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LARGE DIAMETER DEEP BOREHOLE DISPOSAL CONCEPT FOR HLW GLASS

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This paper considers concepts for disposal of canistered high-level (radioactive) waste (HLW) in large diameter deep boreholes. Vitrified HLW pour canisters are limited in diameter to promote glass cooling, and constitute a large potential application for borehole disposal where diameter is constrained. The objective for disposal would be waste packages with diameter of 22 to 29 inches, which could encompass all existing and projected HLW glass inventory in the United States. Deep, large diameter boreholes of the sizes needed have been successfully drilled, and we identify other potentially effective designs. The depth of disposal boreholes would be site-specific, and need not be as deep as the 5 km being investigated in the Deep Borehole Field Test. For example, a 0.91 m (36 inch) diameter borehole drilled to 3 km could be used for disposal from 2.5 to 3 km (8,200 to 9,840 ft). The engineering feasibility of such boreholes is greater today than was concluded by earlier studies done in Sweden and the United States. Moreover, the disposal concept and generic safety case have evolved to a point where borehole construction need not be as elaborate as previously assumed.

Each borehole in the example could accommodate approximately 100 waste packages containing canisters of vitrified HLW. Emplacement of the packages would be through a 32-inch (0.81 m) guidance casing, installed in two sections to reduce hoisting loads, and forming a continuous pathway from the surface to total depth. Above the disposal zone would be a nominal 1 km (3,280-ft) seal interval, similar to previously published concepts. Following those concept studies, the seal system would consist of alternating lifts of swelling clay, backfill and cement. Above the seal zone the borehole would be plugged with cement in the conventional manner for oil-and-gas wells. The function of seals in deep borehole disposal is to maintain the pre-drilling hydrologic regime in the crystalline basement, where groundwater is increasingly saline, stagnant, and ancient. Seals would resist fluid movement and radionuclide transport during an early period of waste heating, but after cooling little fluid movement is expected. Thus, the function of seals could be less important with HLW that has low heat output, and sealing requirements could be limited.

The safety case for deep borehole disposal relies on the prevalence of groundwater that is increasingly saline with depth, stagnant, and ancient, in crystalline basement rock that has low bulk permeability and is isolated from surface processes. The minimum depth for disposal depends on site-specific factors, and may be less than the 2.5 km example. Rough-order-of-magnitude cost estimates show that deep borehole disposal of HLW would be cost-competitive with the lowest cost mine repository options. Thinner overburden, and shallower development of conditions favorable to waste isolation, could make drilling of large-diameter disposal boreholes even more cost effective. The dimensions of the disposal zone and seal zone would be site specific, and would be adjusted to ensure that both are situated in unaltered crystalline basement rock.

I. INTRODUCTION

The deep borehole reference design concept currently under development in the United States (US) consists of drilling a telescoping borehole into crystalline basement rock to a depth of about 16,400 ft (5 km) [1-3]. The radioactive waste-bearing canisters would be emplaced in the lower 6,560 ft (2 km) of the borehole. Above the waste, the interval in the upper 1 km of crystalline basement rock would be sealed using alternating layers of compacted bentonite clay and cement. The 2-km overburden interval would be plugged with cement following existing requirements for plugging oil-and-gas wells. The disposal zone would contain approximately 400 waste canisters, each up to 18.5 ft (5.6 m) long. In the waste disposal zone the hole diameter would be 17 inches (0.43 m), lined with perforated casing having 13-3/8 inch (0.34 m) outer diameter. The wastes amenable for disposal in this design include spent fuel rod assemblies, Cs and Sr capsules and some of the granular waste forms including calcine waste.

Unfortunately, a borehole with these dimensions would not accommodate the 24 inch in diameter vitrified HLW canisters at West Valley and Savannah River, or future vitrified waste pours at Savannah River and Hanford. In addition, the Department of Energy (DOE) plans to package most of the spent nuclear fuel (SNF) it manages into standard canisters that will be 24 inches in diameter. Some waste package diameters could exceed 24 inches such as the 26 inch in diameter canisters proposed for the disposal of the sodium-bearing wastes at the Idaho Nuclear Technology and Engineering Center. These existing and proposed large diameter waste packages has led us to the consider large diameter deep borehole (LDDB) designs.

II. BASIS FOR LARGE DIAMETER DEEP BOREHOLE DESIGN

The basis for our design begins with an examination of well offset data for the largest diameter deep boreholes drilled to date. In addition, we examine other large diameter deep borehole designs that have been proposed within and outside of the US.

The DOE has drilled several hundred large diameter boreholes to depths approaching or exceeding 3,280 ft (1 km) and diameters of 48 to 144 inches (1.2 to 3.66 meters). They were drilled for the purpose of underground nuclear weapons testing [4]. The most impressive of these was completed for the Cannikin nuclear test that took place on the Aleutian island of Amchitka (**Error! Reference source not found.**). A Spartan Missile warhead was detonated in this hole on November 6, 1971. The successful test was the culmination of a massive undertaking involving hundreds of employees and nearly five years of effort.

