DOE-Managed HLW and SNF Research: FY15 EBS and Thermal Analysis Work Package Status

Fuel Cycle Research & Development

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SUMMARY

This report examines the technical elements necessary to evaluate EBS concepts and perform thermal analysis of DOE-Managed SNF and HLW in the disposal settings of primary interest – argillite, crystalline, salt, and deep borehole. As the disposal design concept is composed of waste inventory, geologic setting, and engineered concept of operation, the engineered barrier system (EBS) falls into the last component of engineered concept of operation. The waste inventory for DOE-Managed HLW and SNF is closely examined, with specific attention to the number of waste packages, the size of waste packages, and the thermal output per package. As expected, the DOE-Managed HLW and SNF inventory has a much smaller volume, and hence smaller number of canister, as well a lower thermal output, relative to a waste inventory that would include commercial spent nuclear fuel (CSNF). A survey of available data and methods from previous studies of thermal analysis indicates that, in some cases, thermo-hydrologic modeling will be necessary to appropriately address the problem. This report also outlines scope for FY16 work -- a key challenges identified is developing a methodology to effectively and efficiently evaluate EBS performance in each disposal setting on the basis of thermal analyses results.

TABLE OF CONTENTS

FIGURES

TABLES

ACRONYMS

BWR	Boiling Water Reactor
CSNF	Commercial spent nuclear fuel
DHLW	Defense high-level waste
DOE	US Department of Energy
DOE-NE	US Department of Energy, Office of Nuclear Energy
DPC	Dual Purpose Canister
DSNF	Defense spent nuclear fuel
DWPF	Defense Waste Processing Facility
EMT	Electrometallurgical treatment
HEU	Highly enriched Uranium
HIP	Hot isostatic pressing
HLW	High-level radioactive waste
INL	Idaho National Laboratory
INTEC	Idaho Nuclear Technology and Engineering Center
LEU	Low-enriched Uranium
LLW	Low-level radioactive waste
MCO	Multi-canister overpack
MEU	Medium enriched Uranium
MOX	Mixed oxide (fuel)
PBC	Purpose-built canister
PWR	Pressurized water reactor
RCRA	Resource Conservation and Recovery Act
SBW	Sodium-bearing waste
SMR	Small modular reactor
SNF	Spent nuclear fuel
SRS	Savannah River Site
UFD	Used Fuel Disposition
US	United States of America
WIPP	Waste Isolation Pilot Plant

DOE-MANAGED HLW AND SNF RESEARCH: FY15 EBS AND THERMAL ANALYSIS WORK PACKAGE STATUS

1. INTRODUCTION

1.1 Background

In March 2015, the US President Barak Obama issued a Presidential Memorandum announcing the decision to pursue development of a nuclear waste repository exclusively for the disposal of high-level waste resulting from defense-related atomic energy activities. Section 8 of the Nuclear Waste Policy Act of 1982 (NWPA) require residential evaluation of disposal options for Defense High-level Waste (HLW). In 1985, President Reagan's evaluation found no basis for Defense HLW to be disposed of in a separate repository, and proceeded with the development of a single nuclear waste repository that commingled commercial nuclear waste and defense-related nuclear waste. The NWPA authorizes the development of second repository, specifically for the disposal of Defense HLW, if there is a Presidential finding deeming it necessary.

The 2012 final report from the Blue Ribbon Commission (BRC) on America's Nuclear Future recommended a review of the "single repository" policy, whereby defense-related and commercial nuclear wastes are co-mingled (DOE 2014). In response, the Obama Administration followed the BRC's recommendation and reviewed repository policy in its 2013 *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste.* In October of 2014, DOE released a report entitled, *Assessment of Disposal Options for DOE-Managed High-Level Radioactive Waste and Spent Nuclear Fuel,* herein *Assessment Report*. The *Assessment Report* makes a technical and programmatic evaluation of disposal options for DOE-Managed Nuclear Waste (i.e., waste not classified as commercial in origin), and it contains two key findings: 1) it is technically feasible to dispose of all DOE-Managed HLW and SNF in a single repository, separate from commercial spent fuel, and 2) there are potential programmatic benefits to a separate Defense Waste Repository. In March 2015, DOE released the *Report on Separate Disposal of Defense High-Level Radioactive Waste*, which, on the basis of six evaluation criteria cited in Section 8(b)(1) of the NWPA, concludes that "a strong basis exists to find that a Defense HLW Repository is required" (DOE 2015). It is in this context that Obama's 2015 Presidential Memorandum on the development of a defense-only nuclear waste repository was issued.

