Technical Considerations Associated with Greater-Than-Class C Low-Level Radioactive Waste Disposal and Qualitative Examination of Disposal Challenges

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Enclosure 2

EXECUTIVE SUMMARY:

The objective of the paper is to provide an overview of the radiological and non-radiological characteristics of Greater-Than-Class C (GTCC) waste and discuss the challenges of GTCC waste disposal. It has been accepted practice to dispose of low-level waste with limited concentration of long-lived radioactivity in facilities located near the surface, with favorable topographic and geological characteristics, in remote areas with dry climates, and with engineered barriers, and other features that impede or limit the eventual release of radionuclides from those facilities. This has not been the case for GTCC waste disposal, which has greater disposal challenges due to various waste streams having higher specific activities and higher concentrations of long-lived radioactivity. However, findings from analyses and assessments may determine that certain GTCC waste streams could be safely disposed and isolated from the biosphere similar to the current disposal of Class C low-level waste or could, alternatively, determine that some GTCC waste streams have characteristics similar to high-level waste requiring a higher degree of isolation from the public. Better knowledge of the radiological characteristics and of the disposal challenges', including plausible inadvertent intrusion scenarios, provides a more comprehensive understanding of the risks associated with site characteristics and disposal methods when considering GTCC disposal. This increased understanding could help regulators reviewing future potential site-specific performance assessments and inadvertent intrusion assessments for near-surface disposal of GTCC waste for licensees wanting to demonstrate alternative classification per 10 CFR § 61.58 or an exemption per 10 CFR § 61.6.

This paper presents important aspects that need to be considered before disposal and discusses disposal challenges under different environmental settings and scenarios. It contains insights from a qualitative examination of individual GTCC waste streams, disposal methods, disposal environments, relevant receptor scenarios, and the interrelationships between these disposal aspects. Aspects of GTCC waste disposal that are not examined in this paper include waste processing and transport, risks during the operational phase, availability or evaluation of potential disposal facilities, future technologies, and disposal costs. Although these aspects are relevant, and depending on the disposal setting, important to GTCC waste disposal, they are beyond the intended scope of this paper. Section 2 of the paper presents a summary of the various GTCC waste groups and waste types based on the 2011 U.S. Department of Energy's Draft Environmental Impact Statement, "Draft Environmental Impact Statement for the Disposal of Greater-Than-Class C (GTCC) Low-Level Radioactive Waste and GTCC-Like Waste" (DOE/EIS-0375-D) (2011 Draft EIS). This document is currently the most comprehensive and detailed source of GTCC waste types and inventories; disposal methods including conceptual facility designs; potential disposal sites for GTCC waste; and post-closure human health impact analyses of disposal at potential disposal locations. The categorization of GTCC waste types in the 2011 Draft EIS (i.e., activated metals, sealed sources, and GTCC "Other Waste") was also used in this paper. Section 3 presents the characteristics of GTCC waste and waste forms including radiological, physical, and chemical characteristics and decay curves from radionuclides common in GTCC waste. In addition, Section 3 also looks at the various GTCC waste streams.

A performance assessment for a disposal site containing GTCC will need to examine various aspects of disposal. Disposal methods, disposal environments, receptor scenarios, and the interrelationships between these disposal aspects are each examined in separate sections.

Section 4 discusses possible disposal methods, including: disposal in concrete structures or in trenches near the surface; disposal in borehole and shafts at greater depths; or disposal in a deep geologic repository. The present and future environment of a disposal site is a significant factor in determining the level of performance and the ability to ensure adequate protection for public health and safety. The disposal environment is a determining factor regarding the applicability of the disposal methods and the relevancy of the receptor scenarios for the site. Section 5 presents various meteorological, hydrological, and geological features and processes as well as plausible disruptive future events for disposal environments. Section 6 discusses pertinent receptor scenarios as a key component of the technical analyses to demonstrate that the performance objectives from 10 CFR Part 61 are met. Generic receptor scenarios are presented as reasonably conservative for estimating potential radiological exposures to an inadvertent intruder while limiting excessive speculation about future human activities. Section 6 also discusses the site-specific receptor scenarios, which are developed by the licensee and would give licensees greater flexibility in developing the necessary receptor scenarios to demonstrate that inadvertent intruder performance objectives are met. Section 7 is a qualitative examination of the disposal aspects presented in the previous sections and of the interrelationships between them. The three main subsections of Section 7 are the range of potential GTCC waste disposal depths: deep geologic disposal, disposal at intermediate depths, and near-surface disposal. The disposal of activated metals, sealed sources, and GTCC Other Waste at these various depths is then examined by comparing possible disposal environments and relevant receptor scenarios, including both inadvertent intruder and groundwater transport. Section 8 presents the results of the qualitative examination from Sections 4 through 7 in tabular form.

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1 Introduction

Background

The regulations in Title 10 of the *Code of Federal Regulations* (CFR) Part 61 were promulgated to ensure the safe land disposal of low-level radioactive waste (LLRW). The regulations currently specify that GTCC waste is not generally acceptable for disposal in the near-surface and must be disposed in a geologic repository as defined in 10 CFR Part 60 or 10 CFR Part 63 unless proposals for disposal of such waste in a disposal site licensed pursuant to 10 CFR Part 61 are approved by the Commission. Therefore, unless approved by the Commission, GTCC waste must be disposed of in a geologic repository.

The 10 CFR Part 61 includes performance objectives, technical requirements, and other requirements, that would apply to any land disposal facility. If disposal of GTCC waste in a near-surface disposal facility were proposed, the licensee would need to meet the technical requirements to demonstrate that public health and safety would be protected. GTCC waste contains radionuclides in concentrations that exceed those in the waste classification requirements in 10 CFR § 61.55; the waste classification requirements are designed to ensure protection of an inadvertent intruder. The regulations at 10 CFR Part 61 do not specify how to demonstrate protection for an inadvertent intruder for GTCC waste in a near-surface disposal facility.

If disposal of GTCC waste in a land disposal facility other than near-surface disposal were proposed, the Commission could develop specific technical requirements, including waste classification requirements, for disposal of GTCC waste using other disposal methods. Alternatively, the Commission could require a site-specific analysis to demonstrate that any proposed land disposal facility for GTCC waste would meet the 10 CFR Part 61 performance objectives. As part of the ongoing rulemaking for 10 CFR Part 61, NRC staff has proposed guidance for conducting site-specific analyses that could be useful for analyses of GTCC waste as well. “Guidance for Conducting Technical Analyses for 10 CFR Part 61, Draft Report for Comment” (NUREG-2175) provides guidance on conducting technical analyses (i.e., performance assessment, inadvertent intruder assessment, assessment of the stability of a low-level waste disposal site, defense-in-depth analyses, protective assurance period analyses, and performance period analyses) to demonstrate compliance with the performance objectives in 10 CFR Part 61.

Objective

The objective of the paper is to provide an overview of the radiological and non-radiological characteristics of GTCC waste and discuss the challenges of GTCC waste disposal. This document presents aspects that need to be considered with respect to GTCC waste disposal and discusses disposal challenges under different environmental settings and scenarios and, in addition, contains insights from a qualitative examination of individual GTCC waste streams, disposal methods, disposal environments, relevant receptor scenarios, and the interrelationships between these disposal aspects. The 2011 U.S. Department of Energy’s Draft Environmental Impact Statement, “Draft Environmental Impact Statement for the Disposal of Greater-Than-Class C (GTCC) Low-Level Radioactive Waste and GTCC-Like Waste” (DOE/EIS-0375-D) (2011 Draft EIS) provides the most comprehensive analysis of impacts resulting from groundwater release of GTCC LLRW contaminants. This examination gleans insights from the Draft EIS analysis; however, this paper does not critique, evaluate, or endorse the methodology or results used and given in the Draft EIS. Aspects of GTCC waste disposal

that are not examined in this document include waste processing and transport, risks during the operational phase, availability or evaluation of potential disposal facilities, future technologies, and disposal costs. Although these aspects are relevant and, depending on the disposal setting, important to GTCC waste disposal, they are beyond the intended scope of this examination. Previous work has been done in this area (e.g., NUREG/CR-3774, 6 Vols. (1984-1986) and NUREG/CR-4370 (1986)) and pertinent information from these sources and other sources have been included in this document.

2 Summary of GTCC Waste Groups and Waste Types based on the U.S. Department of Energy's Draft Environmental Impact Statement

The focus of the U.S. Department of Energy's (DOE) 2011 Draft EIS was developed to evaluate the potential environmental impacts from the construction, operation, closure and post-closure performance of a disposal facility for GTCC LLRW.

2.1 Waste Groups: Group 1 and Group 2

The 2011 Draft EIS divided the GTCC waste streams into two groups based on the uncertainties associated with their generation. Group 1 consists of wastes from currently operating facilities (e.g., commercial nuclear power plants). All stored GTCC LLRW wastes are included in Group 1. Some of the Group 1 wastes have already been generated and are in storage awaiting disposal. Group 2 consists of projected wastes from proposed actions or planned facilities not yet in operation. Some or all of the Group 2 waste may never be generated, depending on the outcomes of proposed actions that are independent of the 2011 Draft EIS. For example, some of the waste from Group 2 is associated with the West Valley site; circa 4,300 m^3 (150,000 ft^3) of GTCC LLRW could be generated should a decision be made to exhume the waste at the site. No stored GTCC LLRW and GTCC-like[1] wastes are included in Group 2 waste.

2.2 Waste Types

The 2011 DOE EIS described three categories for GTCC waste: activated metals, sealed sources, and "Other Waste." The activity levels of these various materials span a wide range. Some of the radionuclide concentrations in these waste streams will be close to their respective Class C concentration limits. On the other hand, a small portion of the GTCC waste contains radioactivity that is greater than the activity range for high-level waste, which typically has levels of activity concentrations in the range of 10^4-10^6 TBq/m^3 (0.3-30 MCi/m^3) (IAEA, 2009a). DOE has forecasted the stored and projected volume of GTCC LLRW from these three categories (Table 2-1). The total stored and projected volume of GTCC waste will be approximately 8,800 m^3 (311,000 ft^3) and the projected activity of that waste will be 5.92×10^6 TBq (160 MCi) with generation activities assumed to end in 2083 (DOE, 2011).

[1] The term GTCC-like waste in the 2011 Draft EIS refers to radioactive waste that is owned or generated by the DOE and has characteristics similar to those of GTCC LLRW such that a common disposal approach may be appropriate. GTCC-like waste consists of LLRW and potential non-defense-generated transuranic waste that has no identified path for disposal. The term is not intended to, and does not, create a new DOE classification of radioactive waste. The NRC LLRW classification system does not apply to radioactive waste that is owed or generated by DOE and/or waste disposed of in DOE facilities so that the focus in this document will be on commercially generated GTCC waste and not on the GTCC-like waste

Table 2-1: Current Stored and Future Projected Volumes of GTCC LLRW[2] (DOE, 2011)

GTCC LLRW	In Storage		Projected		Total Stored and Projected	
Waste Type	Volume (m^3)	Activity (MCi)	Volume (m^3)	Activity (MCi)	Volume (m^3)	Activity (MCi)
Groups 1 and 2						
Activated Metals (RH)	59	1.4	1900	160	1959	161.4
Sealed Sources (CH)	a	a	2900	2	2900	2
Other Waste (CH)	42	0.00091	1600	0.024	1642	0.02491
Other Waste (RH)	33	0.0042	2300	0.51	2333	0.5142
Total	134	1.41	8700	163	8834	164

[a] NRC licensees currently possess sealed sources that may become GTCC waste when no longer needed by the licensee; the estimated volume and activity of those sources are included in the projected inventory.

2.2.1 Activated Metals

At the time of disposal, the neutron activation products expected to be most dominant in activated metals are C-14, Mn-54, Fe-55, Ni-59, Co-60, Ni-63, Mo-93, and Nb-94. Lower concentrations of some fission products such as Sr-90, Tc-99, I-129, and Cs-137 and actinides (such as various isotopes of plutonium) are also expected to be present on these materials as surface contamination (DOE, 2011). In activated metals the isotopes primarily responsible for the waste being classified as GTCC waste are Ni-59, Nb-94, and C-14.

The total packaged volume of GTCC LLRW for pressurized-water reactors (PWR) or boiling-water reactors (BWR) at shutdown is estimated by multiplying the reactor operating capacity by the volume scaling factor for either the reference PWR [9.40E-03 m^3/MW(e)] or reference BWR [6.03E-03 m^3/MW(e)] (Argonne National Laboratory, 2010).

2.2.2 Sealed Sources

The GTCC sealed sources can be divided into two groups: industrial cesium sources and commercial plutonium, americium and curium sources. Currently, there is no disposal capacity for disused sealed sources that may be classified as GTCC waste. These sources are being managed as radioactive material until the path to final disposition becomes clear.

2.2.3 GTCC Other Waste

GTCC Other Waste consists of a wide variety of materials, such as contaminated equipment, sludges, salts, charcoal, scrap metal, glove boxes, solidified solutions, particulate solids, filters, resins, soils, and organic and inorganic debris, including debris from future decontamination and decommissioning activities, the production of Pu-238 radioisotope power systems, and the production of medical isotopes (Mo-99). This category of waste includes the GTCC LLRW that does not fall into one of the other two categories (activated metals or sealed sources). These

[2] As used in DOE's Draft EIS (2011), contact-handled waste refers to GTCC waste that has a dose rate of less than 200 mrem/h (2.0 mSv/hr) on the surface of the package. Remote-handled waste refers to GTCC waste that has a surface dose rate of 200 mrem/h (2.0 mSv/hr) or more.

wastes can come in a number of physical forms, and a wide range of radionuclides may be present.

3 GTCC Waste and Waste Streams

3.1 Characteristics of GTCC Waste and Waste Forms

The radionuclides present in GTCC waste can generally be placed in three categories: neutron activation products, radioactive fission products, and actinides (i.e., radionuclides that are higher than actinium) (Knolls Atomic Power Laboratory, 2010). The main source of activity in activated metals is neutron activation products, while fission products and actinides are the main radionuclides present in sealed sources and GTCC Other Waste. Fission products and some actinides are also present in relatively low concentrations in activated metals. The actinides include some of the transuranic (TRU) radionuclides but not all of them.

3.1.1 Radiological Characteristics

3.1.1.1 Half-Life of Radionuclides

Group 1 GTCC waste contains a total of 4.1 x 10^6 TBq (110 MCi) of radionuclide activity, mainly from the decommissioning of commercial nuclear power reactors currently in operation. Group 2 GTCC waste contains a total activity of 1.8 x 10^6 TBq (49 MCi).

Table 3-1: Half-Life of Activated Metal Radionuclides (Knolls Atomic Power Laboratory, 2010)

Parent Isotope	Half Life (yr)	Parent Isotope	Half Life (yr)	Parent Isotope	Half Life (yr)
H-3	1.23E+01	Ni-63	1.00E+02	Cs-137	3.01E+01
C-14	5.70E+03	Mo-93	4.00E+03	Pu-238	8.77E+01
Mn-54	8.55E-01	Nb-94	2.03E+04	Pu-239	2.41E+04
Fe-55	2.74E+00	Sr-90	2.88E+01	Pu-241	1.43E+01
Ni-59	1.01E+05	Tc-99	2.13E+05	Am-241	4.33E+02
Co-60	5.27E+00	I-129	1.57E+07		

Table 3-2: Half-Life of Sealed Source Radionuclides (Knolls Atomic Power Laboratory, 2010)

Parent Isotope	Half Life (yr)
Cs-137 (Irradiators)	3.02E+01
Pu-238	8.77E+01
Pu-239	2.41E+04
Pu-241	1.43E+01
Cm-244	1.81E+01

Table 3-3: Half-Life of Other Waste Radionuclides (Knolls Atomic Power Laboratory, 2010)

Parent Isotope	Half Life (yr)	Parent Isotope	Half Life (yr)	Parent Isotope	Half Life (yr)
C-14	5.70E+03	Cs-137	3.01E+01	Pu-239	2.41E+04
Mn-54	8.55E-01	Pb-210	2.23E+01	Pu-240	6.56E+03
Fe-55	2.74E+00	Th-229	7.40E+03	Pu-241	1.43E+01
Ni-59	1.01E+05	Th-230	7.56E+04	Am-241	4.33E+02
Co-60	5.27E+00	U-233	1.59E+05	Pu-242	3.75E+05
Ni-63	1.00E+02	U-235	7.04E+08	Am-243	7.37E+03
Sr-90	2.88E+01	Np-237	2.14E+06	Cm-244	1.81E+01
Tc-99	2.13E+05	Pu-238	8.77E+01		

3.1.1.2 Activity

Reported values for stored waste were decayed from 2007 to 2019 to obtain the values in Table 3-4 because stored waste is assumed to become available for disposal in 2019. The GTCC waste radionuclides that are being tracked in this analysis were chosen because they would be the important contributors to dose (Ragan 2002; Leigh et al., 2005).