The test achieved many technical firsts including

- longest single-lift shaft in the US at the time;
- deepest 90-inch hole to a depth of 6,150 ft (1.875 km);
- fully cased using 54-inch steel casing (52-inch inner diameter); the casing weight was 1820 tons (3.6 million lbs); and
- largest emplacement drill rig, with a 1,000-ton derrick.

The effort required nearly two years of drilling in volcanic rock without the use of a blowout preventer (BOP). A 52-foot-wide (15.8 m) cavity was then mined at the bottom by hand using conventional mining tools [5].

In 1984-1986, Standard Oil Production Company drilled and completed the ultra-deep gas well L.W. Magoun No. 1 in Concordia Parish, LA [6]. This well was drilled to a total depth of 25,015 ft (7.6 km). During the completion process, the well was drilled to an intermediate depth of 12,455 ft (3.8 km) at a diameter of 26 inches. A world-record setting string of 20-inch casing weighing more than 2.1 million lb was then run and cemented over this interval [7].

III. PREVIOUS LARGE DIAMETER DEEP BOREHOLE CONCEPTS

Woodward-Clyde Consultants (1983) – Current DBD concepts can be traced to this 1983 feasibility study [8] for disposal of commercial SNF in the US (which also includes a brief review of studies prior to 1983). Fuel canisters with 12.75-inch outer diameter would be assembled in modules with 16-inch diameter, and emplaced in an open borehole with nominal 20-inch diameter. The borehole would be drilled using rotary drilling with conventional mud circulation, or another method as determined from site specific experience. The minimum depth for disposal was not identified, but would be determined from current advances in drilling technology.

A module would contain three canisters end-to-end, but would be short enough to handle underneath a specially configured drilling rig. Canisters would be thin-walled (approximately 3/8 inch) and completely filled with a solid void filler to bear the external loading from pressure in the borehole. Package and module materials (stainless steel, low-alloy steel) would be selected for short-term containment performance (a few years) during the operational period and final plugging/sealing. A module would be emplaced on drill pipe, then the same pipe would be used to inject first mud, then cement through the module and back up the rock annulus, cementing the module and its waste packages. Emplacement operations would proceed one module (three packages) at a time. Two types of accidents were identified: dropping a module or drill string, and getting a module stuck. Mitigation measures were identified but no recovery program for either type of accident was described.

The discussion of emplacement methods did not consider use of guidance casing in segments (liner and tieback) as proposed by Arnold et al. [2]. As a result of not using guidance casing, their concept would increase the likelihood of interference in the open borehole sections. They identified the inability to push or twist packages during emplacement as a disadvantage of other methods such as wireline [9]. As a result of using a drill string for emplacement, they did not foresee an advantage from borehole fluid slowing an accidentally dropped assembly.

A permanent liner in the disposal zone (DZ) also allows additional options for emplacing clay or cement slurry after emplacement [9]. With a permanent liner in the DZ, a removable tieback can be used to connect to the surface, allowing casing removal for sealing above the DZ. Also, the use of a tieback above the DZ facilitates fishing of stuck waste packages by removing the casing as a last resort.

Juhlin and Sandstedt (1989) – This early Swedish study proposed to drill a large diameter (32 inches in the DZ) borehole with emplacement from 2 to 4 km [10]. A light bentonite mud would be used for drilling and to fill the borehole during emplacement. Rotary drilling with reverse circulation and air assist was identified as a most promising drilling method. Waste packaging materials would be selected for extended containment lifetime (Cu or Ti). A slotted or perforated liner, or basket ("high void ratio" with 25-inch OD) would be hung in the DZ prior to emplacement. Non-ferrous material, selected for compatibility with waste packaging, would be used for the liner to prevent later buildup of hydrogen gas. The study proposed construction of a full clay buffer around each waste package in situ. A dump bailer would deposit a stiff clay-water mixture ("deployment mud") on the bottom, then a package would be forced into this by pushing with the string of pipe used for lowering. Plugs of compacted, dehydrated clay would be deposited between packages. The buffer (especially the plugs) would expand through the DZ liner and contact the host rock directly. The sealing zone above the DZ would be lined with slotted or perforated Cu or Ti casing, to provide a guidance pathway for emplacement of alternating lifts of compacted clay and other sealing materials.

The full buffer construction was proposed although it would be difficult to verify for performance credit, and the buffer would be subject to homogenization and creep processes in situ. Buffer installation could be difficult with large breakouts. Risk discussion included wellbore instability and breakout, and premature unlatching (dropping) of waste packages, or failure to unlatch. The possibility of getting stuck was not discussed, and the "high void ratio" casing types in the DZ and the seal zone above, would have limited strength for recovering stuck packages or pipe.