The development of a separate repository for Defense HLW (herein DOE-Managed HLW and SNF) necessitates a Research and Development Plan for implementation. DOE's Used Fuel Disposition Campaign is implementing such an R&D plan. This report describes a work package that investigates the Engineered Barrier System (EBS) concepts and associated thermal analyses that are specific to design optimization for DOE-Managed HLW and SNF.

1.2 Purpose and Scope

The purpose of this report is to both survey existing literature and outline a strategy to address the technical elements necessary to evaluate the preliminary design concepts for the inventory within select media. Specific geologic media under consideration are those currently investigated within the Used Fuel Disposition Campaign (argillite, crystalline, deep borehole, and salt). The main focus will be on EBS concepts within select media and will examine the interplay between EBS design concepts, geologic setting/host media, and the ensuing thermal evolution in the repository.

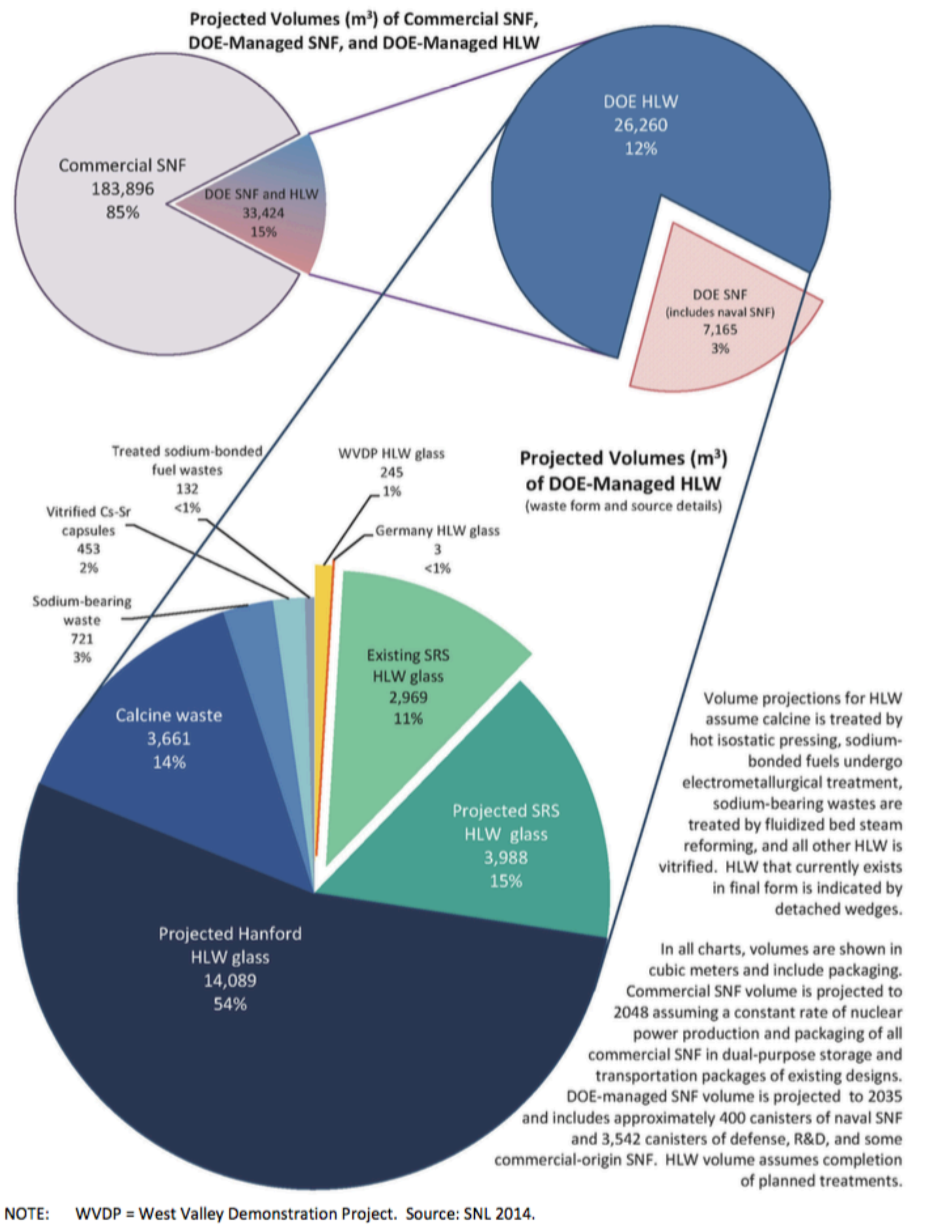
2. Survey of Engineered Barrier System (EBS) Design Elements