Table 3-4: Radionuclide Activities for GTCC LLRW and DOE GTCC-like Waste (Sandia National Laboratories, 2008)[a]

Waste	Activity at the Time Waste is Available for Disposal (Ci)								
	^{14}C	^{54}Mn	^{55}Fe	^{59}Ni	^{60}Co	^{63}Ni	^{90}Sr	^{93}Mo	^{94}Nb
Stored CH	5.60E+03	1.06E-04	2.57E+02	2.90E-04	5.07E+00	3.61E-02	4.17E+03	0	3.31E-04
Stored RH	6.00E+03	5.67E-04	2.43E+02	9.75E+03	1.29E+04	5.69E+05	3.09E+05	0	6.01E+00
Projected CH	4.44E+03	7.09E+00	7.10E+03	2.34E+02	8.32E+01	6.79E+02	4.89E+03	0	2.27E+02
Projected RH	2.76E+03	4.41E+00	2.70E+02	2.19E+01	1.98E+02	1.92E+03	7.39E+04	7.77E-03	2.32E-02
Total	1.88E+04	6.85E+01	2.49E+04	1.00E+04	8.16E+04	6.29E+05	5.18E+05	7.77E-03	2.33E+02
	^{99}Tc	^{137}Cs	^{210}Pb	^{229}Th	^{230}Th	^{233}U	^{235}U	^{237}Np	^{238}Pu
Stored CH	3.31E-04	2.11E+02	2.37E+03	3.18E-04	9.34E+02	1.68E+02	6.46E+03	2.10E+01	4.86E+05
Stored RH	6.01E+00	9.75E+03	2.67E+05	4.64E-09	4.52E+00	1.65E+00	9.75E+02	7.87E+01	1.16E+04
Projected CH	2.27E+02	1.73E+02	2.77E+03	6.72E-06	7.39E+02	1.33E+02	5.10E+03	1.63E+01	4.28E+05
Projected RH	2.32E-02	1.13E+02	3.92E+05	1.51E-10	4.60E+02	8.28E+01	3.17E+03	1.65E+01	2.70E+05
Total	2.33E+02	1.03E+04	7.66E+05	4.98E-04	2.14E+03	3.86E+02	1.57E+04	1.32E+02	1.20E+06
	^{239}Pu	^{240}Pu	^{241}Pu	^{241}Am	242Pu	^{243}Am	^{244}Cm		
Stored CH	3.74E+05	2.99E+05	4.48E+06	1.32E+06	1.87E+03	1.44E+04	5.81E+02		
Stored RH	9.42E+04	7.11E+04	2.24E+05	8.44E+04	2.36E+02	5.26E+03	1.23E+03		
Projected CH	2.96E+05	2.36E+05	6.94E+06	1.06E+06	1.48E+03	1.14E+04	7.84E+02		
Projected RH	1.84E+05	1.47E+05	4.32E+06	6.63E+05	9.20E+02	7.08E+03	5.86E+02		
Total	9.48E+05	7.54E+05	1.60E+07	3.13E+06	4.50E+03	3.81E+04	3.18E+03		

[a]From Appendix F: Trone (2008). 1 Ci = 3.7×10^{10} Bq

3.1.1.3 Decay Curves from Radionuclides Common in GTCC Waste

The following graphs indicate that some of the short-lived[3] neutron activation products will decay to a level that prevents these radionuclides from being classified as GTCC waste (e.g., Co-60 and Fe-55).

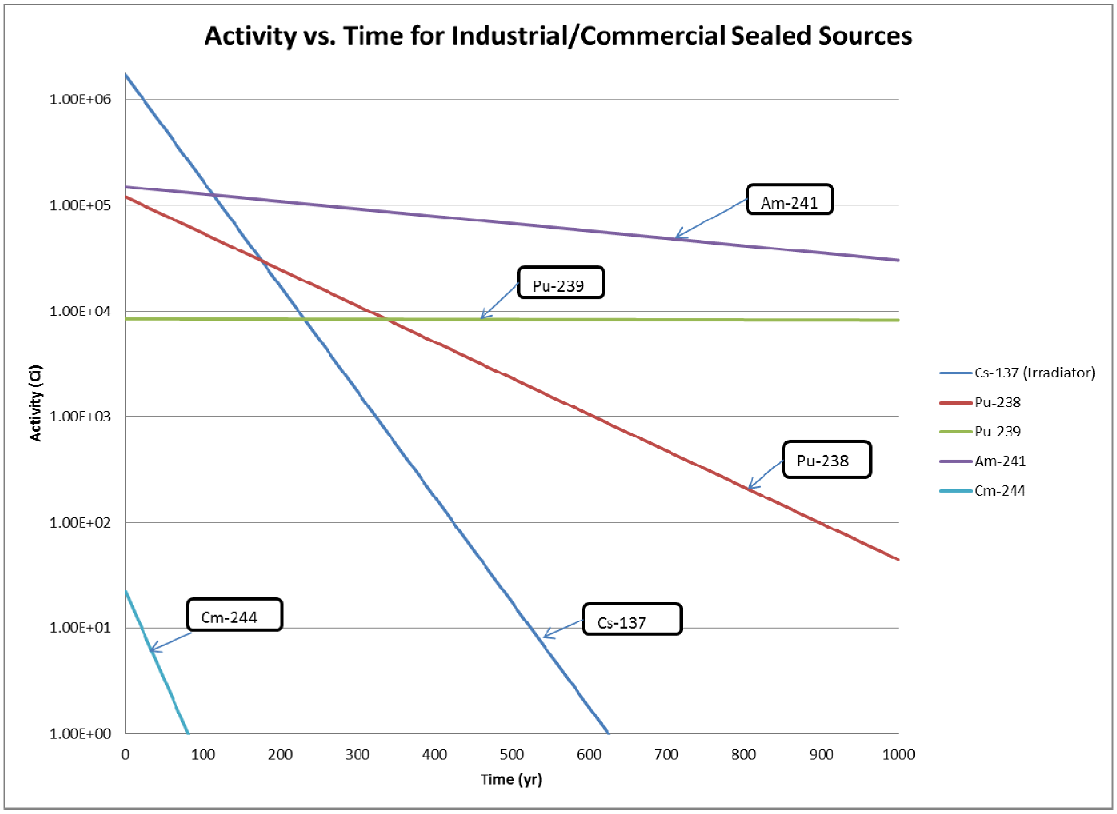

Figure 3-1: Industrial/Commercial Sealed Sources

[3] Long-lived radionuclides are identified in Table 1 of 10 CFR § 61.55 and short-lived radionuclides are identified in Table 2 of 10 CFR § 61.55.

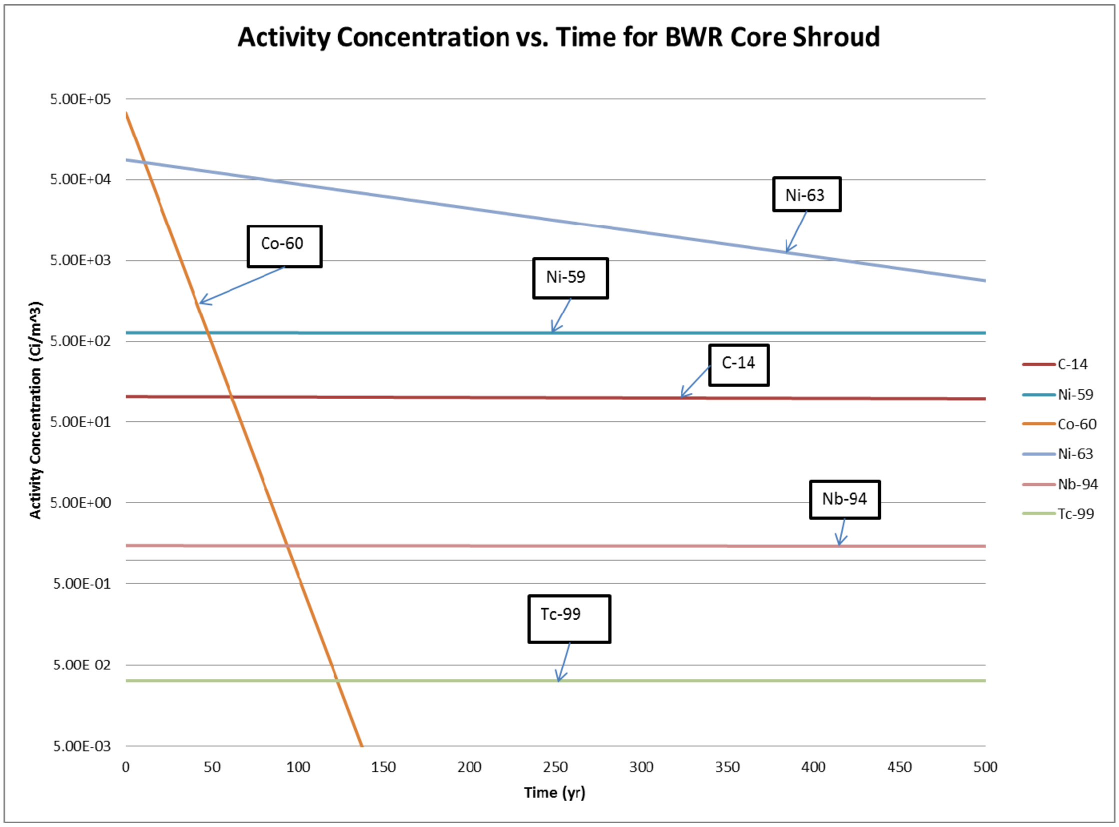

Figure 3-2: Activated Metals (BWR Core Shroud)

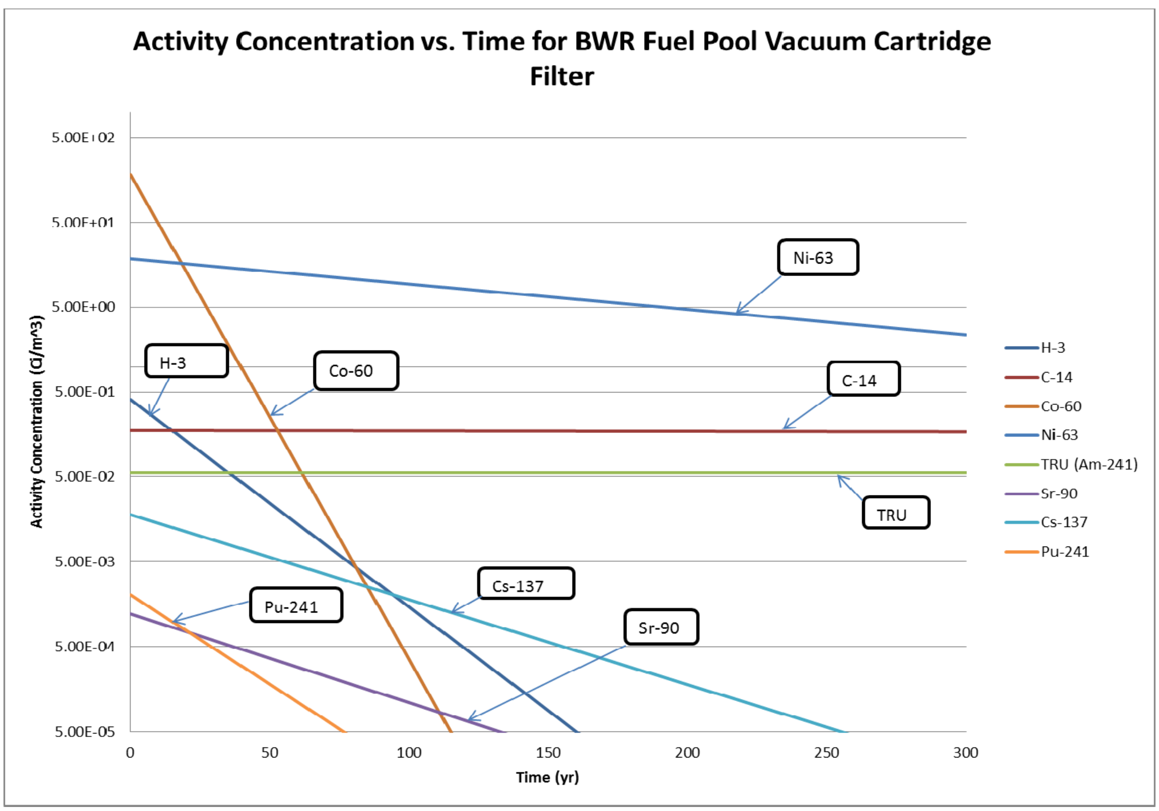

Figure 3-3: Other Waste (BWR Cartridge Filter)

3.1.2 Quantity of Waste

The total GTCC waste volume is 8,800 m^3 (311,000 ft^{33}) in 2011 Draft EIS. Some of this waste is associated with the West Valley Site. An additional 4,300 m^3 (150,000 ft^3) of GTCC LLRW could be generated should a decision be made to exhume the NRC-licensed disposal area [NDA] and state-licensed disposal area [SDA]. Most of the GTCC waste from these disposal areas would be GTCC LLRW.

The total estimated volume of mixed waste in Group 1 is about 170 m^3 (6,000 ft^3), which represents less than 4 percent of the total volume Group 1 waste. Available information indicates that much of this waste is characteristic hazardous waste as regulated under the Resource Conservation and Recovery Act (RCRA); therefore, the 2011 Draft EIS assumes that for the land disposal methods, the generators will treat the waste to render it nonhazardous under Federal and State laws and requirements.

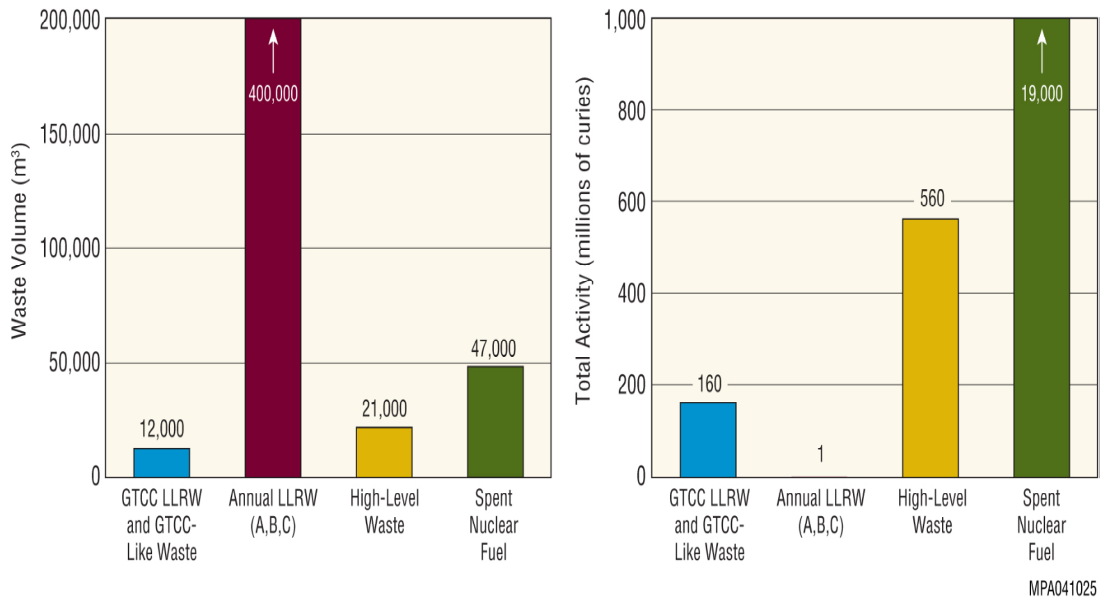

Figure 3-5: Comparison of GTCC Waste with Other Radioactive Wastes (DOE, 2011)

3.1.3 Physical Characteristics

The activated metal waste consists of steel, stainless-steel, and a number of specialty alloys used in nuclear reactors. Portions of the reactor assembly and other components near the nuclear fuel are activated by high fluxes of neutrons for long periods of time during reactor operations, and high concentrations of some radionuclides are produced. This waste will need a significant amount of shielding to reduce the levels of radiation to acceptable levels and/or will have to be handled remotely. RH waste refers to radioactive waste that must be handled at a distance (remotely) to protect workers from unnecessary exposure (e.g., waste with a dose rate of 2 millisievert per hour (200 millirem per hour [mrem/h]) at the surface of the waste package). The physical form of this waste is solid metal (DOE, 2011).

Sealed sources typically consist of concentrated radioactive material encapsulated in relatively small containers made of titanium, stainless-steel, or other metals. Only a small fraction of the

sealed sources are GTCC LLRW, depending upon the activity and half-life of the specific radionuclide present in the source. While there are some sealed sources currently in storage, it is assumed that most of this waste will be generated in the future. These sources are commonly used to sterilize medical products, detect flaws and failures in pipelines and metal welds, determine the moisture content in soil and other materials, and diagnose and treat illnesses such as cancer. Sealed sources can encompass several physical forms, including ceramic oxides, salts, or metals.

In addition to small sealed sources, there are 1,435 large Cs-137 irradiators in the waste inventory, each with an assumed volume of 0.71 m^3 (25 ft^3). Because of their size, these irradiators cannot be packaged in 208-L (55-gal) drums and are assumed to be disposed of individually in their original shielded devices. In these irradiators, the Cs-137 source is contained within a very robust shielded device, which would be expected to help the waste form retain its integrity. Cesium chloride salt was generally used in older Cs-137 sources, and newer small sources typically have the radionuclide bonded in a ceramic. Of these two forms, cesium chloride salt is much more water-soluble. For the Draft EIS (DOE, 2011), all of the Cs-137 sources are assumed to be present as cesium chloride salt.