PASS Program Report (SKB 1993) – This study compared deep borehole disposal with three mined geologic repository concepts: KBS-3, medium-length hole (MLH), and very long hole (VLH). The Project on Alternative Systems Study (PASS) followed the previous concept from Juhlin and Sandstedt (1989) with few modifications [10]. Waste packaging was preferred to be a corrosion-resistant Ti container, with concrete filler to resist external pressure loading. Copper packaging by hot-isostatic pressing Cu sinter around a set of SNF assemblies was also proposed. The analysis conservatively neglected differences between these canister alternatives (Ti, Cu) because of uncertainty in damage occurrence during emplacement and buffer installation.

Deutag Drilling Review (Harrison 2000) – This review was from a drilling organization closely involved with drilling the KTB super-deep borehole in Germany [11]. It recommended drilling with a downhole hammer and stiff air foam as circulating fluid to maximize verticality and the rate of penetration. A hole diameter of 33 inches, with 30-inch casing was recommended for the DZ. Waste packages with 20-inch outer diameter would be centralized in the casing, embedded in buffer material. After drilling a clay-based, normally weighted "deployment mud" would be circulated, and the waste package deposition process would be as described by Juhlin and Sandstedt (1989) [10]. A perforated steel liner would be used in the DZ instead of non-ferrous, if hydrogen gas generation is shown to be insignificant.

IV. APPLICATION OF PREVIOUS CONCEPTS

Both SNF and high-level waste glass have been considered for borehole disposal, and the SNF concepts have included both intact assemblies and rod consolidation. In this respect previous concepts are similar to the Sandia reference concept [2].

Large diameter drilling to depth (3 to 4 km) has been considered technically feasible and cost effective for 30 years, but with limited experience in crystalline rock, and potentially high initial cost. The combination of large diameter (e.g., 30 to 36 inches) and depth to 4 km, remains on the margin of proven results presented by Beswick et al. (2014) [4].

Short-lived (a few years) steel packaging was selected previously, consistent with a safety strategy that relies on natural barriers and does not require package containment for long-term isolation [8]. Such reliance could greatly reduce the complexity and cost associated with adapting engineered barrier concepts from mined repository designs, as has been done by the Swedish program.

Much of the risk analysis published for DBD has been qualitative and incomplete. Previous studies of drill-string emplacement have acknowledged the possibility of dropping a very heavy assembly with waste packages attached or beneath. A previous study of possible consequences from packages dropping or becoming stuck, did not consider the likelihood of either outcome [12]. More rigorous comparison of risk for different emplacement methods (SNL 2016) has informed the selection of wireline emplacement.

V. PROPOSED LDDB DESIGN

With consideration of existing and proposed large diameter borehole designs, a borehole capable of accommodating large diameter waste canisters is described below and illustrated in Figure 1 [13]. It is similar to that proposed by Beswick et al. (2014) and considers the engineering challenges of drilling large diameter holes beyond 9,840 ft (3 km).

From the surface down the design is as follows:

Conductor hole, 72-inch (1.83 m) diameter with 60-inch (1.52 m) conductor pipe to ~50 ft (15 m) depth (not shown in Figure 1).

Surface hole, 58-inch (1.47 m) diameter with 50-inch (1.27 m) surface casing fully cemented to approximately 984 ft (300 m).

Intermediate section, 46-inch (1.17 m) diameter, lined with 42-inch (1.02 m) casing to 4,921 ft (1.5 km), hung from the bottom of the surface casing then fully cemented. The maximum depth of this section corresponds to the top of the seal zone, so the length specified here allows for overburden thickness of approximately 4,592 ft (1.4 km). Assuming that rock strength in the disposal formation (e.g., crystalline basement) is superior to that in the overburden, the intermediate section would be drilled approximately 100 m into the disposal formation to anchor the guidance casing. The intermediate liner would weigh approximately 1.5 million pounds, requiring special procedures for assembly and installation.

Seal zone section, 36-inch (0.91 m) diameter, drilled approximately 3,280ft (1 km) below the intermediate section, left unlined until completion of the disposal zone section, then cased with 32-inch (0.81 m) casing as discussed below.

Disposal zone section, 36-inch (0.91 m) diameter, drilled 1,968 ft (600 m) below the seal zone section to a total depth of 9,840 ft (3 km). The disposal zone and seal zone together would be lined with 5,248 ft (1.6 km) of 32-inch (0.81 m) casing, hung from the bottom of the fully cemented intermediate liner discussed above. The 32-inch liner would be cemented over a short interval (100 m or less) just above the disposal zone using an annular casing packer and a port collar, so that after waste emplacement it can be cut above the disposal zone and removed, exposing the seal zone interval. This section of casing would be approximately 5,248 ft (1.6 km) long, and weigh approximately 1.4 million pounds. The upper part of the guidance casing would consist of a 32-inch (0.81 m) diameter tieback, hung from the top of the surface casing and extending down to 4,592 ft (1.4 km). The shoe on the bottom of this tieback would mate with the hanger for the same-diameter guidance casing hung below it. The tieback would be removed for final plugging of the borehole through the overburden section.