An Engineered Barrier System (EBS) Design Concept is inextricably bound to the overall disposal design concept, as the EBS design is one part of the integrated disposal concept. The disposal concept is composed of three distinct elements: 1) waste inventory, 2) geologic media and setting, and 3) the engineering concept of design (Hardin et al. 2011). The EBS Design Concept is implemented as part of the Engineering Concept of Design. Since the Engineering Concept of Design is a function of both waste and inventory and the geologic setting, the EBS Design Elements themselves will be subject to constraints and conditions imposed on the repository system by host media and setting, as well as by the waste form and waste package design. The waste inventory and geologic setting directly influence the thermal, hydrologic, mechanical, and chemical (THMC) environment. In other words, both the waste inventory and the disposal media setting control the selection, design and implementation of EBS Design Elements.

The waste inventory exerts its influence by means of its thermal output, the resultant size and number of waste packages, and the chemical compatibility of both waste form and waste package with the host media. The host media plays a critical role in both the thermal response of the design concept, and the transport of radionuclide to both the far and near field environments. The geochemical conditions (e.g., oxidizing or reducing) of the host media play significant roles in predicting degradation rates of EBS components, which, in turn, is critical to predicting release rates of radionuclides. The selection of materials for waste package/overpack is a prime example of the interplay between EBS and host media geochemistry, as repository design seeks to minimize degradation of EBS components by choosing materials with the best durability in a given host media. The geomechanical and physical properties of the host media also plays a significant role in the EBS Design – the formation thickness, depth, composition, and geomechanical and hydrologic response to repository mining operations, heat, and waste package load are all important parameters that have critical influence an thermal response and ultimate permeability of the disposal design concept.

2.1 Waste Groups, Waste Forms, Waste Package Size, and Thermal Characteristics

The DOE-Managed HLW and SNF waste is stored in various locations in the continental US, and in its totality represents approximately 15% of the total projected US nuclear waste inventory (by volume). Of this 15%, the DOE-Managed Waste (both HLW and SNF) is approximately composed of 70% from projected HLW glass from Hanford (54% of all DOE-Managed Waste) and Savannah River (15% of all DOE-Managed Waste). Of the existing waste in the DOE-Managed Waste inventory, 14% is from calcine waste at INL, 11% from existing HLW Glass at SRS, and ~5% composed from a combination of Cs-Sr capsules at Hanford, FRG HLW Glass at Hanford, West Valley HLW Glass in West Valley, NY, and Na-bonded fuel wastes at INL (DOE 2014). Figure 1 summarizes the aforementioned breakdown of various waste groupings.



- Figure 1. Projected values of CSNF, DOE-Managed SNF, and DOE-Managed HLW (DOE 2014, source: SNL 2014). NOTE: Volume estimates assume calcine processed by hot isostatic pressing with additives, sodium-bearing waste treated by fluidized bed steam reforming, sodium-bonded fuels undergo electrometallurgical treatment, and all other waste forms are vitrified. FRG = Federal Republic of Germany; SRS = Savannah River Site; WVDP = West Valley Demonstration Project.

The disposal options reports by SNL (2014) and DOE (2014) provide an exhaustive study on waste inventory and disposal concepts for different DOE waste types. The disposal concepts include disposal in mined repositories (salt, clay/shale and crystalline geologic media) and in deep boreholes. The waste inventory includes waste types, waste forms and groupings of the waste. Figure 1 is an illustration of the relative volumes of different existing and projected DHLW types. Table 1 gives actual volumes of DHLW and DSNF waste to be disposed. The DHLW part can be subdivided into general classifications:

- HLW Glass 21, 046 m^3 (i.e. 80%)
- Calcine waste 3, 661 m^3 (i.e. 14%)
- Smaller sources 1,554 m^3 (i.e. 6%)

The DSNF and DHLW waste inventory is classified into 43 waste types (SNL, 2014), which result in 50 waste forms when considering different waste treatment options. The 50 waste forms have been grouped into 10 waste groups that have similar disposal characteristics. Table 2 shows the 10 different waste groups, which includes two groupings for commercial SNF that compare purpose-built canister (PBC) packaging vs. dual-purpose canister (DPC) packaging.