GTCC Other Waste consists of a wide variety of materials, including contaminated equipment, debris, scrap metal, glove boxes, filters, resins, soil, solidified sludges, and other materials. GTCC Other Waste can come in a number of physical forms, and a range of radionuclides may be present. About 58 percent of the GTCC Other Waste is RH waste, and 42 percent is CH waste. It is assumed for purposes of analysis in the 2011 Draft EIS that the radionuclides in GTCC Other Waste can leach out somewhat readily when exposed to water. Although grout can be damaged by high radiation fields, it is assumed in the 2011 Draft EIS that the GTCC Other Waste would be stabilized with grout or another matrix prior to being shipped to a disposal facility.

3.1.4 Chemical Characteristics

When disposing of large amounts of waste, even compounds with low non-radiological hazard may become problematic. Mobilizing agents may be created as a result of chemical reactions, for example, from the many materials that form part of a disposal facility, some may interact or react to form new complex ligands and previously insoluble radionuclides may become mobile. The solubility and mobility of radionuclides influence the overall performance of a disposal facility. For example, radionuclides with high solubility and low sorption, such as Cl-36 and I-129, can be important in safety assessments although they have relatively low radiotoxicity. In contrast, due to slow transport, highly radiotoxic plutonium isotopes often contribute dose to a critical group at a later time (e.g., after 1000 or 10,000 yr).

The chemical characteristics of the waste and the chemical conditions of the disposal facility can lead to corrosion of activated metals. The activated metal waste consists of steel, stainless steel, and a number of alloys used in nuclear reactors, while some of the encapsulating material of sealed sources is made from stainless steel. Carbon steel will corrode under certain environmental conditions to produce hydrogen gas at a low rate under oxygen free conditions. Gas will tend to migrate due to buoyancy and, where this occurs, it could cause unwanted movements of pore water and/or the surrounding groundwater. The corrosion of carbon steel in fresh water is dependent on a number of factors, including mineral content, pH, presence or absence of dissolved oxygen, velocity, and temperature. However, if the waste form (e.g., activated metals) is grouted, then the high pH of the grout provides a protective oxide film over the steel and reduces chemical reactions. Water chemistry, in particular, the levels of oxygen

and other dissolved gases, influences the corrosion rate in natural waters (i.e., at ordinary temperatures in neutral or near neutral water), dissolved oxygen is necessary for appreciable corrosion of steel. Water hardness, in particular hard water that contains high levels of calcium and magnesium salts, tend to deposit a protective layer of calcium carbonate on metal surfaces. This mineral layer impedes oxygen diffusion and thereby reduces corrosion rate.

As described in the example above, grout can have additional properties that enhance containment besides those characteristics that provide site stability. Cementitious grout is typically used to give a waste form a certain stability to prevent waste form collapse and subsidence at the surface of a site; however, cementitious grout can also change the chemistry of the near-field environment and create reducing conditions with high pH values. For example, Tc is relatively insoluble and strongly sorbs under reducing conditions but is mobile under oxidized conditions. If blast furnace slag is added to a cementitious grout, a reducing condition could delay the mobilization of Tc-99. The use of blast furnace slag and the use of fly ash in the grout formulation also are known to have the added benefits of reducing heat evolution during hydration, decreasing hydraulic conductivity, and increasing strength and sulfate resistance.

Neutron activated stainless steel components include the reactor vessel cladding and internals. Stainless steel corrodes in all natural waters exclusively by pitting, with the extent and rate of pitting determined predominantly by the chloride level, and then only in waters containing levels of 100 ppm chloride or more. Water pH has some effect on corrosion of stainless steels, although minor in comparison with that of the chloride level.

NUREG/CR-4370 (NRC, 1986) calculated corrosion rates for carbon and stainless steel components exposed to aqueous environments. Aqueous corrosion of carbon steel was estimated at 0.01 cm/yr (0.004 in/yr). This assumes immersion in river water. The corrosion rate does not differ appreciably in other types of water, with virtually all waters, fresh and salt, falling in the range of 0.003 – 0.02 cm/yr (0.001 – 0.0077 in/yr). Aqueous corrosion of stainless steel differs from that of carbon steel in that corrosion is localized, in the form of pitting. Stainless steel components immersed in fresh water were not expected to corrode measurably. Seawater and brackish waters were considered capable of inducing rapid pitting in stainless steels.

The neutron activation products expected to be most dominant in activated metals at the time of disposal are C-14, Mn-54, Fe-55, Ni-59, Co-60, Ni-63, Mo-93, and Nb-94. GTCC waste concentration in activated metals is primarily driven by the concentrations of Ni-59, Nb-94, and C-14. Typically, C-14 is a concern due to potential inhalation of $^{14}CO_2$, uptake by plants, and its mobility in groundwater (Platfoot, 2010). Soil distribution coefficients (K_d) for C-14 are often assumed to be zero or near zero. In groundwater systems, the common forms of carbon in the environment are carbonate and bicarbonate which are negatively charged so that they do not readily absorb onto negatively charged soils. Carbon compounds have been found to dissociate completely in the groundwater, meaning that solubility will not be a limiting factor in concentration calculations.

Depending on pH and soil type, nickel will be easily absorbed by soils and is found in abundance in the environment. Nickel K_d values have been measured in a wide range of values from less than 100 to 5,000 mL/g (Idaho National Engineering Laboratory, 1996) so that nickel will not be transported any significant distance if environmental conditions remain the same.

Measured K_d values for niobium are usually high, and similar to those for nickel (Idaho National Engineering Laboratory, 1996) and will also not be transported any significant distance if

environmental conditions remain the same. Niobium is typically found in compounds in an oxidation state of +5, such as in Nb_2O_5, but it also often forms compounds in the +4 or +2 oxidation states. Niobium compounds will completely dissociate in the groundwater, so that solubility will not be a limiting property in radionuclide concentrations in groundwater (Platfoot, 2010). The general behavior of radionuclides in the environment is dependent to a large degree on climate and soil properties, and climate and soil properties will depend heavily on the site's location.

3.2 GTCC Waste Streams

"Waste stream" is defined here as meaning waste with relatively uniform radiological and physical properties. Often the waste results from a single process.

3.2.1 Activated Metals

The activated metal GTCC LLRW is steel or stainless steel materials that have been subjected to neutron flux for long periods of time, causing activation of impurities in the metal. These materials are typically highly radioactive, with the initial radioactivity decreasing rapidly due to the decay of short-lived radionuclides. The types of activated metals are relatively both chemically and physically inert. Much of the activated metals GTCC waste will result from the decommissioning of power reactors. Currently, 18 power reactors are undergoing decommissioning and 100 nuclear power plants operating in the United States will undergo decommissioning in the future: 65 PWRs and 35 BWRs.

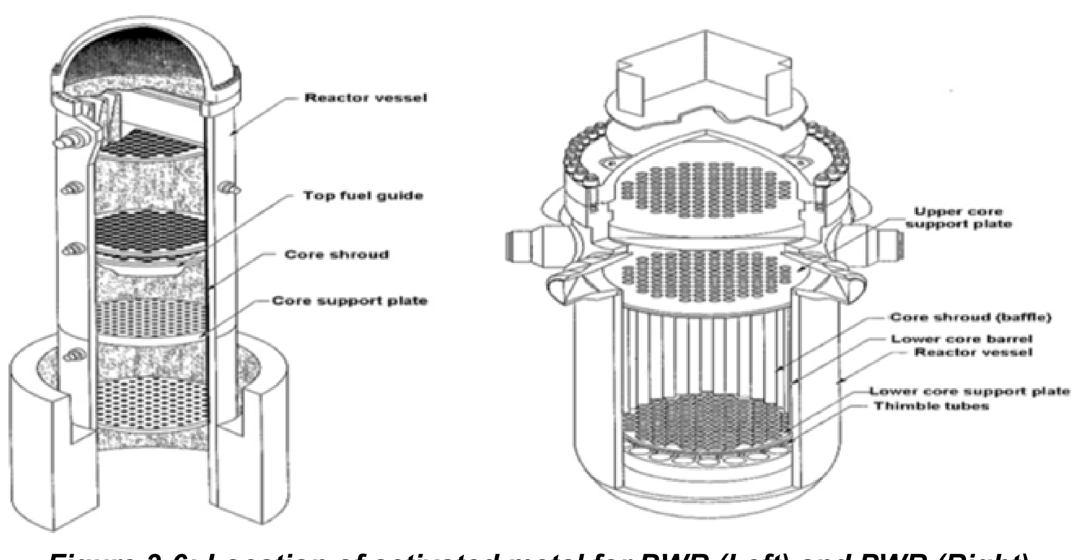

Figure 3-6: Location of activated metal for BWR (Left) and PWR (Right) (DOE, 2011)

3.2.2 Sealed Sources

The GTCC sealed sources can be divided into two groups: industrial cesium sources and commercial plutonium, americium and curium sources.

3.2.2.1 Small Sealed Sources

Estimates of the total projected inventory for sources containing the long-lived nuclides Pu-238, Pu-239, and Am-241 (Sandia National Laboratories, 2008) include 8,634 Pu-238 sources (0.188 TBq (5.07 Ci)), 1,819 Pu-239 sources (0.0618 TBq (1.67 Ci)), and 44,079 Am-241 sources (0.0466 TBq (1.26 Ci each)), for a total additional increment of 3,737 TBq (0.101 MCi) in 54,262 sources.

3.2.2.2 Large Irradiators with Cs-137

Large Cs-137 sources cannot be packaged in 0.21 m^3 (55-gallon) drums; instead it is assumed the 1,435 commercial Cs-137 sources will be disposed in their original shielded devices, which will reduce the worker dose levels during processing and disposal. Since the volume of most of these source devices is unknown, an estimated single package volume of 0.71 m^3 (25 ft^3) was assumed in the 2011 Draft EIS. The activity range for the Cs-137 sources used in this model is between 63 TBq (1.7 kCi) and 189 TBq (5 kCi). The average activity of the 1,435 Cs-137 blood irradiators that are projected to be disposed of will be approximately 44 TBq (1.2 kCi) (DOE 2011).

3.2.3 GTCC Other Waste

A spectrum of radionuclides is present in these wastes, with the isotopes of various actinides (uranium, neptunium, plutonium, americium, and curium) being of most concern for long-term management. The total activity in the Group 1 and Group 2 GTCC Other Waste is 48,100 TBq (1.3 MCi), and many of the radionuclides present in this waste have very long half-lives (DOE, 2011).

3.2.3.1 West Valley Site

If DOE decides to remove the buried waste at the West Valley Site, the volume of GTCC LLRW and GTCC-like waste that could be generated is projected to be about 4,300 m^3 (150,000 ft^3) and is included in the Group 2 inventory evaluated in the 2011 Draft EIS. The 4,300 m^3 (150,000 ft^3) includes 3,500 m^3 (120,000 ft^3) of GTCC Other Waste, 740 m^3 (26,000 ft^3) of activated metals, and 22 m^3 (780 ft^3) of sealed sources (DOE, 2011).

Currently stored GTCC-like waste at the West Valley Site has also been included in the Group 1 inventory for the 2011 Draft EIS. The volume of stored GTCC-like waste at the West Valley Site is 880 m^3 (31,000 ft^3). In addition to this stored waste, a total of 1,400 m^3 (49,000 ft^3) of GTCC-like waste would be generated from decontamination and decommissioning the West Valley Site in the future. About 370 m^3 (13,000 ft^3) of this projected waste is included in the Group 1 inventory, and 980 m^3 (35,000 ft^3) is included in the 2011 Draft EIS' Group 2 inventory (Argonne National Laboratory, 2010).

As announced in the April 20, 2010, Record of Decision (ROD) for the *Final Environmental Impact Statement for Decommissioning and/or Long-Term Stewardship at the West Valley Demonstration Project and Western New York Nuclear Service Center*, DOE decided to implement the Preferred Alternative, Phased Decision-making. Under this alternative, exhumation of the NDA and SDA wastes is deferred until Phase 2 decision (to be made within 10 years of the ROD). DOE has not announced its decision at this time.

3.2.3.2 Current Storage

Two facilities are currently being used to store GTCC Other Waste (Babcock and Wilcox in Virginia and Waste Control Specialists in Texas) and included in DOE's 2011 Draft EIS. The volume of stored waste is reported to be 75 m^3 (2,600 ft^3), and an additional 1 m^3 (35 ft^3) is projected to be generated in the future. These wastes are included in the Group 1 inventory (DOE, 2011).

3.2.3.3 Molybdenum (Mo)-99 Production Projects

Waste associated with the future production of Mo-99 is also included in DOE's 2011 Draft EIS inventory. The Draft EIS speculated that Missouri University Research Reactor (MURR) and B&W would be the primary domestic Mo-99 producers. As of 2015 B&W is no longer planning on producing Mo-99 and the MURR design is still in the design phase. Other potential candidates are examining the feasibility of domestic Mo-99 production. The potential waste streams that from these designs are currently unknown.

Use of the MURR involves irradiating solid targets containing low-enriched uranium in the research reactor and processing the targets to extract Mo-99. This process is estimated to produce an annual volume of 0.46 m^3 (16 ft^3) of GTCC LLRW containing a total activity of about 115 TBq (3,100 Ci).

4 Disposal Methods

Currently, much of the disposal of LLRW with limited concentration of long-lived radioactivity occurs near the surface, with favorable topographic and geological characteristics, and with engineered barriers and other features that impede or limit the eventual release of radionuclides from those facilities. The goal of disposal is to isolate or limit the release of radioactive waste to the environment for hundreds to thousands of years when its radioactivity poses a risk to humans. For disposal sites with favorable geological and climatic characteristics, natural barriers will reduce the number of man-made, engineered barriers needed to slow contaminant release into the groundwater and atmosphere. However, modern disposal practices include multi-barrier systems that employ both natural and man-made engineered barriers. The disposal methods chosen for GTCC waste disposal will be critical to ensure long-term safety.

For the purpose of this examination, the lower boundary of a near-surface disposal site is considered to lie at 30 m, as defined in 10 CFR Part 61, or about 100 ft below the surface or, in undulating terrain, 30 m below the local topographic low point since 30 m is considered the maximum depth of excavation considered likely for the foundations of tall buildings (OECD, 1987). No generally agreed upon intermediate depth exists, however most of the literature uses depths that start at the near-surface border (30 m [100 ft] under the surface) and include depths down to 100 - 150 m or about 300 to 500 ft under the surface (IAEA, 2009; U.S. Congress, 1988).

4.1 Deeper Disposal Depth: Deep Geologic Repository

Waste with higher contents of long-lived radionuclides is usually disposed of at deeper depth. Engineered underground tunnels or caverns are excavated within these deeper geologic formations and form the central part of a geologic repository. Engineered underground excavations are usually deeper than 100-150 m (300-500 ft), and although depth alone is not a guarantee that waste will be isolated and contained, increasing depth is typically correlated with a decrease in the number of man-made barriers that are required to ensure safety. The geologic, hydrologic, and geochemical features and processes of the geologic repository area are critical components to determining long-term performance. In addition to the engineered underground excavations, a geologic repository normally includes a radioactive waste disposal facility at or near the surface to handle the waste.

Excavations may take the form of a tunnel, a chamber, or a silo. Walls can be covered and void spaces sealed with a low permeability material such as grout or bentonite to control groundwater movement. Long-term stabilization of excavated openings by backfilling may be necessary in some host rocks. The likelihood of human intrusion after repository closure is much lower, since the access to a closed underground facility requires greater technical effort. A further advantage of deep disposal is that the need for institutional controls after closure is much diminished and with proper management the land could be put to a range of uses.

Many different rock types could host a geologic repository. Granite, salt, clay, tuff and other rocks have been considered. The tunnels and caverns from the one deep geologic repository that exists in the U.S., the Waste Isolation Pilot Plant (WIPP), were excavated in rock salt. As the only deep geologic repository evaluated in DOE's 2011 Draft EIS for GTCC waste disposal, the WIPP disposal area is located about 655 m (2,150 ft) beneath the ground surface. A series of caverns about 91 m (300 ft) long, 10 m (33 ft) wide, and 4 m (13 ft) high were excavated in the salt formation. The plastic property of the salt should enable the salt to slowly move into void space so as to allow the salt fractures to close and return to the properties of the original,

intact salt. The underground is connected to the surface by four vertical shafts: the waste shaft, salt handling shaft, exhaust shaft, and air intake shaft. The shafts for waste, salt, and air have permanently installed hoists capable of moving personnel, equipment, and waste between the surface and the underground repository. In addition to the natural barriers provided by the geology of the WIPP repository, engineered barriers are included in the design to provide additional confidence that the repository will isolate the waste. Regulations by U.S. Environmental Protection Agency required both natural and engineered barriers to be used at WIPP.

4.2 Intermediate Disposal Depth: Borehole/Shaft

Several different technologies could be used to place waste at an intermediate depth of between 30 m (100 ft) and 100-150 m (300-500 ft) below the earth's surface. Disposal of some wastes in boreholes drilled from the surface may be a suitable option where waste volumes are limited. The size of the borehole can be several meters in diameter, and the proximity of one borehole to another can vary depending on the design of the facility.

The technology for drilling boreholes is simple and widely available. Drilling technique used depends on the characteristics of the sediments and rocks of the area and local drilling practices for that region. Drillers from different parts of the country prefer different types of equipment and techniques. Different techniques include wash boring, jet percussion, cable-tool or percussion, and mud or hydraulic rotary drilling.