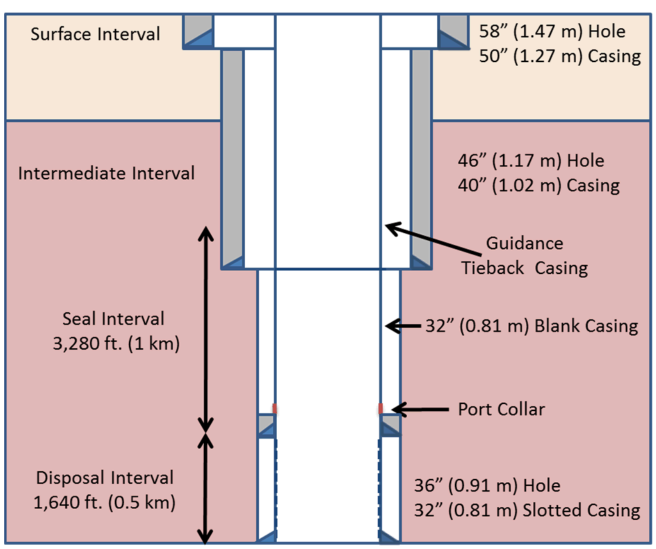

Figure 1. Borehole design for large canister disposal.

The bottom 500 m of the borehole from ~8,200 to 9,840 ft (2.5 to 3 km) depth would contain the waste canisters (Figure 1). Each disposal borehole could accommodate approximately 100 waste packages containing vitrified HLW and other waste forms as described above. Emplacement of the packages would be through a 32-inch (0.81 m) guidance casing, installed in two sections continuously between the surface and total depth. In the disposal zone this casing would be permanently installed and could be slotted as indicated above for the reference concept of Arnold et al. (2011), or it could be perforated using some other scheme to allow for cementing, fluid surge during emplacement operations, or thermal expansion as needed.

Above the disposal zone would be a nominal 3,280-ft (1 km) seal interval (of which up to about 100 m would be cemented during construction to stabilize the guidance casing). Similar to the reference concept of Arnold et al. (2011), the seal system for large diameter waste canisters would also limit the movement of water and the migration of contaminants released from waste packages. The seal system would consist of a combination of bentonite and concrete [1]. Above the seal zone, in the intermediate and surface sections, the borehole would be plugged with conventional cement plugs inside cemented casing. In this design, the overburden thickness could be up to 4,592 ft (1.4 km, for a borehole total depth of 3 km), but there could be less overburden than this (which might allow a longer disposal zone). These dimensions would be site specific, and would be adjusted to ensure that the disposal zone and the seal zone are situated in unaltered granite with low porosity and low permeability.

VI. SUPPORTING ENGINEERING ANALYSES

VI.A. Package Stress Analyses

Stress analyses were performed on three waste package options shown in Figure 2. Finite element stress on these package concepts were performed using SolidWorks Simulation® software. Analyses were conducted with an applied a hydrostatic pressure of 4,428 psi (30Mpa) over the external surface of the package at ambient surface temperature.

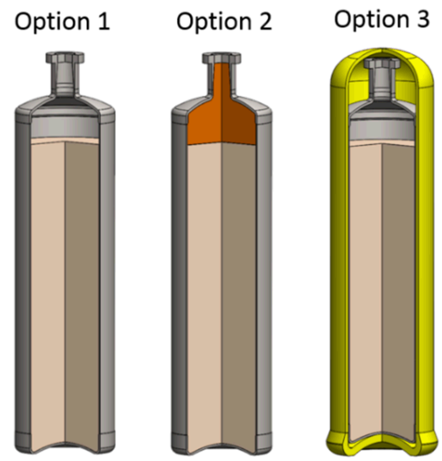

Figure 2. Waste package options analyzed for LDDB disposal design.

Package dimensions are provided in Table 1. The dimensions for option 1 are representative of a Savannah River vitrified HLW package nominally filled with HLW glass to 90% of its capacity. Option 2 has the same dimensions as Option 1 but includes the addition of an expandable cement fill above the glass. Options 3 and 4 represent the HLW package of options 1 and 2 are which are then placed in a stainless steel overpack with a wall thickness of 1inch.

TABLE I. Package dimensions for waste packaging options analyzed

Package Design Option	Nominal Waste Package OD (in)	Nominal Waste Package Wall Thickness (in)	Nominal OD of Waste Package Overpack (in)	Nominal Waste Package Overpack Wall Thickness (in)
1	24	0.375	NA	NA
2	24	0.375	NA	NA
3	24	0.375	26	1

VI.B. Stress Analysis for Package Design Option 1

The result of the stress analysis is shown in Figure 3. As expected the highest von Mises stresses (a measure of the maximum multiaxial stress state for comparison to yield strength) are located in the unsupported section at the top of the waste package above the glass fill level. The external loads result in a von Mises stress as high as 150 ksi on the top of the canister and the wall above the glass fill level indicating it will likely yield at the top and along the canister walls where the canister is unsupported by glass.