Table 1. Existing and projected disposal inventory of DHLW and DSNF at different locations (DOE, 2014): (SNL, 2014)

Waste	**Present Volume (m^3)**	**Additional Projected Volume in 2048 (m^3)**	**Total Volume (m^3)**
DSNF	7,165	0	7,165
SRS Vitrified HLW	2,969	3,988	6,957
Hanford Site Vitrified HLW	0	14,089	14,089
Calcine waste	0	3,661	3,661
Sodium-bearing waste	0	721	721
Vitrified Cs-Sr capsules	0	453	453
WVDP vitrified HLW	245	0	245
Treated sodium-bonded fuel	0	132	132
FRG HLW glass	3	0	3
Total	10,382	23,044	33,436

Table 2. Waste group descriptions (SNL, 2014)

Waste Group	Description (SNL, 2014)
WG1	All commercial SNF packaged in purpose-built disposal containers
WG2	All commercial SNF packaged in dual-purpose canisters of existing design
WG3	All vitrified HLW (all types of HLW glass, existing and projected, canistered)
WG4	Other engineered waste forms
WG5	Metallic and non-oxide DOE spent fuels
WG6	Sodium-bonded fuels (driver and blanket), direct disposed
WG7	DOE oxide fuels
WG8	Salt, granular solids, and powders
WG9	Coated-particle spent fuel
WG10	Naval fuel

The *Disposal Options Report* (SNL 2014, Appendix E) also provides a detailed analysis for the evaluation of disposal of the 10 waste groups (see Table 2) in the four repository types. The analysis uses evaluation criteria such as "Disposal Option Performance", "Confidence in Expected Performance Bases", "Operational Feasibility", "Secondary Waste Generation", "System-Level Cost", and "Technical Readiness". The results of the analysis indicate that most of the waste groups can be emplaced in the three mined repositories with relatively minor changes. However, disposal in deep boreholes has limitations for most of the waste groups due to the relatively small sized diameter of the borehole.

For the purposes of the Preliminary Design Concepts Work Package and scope of this report, the 10 waste groups as outlined in the *Disposal Options Report* have the most relevance, as these groupings map directly to waste characteristics pertinent disposal, namely, waste form, waste form size, and thermal output. Table 3 and **Error! Reference source not found.** summarize the waste group categorization schema, as well as the waste characteristics of most interest with respect to EBS design concepts, for SNF and HLW, respectively.

Table 3. Waste groups and pertinent characteristics for SNF in the US nuclear waste inventory (source: SNL 2014)

Waste Group	**Description**	**Waste Form**	**Waste Package Dimensions**	[b] **Number of Waste Packages**	[b] **Avg. thermal output per waste package**
[a] WG1	CSNF in PBC	[d] Purpose-built canister (PBC)			<25 kW[c]
		Borehole	10.6” dia by 181.1”	470,063	
		Small	32.3” dia by 196.9”	89,364	
		Medium	50.8” dia by 202.0”	31,163	
		Large	63.0” dia by 202.0”	16,924	
[a] WG2	CSNF in DPC	Dual-purpose canister (DPC)	98” dia. by 197” to 225”	11,413	<25 kW[c]
WG5 – Metallic Spent Fuels WG6 – Sodium bonded fuels WG7 – DOE oxide fuels WG9 – coated particle spent fuels	Heterogeneous mix of DSNF	Multi-canister Overpack (MCO)	24” dia by 166.4”	413	500W or less
		18x10	18” dia by 10’	1,506	
		18x15	18” dia by 15’	1,474	
		24x10	24” dia by 10’	133	
		24x15	24” dia by 15’	27	
WG10 – Naval fuel	Naval SNF	Naval SNF canister	66” dia by 187” 66” dia by 201.5”	90 310	11.8 kW limit 4.25 kW avg.

[a] WG1 and WG2 are not under current consideration as DOE-Managed HLW and SNF. These WG’s are included merely for the purpose of comparison between CSNF and DOE-Managed SNF.
[b] Year 2048, if projected. Thermal output data correspond to thermal output per waste package in the year 2048.
[c] Stipulated by regulation to be <25kW
[d] Assumes only one size PBC is used for all the CSNF waste, such that the number of waste packages (solely for CSNF in PBC’s) corresponds to the number of PBC’s, all of a particular size, that would be needed for all CSNF. For example, if all CSNF were to be disposed of in borehole-sized PBC’s, 470,063 of these canisters would be needed to contain all of the CSNF waste.

