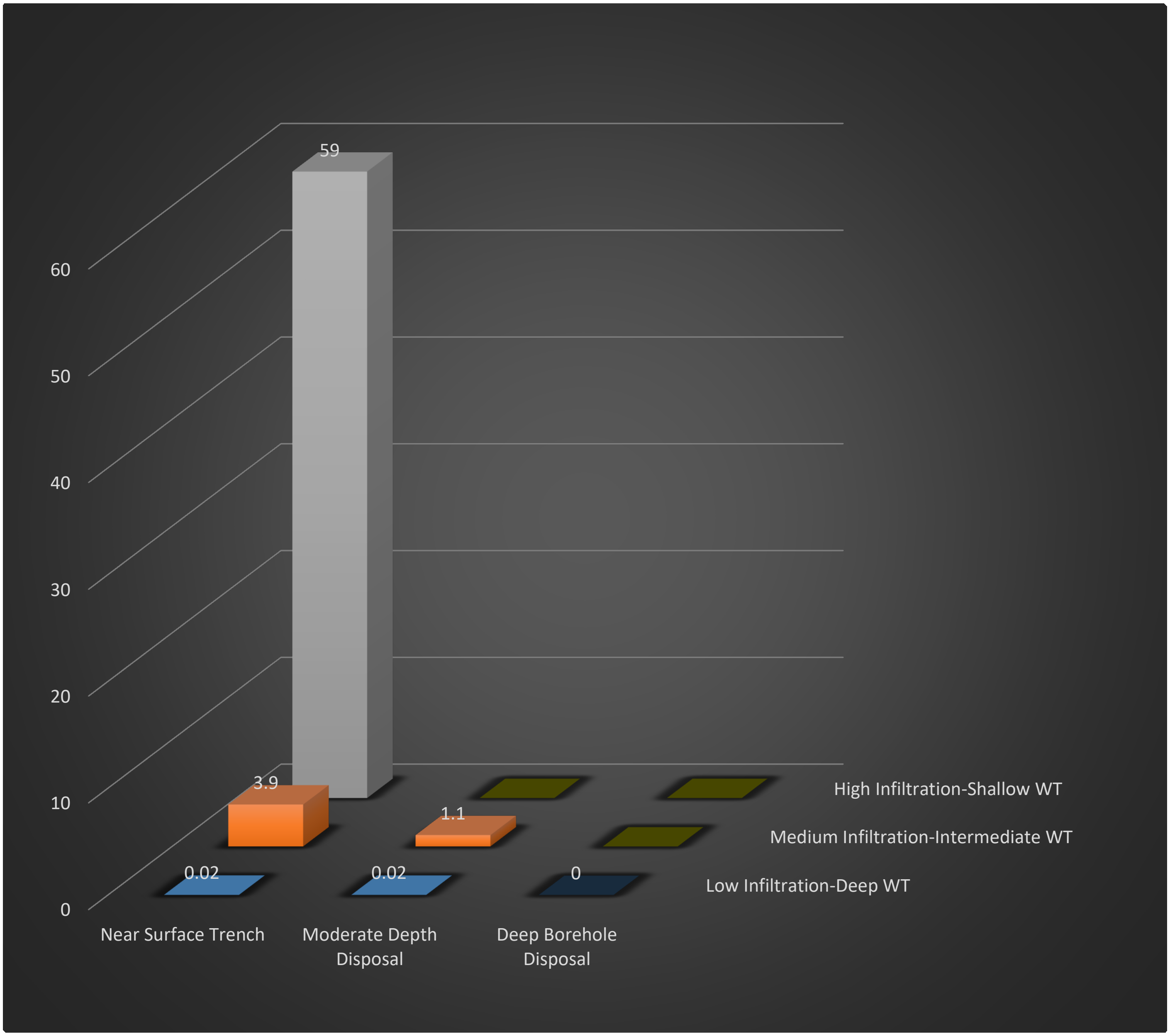

Figure A–13. Peak expected dose [mrem/yr] before 10,000 years versus disposal cell configuration {near surface trench [5m-thick], moderate depth disposal unit [10m-thick], Deep borehole disposal [100m-thick]) and disposal environment (low infiltration-deep WT [mean annual infiltration (MAI) 0.1 to 10mm/yr] with deep water table (WT) [135 to 200 m], medium infiltration-intermediate depth WT [MAI 10 to 50 mm/yr] with intermediate depth water table [50 to 135 m], High Infiltration-Shallow WT [MAI 50 to 200 mm/yr] with shallow water table [20 to 50 m]) for Group 2b GTCC Contact-Handled Other Waste from Decommissioning West Valley (Waste Stream 14). Yellow shaded columns without number labels are for configuration-environment combinations that were not evaluated because they would require disposal in the saturated zone. For larger doses, the primary dose contributors are Pu-239, Pu-240, and U-234. For smaller doses, the primary dose contributors are C-14 and Pa-231.

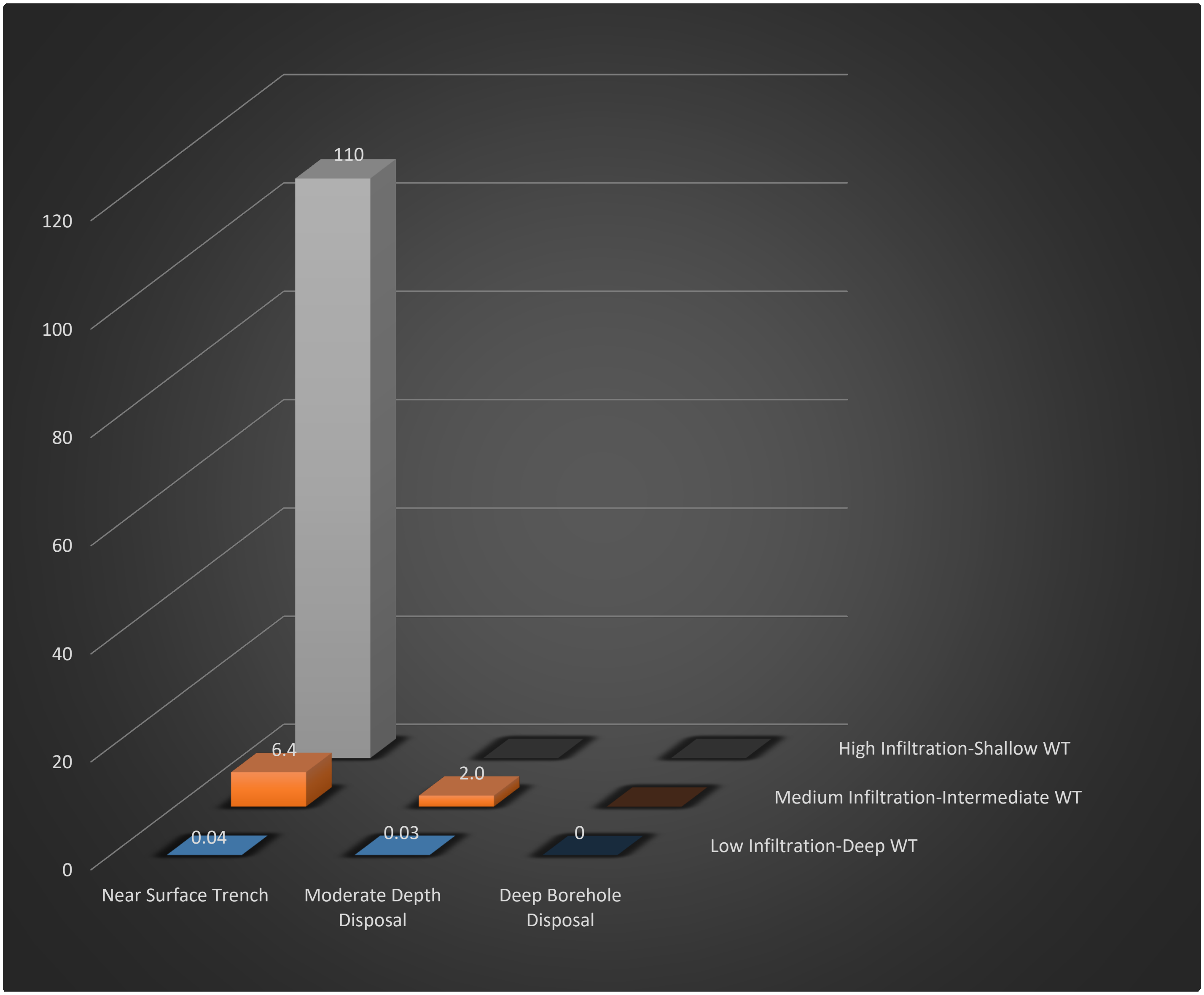

Figure A–14. Peak expected dose [mrem/yr] before 10,000 years versus disposal cell configuration {near surface trench [5m-thick], moderate depth disposal unit [10m-thick], deep borehole disposal [100m-thick]} and disposal environment (low infiltration-deep WT [mean annual infiltration (MAI) 0.1 to 10mm/yr] with deep water table (WT) [135 to 200 m], medium infiltration-intermediate depth WT [MAI 10 to 50 mm/yr] with intermediate depth water table [50 to 135 m], high infiltration-shallow WT [MAI 50 to 200 mm/yr] with shallow water table [20 to 50 m] for Group 2b GTCC remote-handled other waste from decommissioning West Valley (Waste Stream 15). Yellow shaded columns without number labels are for configuration-environment combinations that were not evaluated because they would require disposal in the saturated zone. For larger doses, the primary dose contributors are Pu-239, Pu-240, and U-234. For smaller doses, the primary dose contributors are C-14 and Pa-231.