In addition, a bucket auger could be used to drill large-diameter boreholes for unconsolidated material. It can involve boring a hole, typically measuring 2.5 m (approx. 8 ft) or more in diameter, into the ground and pouring a concrete foundation in the bottom of the hole. A smaller diameter steel or fiberglass liner could then be lowered into the hole until it rests on the concrete foundation. This liner is then surrounded on the outside with a layer of concrete or cement grout, typically measuring about 0.3 m (1 ft) thick. Waste packages are then lowered and positioned as desired and after the liner has been filled with waste, grout is poured around the waste to form a solid cement-waste matrix inside the liner. A concrete cap is then placed on top of the hole, and any remaining part of the hole is backfilled with soil (U.S. Congress, 1988).

Augered holes with depths of 6 m (20 ft) to over 30 m (100 ft) have been used over the last several years at DOE's national laboratories for the disposal of some defense LLRW similar in radioactivity to Class B, C, and some GTCC waste. For example, unpackaged reactor fuel cladding and well-packaged tritium have been disposed of at the Nevada Test Site in a few unlined augered holes measuring about 37 m (120 ft) deep. The depths considered in the borehole disposal action alternative as described in DOE's 2011 Draft EIS for GTCC waste disposal are considerably deeper. The 2011 Draft EIS' borehole disposal entails emplacement of waste in boreholes at depths deeper than 30 m (100 ft) but above 300 m (1,000 ft) under the surface. About 44 ha (110 ac) of land would be required to accommodate the approximately 8,930 boreholes needed to dispose of the waste packages.

4.3 Near-Surface Disposal Depth

Near-surface disposal is the technology that is presently used for the disposal of Classes A, B, and C LLRW. Waste packages are often disposed of in near-surface earthen trenches that are generally up to 300 m (1000 ft) long. To reduce subsidence of the cover, Class B and C LLRW must be packaged to remain structurally stable for at least 300 years. Class B and Class C waste are segregated from structurally unstable Class A waste. In addition, Class C waste must

be disposed of at least 5 m (16 ft) below ground or covered with a barrier (usually made of concrete) that will last at least 500 years. The purpose of this intruder barrier is to prevent people from digging into the waste once the site is closed and the institutional period has ended. During the institutional period, monitoring and surveillance of the site must be maintained.

Among the most discussed enhanced near-surface disposal alternatives are: trenches, landfills, above- and below-ground concrete vaults, and combinations of several disposal technologies. Cementitious material (e.g., concrete or grout) would be used in the construction of all of these enhanced facilities. Numerous designs of concrete vaults or structural units below-ground have been proposed and built. These can range from a concrete vault in a simple excavation in the near-surface environment to a multitude of concrete structural units in a landfill. Although the variations in size and components between the designs can be great, the commonality among them is that the structural material is concrete, basically cement and aggregate, and all of them are underground and face similar physical and chemical processes that decrease isolation and weaken the containment features. Infiltrating water and the chemistry of the water and soil surrounding the concrete will effect and degrade cementitious material in the long term, although many other features (e.g., waterproof coatings, internal and external drainage, etc.) can be incorporated into facility designs to minimize the infiltration of surface water and to keep the waste as dry as possible.

4.3.1 Trench

For some wastes with higher concentrations of radionuclides, trench disposal has commonly been used in the past. The basic design for the enhanced trench disposal facilities described in DOE's 2011 Draft EIS for GTCC waste disposal are 3 m (10 ft) wide, 11 m (36 ft) deep, and 100-m (330 ft) long. The side walls of the trench are normally vertically constructed. A well-compacted material would be placed on top of the native material in the floor of the trench. A layer of sand or gravel (0.3 m [1 ft]) would be placed on top of the compacted material to improve stability. The nature of the compacted material would be selected to be compatible with the surrounding geologic material. The trench sidewalls would be constructed with temporary metal shoring. The metal shoring would be removed when the trench was closed. The waste packages would be placed into the trench about 5 to 10 m (15 to 30 ft) under the surface, and a fine-grained cohesionless fill (sand) would be used to backfill around the waste containers to fill voids. For higher activity waste, waste packages are placed in vertical reinforced concrete cylinders with concrete shield plugs on top of the concrete cylinders. After a trench is filled with the waste containers and backfilled, the barriers of the trench are enhanced with a reinforced concrete layer which would be placed over the waste packages to help mitigate any future inadvertent intrusion and also impede infiltrating water. Clean fill from construction would be available to backfill the trench above the concrete layer. Each trench could be capped with a cover system consisting of a geotextile membrane overlain by gravel, sand, and topsoil. In the case of the trench, the top of the cover system would be flush with or slightly elevated above the surrounding ground surface, depending on the final design.

4.3.2 Concrete Structural Containment

As used in this document, below-ground vault refers to any enclosed, engineered concrete structure located entirely below the natural grade. This structure would consist of reinforced concrete floors, walls, and roof. Below-ground vaults allow the disposal of wastes below-ground, provide stability, and, in conjunction with covers, restrict the movement of water downward through the waste. Below-ground vault disposal uses a sealed structure built of masonry blocks, fabricated metal, concrete or other materials that help prevent waste migration

in addition to a drainage channel, clay top layer, concrete roof, porous backfill, and a drainage pad for the concrete vault. The soil cover on top is an additional barrier to infiltration of water into the waste, which greatly reduces the likelihood of human, plant, or animal intrusion, and further reduces gamma exposure rates at the surface.

The above-grade vault system in DOE's 2011 Draft EIS for GTCC waste disposal is an alternative disposal method. GTCC waste disposal placement is assumed to be about 4.3 to 5.5 m (14 to 18 ft) above ground surface; however, an engineered cover with a thickness of about 5 m (16 ft) would be placed over the top of the vault after disposal activities were completed so that the entire facility would be below ground. In the 2011 Draft EIS, DOE states that the design includes footings and vault floors that are situated in a slight excavation just below the frost line. This design is similar to a below-ground vault option for LLRW disposal (NRC, 1987) that was previously investigated by the U.S. Army Corps of Engineers. Each vault would be 11 m (35 ft) wide, 94 m (310 ft) long, and 7.9 m (26 ft) tall, with 11 disposal cells situated in a linear array. Interior cell dimensions would be 8.2 m (27 ft) wide, 7.5 m (25 ft) long, and 5.5 m (18 ft) high, with an internal volume of 340 m^3 (12,000 ft^3) per cell. Double interior walls with an expansion joint would be included after every second cell.

4.4 Variations and Combinations of Near-Surface and Intermediate Depth Disposal

The brief description in the previous paragraphs of different disposal methods at various depths are generalized since each method can be varied in application and combined with other types or techniques during design. The disposal structures themselves can be varied by combining original features with different components of other designs. For example, a trench may have a concrete vault built within it, or a disposal structure may retain the same basic design but additional significant barriers could be added during construction (e.g., layers of high density polyethylene) so that the original main barrier such as a concrete vault would become one barrier out of a multitude of barriers. Earth-mounded concrete bunkers are an example of a combination of disposal types and methods and have been used in France (NRC, 1984).

The earth-mounded concrete bunkers disposal facility for radioactive waste consists of two distinct disposal technologies that are used at the same site. The earth-mounded portion is for the disposal of less concentrated radioactive waste above grade with an earth cover. The concrete bunker is designed for below-ground disposal of more concentrated LLRW (e.g., Class C) and for providing structural stability. Earth-mounded concrete bunkers are equipped with a drainage system and covered with impermeable clay and topsoil, giving the facility a rounded shape. The possibility of inadvertent intrusion is reduced by the use of a tumulus, waste encapsulation, and multiple barriers.

Drilling boreholes and mining shafts are normally used at intermediate depths (30 to 100-150 m (98 to 328-492 ft)), however these could also be used for both shallower depths and deeper depths. The technical hurdles (and expense) of drilling and placing waste increase with depth, but may become less of an obstacle in the future because of advances in the field of drilling. Another disposal variation example pertains to engineered underground excavations or deep geological repositories. If hydrogeological conditions are right, a repository could be constructed at an intermediate depth. Sweden has developed an intermediate-depth repository under the Baltic Sea, about half a mile offshore and 61 m (200 ft) below the sea floor. The facility, which has been operating since April 1988, is excavated into granite. It is designed with four large rooms to hold LLRW and a concrete silo, about 61 m (200 ft) high and 30 m (100 ft) in diameter, to contain intermediate-level waste (U.S. Congress, 1988).

The type of backfill can also be varied. For example, basic backfill alternatives could include natural (local) soil, granular material, and grout. Natural soil can vary from a very sandy to a very clayey texture. This type of backfill would normally consist of soil previously excavated when constructing the disposal cells. The sandy backfill would be expected to readily sift down into the interstitial spaces between waste packages and therefore help reduce the presence of voids in a disposal cell. A sandy backfill allows water to quickly flow past disposed waste to the bottom of the trench, thereby reducing the contact time and the potential for leaching of radionuclides out of the waste. This has been the experience at some existing disposal facilities. Another potential backfill alternative is to fill void spaces between waste packages with a cement grout. The grout would help stabilize the disposed waste and reduce subsidence of the disposal cell contents and disposal cell covers, thus reducing rainwater infiltration into the disposed waste. In the case of the concrete disposal methods (concrete trench, above-ground bunker, concrete slit trench, and concrete caisson), use of the concrete grout would turn the disposal cells into solid blocks of concrete interspersed with waste packages.

A newly constructed disposal facility owned and operated by Waste Control Specialists, LLC (WCS) located in Andrews County, Texas is a disposal type that combines various aspects of the previous discussed disposal methods. Underground concrete vault-like structures will be used (i.e., 1 ft reinforced concrete liners), however, instead of a trench or series of trenches, the concrete liners will be part of a deep landfill that extends down to about 37 m (120 ft). The Federal Waste Facility (FWF) is part of the WCS disposal facility. That portion of the FWF that lies below 30 m (100 ft), and therefore is at an intermediate disposal depth, is considered by WCS to be appropriate for GTCC waste disposal (lower-level LLRW could be placed above the GTCC waste). Additional components of the FWF include compacted clay layers, drainage layers, geosynthetic layers, a biointrusion layer, and an evapotranspiration layer within an engineered cover system that is not mounded at the surface, but rather, flush with the ground surface. GTCC waste would be placed in steel-reinforced concrete canisters and the canisters would be grouted after they are filled. The canisters are approximately 3.3 m (10 ft) high so that two on top of one another could be placed at the bottom of the FWF and potentially lie greater than 30 m (100 ft) below ground surface which would be intermediate depth disposal.

The potential number of available disposal technologies and operational practices are as numerous as the number of available waste processing options. Operational variations considered included options on (1) waste and chemical segregation (none, stability-based, and organic chemical-based); (2) waste emplacement (random, layered, stacked, and decontainerized); (3) compaction of disposal cells (minimal, moderate, and extreme); (4) backfill (onsite soil, sand, and grout); and (5) cover of disposal cells (minimum, improved, and intruder barrier) (NRC, 1986).

There are a relatively large diversity of engineered surface cover types and possible variations of engineered barriers within them. The two main cover categories are compacted resistive covers and evapotranspiration covers; the former relying on lower permeable material diverting water away from the waste and the latter by having the water removed by transpiring plants and by evaporation. These two categories can be mixed, and cover designs for many of today’s radioactive disposal sites often possess multiple types of barriers and can be better described as engineered surface barrier systems.

5 Disposal Environments

The natural environment in which the waste will be disposed can be expected to have a significant impact on projected doses from release of radioactivity from a disposal facility. When the regulations at 10 CFR Part 61 were developed, the NRC recognized that the site-specific nature of the disposal environment would be important for certain radionuclides and in particular for releases to the general environment. Consequently, the regulations 10 CFR § 61.13(a) require an analysis of the releases of radioactivity through various environmental pathways that clearly differentiates the role played by the natural environment from design features in isolating and segregating the waste.

The NRC staff expects that site-specific features, events, and processes associated with any disposal environment would be important to consider when demonstrating that GTCC waste, particularly associated long-lived radionuclides, can be safely disposed. Key features, events, and processes associated with a disposal site's environment that may need to be considered in analyzing a potential site can be generally categorized as meteorological, physical, hydrogeological, geochemical, and disruptive plausible future events. The importance of these features, events, and processes are expected to vary depending upon the disposal method and the particular disposal site characteristics. Some of the features, events, and processes are briefly discussed below.

Meteorological Features and Processes
Meteorological processes include the regional climate and its associated properties such as precipitation. Meteorological processes can affect the release and transport of radionuclides from the waste primarily through the amount of water that is available for mobilizing the radionuclides within the waste. The regulations for the near-surface disposal of LLRW (10 CFR Part 61) reflect the importance of minimizing water contact with the waste. The regulations emphasize the need to minimize water infiltration because of previous challenges associated with infiltration at near-surface land disposal facilities receiving LLRW prior to the development of the regulations. Meteorological processes are site-specific and their impact may vary depending on the disposal method. Therefore, meteorological processes are generally best considered in the context of a site-specific analysis. Further, because of the long-lived radionuclides often associated with GTCC waste, the evolution of meteorological processes over long time periods in the future will present challenges to demonstrating that public health and safety will be protected. A variety of methods are available, however, to provide model support for processes associated with long time frames.

Hydrogeological Features and Processes
Physical processes include advective-dispersive mechanisms that act to redistribute radionuclides from the waste through the surrounding environment. Physical processes can affect the movement of radionuclides through air, water, and soil pathways. Releases through the water pathways, in particular, via groundwater, tend to be the predominant releases from land disposal facilities for radioactive waste although in very arid environments other release pathways could be more significant. In groundwater pathways, advection, or the bulk movement of radionuclides with the flow of water, and dispersion of radionuclides due to heterogeneities in the flow velocity profile of groundwater at various spatial scales will affect radionuclide movement.

Geochemical Processes
Geochemical processes include physical-chemical interactions between liquid, solid, and gas phases within the disposal site and surrounding environment, such as dissolution-precipitation,

sorption-desorption, oxidative-reductive, and gas-solution interactions. Many of these processes can significantly affect the phase (i.e., solid, liquid, and gas) with which a radionuclide is associated and thus, the radionuclide's rate of movement out of the waste contained within the disposal units and through the surrounding environment. For example, the capacity of hydrogeological units to adsorb radionuclides moving with the groundwater can have a significant effect on how quickly contaminates can reach areas beyond the disposal facility. Demonstration of geochemical controls particularly for long-lived radionuclides such as those commonly associated with GTCC waste would likely need adequate model support given the long time frames associated with disposal of long-lived radionuclides and need to be evaluated on a case-by-case basis to ensure compatibility with the site environment.

Disruptive Plausible Future Events
Disruptive plausible future events include tectonic, igneous, and other processes such as flooding that may significantly impact the ability of the land disposal facility to protect public health and safety. Depending upon the site, disruptive processes could pose a challenge, though the effects of these processes are generally limited by site suitability requirements, such as those in 10 CFR § 61.50, which require avoidance of locations where tectonic processes such as faulting, folding, seismic activity, or volcanism may occur with such frequency and extent to significantly affect the ability to meet performance objectives. In this case, the site suitability requirements would require an evaluation to determine that there is reasonable assurance that these processes would not occur with such frequency and extent to significantly impact public health and safety. These future events would be best evaluated on a case-by-case basis to account for actual site conditions and the disposal method. At sites where disruptive processes may be significant, challenges are often associated with demonstrating the frequency of the events over long timeframes associated with the disposal of long-lived radionuclides.

6 Receptor Scenarios

A key component of the technical analyses performed to demonstrate that the performance objectives are met is the set of pertinent receptor scenarios. In general, the regulations at 10 CFR Part 61 for LLRW disposal seek to ensure (1) protection of the general population from releases of radioactivity from the disposal facility, (2) protection of individuals who may occupy the site and unknowingly come into contact with the waste or be exposed to radiation from the waste (i.e., inadvertent intruders); (3) protection of individuals during operations; and (4) stability of the site.

In developing 10 CFR Part 61, the NRC recognized that because the mobility of certain radionuclides in the environment can vary significantly from site to site, site-specific analyses would be more appropriate to assess the risk resulting from releases of radioactivity from a land disposal facility. Thus, the regulations require an analysis of pathways to demonstrate that the general population will be protected from releases of radioactivity. Likewise, the regulations require site-specific analyses of risks to individuals during operations and long-term stability of the site. The NRC recognized that various facilities may differ in the type of waste received for disposal and in the methods used to dispose of the waste. Therefore, site-specific analyses are required to demonstrate protection of individuals during operations. The NRC also recognized that various facilities may be sited in different locations and subject to different natural processes as a result. Therefore, site-specific analyses are required to demonstrate that long-term stability of the disposal site will be maintained.

Unlike the other three performance objectives, the NRC determined that a uniform waste classification system could be used to ensure protection of inadvertent intruders when combined with intruder barriers. Therefore, licensees must demonstrate that the waste classification and segregation requirements in Part 61 are met and that intruder barriers are provided, rather than perform site-specific analyses. To develop the classification and segregation requirements, the NRC considered a variety of potential inadvertent intruder receptor scenarios. The NRC determined that reasonably conservative generic receptor scenarios that were considered typical of human activities (e.g., construction of a residence and agriculture) were suitable for developing the criteria that would protect an inadvertent intruder at a near-surface disposal facility.