From Table 3 it is clear that, on a per container basis, the CSNF has a higher thermal output, 25kW vs. 500W and 4.25 kW, for the DSNF minus Naval Fuel, and for the Naval Fuel, respectively. As shown in Figure 1, the projected/existing volume of CNSF is over 20-fold that of projected/existing DSNF, and the data in Table 3 shows that the number of canisters of CSNF will far exceed the ~4,000 canisters of DSNF (even if DPC's are employed for CSNF).

As shown in Table 4, the situation is more complicated for the HLW, though, as with DSNF, there is still a much lower thermal output for HLW in comparison to the CSNF. Table 4 perhaps appears slightly over-complicated as projected vs. existing HLW are treated separately, but as a whole the HLW consists of several distinct sources, many of which have multiple pre-disposal treatment scenarios under consideration. For example, the calcine waste at INL can be disposed along one of three disposal pathways: 1) Vitrification and packaging in HLW canister, 2) Direct disposal in a purpose built canister, or 3) Hot Isostatic Pressing (HIP), of which there are HIP-A and HIP-B that differ by the addition of Si, Ti, and Ca SO_4 (HIP-A) to produce a RCRA-compliant glass ceramic waste form. Italics are used in the "description" field of Table 4 to denote wastes that have multiple disposal pathways under consideration.

It should also be pointed out that the Sodium-Bonded Spent Nuclear Fuels appear in both Table 3 and Table 4 (referred to as Metallic Sodium Bonded). Direct disposal of Sodium-Bonded Fuels (i.e. as SNF) is problematic, given the relative chemical instability (SNL 2014), making the EMT the preferred disposal pathway. Table 3 estimates for the number of DSNF canisters does not include contributions from the Sodium-Bonded SNF, and is included in Table 3 only to preserve consistency with the *Disposal Options Assessment* schema for waste group classification.

Table 4. Non-SNF Waste Groups including HLW and other waste forms

Waste Group	Description	Waste Form	Waste Package Dimensions	[a] Number of Waste Packages	[a] Avg. thermal output per waste package
WG3 – HLW Glass	Existing SRS HLW Glass	SRS canister	24" dia by 118"	3,339	30 W
	Existing West Valley HLW Glass	WVDP canister	24" dia by 118"	275	238W
	FRG HLW Glass	FRG canister	11.8" dia by 47.2"	34	[b] 950W
	Projected Hanford HLW Glass	Hanford canister	24" dia by 177"	10,586	29W
	Projected SRS HLW Glass	SRS canister	24" dia by 118"	4,485	30W
	Calcine Waste (vitrified)	Vitrified Calcine Waste Canister	24" dia by 118"	11,400	1.2-15.4 W
	Cs/Sr capsules at Hanford (vitrified)	Vitrified Cs/Sr waste in Hanford HLW Glass canister	24" dia by 177"	340	905W
WG4 – other Engineered waste forms	[c] *Metallic sodium bonded*	Glass-bonded sodalite from EMT	24"dia by 118"	64	2,240W
		INL Metal waste from EMT	24"dia by 118"	64	neglible
	[d] *Calcine waste Hot Isostatic Pressing (HIP – A)*	HIP canister (encloses 10 HIP cans)	66" dia by 204"	3,200	40-540W
	Calcine waste (HIP – B)	HIP canister (encloses 10 HIP cans)	66" dia by 204"	1,600	80-1080W
WG8 –salt, granular solids, powders	*Metallic sodium bonded*	Salt waste from EMT direct disposal canister	24"dia by 118"	64	2,240 W
	Calcine Waste (Direct Disposal)	Direct disposal canister	26" dia by 121"	4,900	2.4-36W
	Sodium bearing waste (SBW) at INL	SBW canister	26" dia by 120"	688	2.5W
	Cs/Sr Capsules (Direct Disposal)	Untreated in overpack/canister	24" dia by 120" (6 capsules per canister)	Cs- 267 Sr - 121	800W 1,170W

[a] Year 2048, if projected. Thermal output data correspond to thermal output per waste package in the year 2048.
[b] Final configuration not selected. The canisters listed in Table 4 could be disposed of individually or stacked 2 or 3 per container.
[c] Metallic sodium bonded fuels can be processed by electro-metallurgical treatment (EMT) to produce either 1) metal waste and glass-bonded sodalite or 2) metal waste and salt waste.
[d] An alternative to HIP-B, HIP-A includes calcine waste plus Si, Ti, and $CaSO_4$ to produce RCRA-compliant glass ceramic waste form.