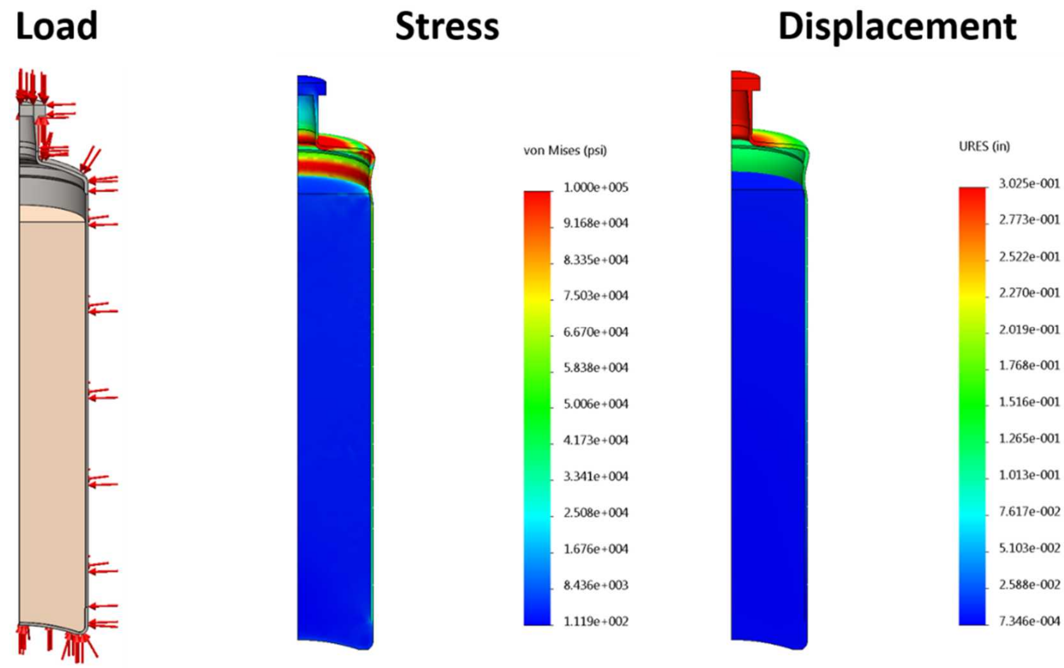

Figure 3. Result of stress analysis on package design Option 1.

VI.C. Stress Analysis for Package Design Option 2

A stress analysis of design Option 2 was performed on a HLW glass canister where the void space is filled with Hydrostone™, an expandable cement material with an unconfined compressive strength of 6 ksi and a modulus of 2.5 x 10^6 psi. The result of the stress analysis is shown in Figure 4. Maximum von Mises stresses experienced by the filled canister are considerably lower than those observed in Option 1 with a maximum value of 6 ksi. This canister is likely to survive the downhole pressures without the use of an overpack.

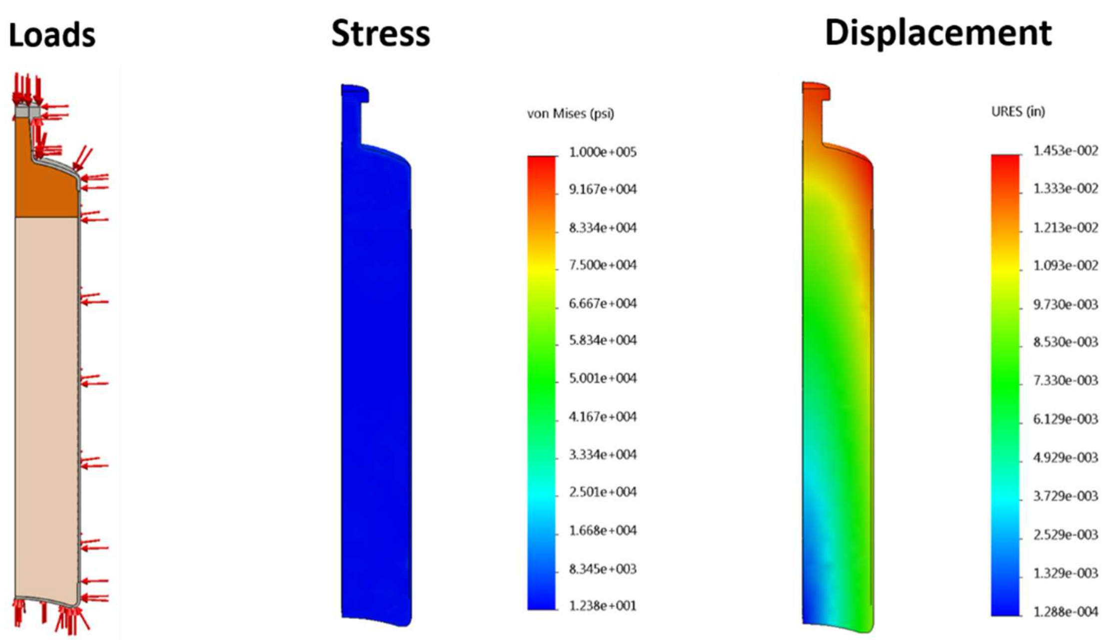

Figure 4. Result of stress analysis on package design Option 2.