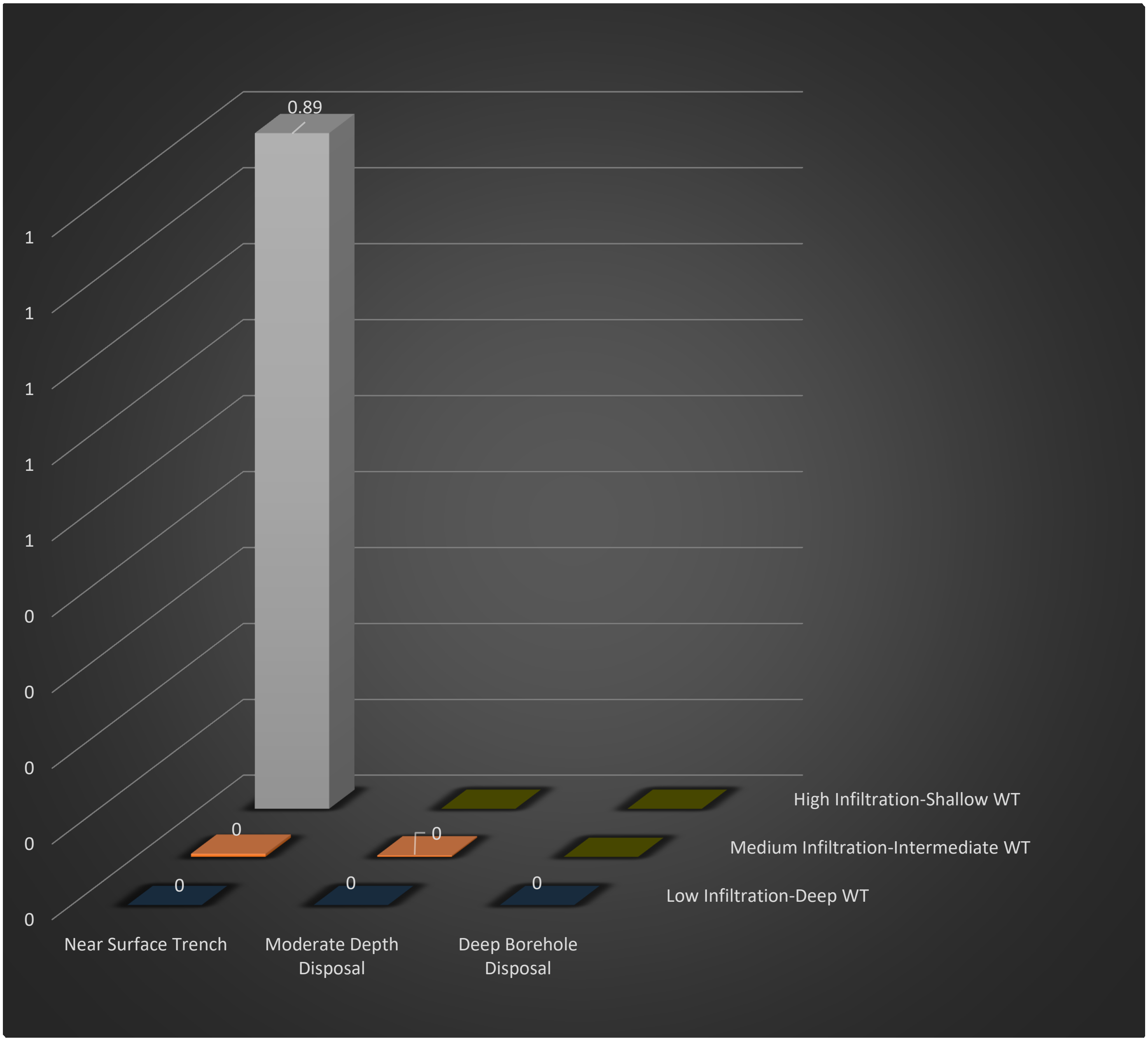

Figure A–15. Peak expected dose [mrem/yr] before 10,000 years versus disposal cell configuration {near surface trench [5m-thick], moderate depth disposal unit [10m-thick], deep borehole disposal [100m-thick]) and disposal environment (low infiltration-deep WT [mean annual infiltration (MAI) 0.1 to 10mm/yr] with deep water table (WT) [135 to 200 m], medium infiltration-intermediate depth WT [MAI 10 to 50 mm/yr] with intermediate depth water table [50 to 135 m], high infiltration-shallow WT [MAI 50 to 200 mm/yr] with shallow water table [20 to 50 m]) for Group 2b GTCC-like contact-handled other waste from Pu-238 production (Waste Stream 16). Yellow shaded columns without number labels are for configuration-environment combinations that were not evaluated because they would require disposal in the saturated zone. For larger doses, the primary dose contributors are Pu-239, Pu-240, and Np-237. For smaller doses, the primary dose contributor is Pa-231.

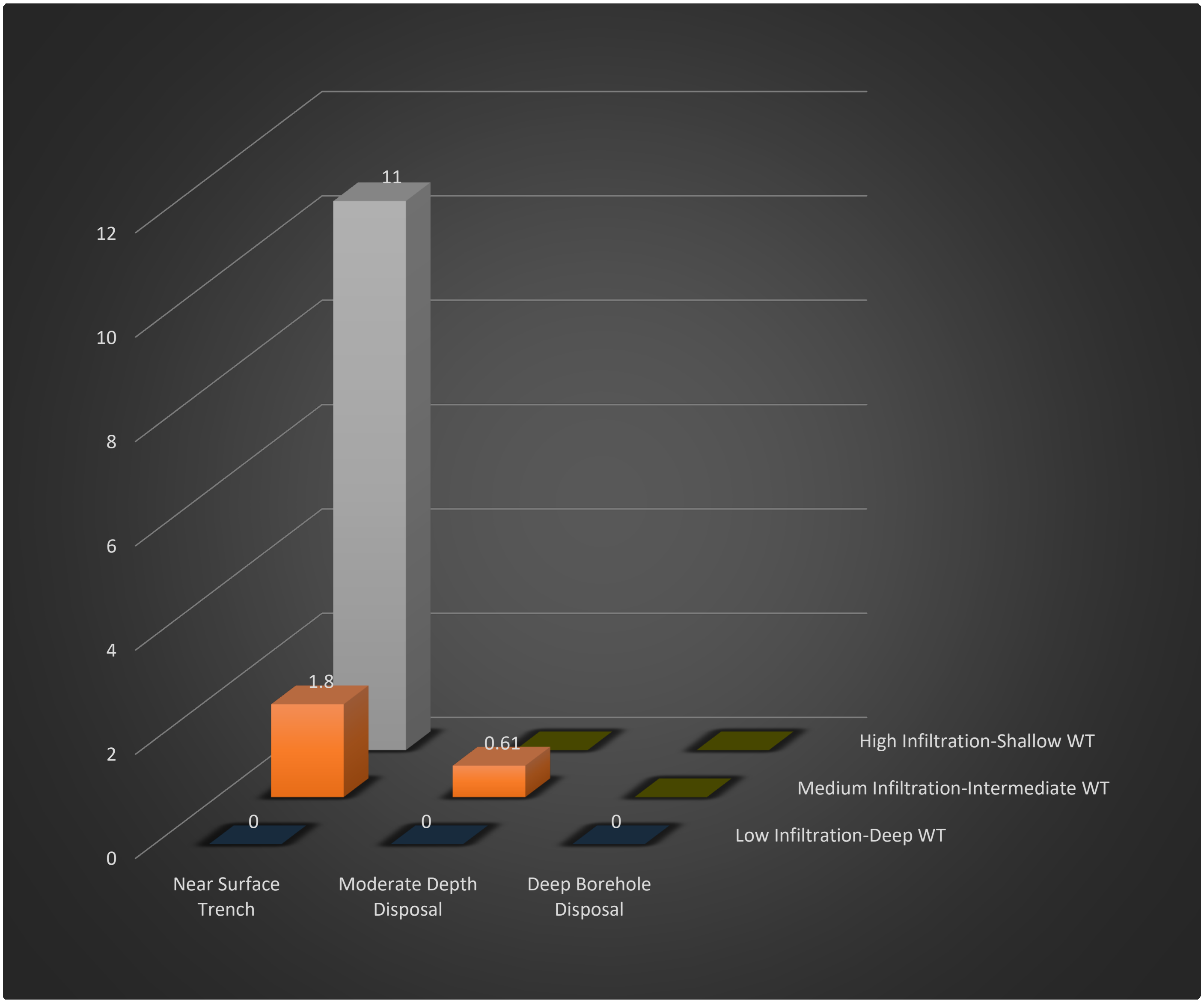

Figure A–16. Peak expected dose [mrem/yr] before 10,000 years versus disposal cell configuration {near surface trench [5m-thick], moderate depth disposal unit [10m-thick], deep borehole disposal [100m-thick]} and disposal environment (low infiltration-deep WT [mean annual infiltration (MAI) 0.1 to 10mm/yr] with deep water table (WT) [135 to 200 m], medium infiltration-intermediate depth WT [MAI 10 to 50 mm/yr] with intermediate depth water table [50 to 135 m], high infiltration-shallow WT [MAI 50 to 200 mm/yr] with shallow water table [20 to 50 m] for Group 2b GTCC-like remote-handled other waste from Pu-238 Production (Waste Stream 17). Yellow shaded columns without number labels are for configuration-environment combinations that were not evaluated because they would require disposal in the saturated zone. The primary dose contributor is Np-237.