The waste classification criteria delineate when waste is Class A, B, C, or GTCC. The regulations specify that Class A, B, and C waste streams are suitable for near-surface disposal, but GTCC waste is typically not. Therefore, the waste classification and segregation requirements do not specify how a licensee would demonstrate that the performance objective for the protection of an inadvertent intruder would be met for the disposal of GTCC waste. Likewise, the waste classification and segregation requirements are specific to near-surface disposal. Therefore, they do not specify how a licensee would demonstrate that the performance objective would be met for disposal methods other than near-surface disposal.

For disposal of GTCC waste using methods other than near-surface disposal (e.g., geologic disposal is proposed under 10 CFR § 61.55), alternative consideration of intrusion may be necessary. For example, if GTCC waste were to be disposed in a deep geologic repository regulated to standards and regulations that are similar to regulations at 10 CFR Parts 60 and 63, intrusion may be considered differently than for near-surface disposal in 10 CFR Part 61. For example, the regulations at 10 CFR Part 63 contain specific requirements for the evaluation of a human intrusion scenario at 10 CFR § 63.322, to facilitate an evaluation of a repository's ability to continue to perform after an intrusion event (e.g., ability of the repository to limit

releases of radionuclides and limit exposure to the reasonably maximally exposed individual). These requirements focus the analysis on the timing of the hypothetical intrusion (based on degradation of the engineered barriers) and the impact of releases from the repository as a result of a stylized intrusion event constructed specifically to obtain insights from such an event. Because the regulations focus the analysis on timing and the impact of the overall performance of the repository, they do not require an assessment of the direct impacts to the intruder (e.g., the potential for direct contact of a driller with spent fuel).

6.1 Generic Inadvertent Intruder Receptor Scenarios

The NRC staff continues to view the generic receptor scenarios used to develop 10 CFR Part 61 as reasonably conservative for estimating potential radiological exposures to an inadvertent intruder while limiting excessive speculation about future human activities. These receptor scenarios are normal activities in which humans typically engage in a variety of environments and they contain a set of typical exposure pathways that reflect the generic nature of the original analysis for the development of 10 CFR Part 61 (NRC, 1981).

Three direct contact receptor scenarios involve acute exposures, one direct-contact receptor scenario involves chronic exposures, and one groundwater receptor scenario involves chronic exposures as discussed below:

(1) intruder-construction, in which the intruder receives acute exposures while excavating into disposed waste during construction of a dwelling or building;
(2) intruder-discovery, a variant of the intruder-construction receptor scenario, in which the intruder recognizes the presence of waste during excavation and ceases activity;
(3) intruder-drilling, in which the intruder receives an acute exposure while drilling through the waste to install a well;
(4) intruder-agriculture, in which an intruder receives chronic exposures following construction of a dwelling built in the intruder construction receptor scenario; and,
(5) intruder-well, in which an intruder is chronically exposed to contaminated groundwater while living on the disposal facility site.

The following subsections discuss the details of the receptor scenarios themselves and their expected applicability for GTCC waste disposal. The generic receptor scenarios used to develop the 10 CFR Part 61 waste classification criteria may not be appropriate to demonstrate compliance for GTCC waste or certain sites because of the following factors that may limit or alter the activities and exposure pathways for an inadvertent intruder:

(1) characteristics of the disposal site, such as the presence of adequate water;
(2) facility design, particularly the expected long-term capabilities of engineered intruder barriers;
(3) disposal practices, such as waste emplacement as a deterrent to intrusion; and,
(4) waste characteristics, including migration behaviors of radionuclides and progeny.

Intruder-Construction and Intruder-Discovery Receptor Scenarios
For the disposal of GTCC waste, the intruder-construction receptor scenario is not expected to be limiting because the depth of disposal of GTCC waste will typically be greater than the assumed depth of excavation for a dwelling (i.e., 3 meters [10 ft]) used in this receptor scenario. Therefore, this scenario will typically not result in greater estimated exposures than the other generic receptor scenarios. Likewise, the intruder-discovery receptor scenario is not expected to be limiting for GTCC waste unless associated with the intruder-drilling receptor scenario.

Intruder-Drilling Receptor Scenario
In the intruder-drilling receptor scenario the volume of material exhumed is limited to the dimensions of the borehole rather than the dimensions of the dwelling footprint. The ratio of the thickness of waste exhumed to the total depth drilled can result in different mixing than is assumed to occur for the intruder-construction receptor scenario. The depth of waste exhumation is generally tens to hundreds or more feet deeper than the dwelling foundation excavation in order to access groundwater with adequate yields for household supply. Depending on the method of drilling and on the assumed cuttings management practice, the intruder-drilling receptor scenario may result in larger exposures compared to the intruder-construction receptor scenario for GTCC waste if the driller comes into contact with waste that was disposed at greater depths and if that waste is less diluted as a result of potentially more limited mixing than the intruder-construction receptor scenario.

Intruder-Agriculture and Intruder-Well Receptor Scenarios
Originally, the intruder-agriculture receptor scenario used in the waste classification tables did not include consumption of water from an onsite well (as in the intruder-well receptor scenario) because the exposures from migration of radionuclides in groundwater are much more a function of site specific environmental and geohydrological conditions and total activity rather than directly related to waste concentration. However, NUREG-0782 (NRC, 1981) recommended that radionuclides that are important from a migration standpoint have inventory limits established on a site-specific basis, based upon groundwater migration considerations, and that the generic intruder-agriculture receptor scenario should also consider the use of contaminated groundwater from an onsite well in the intruder assessment to demonstrate compliance with 10 CFR § 61.42. Therefore, current intruder-agriculture receptor scenarios consider the consumption of food grown in contaminated soil as well as consumption of contaminated well water and exposure to ground and plant surfaces that are irrigated from the intruder well.

6.2 Site-Specific Receptor Scenarios

Site-specific receptor scenarios, which are developed by the licensee, would give licensees greater flexibility in developing the receptor scenario(s) to demonstrate that the inadvertent intruder performance objective is met. Developing a site-specific receptor scenario or modifying a generic receptor scenario using site-specific information would require a technical basis to support the receptor scenario. The technical basis for site-specific receptor scenarios could consider the capabilities of intruder barriers, site characteristics, likelihoods of contacting certain waste streams, and trends and area land use plans.

The types of site-specific information that could be used to justify selection of a receptor scenario to demonstrate the inadvertent intruder performance objective is met are broadly categorized as physical information and cultural information. Physical properties such as climate, topography, geology, soil types, and water availability of the site may change over time, particularly long time periods; however, the change is expected to be slow compared to changes in the cultural use of the land. Because of the uncertainty in estimating future human disruptive activities, cultural use of the land is anticipated to be very uncertain over long time periods. Therefore, cultural information should not be relied upon as a basis for receptor scenario selection beyond a few hundred years. Rather, the consideration of cultural information should be limited to the operating lifetime of the disposal facility.

7 Qualitative Examination of Disposal Challenges

The objective of this section is to discuss the challenges of GTCC waste disposal. A more comprehensive understanding of the risks associated with site characteristics and disposal methods when considering GTCC LLRW disposal could help regulators when reviewing future potential site-specific performance assessments and inadvertent intruder assessments for disposal of GTCC waste. This section presents aspects that should be considered before disposal and discusses disposal challenges under different environmental settings and receptor scenarios and, in addition, contains insights from a qualitative examination of individual GTCC waste streams, disposal methods, disposal environments, relevant receptor scenarios, and the interrelationships between these disposal aspects.

It is common to classify radioactive waste according to its activity. Limits on the total activity and the activity concentrations of radionuclides contained in waste are normally specified in the waste acceptance criteria. These limits can result from safety analyses being carried out for a particular disposal option and a specific waste form. Human intruder receptor scenarios are often correlated with activity concentration, while doses from contaminated groundwater plumes are often correlated with total repository activity. Inadvertent intruder receptor scenarios involving direct human contact with the disposed waste were used extensively to establish the classification system in 10 CFR Part 61.

Unlike other inadvertent intruder receptor scenarios involving direct human contact with the waste, impacts from the drilling receptor scenarios are governed not only by the radionuclide concentration, but also by the radionuclide quantity of waste a driller brings up and becomes exposed to. The total radionuclide quantity brought to the surface is of concern, which means that in addition to a limit on the radionuclide concentration, a limit is needed in the thickness of the radioactive column accessed. A general way to accomplish this is to specify a radionuclide-specific area concentration limit in units of activity per area, (i.e., a limit in the total activity of a given radionuclide beneath a given surface area). An area concentration limit could be used and be calculated by dividing the radionuclide GTCC concentration limit by the waste stratum thickness used to set the concentration. Horizontal drilling has become more commonplace in recent years, and this development could complicate area concentration limits if this method was frequently used for drilling water wells. Directional drilling is used in urban or suburban environments when trenching or excavating is not practical, or in oilfield and coal operations, but normally not used for single residential water wells, so that this new innovation may not be a complicating factor for calculating an area concentration limit.

Unlike activated metals and sealed sources with their relatively high activity concentration, GTCC Other Waste has, on average, a lower activity concentration so that area concentration limit could be attempted, whereby a limit in the total activity of a given radionuclide beneath a given surface area could be applied by dividing the radionuclide GTCC waste concentration limit by the waste stratum thickness used to set the concentration (NRC, 1986). The physical form of most GTCC Other Waste also lends itself more to an area concentration limit than the more compact forms of activated metals and sealed sources.

Activity concentrations of the GTCC waste are expected to be relatively high and varied, however the overall volume of the GTCC waste is generally small in comparison with other wastes. Deeper disposal methods will make intrusion difficult, but not impossible, due to the depth of disposal; particularly if one assumes that degradation of engineered barriers begins after 500 yr. This assumption and other assumptions made in association with inadvertent

intruder receptor scenarios will have a significant role in the dose rate to a GTCC LLRW intruder.

Duration of intruder barrier effectiveness and disposal depth are two significant factors. If the depth of disposal is below 3 m (10 ft), the set of inadvertent intruder receptor scenarios possible can be reduced to the intruder-drilling receptor scenario. If intruder barriers could be demonstrated to be effective longer than 500 yr, the inadvertent intruder receptor scenarios may not be the limiting scenario that they are currently thought to be. Aside from the regulatory alternatives discussed in Section 6.0, research efforts could focus on efforts to find long-lived material that could stop or break a drill bit before it reaches the waste. Barriers to slow water infiltration may be used as an analogue. For example, past surface covers relied almost exclusively on a compacted clayey soil layer whose effectiveness beyond 10 yr is often disputed. Current engineered surface barriers frequently use a geosynthetic material such as high-density polyethylene. The technical basis for the effectiveness of this material is estimated to be hundreds of years. For intruder barriers, material may exist, or be designed, to provide a similar long-term intruder barrier.

The properties of the GTCC waste types waste forms can have a large impact on the dose output. For example, in order to gain insights on the more probable sequence of events, drilling tests on metals similar to activated metals and on the outer canisters of sealed sources would provide some insights on the likely response of a hypothetical driller. The waste form of activated metal is often bulky in form and would take time to corrode and degrade so that an intruder driller would be prevented from drilling through this waste type for hundreds if not thousands of years. The sealed source radionuclides are generally enclosed in capsules made of stainless steel, titanium, platinum, or other inert metals. Stainless steels corrode in all natural water exclusively by pitting, with the extent of pitting determined predominantly by the chloride level (NRC, 1986), which will vary from region to region. A site with low chloride levels would help keep the outer hull of a sealed source intact and increase the probability that a well driller would notice a stainless steel or titanium canister that requires a high-speed steel drill bit in order to penetrate.

If human intruder receptor scenarios were no longer the limiting scenarios, performance assessment with groundwater transport receptor scenarios would increase in importance. Information concerning possible long-term natural changes to a disposal facility site and the surrounding region become important for long-term performance of the disposal facility; site-specific features, events, and processes become significant. For this reason, both categories of receptor scenarios can provide essential insights for GTCC waste disposal and both inadvertent intruder and groundwater release receptor scenarios will be examined in this section (see Tables 8-1 through 8-5 in Section 8).

Insights from Receptor Scenarios: DOE's 2011 Draft EIS

In their Draft EIS, 2011 Draft EIS evaluated impacts from GTCC waste at generic disposal facilities for borehole, trench, and concrete vault disposal methods to a hypothetical resident farmer located 100 m (330 ft) downgradient from the disposal facility. DOE did not evaluate inadvertent intruder receptor scenarios as all four disposal methods include mitigation features of human intrusion impacts. Four generic sites represented the four major geographic regions of the U.S. (i.e., Region I covers the Northeastern states, Region II the Southeastern states, Region III the Midwestern states, and Region IV the Western states). One of the most important parameters in the evaluation is the depth to groundwater in these four regions. These depths were determined to be as follows: Region I (3.4 m or 11 ft), Region II (13 m or 44 ft), Region III (2.2 m or 7 ft), and Region IV (55 m or 180 ft).

One of the major assumptions in the 2011 Draft EIS was that the GTCC Other Waste would be stabilized with grout or other material and that this stabilizing agent would be effective for 500 years. Consistent with the assumptions used for engineering controls, no credit was taken for the effectiveness of this stabilizing agent after 500 years in the 2011 Draft EIS analysis. That is, it was assumed that any water that would contact the wastes after 500 years would be able to leach radioactive constituents from the disposed-of materials. These radionuclides could then move from the unsaturated zone to the underlying groundwater system. In the 2011 Draft EIS, this assumption is considered to be conservative because grout or other stabilizing materials could retain their integrity for longer than 500 years. It was further assumed that after the first 500 years, the facility covers would still be effective in reducing water infiltration to the top of the facility (i.e., 80 percent reduction is assumed). The 2011 Draft EIS did not describe this latter assumption as being conservative.

The highest estimated annual doses associated with the use of a commercial disposal facility for GTCC wastes were calculated to occur in Region I. A disposal facility in this region is expected to be in a generally humid environment, and the distance to the groundwater table is expected to be relatively short. These properties of a humid site are expected to result in higher radiation doses and risks that would occur at an earlier time than those at more arid sites, such as those expected in Region IV. The peak annual doses in Region III were generally lower than those in Regions I and II. The peak annual doses are lowest in Region IV, and it is predicted that radionuclides would not reach the groundwater table and the well of a hypothetical resident farmer within the first 10,000 years following disposal because of the much lower water infiltration rate assumed for Region IV than for the other three regions.

Potential long-term impacts on human health results from GTCC waste disposal were also analyzed in the 2011 Draft EIS at alternative site-specific locations. Site-specific input parameters were used together with alternative disposal methods such as geologic repository, borehole, trench, and concrete vaults. Potential doses to a hypothetical resident farmer located 100 m (300 ft) from the edge of the disposal facility were calculated using the RESRAD-OFFSITE[4] code. Arid sites once again fared better than the humid sites; however one arid site did not fare as well due to the geology of the site (Idaho National Laboratory site). I-129 and uranium isotopes with site-specific K_d values were assigned values of zero due to basalt layers in the subsurface causing quicker and higher peaks than at the other arid sites.

As for the GTCC waste types, activated metals contributed the most to dose within 10,000 yrs while sealed sources dose contribution was basically nonexistent for the semiarid to arid sites, but saw significant contribution in humid sites due to corrosion of the metals. Sensitivity analyses showed that the infiltration rates, distance of the receptor from the facility, and the longevity of the effectiveness of stabilizing grout to solidify GTCC Other Waste were important parameters for the dose results.

7.1 Deep Geologic Repository

Insights from Previous Examinations of GTCC Waste Disposal

Deep geologic disposal offers the highest level of isolation available within disposal concepts currently actively considered. However, they are expensive to develop and, currently, there is only one deep geologic repository in existence in the U.S. An alternative to developing a new

[4] RESRAD-OFFSITE is an assistance tool that provides technically sound, cost-effective, and user-friendly methods for evaluating human radiation doses and risks associated with exposure to radiological contamination.

deep geologic repository is to consider and examine existing mined cavities. NUREG/CR-3774, Vol. 6 (1986a) stated that existing dry and structurally stable mined cavities in bedded limestone or salt may provide satisfactory waste isolation over the long periods required. Underground coal mines are the most abundant type of enclosed mined cavities, but this type of mine is unsuitable for radioactive waste burial since most coal seams in contact with mined cavities will have high hydraulic conductivities and would become a preferential flow path for released radioactive contaminants. Metallic mineral mines generally were developed in an irregular plan to follow zones of mineralization making such mines unsuitable for waste disposal. Drainage from mines exploiting sulfide ores is corrosive and would be incompatible with most drummed or concrete encased LLRW. The mines for nonmetallic minerals such as limestone, halite and gypsum are developed along bedded materials and offered a better potential for disposal of radioactive wastes.

NUREG/CR-3774, Vol. 6 (1986a) evaluated possible mined cavity disposal and determined that dry, structurally stable mines were required. The current criteria of 10 CFR 61 Subpart D are specifically directed to near-surface disposal. Important differences between near-surface and deeper than near-surface environments exist and some of these differences were examined in NUREG/CR-3774, Vol. 6 (1986a) and are presented below.

An important consideration with near-surface facilities is shielding sufficient to protect a person on the surface from radiation from buried wastes. For this purpose, a cover is required and a minimum depth of burial may be prescribed. For waste disposal in an underground excavation, the rocks that form the roof and walls of an underground excavation provide an automatic cover. The deeper an underground excavation, the greater the thickness of rock available to impede radiation, but even in a relatively shallow underground excavation, the rock overburden must be thick enough to be mechanically stable, and thus should provide a substantial radiation barrier.