VI.D. Stress Analysis for Package Design Option 3

A stress analysis of design Option 3 was performed on a HLW glass canister inside of an overpack. The result of the stress analysis is shown in Figure 5.

Maximum von Mises stresses experienced on the top of the overpack are over 52,000 psi. High collapse strength casing steels used by the drilling industry such as P110 and Q125 with yield strengths of 110,000 and 125,000 psi respectively could be appropriate overpack materials that provide safety factors approaching or exceeding a factor of 2.0.

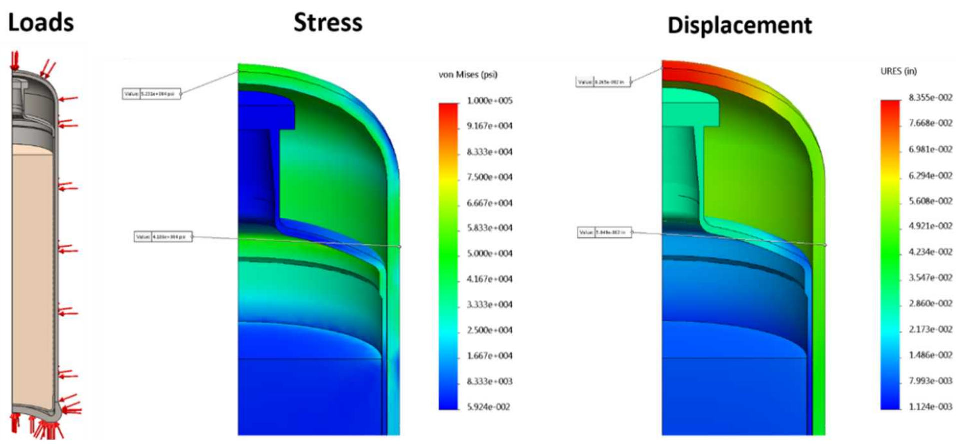

Figure 5. Result of stress analysis on package design Option 3.

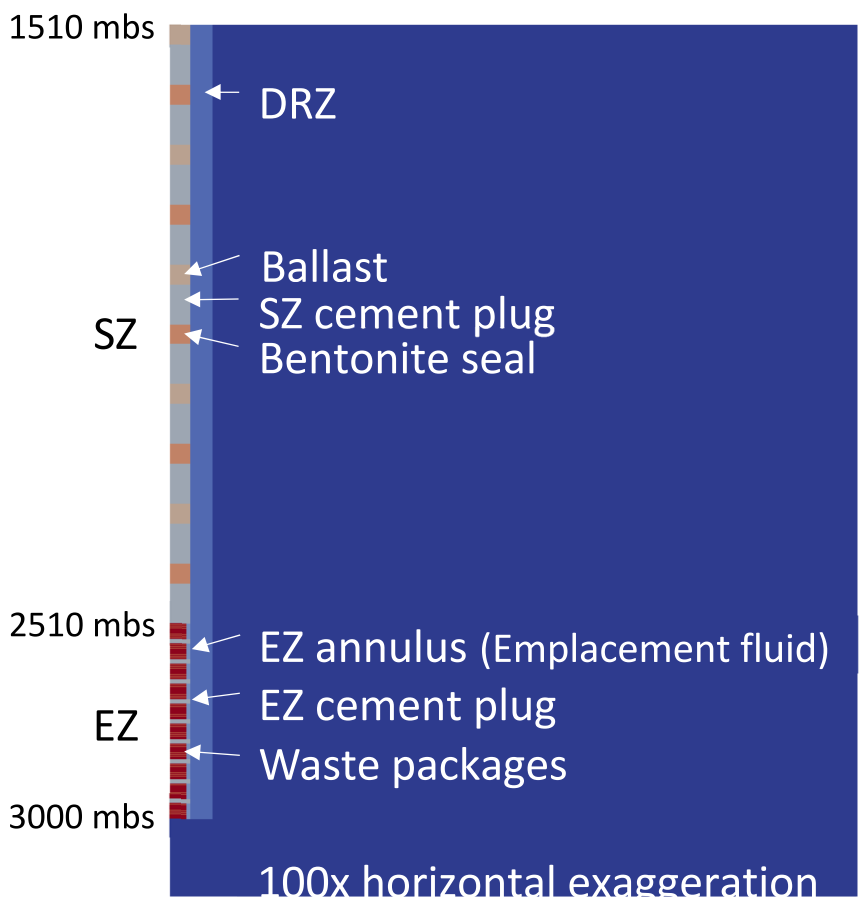

Figure 6. A portion of the PA model domain at 100x horizontal exaggeration.