APPENDIX B

EXPECTED DOSE VERSUS TIME OVER 100,000 YEARS

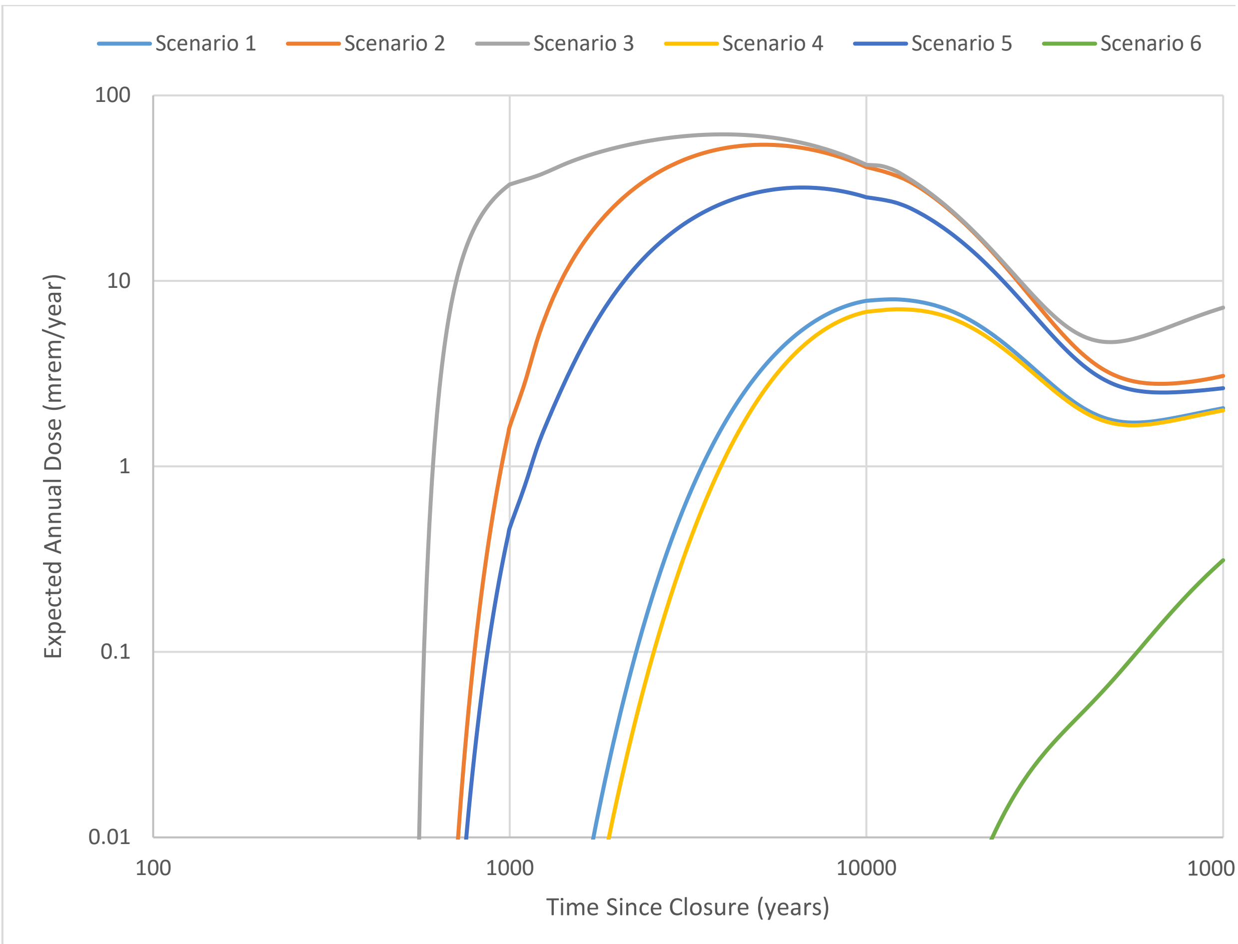

Figure B–1. Expected annual dose [mrem/yr] versus time since closure [years] for the six scenarios defined in Table 9 for Group 1 GTCC remote-handled activated metals from commercial reactors (Waste Stream 1).

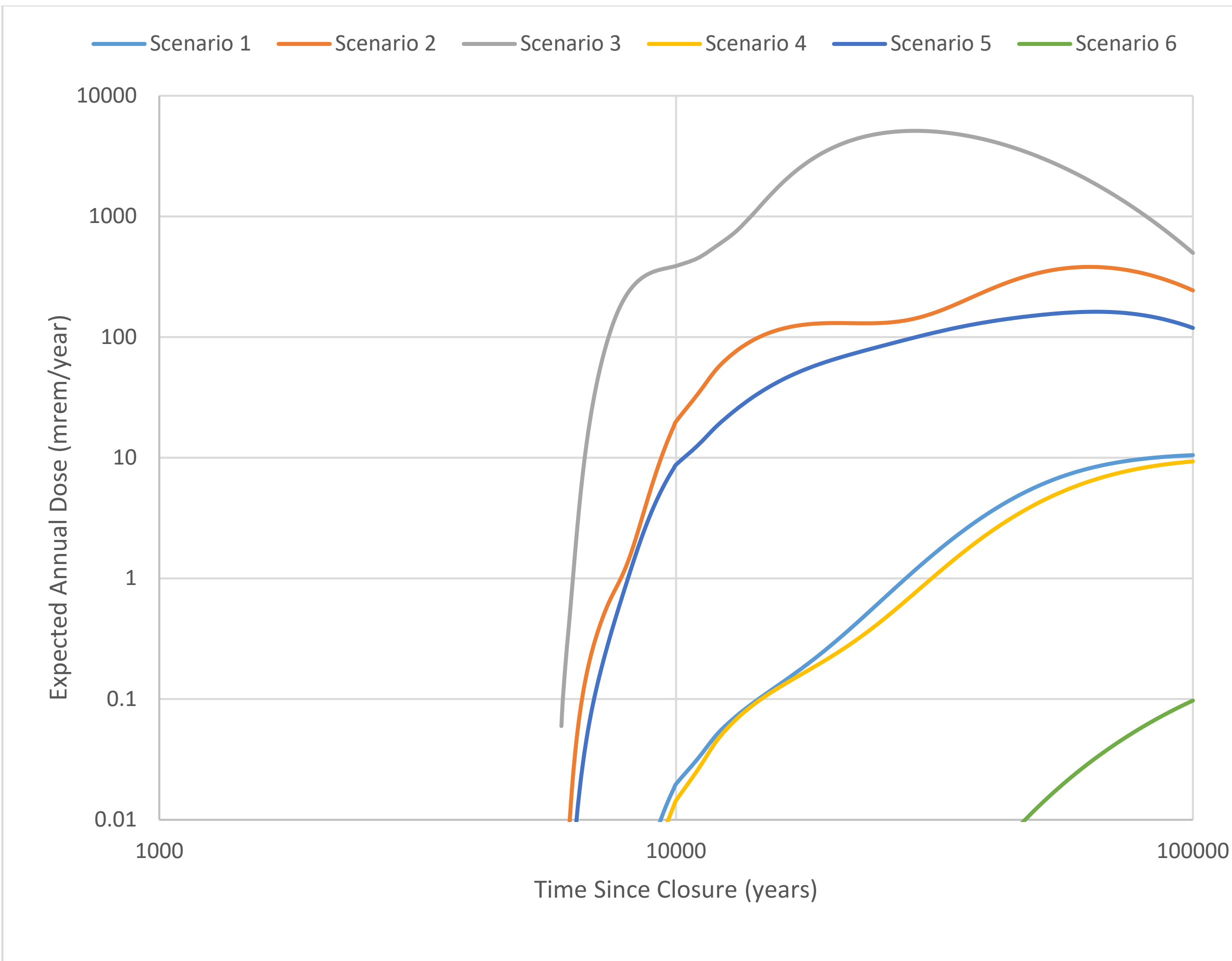

Figure B–2. Expected annual dose [mrem/yr] versus time since closure [years] for the six scenarios defined in Table 9 for Group 1 GTCC contact-handled small sealed neutron sources (Waste Stream 3).

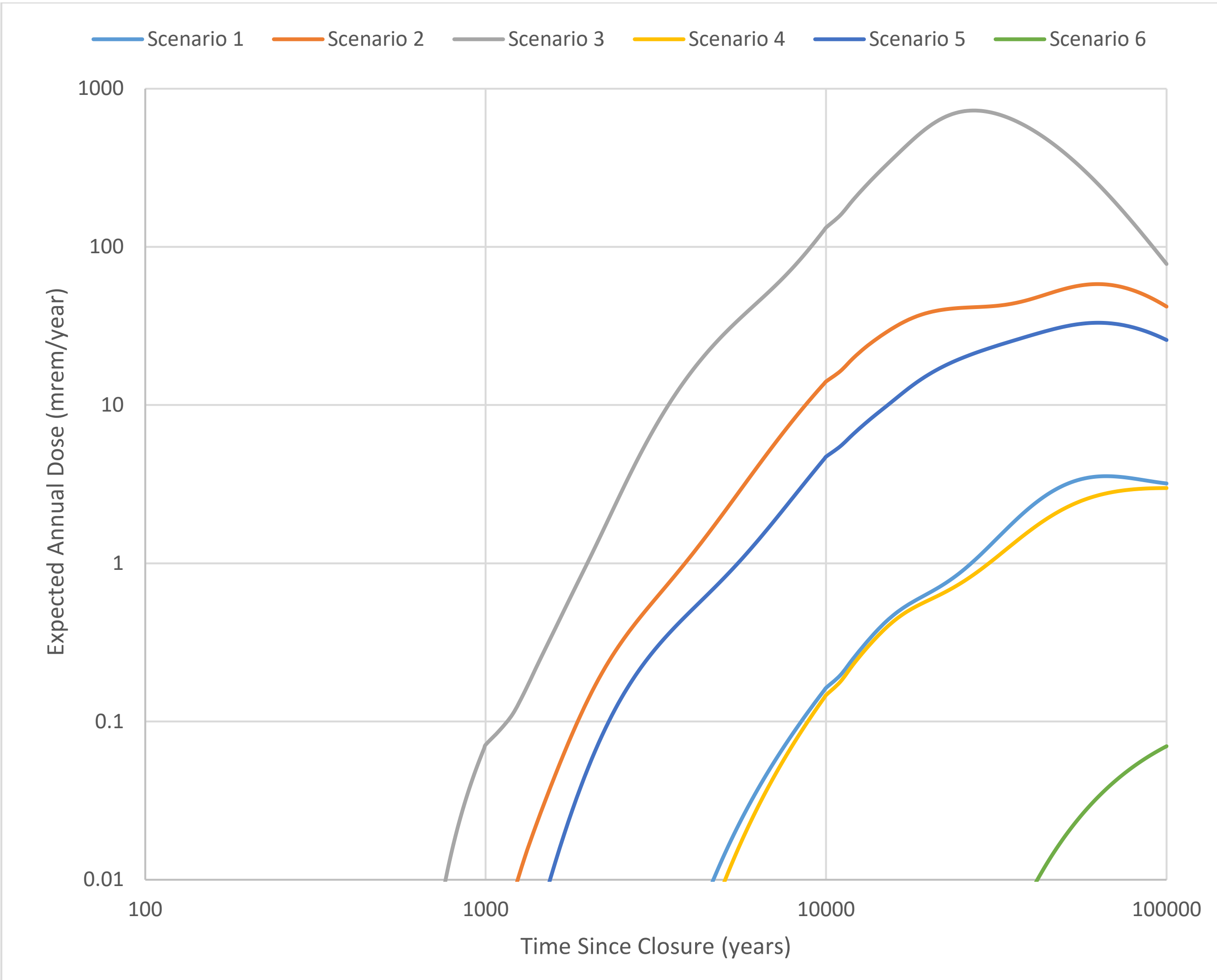

Figure B–3. Expected annual dose [mrem/yr] versus time since closure [years] for the six scenarios defined in Table 9 for Group 1 GTCC-like contact-handled other waste from Decontaminating West Valley (Waste Stream 4).