Overall, the data assembled in Table 3 and Table 4 suggests that when compared with a repository design that includes CSNF, a repository restricted to DOE-Managed Waste (DSNF and DHLW) will have both a lower thermal output per canister, and a smaller number of canisters that is attributable to a much smaller volume of total waste. The lower thermal output will certainly have an impact on the Engineered Concepts of Design for DOE-Managed waste, relative to repository concepts for or including CSNF. The most important impacts would be the effect on waste package spacing and repository layout. One focus of the FY16 Work Package will be to utilize data like those in Table 3 and Table 4 to make assessments that help to quantitatively define and clarify the Engineered Concept of Design for DOE-Managed Waste in each of the selected disposal media.

2.2 Geologic Setting and Engineered Concept of Design

This section will briefly summarize and highlight the key attributes of each disposal media, its associated geologic setting, and the Engineered Concepts of Design employed in the corresponding media.
Four disposal concepts are under consideration for the DOE-Managed HLW and SNF: argillite, crystalline, salt, and deep borehole. Disposal in these four media has been discussed extensively, including the *Disposal Options Assessment* (SNL 2014), which articulates pro's and con's for each waste group (WG1 through WG10) for each disposal media. Other useful studies have more relevance to the interplay between disposal media of interest and EBS materials performance (Bryan et al. 2012), or focus more on repository design features (e.g., emplacement modes, package spacing) and the ensuing effects on the thermal decay in the repository (Hardin et al. 2012, Hardin et al. 2013).

As mentioned earlier, the thermal output and volume of DOE-managed waste is considerably less than an operation that would involve CSNF. This has a potentially significant impact on the Engineered Concept of Operations, as the main effect of both would be a smaller repository footprint. Thermally cooler waste means that waste packages can be spaced more closely, while the smaller volume means that there simply are less waste package to emplace.

2.2.1 Argillite

2.2.1.1 Geologic Setting

This disposal media encompasses both clay and shale host materials. The physical properties can vary among argillaceous materials, from the weakly indurated (e.g. "Boom clay") to laminated, sedimentary shales, to highly indurated clays of France (e.g. "Callovo-Oxfordian"). As a group the argillites share some important physical characteristics, namely low permeability, high sorption affinity for cationic radionuclides, and swelling capacity. Additionally, the geologic setting in argillites tends to be reducing over the long time scale, though the environment tends to be oxic in the post-closure period (Bryan 2012). Belgium, Switzerland, and France have well-established repository design concepts in this media, and their design concepts in argillite rely upon the natural system isolation of radionuclides (via low permeability), and waste containers are expected to isolate waste through the thermal perturbation period, up to ~ 10,000 years. The geologic setting is such that heavy reliance is placed on the natural system to provide waste isolation over long time frames (> 10,000 years).

2.2.1.2 Engineered Concepts of Design

Bentonite buffer is typically employed in this geologic setting, as is carbons steel for overpack/waste package materials. In the Belgian concept, waste packages consist of carbon steel surrounded by a cementitious sheath – the highly alkaline pore fluid of the cementitious material provide a passivation regime to prevent corrosion of the carbon steel. French and Swiss concepts do not include the cementitious buffer, instead exclusively employ bentonite buffer and/or backfill. Waste packages are arranged horizontally, and shafts are employed for mining and waste emplacement operations. Thermal conductivity is low enough that waste package emplacement and repository layout are both important considerations for thermal management. Access to the disposal area is via shafts, and the typical repository depth would be ~500m below the surface.

2.2.2 Crystalline

2.2.2.1 Geologic Setting

The crystalline disposal environment is characterized by a reducing geochemical environment, low matrix permeability, but tends to have high fracture permeability, which could allow for mobility of radionuclides upon failure of EBS components. Unlike the argillite host, where long term isolation was achieved by reliance on the natural system, the crystalline design concept places heavy reliance upon the waste package and bentonite buffer for waste isolation.

2.2.2.2 Engineered Concepts of Design

Finland (Posiva Oy 2013) and Sweden (SKB 2011) have well-established design concepts for crystalline media, and their designs employ copper waste package/overpack with a bentonite buffer. In the reducing environment of the crystalline media, copper degradation rates are sufficiently slow such that long-term durability of the waste package is a significant driver for waste isolation. Bentonite buffer offers an additional waste isolation capability to the system. In this disposal media, design concepts allow for waste packages to be arranged vertically in a borehole or horizontally in drifts. As with the Argillite disposal media, the inclusion of a bentonite buffer in the Crystalline disposal concept requires a limit of 100° C for the peak surface temperature of waste packages. Access to the disposal area is via inclined ramps (rather than shafts), and the typical repository depth would be ~500m below the surface. Another key feature of the operations for this disposal media is the option to ventilate waste packages (“open emplacement”) prior to closure, in order improves the thermal management capabilities.