VI.D. Performance Assessment

A preliminary performance assessment (PA) of the undisturbed scenario was performed. In this scenario it is assumed that 50 canisters of Savannah River glass are disposed in a borehole extending 3000 m below the land surface (mbs) into sparsely fractured crystalline rock (Figure 6).

Intervals of 10 waste packages (each 4 m in length including fishing necks and impact limiters) are separated by 10-m long cement plugs, resulting in a 490-m long emplacement zone (EZ). A 1000-m long seal zone (SZ) directly above the emplacement zone (EZ) is comprised of alternating cement plugs, bentonite seals, and ballast of crushed rock [15]. A disturbed rock zone (DRZ) around the borehole is assumed to have elevated permeability with respect to the adjacent undisturbed host rock due to changes in stress associated with drilling. Parameters describing these materials are listed in Table 2.

TABLE II. Numerical Representation of Materials in the Deterministic PA Simulation

Material	k (m^2)	ϕ	τ	D_e (m^2/s)	Thermal Cond. ($W\ m^{-1}K^{-1}$)	Heat Cap. ($J\ kg^{-1}K^{-1}$)	Dens. (kg/m^3)
Waste Package	$1x10^{-16}$	0.43	1.0	$4.3x10^{-10}$	17	500	7,850
Fishing Neck, Impact Limiter	$1x10^{-16}$	0.43	1.0	$4.3x10^{-10}$	17	500	7,850
EZ Annulus (Emplacement Fluid)	$1x10^{-12}$	0.99	1.0	$9.9x10^{-10}$	0.58	4192	1,100
EZ Cement Plug	$1x10^{-18}$	0.175	0.175	$3.1x10^{-11}$	1.7	900	2,700
SZ Cement Plug	$1x10^{-18}$	0.175	0.175	$3.1x10^{-11}$	1.7	900	2,700
Bentonite Seal	$1x10^{-18}$	0.45	0.45	$2.0x10^{-10}$	1.3	800	2,700
Ballast	$1x10^{-14}$	0.20	0.20	$4.0x10^{-11}$	2.0	800	2,700
Crystalline Rock	$1x10^{-18}$	0.005	0.20	$1.0x10^{-12}$	2.5	880	2,700
DRZ	$1x10^{-16}$	0.005	0.20	$1.0x10^{-12}$	2.5	880	2,700

Equations describing coupled heat and fluid flow and reactive transport are solved numerically with PFLOTRAN [16], a massively parallel multiphase flow and reactive transport code. The 2D axisymmetric model domain extends from 1,000 m below the EZ to 1,000 m above the EZ (the top of the SZ) and has a radius of approximately 1,000 m. Initial temperatures and pressures are established assuming a geothermal heat flux of 60 mW/m^2, a surface temperature of 10 °C and a hydrostatic pressure gradient. The resulting temperature gradient is about 25 °C/km. The initial temperatures and pressures are maintained at the top and radial boundaries of the domain, throughout the simulations. At the bottom boundary a heat flux of 60 mW/m^2 and zero fluid flux are imposed. Simulations include 16 radionuclides (Table 3), the initial concentrations of which are set to 10^{-20} mol/L throughout the model domain. Boundary conditions are such that any fluid entering the domain enters at the initial concentration and any fluid exiting the domain carries with it the ambient concentration. Diffusive flux across the boundaries is disallowed by specifying a zero concentration gradient.

Initial waste package heat output (watts per waste package) and waste form radionuclide inventory are calculated from radionuclide inventories calculated previously (DOE 2008, Table 1.5.1-20) and assume a disposal date of 2038 [17]. As a simplification, waste packages are assumed to breach one year into the simulation. Upon waste package breach, the glass waste form begins to dissolve via a temperature-dependent rate law [18]. Radionuclide solubility limits and sorption coefficients (Table 3) are chosen assuming reducing conditions and NaCl brine [19].

Concentration at 1 million years is shown for ^{129}I which behaves similarly to a conservative tracer due to its long half-life (1.57×10^7 y), unlimited solubility and lack of sorption, and for ^{237}Np (2.14×10^6 y) which both precipitates and sorbs (Figure 7). After 1 My ^{129}I has reached a distance of approximately 500 m beyond the EZ at a concentration of 10^{-15} mol/L, while ^{237}Np has traveled less than 100 m beyond the EZ at the same concentration. Transport is diffusion-dominated. Advection (thermal convection) driven by waste heating transports radionuclides only locally within the borehole annulus and DRZ.