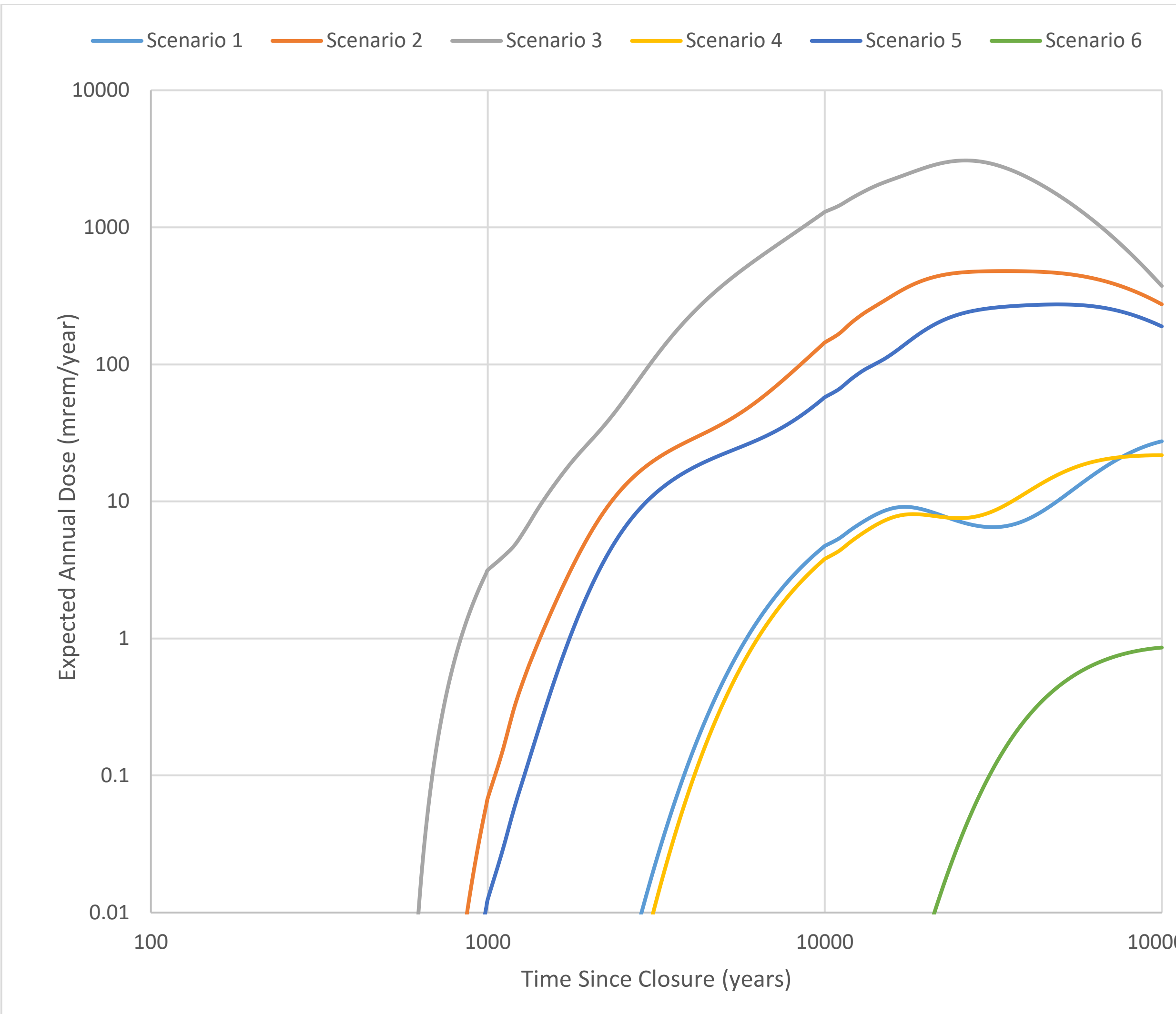

Figure B–4. Expected annual dose [mrem/yr] versus time since closure [years] for the six scenarios defined in Table 9 for Group 1 GTCC-Like West Valley Remote-Handled Other Waste from Decontaminating (Waste Stream 5).

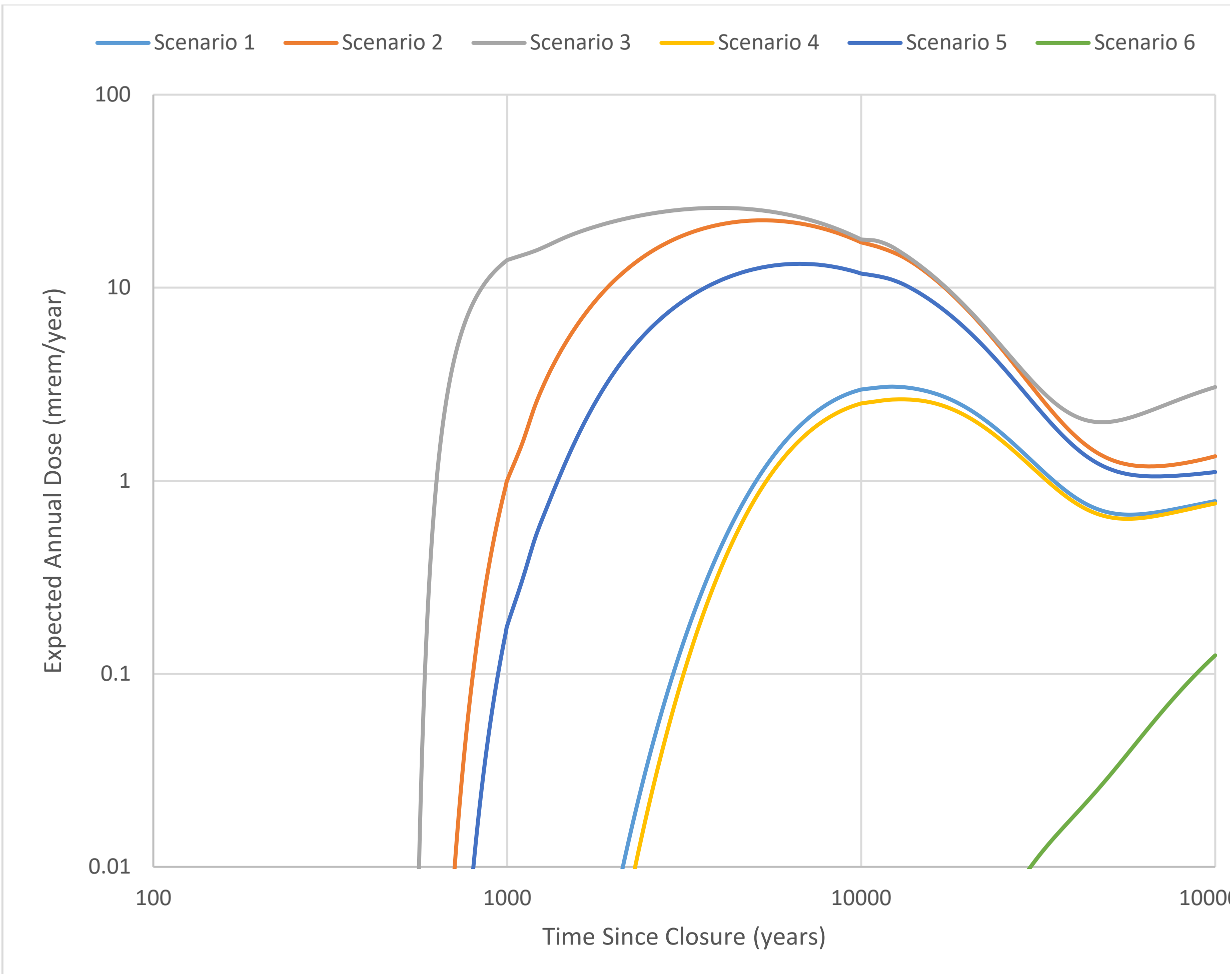

Figure B–5. Expected annual dose [mrem/yr] versus time since closure [years] for the six scenarios defined in Table 9 Group 2a GTCC Remote-Handled Activated Metals from Commercial Reactors (Waste Stream 6).