2.2.3 Salt

2.2.3.1 Geologic Setting

Almost no reliance is given to the waste form or waste package in the salt disposal concept. This is primarily due to the potential for rapid corrosion of waste package materials, if free water happens to be present. As a geologic setting, Salt offers very low permeability, mechanical creep that entombs waste packages, and a relatively high thermal conductivity.

2.2.3.2 Engineered Concepts of Design

Waste packages can be emplaced in drifts or vertical boreholes. Due to the high thermal conductivity of salt, thermal management is less of a concern in this design concept relative to others. Access to the disposal area is via shafts, and the typical repository depth would be 500-1000m below the surface. Both bedded and domal salt formations are candidates – typically, bedded is more favorable given the larger potential footprint. For DOE-managed waste and its smaller volumes, and hence potentially smaller repository footprint, domal salt formations may be more viable candidates for the context.

2.2.4 Deep Borehole (DBH)

2.2.4.1 Geologic Setting

Perhaps a variant of the crystalline disposal concept, if not for some dramatic differences, DBH has similarities to the crystalline concept in terms of geologic setting. DBH is the only repository disposal concept presented here that is not a mined repository. This disposal concept entails drilling a borehole to 5km depth into the crystalline basement. A reducing environment provides relatively slow waste package/waste form degradation, and waste isolation is aided by the low permeability crystalline rock at such low depth.

2.2.4.2 Engineered Concepts of Design

This concept imposes tight constraints on the size of waste packages, such that long slender packages are most optimal for this disposal setting. Some waste groups lend themselves well to disposal in this setting, e.g. the Cs/Sr capsules at Hanford. A heavy reliance would be placed on the natural barrier and the seal system in this disposal concept.

3. Thermal Analysis

3.1 Thermal decay data

Decay heat data for DSNF and DHLW have been documented in various reports. Carter et al. (2012, 2013) provide a more complete thermal data of DHLW at various sites for current and projected inventories. For the purpose of this report we have summarized the thermal data documented in that report. For SRS current inventory the decay heat of canisters was obtained based on radiological inventories of the canisters. Decay heat of future canisters was estimated based on the radionuclide composition of the HLW inventory. The authors provide a summary of nominal decay heat data for SRS canisters at the time of production as shown below (total 7,562 canisters, size: OD = 2 ft. L = 10ft):

- 39% of canisters < 50 W
- 6.1 % 50- 100 W
- 51.4 % 100 – 220 W
- 3.5 % 300 – 500 W

Thus, the maximum decay heat for these canisters is about 500 W.
Carter et al. (2012, 2013) also provide decay heat data for DHLW at Hanford and Idaho sites. The Hanford data are based on projected inventory of the Hanford Waste Treatment Project (WTP). The Idaho decay heat data was based on calcined DHLW currently stored at the Idaho Site of Idaho National Laboratory. Decay heat data for the Hanford and Idaho DHLW are given below.

Hanford Borosilicate Glass (total 11,079 canisters, size: OD = 2ft., L = 15 ft.)

- 83.9 % canisters < 50 W
- 11.1 % 50 – 100 W
- 4.7 % 100 – 220 W
- 0.3 % 220 – 300 W

The nominal decay heat for Idaho Calcine in the year 2016 (4391 canisters) is:

- 100 % canisters < 50 W

The data show that 83.9 % of the Hanford canisters will have decay heat of less than 50 W, and the maximum is about 300 W. For the Idaho Calcine the maximum decay heat is less than 50 W. The authors also give the projected total number of DHLW canisters at all sites and the corresponding decay heat data for all DHLW. A summary is given below.

Projected total number of HLW canisters:

- West valley 275
- Hanford 11,079
- INL (Calcine) 4,391
- INL (Electro-chemical processing) 102
- SRS 7,562
- Potential: 17,100 – 33,600

Decay heat data for all DOE HLW:

- 72.2% of canisters < 50 W
- 7.4% 50- 100 W
- 19.1 % 100 – 220 W
- 0.2 % 220 – 300 W
- 1.1% 300 – 500 W

The projected thermal output from the average, maximum, and minimum heat-output capsules for cesium and strontium is given by Arnold et al. (2014) and shown Figure 2. The decay curves were calculated based on the assumptions that heat comes only from the decay of Cs-137 or Sr-90, that the disposal borehole contains 1.5 capsules per linear meter, and the half-lives of Cs-137 and Sr-90 are 30.17 years and 28.79 years, respectively.