TABLE III. Radionuclide inventory modeled for LDDB Preliminary Performance Assessment

Isotope	Inventory per Canister [20] (g)	Borehole Inventory (g)	Element Solubility Limit [19] (mol/L)	Element K_d in Crystalline Rock [19] (m^3/kg)
^{241}Am	8.3E+01	8.3E+03	6 x 10^{-6}	0.04
^{243}Am	5.9E+00	5.9E+02		
^{238}Pu	4.6E+01	4.6E+03	2 x 10^{-7}	0.5
^{239}Pu	2.4E+02	2.4E+04		
^{240}Pu	3.3E+01	3.3E+03		
^{242}Pu	4.8E+00	4.8E+02		
^{237}Np	3.6E+01	3.6E+03	1 x 10^{-9}	0.2
^{233}U	5.0E+00	5.0E+02	4 x 10^{-10}	0.1
^{234}U	1.0E+01	1.0E+03		
^{236}U	4.9E+01	4.9E+03		
^{238}U	1.2E+05	1.2E+07		
^{229}Th	5.6E-04	5.6E-02	4 x 10^{-7}	0.2
^{230}Th	5.8E-04	5.8E-02		
^{129}I	1.6E+00	1.6E+02	unlimited	0
^{135}Cs	1.8E+01	1.8E+03	unlimited	0.05
^{99}Tc	4.7E+02	4.7E+04	3×10^{-8}	0.05

VII. COST CONSIDERATIONS

A simple scaling factor of 1.8 was calculated based upon the relative volumes of a LDDB to 9,840 ft (3 km) as compared to that of a reference borehole to 16,400 ft (5 km). Arnold et al. (2011) estimated the cost to drill a reference borehole is $27 million. Applying the scaling factor to the reference design cost gives a rough order of magnitude (ROM) cost of $49 million for drilling a LDDB. The total system cost estimate for the reference design borehole is $40.15 million which includes drilling, completing, waste emplacement and sealing [2]. Applying the scaling factor to this cost gives a ROM cost of $72.3 million per LDDB.

VIII. SUMMARY

A preliminary large diameter deep borehole design option has been developed for the disposal of HLW glass and other large diameter radioactive waste packages. The proposed borehole is a telescoping hole drilled to 3 km at a diameter of 36 inches and finished with 30-inch casing. Preliminary analyses of waste packaging options indicate that direct disposal of a HLW canister filled with an expandable cement material may be feasible. Alternatively, the canister could be disposed in an overpack constructed from P110, Q125, or stainless steel alloys which are used by the oil and gas drilling industry when high strength is required. A performance assessment shows that ^{129}I reaches a distance of approximately 500 m beyond the EZ at a concentration of 10^{-15} mol/L, while ^{237}Np has traveled less than 100 m beyond the EZ at the same concentration over a time period of 1 million years.

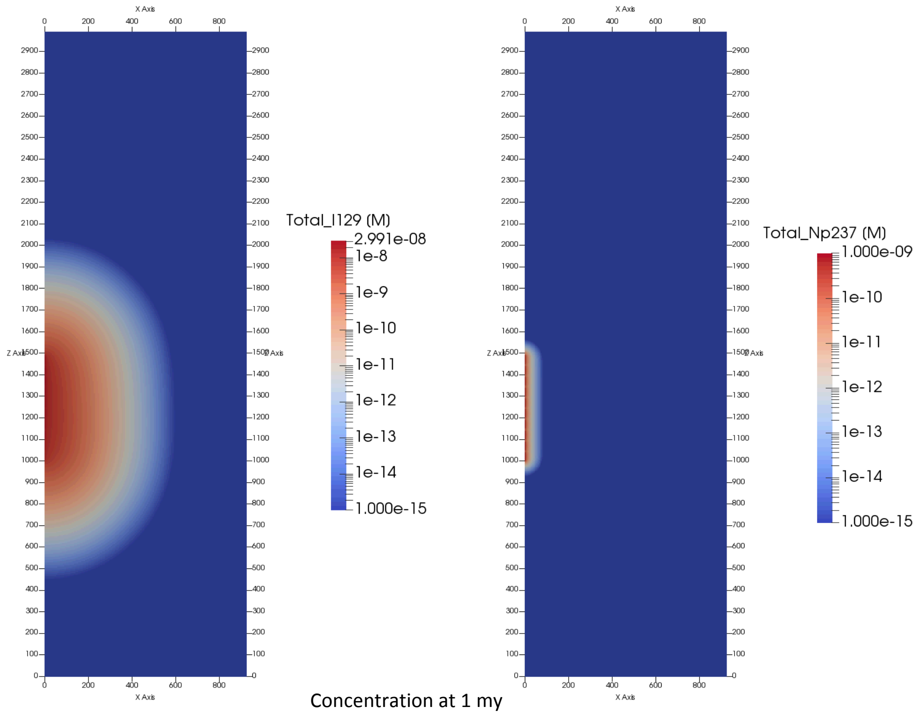

Figure 7. Concentration of 129I and 237Np at 1 million years.

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