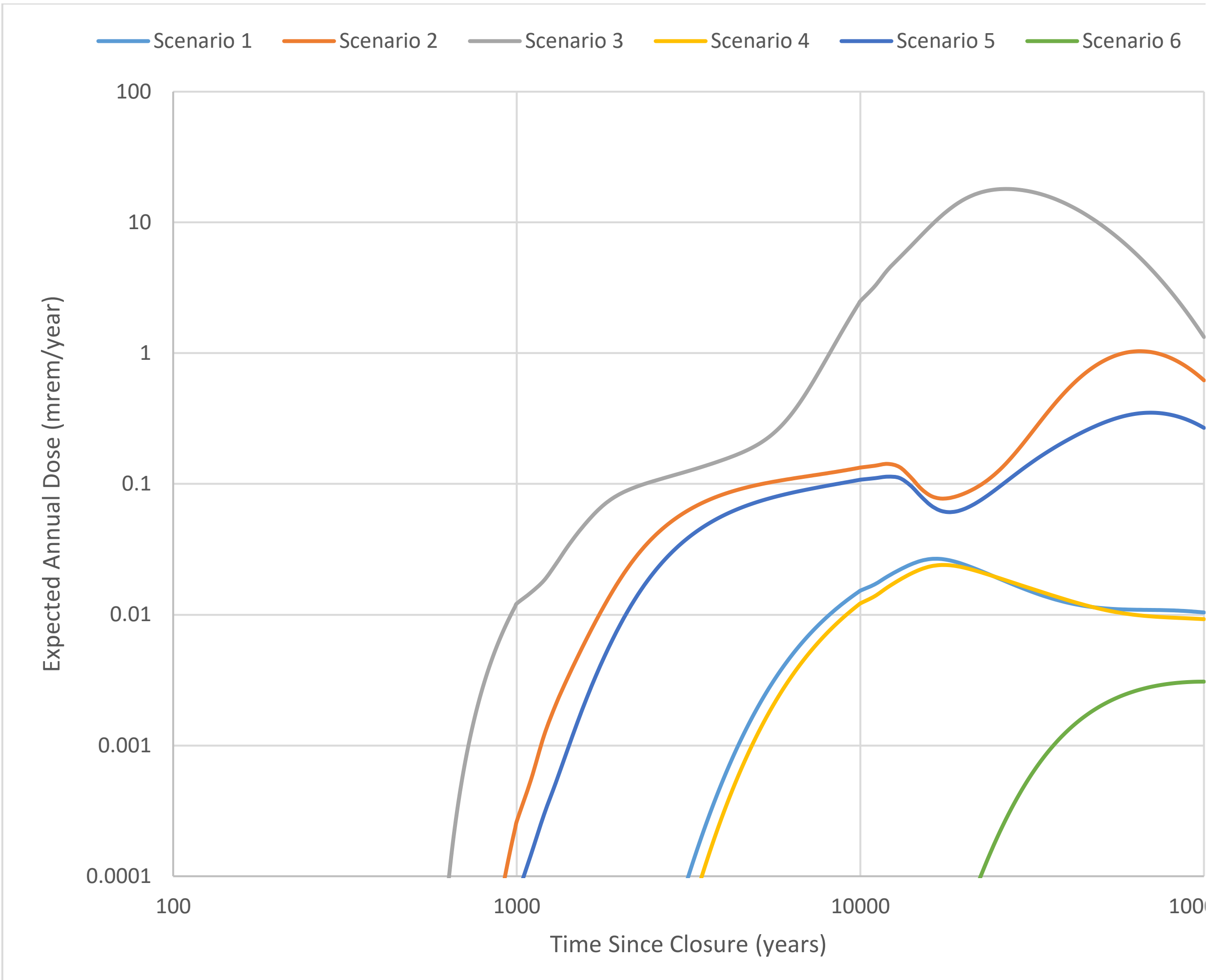

Figure B–6. Expected annual dose [mrem/yr] versus time since closure [years] for the six scenarios defined in Table 9 for Group 2a GTCC Remote-Handled Waste from the production of Mo-99 at the MURR facility (Waste Stream 7).

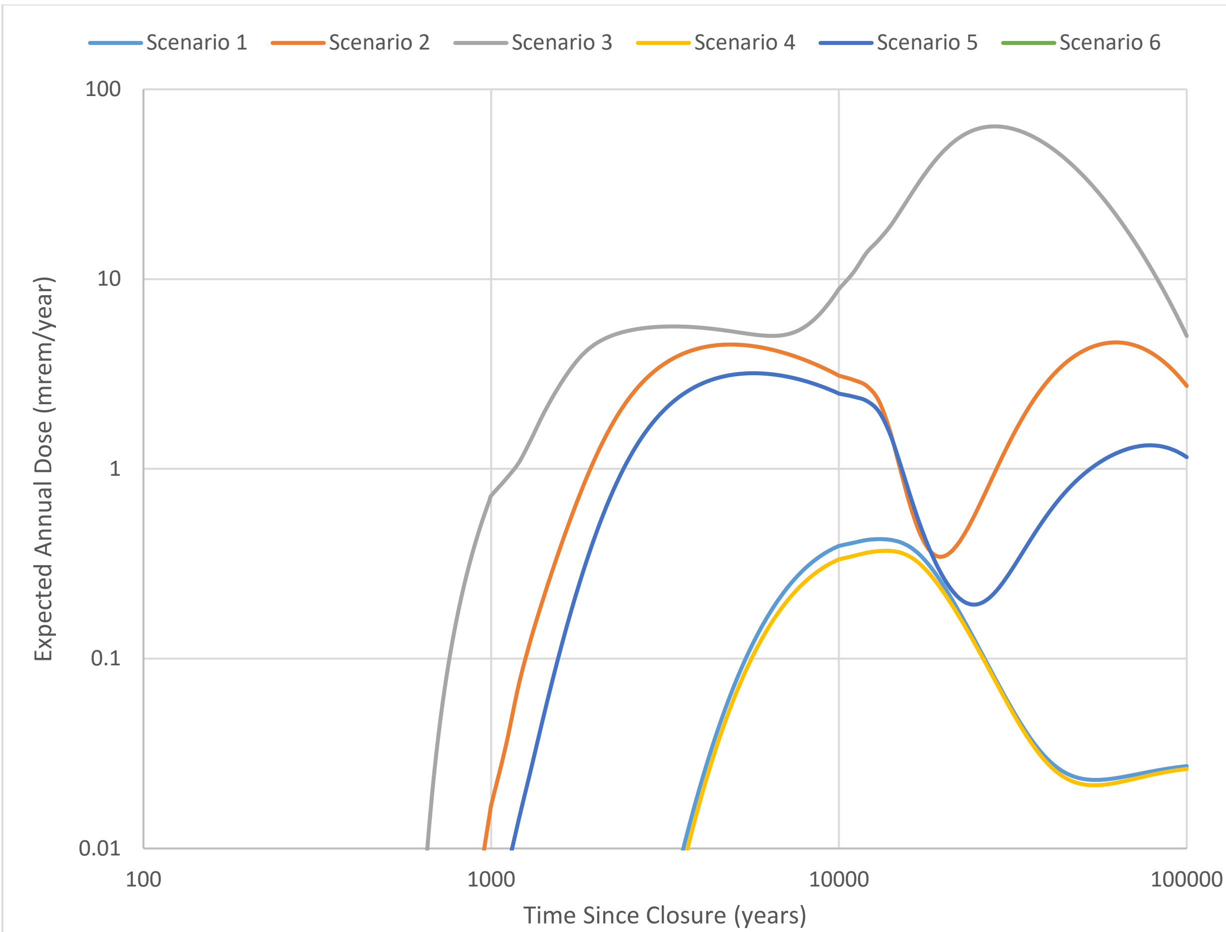

Figure B–7. Expected annual dose [mrem/yr] versus time since closure [years] for the six scenarios defined in Table 9 for Group 2a GTCC Remote-Handled Waste from the production of Mo-99 at the MIPS facility (Waste Stream 8).

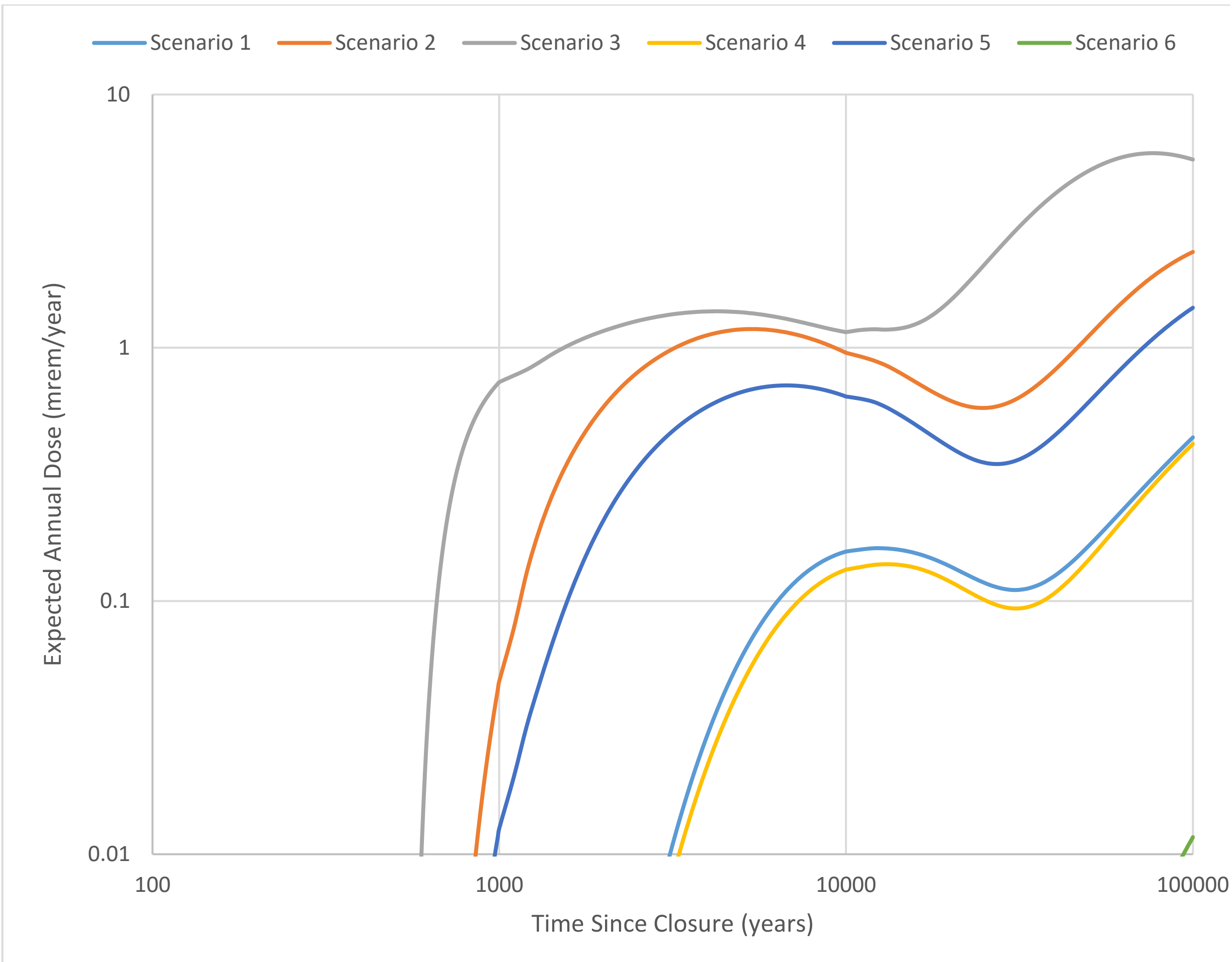

Figure B–8. Expected annual dose [mrem/yr] versus time since closure [years] for the six scenarios defined in Table 9 for Group 2a GTCC Remote-Handled Activated Metals from the NRC-regulated disposal facility at West Valley (Waste Stream 9).