There are several geological and meteorological effects and processes that are important to the design, performance, and stability of a near-surface facility but that have little or no effect on a deep geologic repository. These factors include surface flooding, storms and other weather conditions, surface geological processes, soil mechanics and soil geochemistry.

The position of an underground excavation with respect to the water table is an important matter and a complicated one. As a rule, an underground excavation is far more likely than a near-surface facility to be beneath the water table, simply because of its greater depth. This is particularly true in regions of humid climate. The reason why dryness is a requisite for an underground disposal facility is to prevent escape of radionuclides by leaching. If an excavation becomes flooded after closure, wastes will become soaked, radioactive substances will be leached, and moving groundwater may transport these substances into the environment.

An alternative to keeping a deep underground excavation dry is to let the excavation flood in a setting where the water is already nonpotable and stagnant. Conceivably a deep geologic repository might be situated such that groundwater flow would be so slow that diffusion would be the major solute-displacement mechanism, and a time span of many half-lives of the hazardous nuclides present would elapse before contaminants would reach that part of the hydrosphere taking part in the meteoric hydrologic cycle. Although deep geologic disposal in the saturated zone is under consideration outside of the U.S., for example in Sweden, there are no such proposals in the U.S. and therefore this alternative is not discussed further here.

Insights from the 2011 Draft EIS
The post-closure impacts of disposing of the GTCC wastes in deep geologic repository were evaluated in the 2011 Draft EIS (DOE, 2011), specifically the impacts from potential radiation doses from radionuclide release from waste packages at WIPP and groundwater transport of the radionuclides. Release of radionuclides to the atmosphere was assumed to be zero. DOE's analysis showed that the inventory of GTCC LLRW wastes could be disposed of in WIPP in compliance with existing regulatory requirements.

7.1.1 Deep Geologic Repository Disposal Method for Activated Metals

Insights from Receptor Scenarios
DOE's (2011) evaluation of the WIPP site in New Mexico showed that doses from a groundwater release scenario would be in compliance with existing regulatory requirements. The post-closure performance data package from Sandia National Laboratories (2008) indicated that from the resulting below-compliance doses, activated metals had contributed the most to an increase in the activity concentration release.

For the inadvertent intruder receptor scenarios, the intruder-drilling receptor scenario would be the scenario with the highest likelihood of occurring. The waste is too deep for a construction crew to reach so that an intruder in the intruder-agriculture receptor scenario would be exposed to radiation only from drinking well water and the small percentage of radioactive drill cuttings from the well construction. But also for the intruder-drilling receptor scenario to become plausible, several factors need to be overcome. If a repository is located in the saturated zone, the driller will not drill much deeper than the water table and stop above the repository. If a repository is in the unsaturated zone, the repository would still be located within deep geological units so that drilling would likely become expensive, and a potential resident may find a cheaper alternative to obtain water. The waste packaging will probably include mortar grout, if not concrete, which could be difficult to drill through depending on the drilling method which, in turn, is dependent on the geology of the unsaturated zone. Depending on the assumptions made with regards to degradation and corrosion of the activated metals, the drillers will most likely not be able to drill through the metal. Repositories that would be located in the unsaturated zone would need sufficient space within the unsaturated zone to be operational and therefore require a location that has a relatively deep water table and thick unsaturated zone. These locations are normally found in more arid areas where the precipitation rate is too low to support a high water table. This scarcity of water would slow the degradation or corrosion rate of activated metal so that a drill bit would have difficulties even thousands of years after disposal to penetrate this type of GTCC waste. The assumptions made with regards to activated metal degradation, or the model support and technical justification needed for an applied corrosion rate used in calculations, would be critical to the impact outcome.

Information on the deep geologic repository disposal method for activated metals is also summarized in Table 8.1 in Section 8.

7.1.2 Deep Geologic Repository Disposal Method for Sealed Sources

Insights from Receptor Scenarios
For the inadvertent intruder receptor scenarios, the intruder-drilling receptor scenario would be the scenario with the highest likelihood of occurring. The waste is too deep for a construction crew to reach so that an intruder in the intruder-agriculture receptor scenario would be exposed to radiation only from drinking well water and radioactive drill cuttings from the well construction mixed in with top soil if the cuttings from the sealed sources (e.g., ceramic oxides, salts, metals)

have become indistinguishable from the top soil. A repository located within deep geological units would probably increase the expense of drilling considerably, and a potential resident may find a cheaper alternative to obtain water. Depending on the assumptions made with regards to degradation of stabilizing agents such as grout and the degradation and corrosion of metals, the drillers may have difficulties drilling through grout and the outer metallic hull of a sealed source.

As previously discussed in Section 7.1.1, a deep geologic repository would probably be located in an arid area. This scarcity of water would slow the degradation or corrosion rate of metal so that a drill bit would have difficulties even thousands of years after disposal to penetrate this type of GTCC waste. However, since the thickness of the metallic cover for sealed sources is not as thick as most activated metals, a drill bit might penetrate through the sealed source more easily than a piece of activated metal. DOE's (2011) evaluation of the WIPP site in New Mexico showed that doses from a groundwater release scenario would be in compliance with existing regulatory requirements. The post-closure performance data package from Sandia National Laboratories (2008) indicated that from the resulting below-compliance doses, sealed sources would contribute less than activated metals to the activity concentration release.

Information on the deep geologic repository disposal method for sealed sources is also summarized in Table 8.1 in Section 8.

7.1.3 Deep Geologic Repository Disposal Method for GTCC Other Waste

Insights from Receptor Scenarios
For the inadvertent intruder receptor scenarios, the intruder-drilling receptor scenario would be the scenario with the highest likelihood of occurring. The waste is too deep for a construction crew to reach so that an intruder in the intruder-agriculture receptor scenario would be exposed to radiation only from drinking well water and the small percentage of radioactive drill cuttings from the well construction. A repository located within deep geological units would probably increase the expense of drilling considerably, and a potential resident may find a cheaper alternative to obtain water.

As previously discussed in Section 7.1.1, a deep geologic repository would probably be located in an arid area. This scarcity of water would slow the degradation rate of a stabilizing agent such as grout and the grout could remain resistant to degradation for a long time. However, GTCC Other Waste and its waste form would not be as resistant to drilling as the activated metals or sealed sources, and it is conceivable that a driller would bring up GTCC Other Waste. DOE's (2011) evaluation of the WIPP site in New Mexico showed that doses from a groundwater release scenario would be in compliance with existing regulatory requirements. The post-closure performance data package from Sandia National Laboratories (2008) indicated that from the resulting below-compliance doses, GTCC Other Waste would contribute less than activated metals to the activity concentration release.

Information on the deep geologic repository disposal method for GTCC Other Waste is also summarized in Table 8.1 in Section 8.

7.2 Borehole/Shaft

Insights from Previous Examinations of GTCC Waste Disposal
IAEA (2003) states that the borehole disposal concept entails the emplacement of solid or solidified radioactive waste in an engineered facility of relatively narrow diameter bored and operated directly from the surface. Borehole disposal facilities cover a range of design concepts

with depths ranging from a few meters up to several hundred meters. Their diameters can vary from a few tens of centimeters up to more than one meter. The borehole may have a casing and the waste would normally be contained within an engineered package that is surrounded by backfill material. A disposal facility may consist of a single borehole or a group of boreholes that may or may not be located in conjunction with other nuclear facilities. The underlying common characteristic of all borehole facilities is their small footprint at the surface, which reduces the likelihood of human intrusion into such a facility. Also, the limited radionuclide inventory intrinsically limits the potential hazards to people and the environment. Borehole disposal facilities have a number of potentially favorable characteristics of possible benefit from a waste safety and economic point of view:

(1) Provide long term isolation from humans and the environment for small volumes of high specific activity radioactive waste in high integrity waste packages;
(2) Provide direct access to a suitable geological horizon using readily available technology;
(3) Have minimal impact and require limited land area and infrastructure;
(4) Require short periods of construction, operation, and closure;
(5) Can be developed when required to dispose of waste as it arises;
(6) Require minimal post-closure control over the disposal site; and,
(7) Have a low probability of human intrusion and future disruptive events due to the small footprint of the borehole and the ability to dispose of waste at a suitable depth.

NUREG/CR-3774, Vol. 5 (1985b) evaluated the technical requirements of augered holes and boreholes and found these additional advantages:

(1) Remote handling equipment may be used for high activity wastes to enhance worker safety.
(2) Augered holes are amenable to intermittent or low volume operations.
(3) The operating period for individual holes is relatively short.
(4) Closure of individual holes does not adversely affect nearby holes or closure of the site.

The stated disadvantages were:

(1) Minimization of void spaces, backfilling, and compaction are necessary to minimize settlement and long-term maintenance.
(2) The disposal area cannot be exploited as fully as other methods because of the relatively low volume capacity of the holes and the much higher volume of unused space surrounding each hole.

In the absence of significant groundwater movement or infiltration of surface water, slow diffusion of radioactive ions through surrounding soils is probably the dominant mode of radionuclide migration (NRC, 1985b). The slow diffusion, together with deeper disposal, would help reduce the likelihood of radioactive materials released to the atmosphere at the surface. In addition, protection of individuals from inadvertent intrusion and prevention of plant and animal intrusion is expected to be achieved through the use of the greater disposal depth, thick covers, and the use of sealing plugs and covers, although the shorter distance to the groundwater due to the greater disposal depth in comparison to near-surface disposal would need to be part of any assessment. However, as pointed out previously, direct access to a suitable geological horizon at a particular depth is possible with the borehole method. If that ideal depth has been determined to be in the saturated zone, there should be no technological reason why this couldn't be done. Figure 7-1 is from IAEA (2003) and shows waste located in either the

saturated or unsaturated zone and at different depths. [Note, for this examination, no saturated zone disposal is discussed since no such disposal designs have been proposed in the U.S.]

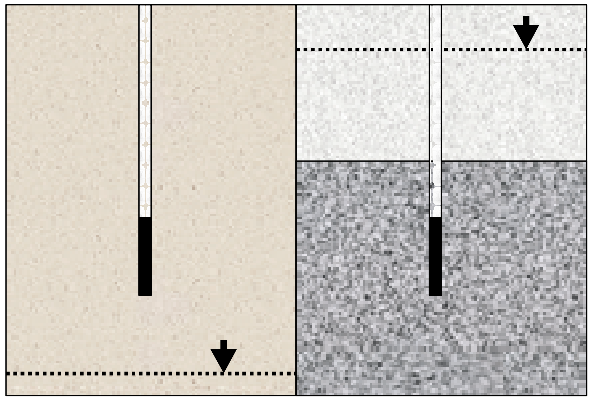

Figure 7-1: **Left side shows waste disposal in the unsaturated zone. Right side shows waste disposal in the saturated zone mostly likely in an aquiclude. (IAEA, 2003)**

Not being limited to the depth ranges considered for near-surface disposal (meters to tens of meters) or geologic disposal (hundreds of meters) gives this disposal method a greater flexibility to reach a desired depth for disposal. IAEA (2003) describes how radionuclide containment requirements can have important consequences for the choice of disposal depth for sealed sources. The distribution of specific radionuclides within and between boreholes could be of importance for the long-term safety of the facility. It may be beneficial to distribute long-lived sources in a number of borehole facilities to lower the potential impact at any receptor point. Similarly, differences in borehole performance may be associated with the location of the sealed source within a borehole. Depending on the dominant scenario, longer-lived sealed sources may be placed at the bottom of the borehole.

Insights from the Draft EIS

The post-closure impacts of GTCC waste disposal using alternative disposal methods at various sites were evaluated in the 2011 Draft EIS, including the borehole disposal method. The 2011 Draft EIS stated that the borehole method would provide better protection against potential exposures from airborne releases of radionuclides because of the greater depth of the cover material. The boreholes would be 30 m (100 ft) under the surface, and this depth of overlying soil would inhibit the diffusion of radon gas, CO_2 gas (containing C-14), and tritiated (H-3) water vapor to the atmosphere above the disposal area. However, because the distance to the groundwater table would be closer from boreholes than from trenches or vaults, radionuclides that leached out from wastes in the boreholes would reach the groundwater table in a shorter time than radionuclides that leached out from the trenches or vaults. Results from post-closure evaluations showed that for each of the alternative sites evaluated, the borehole disposal method produced the earliest peak dose for all of the sites. This normally was a difference of a few thousand years, although never in that range where it influenced the peak occurring before or after 10,000 yrs. For humid sites in the eastern U.S., DOE did not believe these regions to be applicable for the borehole disposal method. That is, a water table would be considered to be too close to the ground surface and therefore the bottom of any borehole would be too close to a potentially fluctuating water table.

When the borehole, trench, and concrete vault disposal methods were compared, the borehole method produced the lowest peak doses for all the sites that did have doses (see Table 8-5).

Most sites with semiarid climates produced two peak doses: the first from radionuclides with extremely low distribution coefficient values such as Tc-99, I-129, and C-14, while the second peak occurred after 10,000 yrs due to radionuclides with higher distribution coefficients such as the uranium isotopes.

With regard to the borehole disposal method, additional factors to consider is that boreholes need only a limited space in comparison to other disposal methods, so that given a certain area, the region that contains waste directly underneath this area would be smaller than for a site using a repository, trench, or vault method.

7.2.1 Borehole Disposal Method for Activated Metals

Insights from Receptor Scenarios

As previously stated in Section 7.2, boreholes would most likely be used, if at all, in non-humid areas with minor rain- and snowfall, since higher precipitation rates do not allow water tables to drop to elevations that allow a thick enough unsaturated zone where a borehole of intermediate depth could be viable (i.e., sufficient distance between bottom of the borehole and the water table). From the semiarid to arid alternative sites that DOE evaluated in the 2011 Draft EIS, all sites showed activated metals contributed the highest percentage to dose. In the evaluation, DOE assumed that after 500 yrs engineered surface barriers would be sufficiently degraded so that 20 percent of the sites' naturally infiltrated water would be in contact with, and be able to corrode, the waste. However, at the Nevada National Security site and the site near the WIPP, that infiltrating rate was so low that either no dose at all occurred or the dose occurred after 10,000 yrs (see Table 8-5).

After a borehole is filled with the waste containers and backfill, a reinforced concrete layer could be placed over the waste packages to help mitigate any future inadvertent intrusion. Use of steel reinforcement (rebar), in two perpendicular layers, would strengthen the concrete. In addition to adding strength to the concrete layer, the spacing of the rebar would provide protection against inadvertent drilling straight down into a borehole. For this reason, the concrete could have two sets of perpendicular steel reinforcement, one near the top face and the other near the bottom face of the barrier. With a spacing of 15 mm (0.6 in), most drill bits would not pass into the borehole without encountering the steel reinforcement first, if they had not initially been stopped by the undegraded concrete itself.

From the inadvertent intruder receptor scenarios described in Section 6, the intruder-drilling receptor scenario would be the scenario with the highest likelihood of occurring. The waste is too deep for a construction crew to reach so that an intruder in the intruder-agriculture receptor scenario would be exposed to radiation only from drinking well water and the small percentage of radioactive drill cuttings from the well construction. However, the intruder-drilling receptor scenario to become plausible, several factors need to be overcome. The most prominent factor from these would be the activated metal waste form. The scarcity of water at an arid site would slow the degradation or corrosion rate of activated metal so that a drill bit would have difficulties even thousands of years after disposal to penetrate this type of GTCC waste. The assumptions made with regards to activated metal degradation, or the model support and technical justification needed for an applied corrosion rate used in calculations, would be critical to the impact outcome.

Information on the borehole disposal method for activated metals is also summarized in Table 8.2 in Section 8.

7.2.2 Borehole Disposal Method for Sealed Sources

Insights from IAEA (2003)
According to IAEA (2003), the borehole disposal concept could possibly provide a solution for the long term management of disused sealed sources at a reasonable cost and provide a good level of safety for human health and the environment.

If sealed sources were to be disposed of at intermediate depths in man-made shafts or boreholes, information on the type of borehole disposal facility that would be required could be gleaned from the number of sources, their half-lives, and their rate of accumulation. For a large number of sources over time, an applicant may decide to develop a disposal facility with an extended lifetime, with borehole disposal at a range of depths and where disposal takes place in phases. If the number of sources is small and contains a very small inventory of long-lived radionuclides and if only one campaign of disposal is envisaged, the applicant may decide to dispose of all sources in a borehole. This will depend on the level of institutional control and site conditions and will need to be assessed on a case-by-case basis.

Insights from Receptor Scenarios
As previously stated in Section 7.2, boreholes would most likely be used, if at all, in semiarid to arid areas since higher precipitation rates do not allow water tables to drop to elevations that allow a thick enough unsaturated zone where a borehole of intermediate depth could be viable (i.e., sufficient distance between bottom of the borehole and the water table). From the semiarid to arid alternative sites that DOE evaluated in their 2011 Draft EIS, all sites showed sealed sources contributing nothing to receptor dose within the first 10,000 yrs (see Table 8-5) with the exception of one alternative site, the Idaho National Laboratory site, with its basalt layers as mentioned in Section 7.0. The lack of dose may be due to the assumed ratio of the relatively small sealed source to the waste packaging around it, slowing the access of infiltrating water. The sealed source radionuclides are generally enclosed in capsules made of stainless steel, titanium, platinum, or other inert metals. Stainless steels corrode in all natural water exclusively by pitting, with the extent of pitting determined predominantly by the chloride level (NRC, 1986), a very site-specific parameter. Titanium and platinum are highly resistant to corrosion. From the semiarid to arid areas evaluated in the 2011 Draft EIS, the Idaho National Laboratory site is the only site where sealed sources contributed to the peak dose within 10,000 yrs (32 mrem/yr [0.32000 mSv/yr]) and for the post-10,000-yr period (74 mrem/yr [0.74000 mSv/yr]).