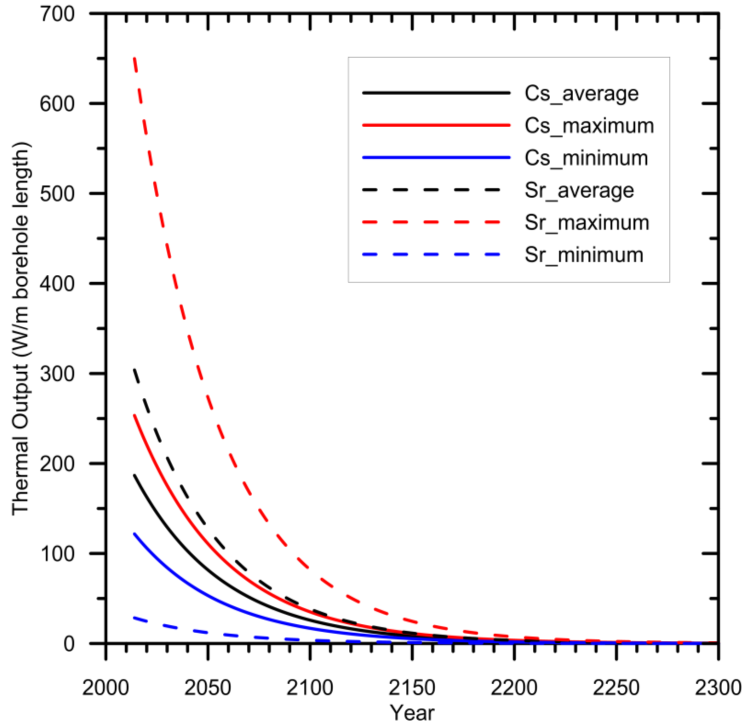


Figure 2. Projected thermal output from Cesium and Strontium capsules (Arnold et al., 2014).

Carter et al. (2012, 2013, Appendix L) provides decay heat data of waste forms from the reprocessing of LWR UOX fuel.

3.2 Thermal limits

Thermal limits are assigned for storage, transportation and disposal. Repository layout and thermal loading management for disposal in different host rocks are based to meet thermal limits. The following were obtained from various sources:

- Limit the peak centerline temperature of borosilicate glass waste forms below 500°C at all times, to avoid devitrification or crystallization (Hardin et al., 2012).
- The decay heat limit is 11.8 kW for each naval waste package (Hardin et al., 2012).
- The thermal limit per canister for Yucca Mountain license application is1.5 kW (Carter et al., 2013)
- For crystalline and clay/shale media a target value of 100°C is used for the maximum waste package temperature, based on potential degradation of clay-based buffer material or clay/shale host rock (Hardin et al., 2012). This value is under reconsideration.
- For salt the target maximum temperature is 200°C, although salt may withstand higher temperatures (Hardin et al., 2012).

3.3 Previous thermal modeling work

Previous modeling studies exist for thermal, thermal-hydrologic and thermal-hydrologic-mechanical cases for disposal of DSNF and DHLW in a generic salt repository. There are also numerous reports of thermal and thermal-hydrologic modeling for disposal of commercial spent nuclear fuel in generic repositories. These reports would be of use for thermal analysis of DSNF and DHLW. Clayton and Gable (2009) and Clayton (2010) conducted thermal-only modeling for disposal of HLW resulting from the recycling of light water reactor spent nuclear fuel. The modeling analysis looked at the feasibility of disposal of HLW in a salt repository by studying temperature distributions near a waste package. The authors assumed an initial heat load of 8.4 kW per canister (2ft. diameter and 9 ft long). The study was later extended to thermal-hydrologic and thermal-hydrologic-mechanical modeling as documented in Jove-Colon et al. (2012) and Hadgu et al. (2013).

4. Next Steps for Analyzing Preliminary Design Concepts

Specific tasks in the FY16 work scope include:

1) Assess feasibility and applicability of EBS concepts in select media for the technical challenges specific to the defense waste inventory (e.g. thermal conditions, waste constituency and compatibility with EBS concepts, etc.).

2) Identify the range of potential repository conditions specific to the context of defense waste disposal that have the potential for significant impact on sealing function/integrity of EBS, and

3) Define framework and methodologies for evaluating EBS concept compatibility within the range of anticipated/predicted conditions.

A key challenge will be to evaluate the EBS performance in both efficiently and effectively on the basis of thermal analyses. An expanded area of research in this work package for FY16 will include investigation into waste package/overpack design, as well as repository layout.

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