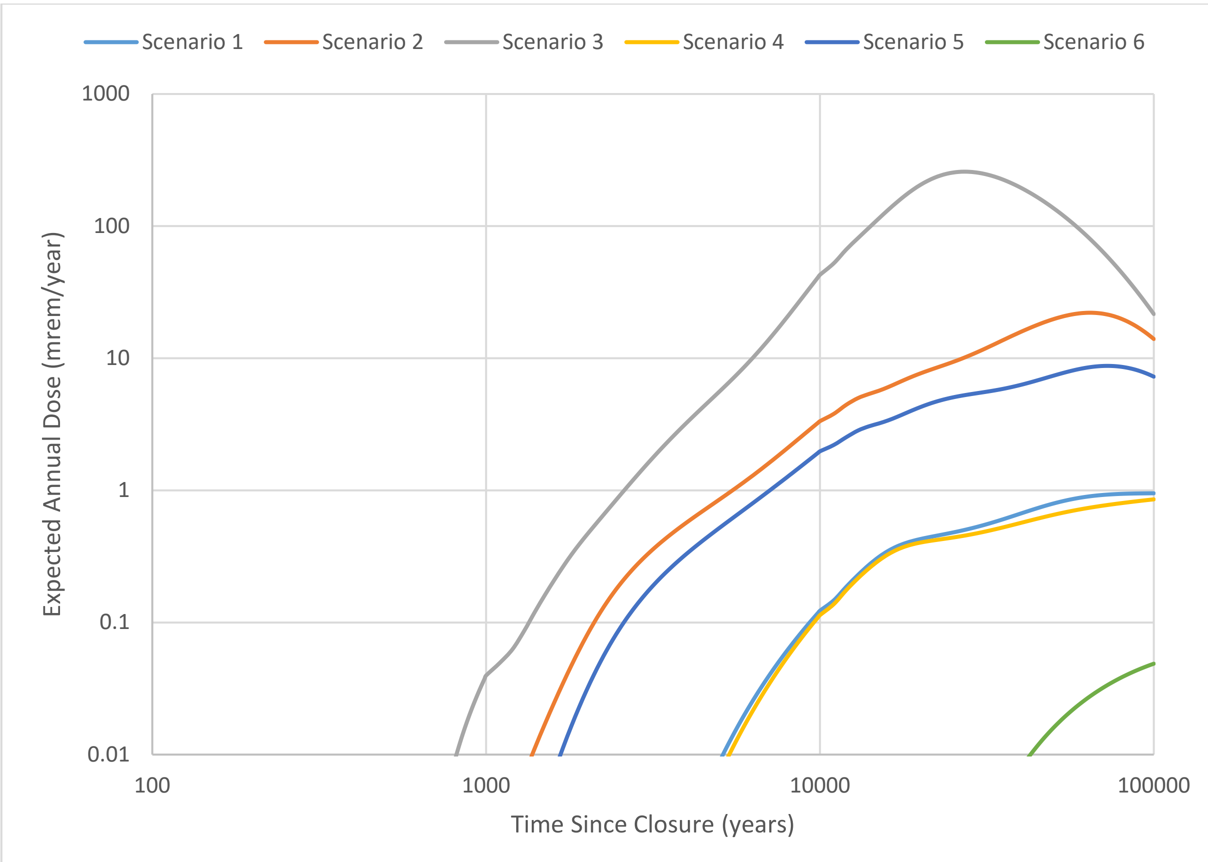

Figure B–9. Expected annual dose [mrem/yr] versus time since closure [years] for the six scenarios defined in Table 9 for Group 2a GTCC Remote-Handled Other Waste from the NRC-regulated disposal facility at West Valley (Waste Stream 10).

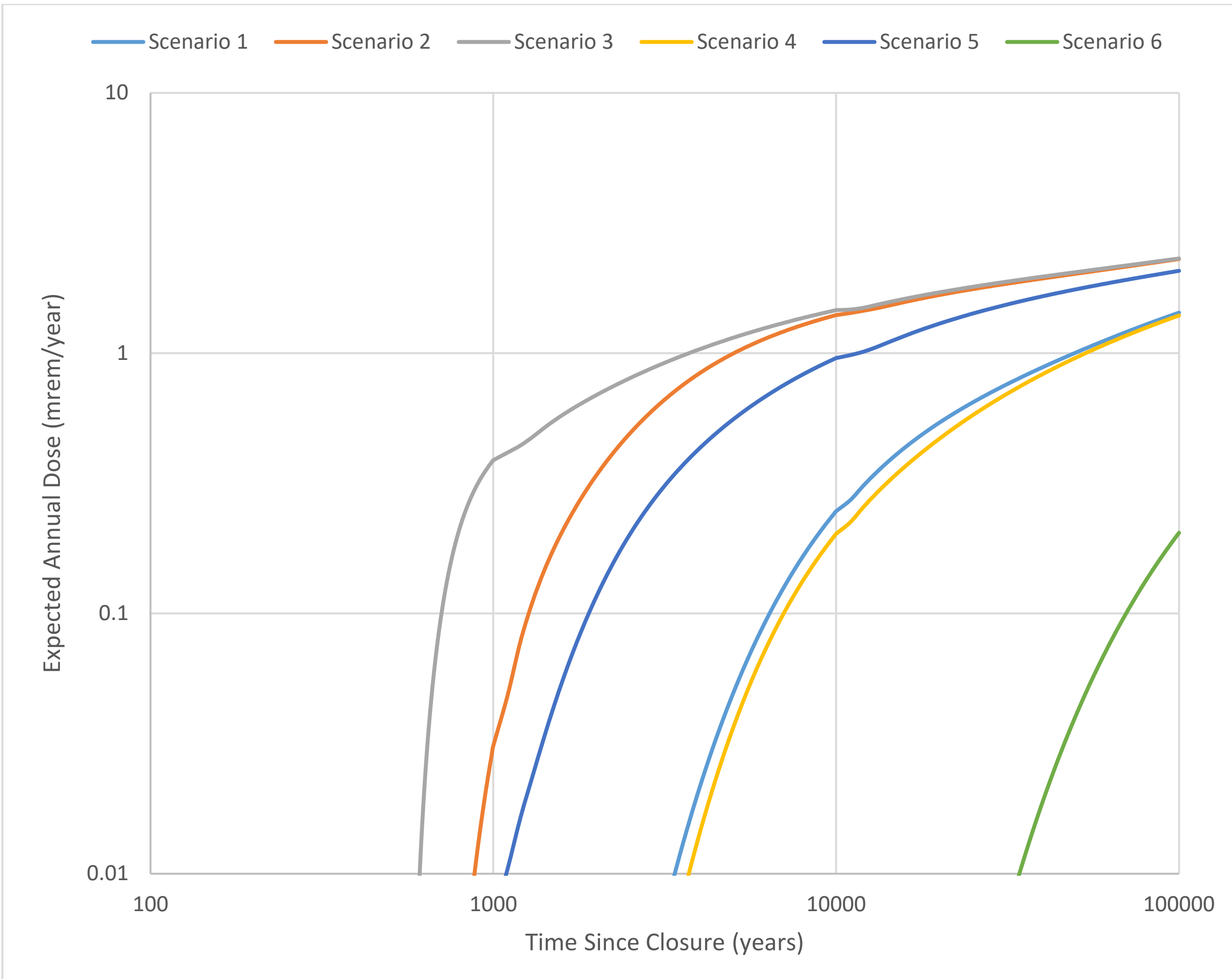

Figure B–10. Expected annual dose [mrem/yr] versus time since closure [years] for the six scenarios defined in Table 9 for Group 2b GTCC Remote-Handled Activated Metals from the New York State-regulated disposal facility at West Valley (Waste Stream 11).

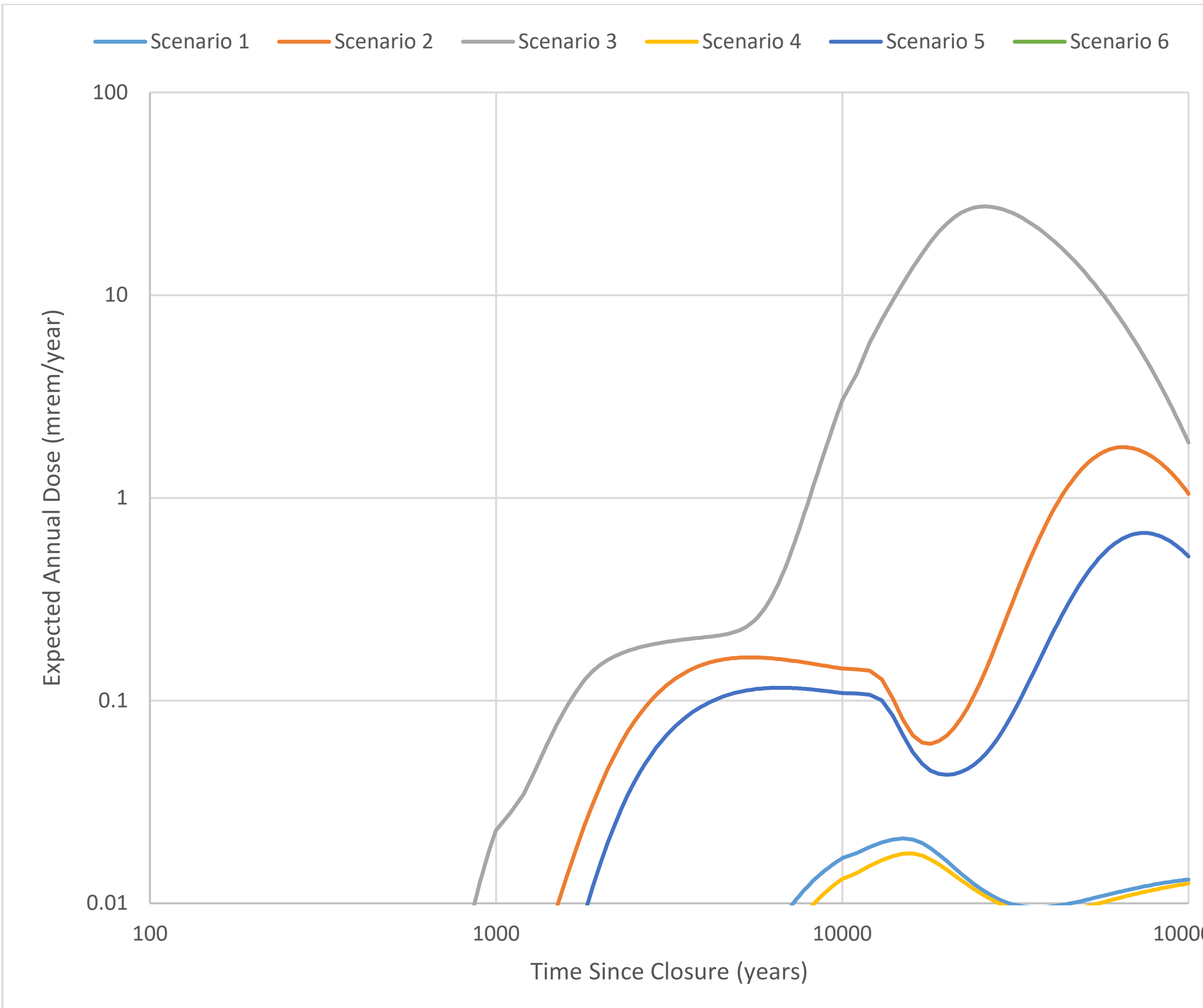

Figure B–11. Expected annual dose [mrem/yr] versus time since closure [years] for the six defined in Table 9 for Group 2b GTCC Contact-Handled Other Waste from the New York State-regulated disposal facility at West Valley (Waste Stream 12).