For the inadvertent intruder receptor scenarios, the intruder-drilling receptor scenario would be the scenario with the highest likelihood of occurring. The waste is too deep for a construction crew to reach so that an intruder in the intruder-agriculture receptor scenario would be exposed to radiation only from drinking well water and the small percentage of radioactive drill cuttings from the well construction. However, for the intruder-drilling receptor scenario to become plausible, several factors need to be overcome. The most prominent factor from these would be the metallic hull of the sealed source. The scarcity of water would slow the corrosion rate so that a driller may notice contact with the metal container hundreds to thousands of years after disposal. In addition, a borehole will in all likelihood have a layering of different waste types so that a driller might notice the change in cuttings well before the drill bit reaches the bottom of the borehole and the GTCC waste. However, since the thickness of the metallic cover for sealed sources is not as thick as most activated metals, a drill bit might penetrate through the sealed source more easily than a piece of activated metal.

With regards to the borehole disposal method, additional factors to consider is that boreholes need only a limited space in comparison to other disposal methods, so that given a certain area,

the region that contains waste directly underneath this area would be smaller than for a site using a repository, trench, or vault method. Sealed sources themselves would be relatively small within their waste packaging in comparison to the other GTCC waste types.

Information on the borehole disposal method for sealed sources is also summarized in Table 8.2 in Section 8.

7.2.3 Borehole Disposal Method for GTCC Other Waste

Insights from Receptor Scenarios

From the semiarid to arid alternative sites that DOE evaluated in the 2011 Draft EIS, GTCC Other Waste did contribute to the receptor dose within the first 10,000 yrs; however, for all sites, the doses were less than the trench and the concrete vault methods. In DOE's evaluation, it was assumed that after 500 yrs engineered barriers would be sufficiently degraded so that 20 percent of the sites' natural infiltration water would be in contact with, and be able to corrode the waste. In addition, and perhaps even more relevant, the GTCC Other Waste was assumed by DOE to have been stabilized with grout and that this would lose all of its effectiveness after 500 yrs so that the one-fifth of the precipitation rate would be in contact with the GTCC Other Waste and be able to leach radionuclides into the groundwater.

For the inadvertent intruder receptor scenarios, the intruder-drilling receptor scenario would be the scenario with the highest likelihood of occurring. A factor to consider is the likely layering of wastes in the borehole with higher activity waste towards the bottom of the borehole and lesser activity wastes towards the top. A driller would notice the change in content first while pulling up the drill cuttings from the upper layer of the borehole and may then decide on a different course of action.

Information on the borehole disposal method for GTCC Other Waste is also summarized in Table 8.2 in Section 8.

7.3 Trench

A common approach for containment of the radionuclides in the waste involves emplacing it, appropriately packaged, above the groundwater table and by limiting or avoiding rainwater percolation with a sufficiently impervious cover. Often these LLRW facilities consist of trenches, especially in remote arid areas. Trench disposal has also been used for wastes with higher radioactive content. Shallow land burial was used by all US LLRW disposal facilities until 1995 (IAEA, 2009). Since then, other disposal options have been successfully used. In the trench land burial facilities, the waste containers are placed in long, lined trenches, 8 m (26 ft) or more deep. The trenches are covered with a clay cap or other low-permeability cover, gravel drainage layers and a topsoil layer. They are then contoured and replanted with vegetation for drainage and erosion control. In addition, an intrusion barrier, such as a thick concrete slab, is added to the Class C LLRW trenches.

Insights from the Draft EIS

The post-closure impacts of GTCC waste disposal using alternative disposal methods at various sites were evaluated in the 2011 Draft EIS, including trench disposal. When the borehole, trench, and concrete vault disposal methods were compared in the evaluation of selected alternative sites by DOE, the trench disposal method produced the second earliest peaks, usually a few hundred years before the concrete vault disposal method. Radiation dose rates

also showed close similarities between trench and vault methods, although the doses were somewhat lower for the trench disposal method in the arid and semiarid sites.

Information on the trench disposal method for GTCC LLRW is also summarized in Table 8.5 in Section 8.

7.3.1 Trench Disposal Method for Activated Metals

Insights from Receptor Scenarios

Unlike deep geological repositories or intermediate depth boreholes, trenches were evaluated in all of DOE's alternative site-specific locations including the more humid sites. Most sites showed activated metals contributing the highest percentage to peak dose with the exception of the humid site. Overall dose levels were higher than for the borehole disposal method.

For the inadvertent intruder receptor scenarios, the intruder-drilling receptor scenario would be the scenario with the highest likelihood of occurring. DOE's enhanced trench design has a 5 m (16 ft) minimum cover that would be deeper than most building construction sites except for high rise buildings. At the bottom of the cover, trench barriers are enhanced by the existence of an intruder barrier. Assumptions based on technical justifications concerning the rate of degradation of engineered barriers and corrosion of activated metals will be critical in the dose projected for the intruder receptor.

Information on the trench disposal method for activated metals is also summarized in Table 8.3 in Section 8.

7.3.2 Trench Disposal Method for Sealed Sources

Insights from Receptor Scenarios

Trenches were evaluated in all of the 2011 Draft EIS' alternative site-specific locations including the more humid sites. For the semiarid to arid sites, sealed sources contributed nothing to the peak dose for the first 10,000 yrs. Water and chloride in contact with the sealed sources was insufficient in rate and concentration to corrode through the metal hull to reach the waste while corrosion of activated metals, in contrast, releases radioactive isotopes immediately from its waste form source. However, sealed source contribution to dose did occur at the Idaho National Laboratory site and the humid sites including the generic Regional sites I, II, and III. Water and chloride in contact with the sealed sources was apparently sufficient in rate and concentration to corrode through the metal hull to leach the waste inside.

During peak dose, not all waste types may be peaking in that particular time. Some waste types may contribute their peak concentration before or after the overall peak dose. For example, sealed sources do not contribute to peak dose for most semiarid to arid sites (see Table 8-5), however will contribute dose at other times within 10,000 yrs. GTCC Other Waste may be leaching radionuclides out of the containment before the outer hull of a sealed source can degrade so that the peak dose may occur due to the combination of activated metals and GTCC Other Waste. A second, smaller peak frequently then develops, either before or after 10,000 yrs, due to the combination of release from activated metals and sealed sources. This is the case for sealed sources at humid sites, and their contribution to post-peak dose at such sites can be considerable before 10,000 yrs and be the dominant dose contributor after 10,000 yrs.

For the inadvertent intruder receptor scenarios, the intruder-drilling receptor scenario would be the scenario with the highest likelihood of occurring. The trench design used in the 2011 Draft

EIS has a 5 m (16 ft) minimum cover that would be deeper than most building construction sites except for high rise buildings. At the bottom of the cover, the design calls for the existence of an intruder barrier. Assumptions based on technical justifications concerning the rate of degradation of engineered barriers and corrosion of the metals that make up the outer sealed source canisters will be critical in the dose projected for the intruder receptor.

Information on the trench disposal method for sealed sources is also summarized in Table 8.3 in Section 8.

7.3.3 Trench Disposal Method for GTCC Other Waste

Insights from Receptor Scenarios

Trenches were evaluated in all of DOE's alternative site-specific locations including the more humid sites. If the total GTCC Other Waste inventory includes Group 1 and Group 2 (i.e., including waste from the West Valley site should a decision be made to exhume the waste at the site), the contribution to peak dose with origin from GTCC Other Waste will be greater than that contributed by activated metals for the humid site-specific and generic regional sites. For the semiarid to arid alternative sites, GTCC Other Waste did not contribute to peak dose as much as the activated metals. GTCC Other Waste was assumed by DOE to have been stabilized with grout and that this would lose all of its effectiveness after 500 yrs so that the one-fifth of the natural infiltration rate would be in contact with the GTCC Other Waste and be able to leach radionuclides into the groundwater. For humid sites, this can lead to significant differences in the results compared to the semiarid and arid sites.

For the inadvertent intruder receptor scenarios, the intruder-drilling receptor scenario would be the scenario with the highest likelihood of occurring. At the bottom of the cover, the design calls for the existence of an intruder barrier. Assumptions based on technical justification for the rate of degradation of the intruder barrier will be important for the outcome of the overall dose. However, if a trench disposal design is similar to the trench disposal method evaluated in DOE's 2011 Draft EIS, then the intruder barrier placed on top of the trench and assumptions associated with it may be less important to performance than for the other disposal methods. Unlike all other disposal methods evaluated by DOE, the trench design envisioned no engineered barriers at the sides of the waste. The trench sidewalls would be constructed by using temporary metal shoring, which would be removed when the trench is closed. Horizontal drilling is commonly practiced nowadays, as discussed in Section 7.0, and this development could complicate area concentration limits if this method were to be applied. Assumptions will have to be developed as to the likelihood of such alternative drilling methods being used for the intruder-drilling receptor scenario. An additional factor to consider is the likely layering of wastes in the trench with higher activity waste towards the bottom of the trench and lesser activity wastes towards the top. A driller would notice the change in content first while pulling up the drill cuttings from the upper layer of the trench and may then decide on a different course of action.

Information on the trench disposal method for GTCC Other Waste is also summarized in Table 8.3 in Section 8.

7.4. Concrete Structural Containment

Insights from Previous Examinations of GTCC Waste Disposal

Engineered surface repositories are often equipped with one or more concrete structural containment and an engineered surface cover. The engineered barrier system may include

drainage collectors to channel out infiltrating water and additional barriers might be constructed around the disposal unit to control the movement of water (IAEA, 2009). Below-ground concrete vault disposal frequently uses a sealed structure built of masonry blocks, fabricated metal, concrete or other materials that provide a barrier to prevent waste migration. It has a drainage channel, a clay top layer and a concrete roof to keep water out, a porous backfill, and a drainage pad for the concrete vault. Earth-mounded concrete bunkers are equipped with a drainage system and covered with impermeable clay and topsoil, giving the facility a rounded shape. The waste is placed in below-ground, concrete monoliths, and less radioactive waste is placed on top of the monoliths to create the mounds.

NUREG/CR-3774, Vol. 2 (1985) and Vol. 4 (1985a) evaluated the technical requirements for different methods of concrete structural containment and the findings are summarized below. Below-ground vaults were found to have the following advantages:

(1) They are not susceptible to damage or exposure of the waste packages from erosion, weathering, predictable seismic events, surface disturbances, or soil settlement.
(2) They are visually unobtrusive.
(3) They provide an effective extra barrier to plant or animal intrusion.
(4) They provide an effective barrier to inadvertent human intrusion.
(5) They are resistant to infiltration of surface and groundwater and slow radionuclide migration.
(6) They are structurally stable.
(7) Design and construction could be standardized for safe, efficient operations.

The stated disadvantages were:

(1) Below-ground vaults must be protected against flooding during construction and operations.
(2) They are not amenable to visual inspection and monitoring after closure of the unit.
(3) They are not amenable to the use of remote handling equipment.
(4) Exposure of workers to radiation hazards could be high unless temporary covers or shields are used.
(5) Below-ground vaults must be protected from degradation caused by corrosive soils.

The post-closure impacts of GTCC waste disposal using alternative disposal methods at various sites were evaluated in the 2011 Draft EIS, including disposal within concrete vaults. When the borehole, trench, and concrete vault disposal methods were compared in the evaluation of selected alternative sites by DOE, the last peaks to occur at all the sites evaluated were associated with the concrete vault disposal method. However, the peak doses were slightly higher than the peaks of the trench methods, although never more than a factor of two.

In the 2011 Draft EIS, a reinforced concrete vault would be about 11 m (36 ft) wide, 94 m (310 ft) long, and 7.9 m (26 ft) tall, with 11 disposal cells situated in a linear array. The base of the vault would be only slightly below grade so that GTCC waste disposal placement is assumed to be about 4.3 to 5.5 m (14 to 18 ft) above the ground surface with an engineered cover placed over the vault after completion of the disposal so that the entire facility would be then be below-ground. Without precautions, the engineered surface barrier would be susceptible to erosion and increase the risk of inadvertent intrusion.

Information on the concrete structural containment disposal method for GTCC LLRW is also summarized in Table 8.5 in Section 8.

The newly constructed WCS disposal facility located in Andrews County, Texas (the FWF was discussed in Section 4.3.2) is a disposal type that combines various aspects of the previous discussed disposal methods. The concrete vault-like structures are within a deep landfill where the 1-ft (0.3-m) reinforced concrete liners were constructed at an angle so that the bottom (37 m [120 ft] deep) is narrower than the top of the landfill. Additional components of the FWF include compacted clay layers, drainage layers, geosynthetic layers, a biointrusion layer, and an evapotranspiration layer within an engineered cover system that is not mounded at the surface, but rather, flush with the ground surface. GTCC waste would be placed in steel-reinforced concrete canisters and when filled, grouted. Although the assumptions and technical justification of the rate of degradation of engineered barrier will be critical in the dose projected for various receptor scenarios, the multi-barrier system has many of the features that a defense-in-depth approach would require, both for the intruder (that is, greater depth and steel-reinforced concrete canisters) and for the natural processes (for example, drainage layers and cover that is flush with the ground surface to minimize erosion).

7.4.1. Concrete Structural Containment Disposal Method for Activated Metals

Insights from Receptor Scenarios

For most concrete containment structures, the exterior walls and roof would be composed of thick reinforced concrete. In addition to adding strength and durability to the vault, the thick concrete would attenuate the radiation emanating from the higher activity waste component of the GTCC waste. The most hazardous of the wastes in this respect would be the activated metals from reactor decommissioning. Their external radiation rates, primarily from Co-60, could be a few thousand roentgens per hour at the waste package surface (Sandia National Laboratories, 2008). With an attenuation of Co-60 gamma rays of one-half for about every 6.2 cm (2.4 in.) of concrete (Shleien, 1992), a reduction in radiation (by a factor of more than 260,000) to near background levels is expected.

Unlike all other disposal methods, concrete vaults were evaluated in all alternative site-specific locations and all of the generic regional locations in the 2011 Draft EIS since depth to the water table did not influence if this disposal method could be used or not. Most semiarid to arid sites showed activated metals contributed the highest percentage to peak dose. For the humid sites, which included all the generic regional locations except for Region IV, the percent contribution to peak dose is smaller than GTCC Other Waste if the calculation included the waste currently buried the West Valley site.

For the inadvertent intruder receptor scenarios, the intruder-drilling receptor scenario would be the scenario with the highest likelihood of occurring. Below the 5 m (16 ft) minimum cover is the concrete ceiling of the vault, which serves as an intruder barrier. The concrete vault ceiling would use 6-in (15 cm) steel rebar in two perpendicular layers, one near the exterior face and the other near the interior face of the cover. Most drill bits would not pass into the vault without encountering the undegraded steel reinforcement first. Steel reinforcement in the sidewalls was included because of the increased prevalence of using directional drilling at deeper depths for utility work, which can expose the walls as well as the top of the vault to drilling. Assumptions based on technical justifications concerning the rate of degradation of engineered barriers and corrosion of activated metals will be critical in the dose projected for the intruder receptor.

Information on the concrete structural containment disposal method for activated metals is also summarized in Table 8.4 in Section 8.

7.4.2. Concrete Structural Containment Disposal Method for Sealed Sources

Insights from Receptor Scenarios

Concrete vaults were evaluated in all of the alternative site-specific locations and all generic regional sites in the 2011 Draft EIS. For the semiarid to arid sites, sealed sources contributed nothing to the peak dose for the first 10,000 yrs. Water and chloride in contact with the sealed sources was insufficient in rate and concentration to corrode through the metal hull to reach the waste while corrosion of radioactive activated metals, in contrast, releases radioactive isotopes immediately from its waste form source. However, sealed source contribution to dose did occur at the Idaho National Laboratory site and the humid sites including the generic Regional sites I, II, and III. For a humid site, water and chloride in contact with the sealed sources was apparently sufficient in rate and concentration to corrode through the metal hull to leach the radioactive waste inside.

During the overall peak dose, some waste types may be contributing very little or no contaminates at all to that peak dose. Some waste types may contribute their peak concentration before or after the overall peak dose. For example, sealed sources do not contribute to peak dose for most semiarid to arid sites, however will contribute dose at other times within 10,000 yrs. GTCC Other Waste may be leaching radionuclides out of the containment before the outer hull of a sealed source can degrade so that a peak dose may occur due to the combination of activated metals and GTCC Other Waste radionuclides. A second, smaller peak frequently follows, either before or after 10,000 yrs, due to the combination of releases from activated metals and sealed sources. This is the case for sealed sources at humid sites, and their contribution to post-peak dose at humid sites can be considerable before 10,000 yrs and be the dominant dose contributor after 10,000 yrs. In the case of humid site at the Region I generic disposal facility, sealed sources were the main contributor to the peak dose (see Table 8-5).