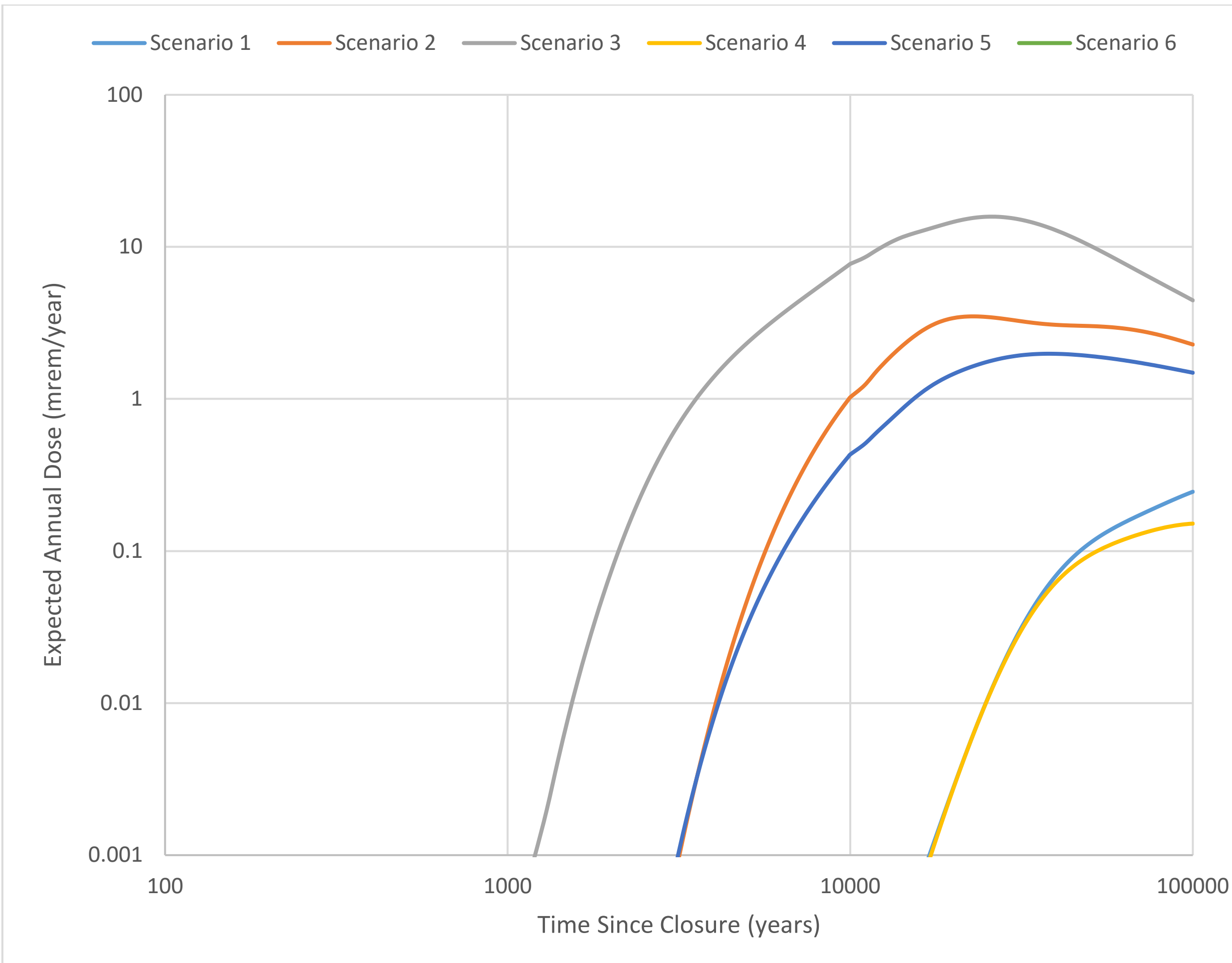

Figure B–12. Expected annual dose [mrem/yr] versus time since closure [years] for the six defined in Table 9 for Group 2b GTCC Contact-Handled Special Nuclear Auxiliary Power Other Waste from the New York State-regulated disposal facility at West Valley (Waste Stream 13).

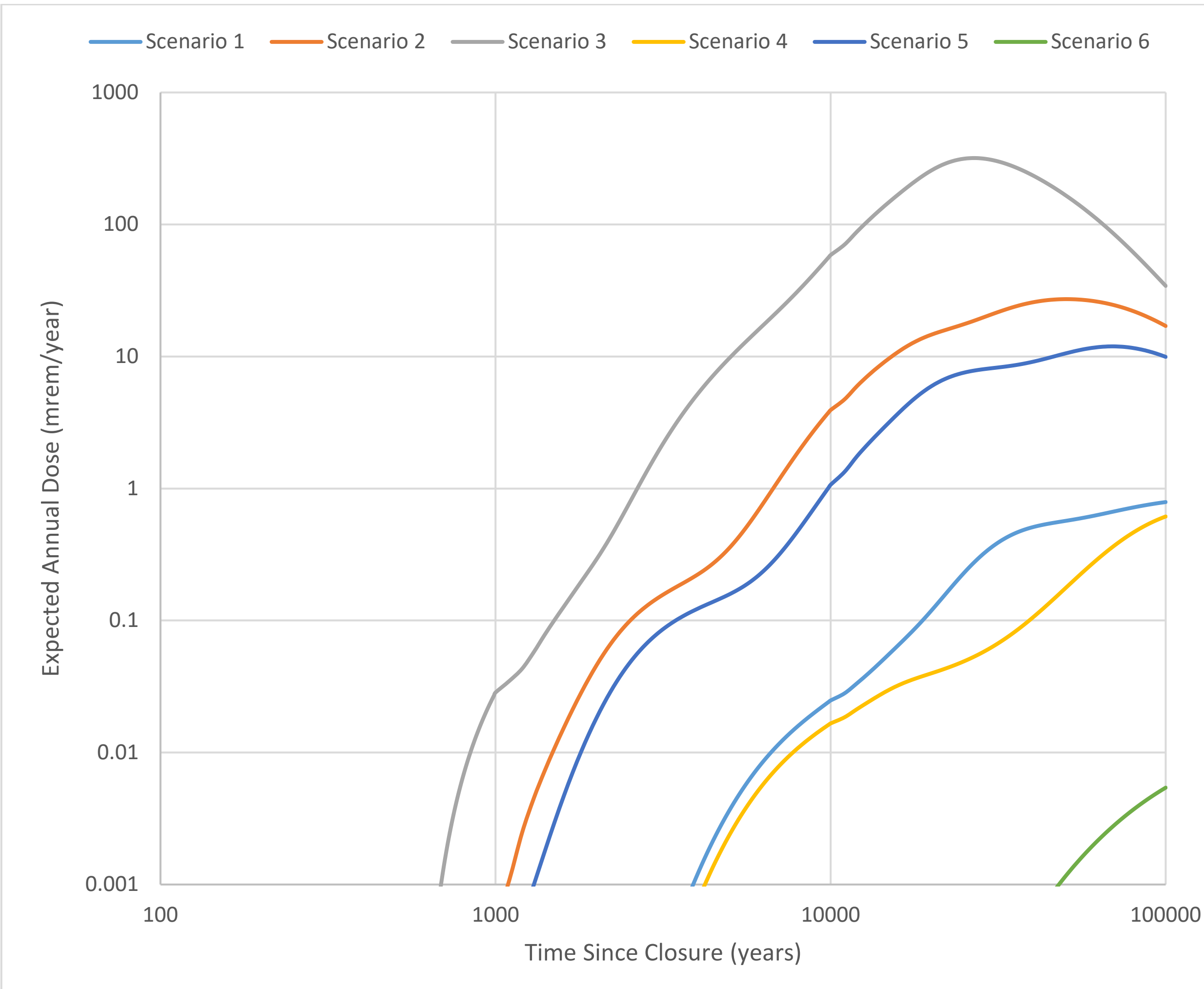

Figure B–13. Expected annual dose [mrem/yr] versus time since closure [years] for the six scenarios defined in Table 9 for Group 2b GTCC Contact-Handled Other Waste from Decommissioning West Valley (Waste Stream 14).

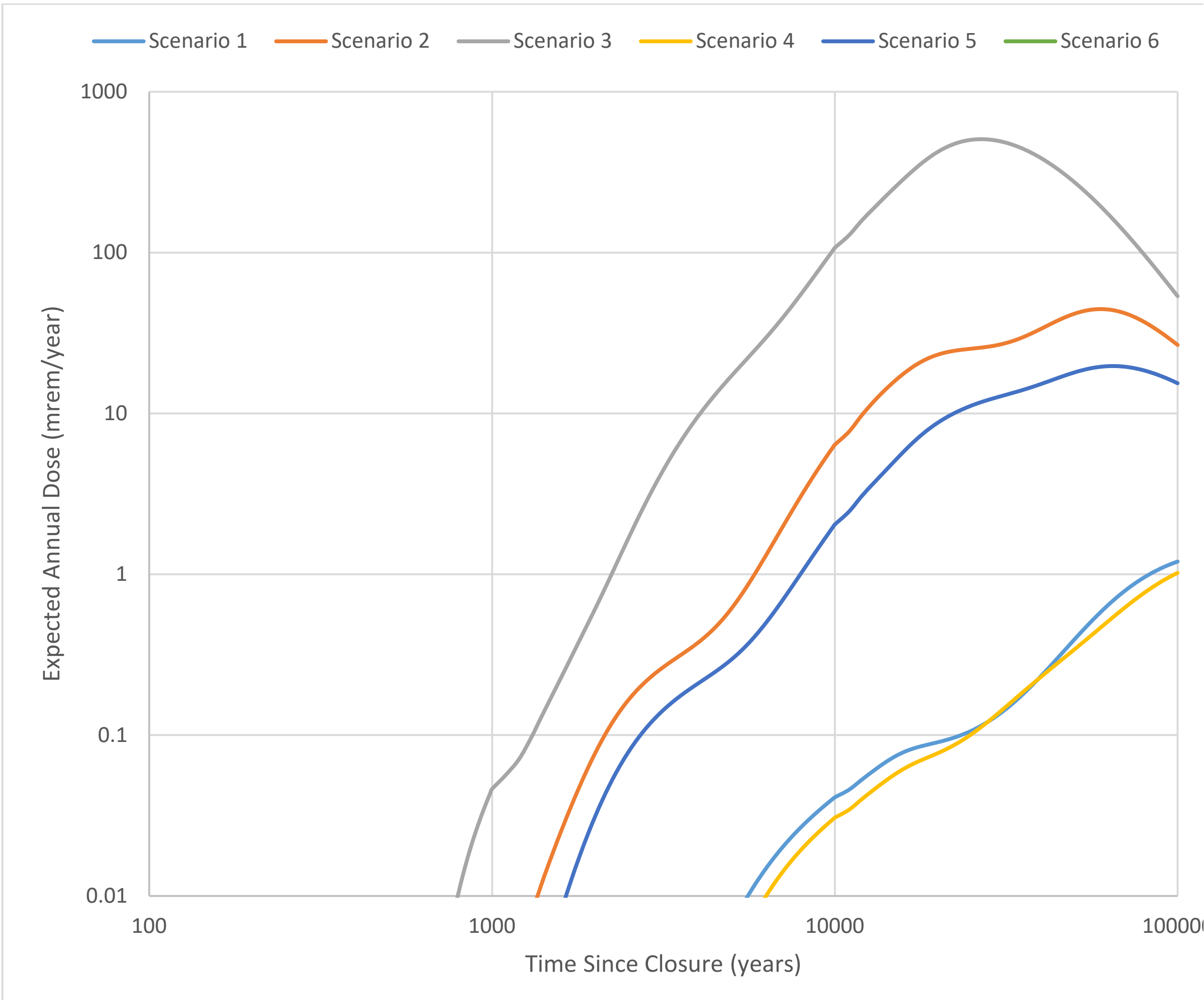

Figure B–14. Expected annual dose [mrem/yr] versus time since closure [years] for the six scenarios defined in Table 9 for Group 2b GTCC Remote-Handled Other Waste from Decommissioning West Valley (Waste Stream 15).

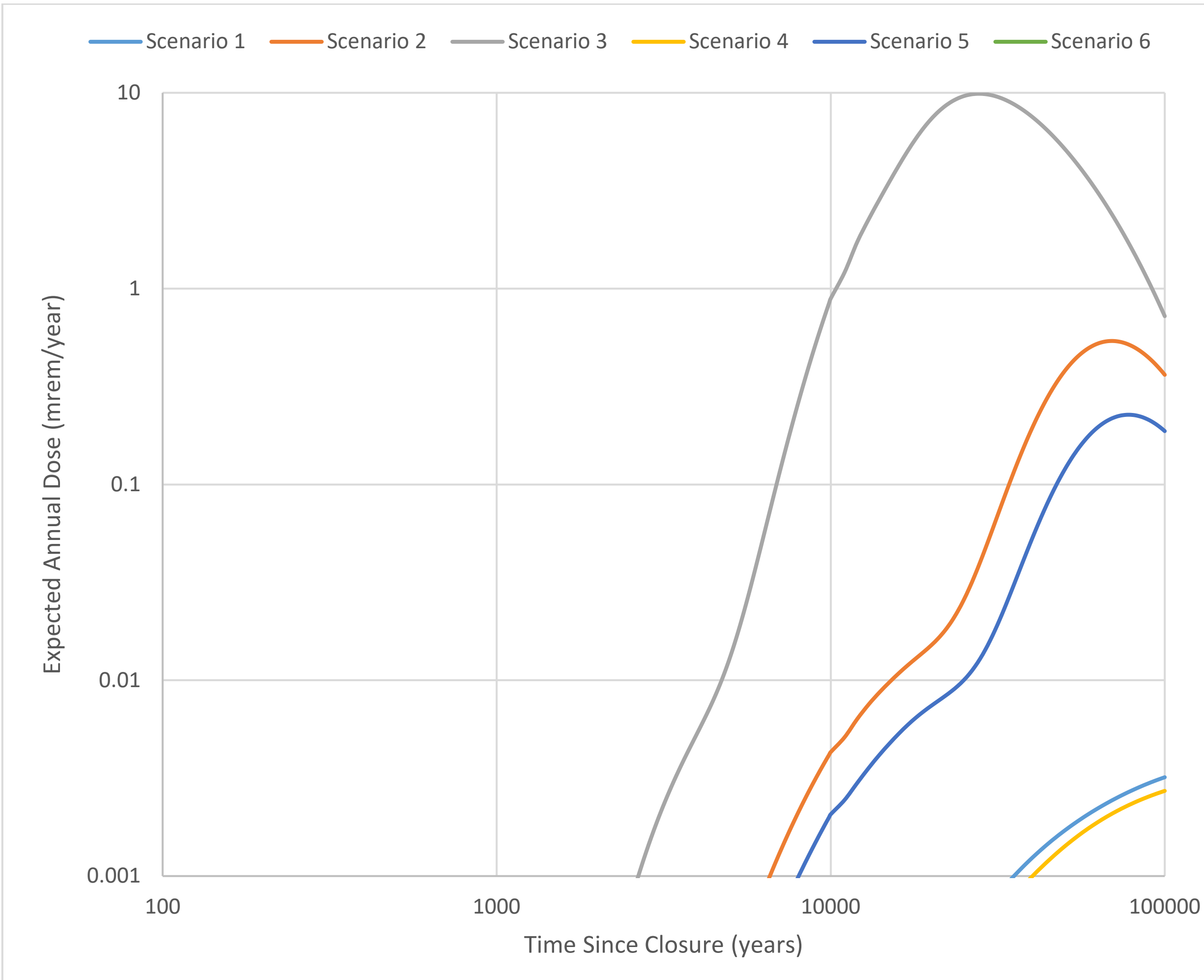

Figure B–15. Expected annual dose [mrem/yr] versus time since closure [years] for the six scenarios defined in Table 9 for Group 2b GTCC-Like Contact-Handled Other Waste from Pu-238 Production (Waste Stream 16).

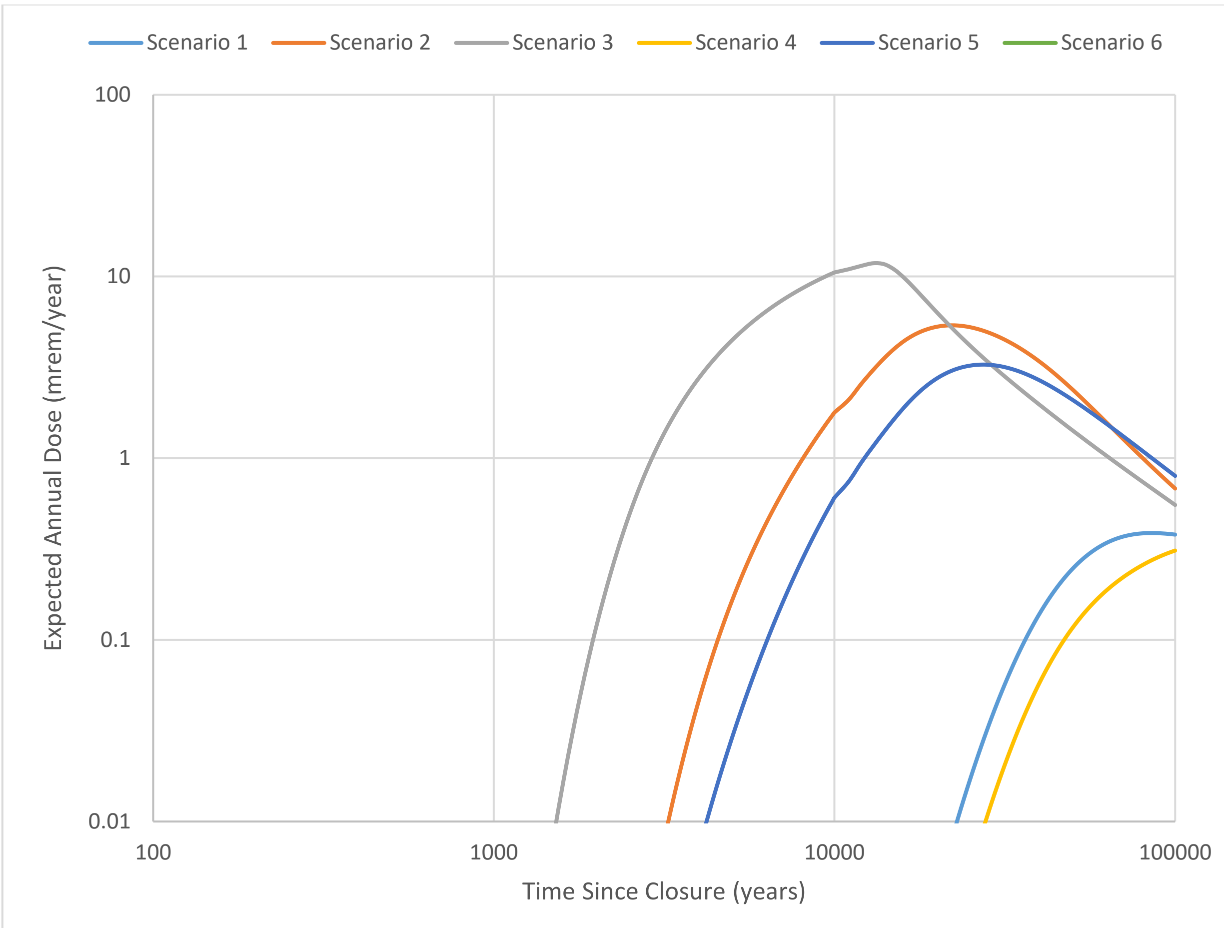

Figure B–16. Expected annual dose [mrem/yr] versus time since closure [years] for the six scenarios defined in Table 9 for Group 2b GTCC-Like Remote-Handled Other Waste from Pu-238 Production (Waste Stream 17).