The 2011 Draft EIS evaluation results indicate that the rate of infiltration is a significant process for determining how quickly and how severely the source material within the sealed sources will escape their confinement. A potential vulnerability for the concrete vault design considered in the 2011 Draft EIS is the above-grade nature of the waste disposal placement. Although the base of the vault will be below grade, most of the vault will not be. Instead, backfill and a multi-layered engineered surface barrier will be built over the concrete vaults so that no part of the vault is less than 5 m (16 ft) below the new ground surface. However, any engineered cover that is higher than the original ground surface does makes it susceptible to more degradation processes. After the institutional control period ends, vegetation will dominate the top of the engineered barrier and, depending on the ecological system in which the disposal facility is located, plant roots may quicken the degradation of the cover system, if not the vault ceiling itself. If the vegetation is inadequate to prevent erosion (e.g., by fire, disease, drought, etc.) the thickness of the cover will decrease and if precipitation rates increase, so would probably the infiltration rate to the concrete vault. Increased moisture usually accelerates degradation of cementitious material, including concrete.

For the inadvertent intruder receptor scenarios, the intruder-drilling receptor scenario would be the scenario with the highest likelihood of occurring. Below the 5 m (16 ft) minimum cover is the concrete ceiling of the vault, which serves as an intruder barrier. The concrete vault ceiling would use 6-in (15 cm) steel rebar in two perpendicular layers, one near the exterior face and the other near the interior face of the cover. Most drill bits would not pass into the vault without encountering the undegraded steel reinforcement first. Steel reinforcement in the sidewalls was included because of the increased prevalence of using directional drilling at deeper depths for

utility work, which can expose the walls as well as the top of the vault to drilling. Assumptions based on technical justifications concerning the rate of degradation of engineered barriers and corrosion of the sealed sources outer canisters will be critical in the dose projected for the intruder receptor.

Information on the concrete structural containment disposal method for sealed sources is also summarized in Table 8.4 in Section 8.

7.4.3. Concrete Structural Containment Disposal Method for GTCC Other Waste

Insights from Receptor Scenarios
Concrete vaults were evaluated in all of the alternative site-specific locations and all generic regional sites in the 2011 Draft EIS. If the total GTCC Other Waste inventory includes Group 1 and Group 2 (i.e., including waste from the West Valley site should a decision be made to exhume the waste at the site), the contribution to peak dose with origin from GTCC Other Waste will be greater than that contributed by activated metals for the humid site-specific and generic regional sites. For the semiarid to arid alternative sites, GTCC Other Waste did not contribute to peak dose as much as the activated metals. GTCC Other Waste was assumed by DOE to have been stabilized with grout and that this would lose all of its effectiveness after 500 yrs so that the one-fifth of the natural infiltration rate would be in contact with the GTCC Other Waste and be able to leach radionuclides into the groundwater. For humid sites, this can lead to significant differences in the results compared to the semiarid and arid sites. Waste disposal placement would be above grade so there is a potential vulnerability to erosion of cover.

For the inadvertent intruder receptor scenarios, the intruder-drilling receptor scenario would be the scenario with the highest likelihood of occurring. Below the 5 m (16 ft) minimum cover is the concrete ceiling of the vault, which serves as an intruder barrier. The concrete vault ceiling would use 6 in (15 cm) steel rebar and most drill bits would not pass into the vault without encountering the undegraded steel reinforcement first. Steel reinforcement in the sidewalls was included because of the increased prevalence of using directional drilling at deeper depths for utility work, which can expose the walls as well as the top of the vault to drilling. Assumptions on degradation of stabilizing agent (grout) and concrete are important. Area concentration limit could be used.

Information on the concrete structural containment disposal method for GTCC Other Waste is also summarized in Table 8.4 in Section 8.

8 Summary

This document presents aspects that need to be considered before disposal of GTCC waste and discusses disposal challenges under different environmental settings and scenarios. In addition, this document contains insights from a qualitative examination of individual GTCC waste streams, disposal methods, disposal environments, relevant receptor scenarios, and the interrelationships between these disposal aspects. Aspects of GTCC waste disposal that were not examined in this document include waste processing and transport, risks during the operational phase, availability or evaluation of potential disposal facilities, future technologies, and disposal costs. Also, "GTCC-like" waste (i.e., waste similar to GTCC LLRW but owned and generated by DOE) was not part of this qualitative examination. Nevertheless, despite these exclusions, the number of aspects considered, and the interrelationships between the disposal aspects, is considerable so that an attempt is made below to place the results of the qualitative examination from Sections 4 through 7 in tabular form. The technical considerations give in Tables 8-1 through 8-4 are brief; Section 7 discusses these considerations in more detail. The three GTCC LLRW waste types are included in the tables as is the "Total GTCC Waste" for groundwater transport, however "Total GTCC Waste" is not included with the intruder assessment. Contaminants from all three waste types could comingle in a plume close to a well, however it is unlikely that all three waste types would be intersected while drilling one borehole. Table 8-5 shows the doses each GTCC waste type contributes to the estimated peak doses from the use of GTCC LLRW contaminated groundwater within 10,000 yrs of disposal at the 2011 Draft EIS' site-specific locations.

Table 8-1: Brief Technical Considerations of Using Deep Geologic Repository Disposal Method for GTCC Waste Disposal

Disposal Method	Disposal Environment	Receptor Scenario	Waste type	Considerations
Deep Geologic Repository	Humid	Performance Assessment (groundwater transport)	Activated Metals (Sec. 7.1.1)	Unsaturated zone of insufficient depth for deep geologic repository. Geologic repository in saturated zone not considered.
			Sealed Sources (Sec. 7.1.2)	Same as above.
			GTCC Other Waste (Sec. 7.1.3)	Same as above
			Total GTCC Waste (Sec. 7.1)	Same as above.
		Intruder Assessment (exhumation)	Activated Metals (Sec. 7.1.1)	Same as above.
			Sealed Sources (Sec. 7.1.2)	Same as above.
			GTCC Other Waste (Sec. 7.1.3)	Same as above.
	Semiarid to Arid	Performance Assessment (groundwater transport)	Activated Metals (Sec. 7.1.1)	Sandia National Lab (2008) indicated that activated metals contributed the most to an increase in the activity concentration release.
			Sealed Sources (Sec. 7.1.2)	Contributed less than activated metals to the activity concentration release.
			GTCC Other Waste (Sec. 7.1.3)	Contributed less than activated metals to the activity concentration release.
			Total GTCC Waste (Sec. 7.1)	DOE (2011) evaluations showed that releases from the WIPP would be in compliance with existing regulatory requirements.
		Intruder Assessment (exhumation)	Activated Metals (Sec. 7.1.1)	Only intruder drilling is considered plausible. Drilling would need to go very deep. Assumptions on corrosion and degradation important.
			Sealed Sources (Sec. 7.1.2)	Only intruder drilling is considered plausible. Drilling would need to go very deep. Assumptions on degradation stabilizing agent (grout) and corrosion of metals important.
			GTCC Other Waste (Sec. 7.1.3)	Only intruder drilling is considered plausible. Drilling would need to go very deep. Assumptions on degradation stabilizing agent (grout) important.

Table 8-2: Brief Technical Considerations of Using Borehole Disposal Method for GTCC Waste Disposal

Disposal Method	Disposal Environment	Receptor Scenario	Waste type	Considerations
Borehole/Shaft/ Augered Hole	Humid	Performance Assessment (groundwater transport)	Activated Metals (Sec. 7.2.1)	Unsaturated zone of insufficient depth for boreholes of intermediate depth. Disposal in saturated zone not considered.
			Sealed Sources (Sec. 7.2.2)	Same as above.
			GTCC Other Waste (Sec. 7.2.3)	Same as above.
			Total GTCC Waste (Sec. 7.2)	Same as above.
		Intruder Assessment (exhumation)	Activated Metals (Sec. 7.2.1)	Same as above.
			Sealed Sources (Sec. 7.2.2)	Same as above.
			GTCC Other Waste (Sec. 7.2.3)	Same as above.
	Semiarid to Arid	Performance Assessment (groundwater transport)	Activated Metals (Sec. 7.2.1)	All DOE (2011) evaluated sites showed this waste type had highest contribution. Very arid sites had no dose. Corrosion rate assumptions important.
			Sealed Sources (Sec. 7.2.2)	All DOE (2011) evaluated sites showed this waste type did not contribute to dose except for one site. Assumptions on outer canister corrosion by chloride important.
			GTCC Other Waste (Sec. 7.2.3)	Contributed to dose and peak dose. Assumptions on grout degradation and on infiltration rates through barriers important.
			Total GTCC Waste (Sec. 7.2)	DOE (2011) comparisons of borehole, trench, and vault disposal methods showed earliest peak dose, however borehole is the lowest peak dose of the three methods.
		Intruder Assessment (exhumation)	Activated Metals (Sec. 7.2.1)	Only intruder drilling is considered plausible. Drilling would need to go deep. Assumptions on corrosion and degradation important. Layering of waste (lower LLRW on top) in borehole may be important.
			Sealed Sources (Sec. 7.2.2)	Only intruder drilling is considered plausible. Drilling would need to go deep and be precise to hit waste type. Assumptions on degradation of outer canister and concrete important.
			GTCC Other Waste (Sec. 7.2.3)	Only intruder drilling is considered plausible. Drilling would need to go deep. Assumptions on degradation stabilizing agent (grout) and concrete important. Area concentration limit possible.

Table 8-3: Brief Technical Considerations of Using Trench Disposal Method for GTCC Waste Disposal

Disposal Method	Disposal Environment	Receptor Scenario	Waste type	Considerations
Trench	Humid	Performance Assessment (groundwater transport)	Activated Metals (Sec. 7.3.1)	DOE (2011) showed other waste types contributed more to dose and peak dose.
			Sealed Sources (Sec. 7.3.2)	Higher dose rate contributions due to higher infiltration and corrosion of outer hull.
			GTCC Other Waste (Sec. 7.3.3)	Main contributor to peak dose due to higher infiltration and degradation of stabilizing grout. West Valley site waste included in calculations.
			Total GTCC Waste (Sec. 7.3)	Higher peak dose for humid climate than for arid. DOE (2011) comparisons of borehole, trench, and vault disposal methods showed trench had higher peak dose than borehole method.
		Intruder Assessment (exhumation)	Activated Metals (Sec. 7.3.1)	Only intruder drilling is considered plausible. Assumptions on corrosion of waste type and degradation intruder barrier important; both accelerated due to increased infiltration rate.
			Sealed Sources (Sec. 7.3.2)	Only intruder drilling is considered plausible. Assumptions on degradation of outer hull and degradation of intruder barrier important; both accelerated due to increased infiltration rate.
			GTCC Other Waste (Sec. 7.3.3)	Only intruder drilling is considered plausible. Assumptions on degradation stabilizing agent (grout) and concrete important; both accelerated due to increased infiltration rate. Lack of concrete sidewall may be important.
	Semiarid to Arid	Performance Assessment (groundwater transport)	Activated Metals (Sec. 7.3.1)	DOE (2011) showed this waste type contributed the most to dose and peak dose. Corrosion rate assumptions important.
			Sealed Sources (Sec. 7.3.2)	All DOE (2011) evaluated sites showed this waste type did not contribute to dose. Assumptions on canister corrosion by chloride important.
			GTCC Other Waste (Sec. 7.3.3)	Contributed to dose and peak dose. Assumptions on grout degradation and on infiltration rates through barriers important.
			Total GTCC Waste (Sec. 7.3)	Lower peak dose for arid climate than for humid. DOE (2011) comparisons of borehole, trench, and vault disposal methods showed trench had higher peak dose than borehole method.
		Intruder Assessment (exhumation)	Activated Metals (Sec. 7.3.1)	Only intruder drilling is considered plausible. Assumptions on corrosion of waste type and degradation intruder barrier important. Lack of concrete sidewall may be important.
			Sealed Sources (Sec. 7.3.2)	Only intruder drilling is considered plausible. Assumptions on degradation of outer hull and degradation intruder barrier important. Lack of concrete sidewall may be important.
			GTCC Other Waste (Sec. 7.3.3)	Only intruder drilling is considered plausible. Assumptions on degradation stabilizing agent (grout) and lack of concrete sidewalls important. Area concentration limit possible.

Table 8-4: Brief Technical Considerations of Using Concrete Structural Containment Disposal Method for GTCC Waste Disposal

Disposal Method	Disposal Environment	Receptor Scenario	Waste type	Considerations
Concrete Structural Containment (vault)	Humid	Performance Assessment (groundwater transport)	Activated Metals (Sec. 7.4.1)	DOE (2011) showed other waste types contributed to more to dose and peak dose. Waste disposal placement above grade; potential vulnerability to erosion of cover.
			Sealed Sources (Sec. 7.4.2)	Much higher dose rate contributions due to higher infiltration and corrosion of outer hull. Waste disposal placement above grade; potential vulnerability to erosion of cover.
			GTCC Other Waste (Sec. 7.4.3)	Main contributor to peak dose due to higher infiltration and degradation of stabilizing grout. West Valley site waste included in calculations. Potential vulnerability to erosion of cover.
			Total GTCC Waste (Sec. 7.4)	Higher peak dose for humid climate than for arid. DOE (2011) comparisons of borehole, trench, and vault disposal methods showed vault had higher peak dose than trench method.
		Intruder Assessment (exhumation)	Activated Metals (Sec. 7.4.1)	Only intruder drilling is considered plausible. Assumptions on corrosion of waste type and degradation intruder barrier important; both accelerated due to increased infiltration rate.
			Sealed Sources (Sec. 7.4.2)	Only intruder drilling is considered plausible. Assumptions on degradation of canister and degradation of intruder barrier important; both accelerated due to increased infiltration rate.
			GTCC Other Waste (Sec. 7.4.3)	Only intruder drilling is considered plausible. Assumptions on degradation stabilizing agent (grout) and concrete important; both accelerated due to increased infiltration rate.
	Semiarid to Arid	Performance Assessment (groundwater transport)	Activated Metals (Sec. 7.4.1)	DOE (2011) showed this waste type contributed the most to dose and peak dose. Corrosion rate assumptions important.
			Sealed Sources (Sec. 7.4.2)	All DOE (2011) evaluated sites showed this waste type did not contribute to dose. Assumptions on canister corrosion by chloride important.
			GTCC Other Waste (Sec. 7.4.3)	Contributed to dose and peak dose. Assumptions on grout degradation and on infiltration rates through barriers important.
			Total GTCC Waste (Sec. 7.4)	Lower peak dose for arid climate than for humid. DOE (2011) comparisons of borehole, trench, and vault disposal methods showed vault had higher peak dose than trench method.
		Intruder Assessment (exhumation)	Activated Metals (Sec. 7.4.1)	Only intruder drilling is considered plausible. Assumptions on corrosion of waste type and degradation intruder barrier important.
			Sealed Sources (Sec. 7.4.2)	Only intruder drilling is considered plausible. Assumptions on degradation of canister and degradation intruder barrier important
			GTCC Other Waste (Sec. 7.4.3)	Only intruder drilling is considered plausible. Assumptions on degradation stabilizing agent (grout) and concrete important. Area concentration limit possible.

Table 8-5: GTCC Waste Type Dose Contributions to Modeled Peak Doses (in mrem/yr) from the Use of GTCC LLRW Contaminated Groundwater within 10,000 yrs of Disposal for 2011 Draft EIS' Reference Locations and Generic Disposal Sites

Borehole Disposal Method	Activated Metals	**Sealed Sources**	**Other Waste**
Savannah River Site	UZ insufficient thickness*	UZ insufficient thickness*	UZ insufficient thickness*
Los Alamos National Laboratory Site	71	0	13.4
Idaho National Laboratory Site	62.6	32	30.1
Hanford Site	4.1	0	0.07
Nevada National Security Site	0	0	0
Waste Isolation Pilot Plant Vicinity Site	0	0	0
Region I Generic Disposal Facility	UZ insufficient thickness*	UZ insufficient thickness*	UZ insufficient thickness*
Region II Generic Disposal Facility	UZ insufficient thickness*	UZ insufficient thickness*	UZ insufficient thickness*
Region III Generic Disposal Facility	UZ insufficient thickness*	UZ insufficient thickness*	UZ insufficient thickness*
Region IV Generic Disposal Facility	0	0	0
Trench Disposal Method	Activated Metals	**Sealed Sources**	**Other Waste**
Savannah River Site	51.2	0	474.0
Los Alamos National Laboratory Site	120.2	0	39.3
Idaho National Laboratory Site	43.7	0	80.5
Hanford Site	7.8	0	1.6
Nevada National Security Site	0	0	0
Waste Isolation Pilot Plant Vicinity Site	0	0	0
Region I Generic Disposal Facility	UZ insufficient thickness*	UZ insufficient thickness*	UZ insufficient thickness*
Region II Generic Disposal Facility	26.2	0	215.3
Region III Generic Disposal Facility	UZ insufficient thickness*	UZ insufficient thickness*	UZ insufficient thickness*
Region IV Generic Disposal Facility	0	0	0
Concrete Vault Disposal Method	Activated Metals	**Sealed Sources**	**Other Waste**
Savannah River Site	46	0	237.8
Los Alamos National Laboratory Site	154	0	41.1
Idaho National Laboratory Site	37.5	0	89.8
Hanford Site	6.3	0	1.7
Nevada National Security Site	0	0	0
Waste Isolation Pilot Plant Vicinity Site	0	0	0
Region I Generic Disposal Facility	4.1	400	288.4
Region II Generic Disposal Facility	20.1	0	215.3
Region III Generic Disposal Facility	36.8	0	85.1
Region IV Generic Disposal Facility	0	0	0

* UZ stands for unsaturated zone

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