Safety Case Considerations for Deep Borehole Disposal of Cs/Sr Capsules – 16294

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ABSTRACT

The U.S. Department of Energy Office of Nuclear Energy (DOE-NE) performed an assessment of disposal options that recommended the consideration of deep borehole disposal of smaller DOE-managed waste forms, such as cesium (Cs) and strontium (Sr) capsules. To assess the feasibility of the deep borehole disposal concept for Cs/Sr capsules, safety case considerations are identified and examined.

A safety case includes quantitative (e.g., safety assessments) and qualitative information related to both pre-closure (operational) and post-closure safety. For deep borehole disposal of Cs/Sr capsules, pre-closure safety considers potential hazards associated with waste package surface handling and downhole emplacement activities; post-closure safety considers scenarios for long-term radionuclide transport to the biosphere.

A preliminary list of qualitative indicators of pre-closure and post-closure safety is presented. Research, development, and demonstration (RD&D) activities that can provide a quantitative basis for these indicators are discussed. In particular, DOE-NE has initiated a Deep Borehole Field Test, using surrogate test packages without radioactive waste, to further investigate various aspects of site characterization, deep drilling, and waste package handling and emplacement that would be needed for a full-scale disposal facility for Cs/Sr capsules or other DOE-managed waste forms.

Finally, preliminary results from pre-closure hazard analyses and post-closure performance assessment (PA) calculations are presented as examples of supporting information for the quantitative safety case considerations. These preliminary results suggest that a favorable safety case can be developed for deep borehole disposal of Cs/Sr capsules.

INTRODUCTION

Deep borehole disposal for the geologic isolation of spent nuclear fuel (SNF) and/or high-level radioactive waste (HLW) has been considered for many years [1, 2, 3, 4] beginning with evaluations by the US National Academy of Sciences in 1957 [5]. More recently, the DOE-NE Used Nuclear Fuel Disposition Campaign (UFDC) has conducted research on generic deep geologic disposal options, including deep borehole disposal in crystalline basement rock [6, 7, 8, 9].

In 2012, the Blue Ribbon Commission on America's Nuclear Future (BRC) reviewed prior research on deep borehole disposal, concluded that the concept may hold

promise, and recommended further RD&D to fully assess its potential [10]. In 2013, consistent with BRC recommendations, the DOE identified developing a research and development plan for deep borehole disposal as a key strategy objective [11]. In accordance with the BRC recommendations and DOE strategy objective, UFDC is conducting RD&D activities to evaluate the feasibility of siting and operating a deep borehole disposal facility [7,9], including a Deep Borehole Field Test [12, 13]. In 2014, DOE-NE performed an assessment of disposal options that recommended the consideration of deep borehole disposal of smaller DOE-managed waste forms, such as Cs and Sr capsules [14].

To support the assessment of the feasibility of the concept, the remainder of this paper identifies and examines preliminary safety case considerations for deep borehole disposal of Cs/Sr capsules.

Deep Borehole Disposal Concept

A generalized deep borehole disposal concept is illustrated in Fig. 1, showing that waste in a deep borehole disposal system is several times deeper than typical mined repositories (e.g., Onkalo and WIPP). The typical maximum depth of fresh groundwater resources is also shown in Fig. 1, as indicated by the dashed blue line. Safety of the deep borehole disposal concept relies primarily on the natural barriers (great depth of burial and the isolation provided by the deep natural geological environment) and, to a lesser extent, on the engineered barriers (the durability of the waste packages and waste forms and the integrity of the borehole seals).

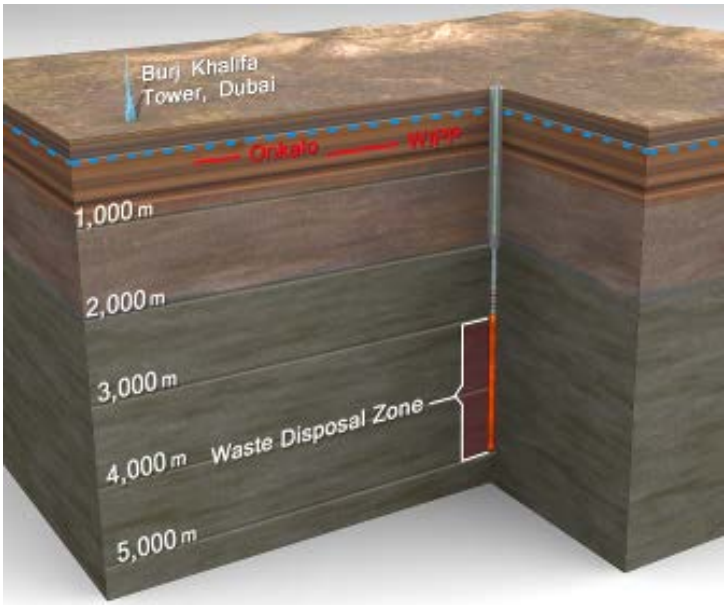


Fig. 1. Generalized schematic of the deep borehole disposal concept.

Several design alternatives exist that satisfy this basic concept, dependent on a variety of factors, most notably the size and characteristics of the waste form and packaging. Initial deep borehole disposal studies [6] proposed waste packages that contained commercial SNF. Specifically, the waste package was designed to

encapsulate a single PWR assembly, requiring a borehole with a bottom-hole diameter of 0.43 m (17 in). More recently, DOE has recommended "a focused RD&D program addressing technologies relevant to deep borehole disposal of smaller DOE-managed waste forms" [14].

The DOE-managed inventory includes 1,936 Cs and Sr capsules currently stored at the Hanford Waste Encapsulation and Storage Facility (WESF) that are all less than 0.09 m (3.5 in) in diameter [14]. These Cs/Sr capsules contain short-lived Sr-90 and Cs-137, and long-lived Cs-135; other radionuclides have decayed away [15].

For the purposes of the preliminary safety analyses, a baseline deep borehole disposal concept for Cs/Sr capsules (Fig. 2) consists of a borehole drilled to a depth of 5,000 m into crystalline basement rock, with a bottom-hole diameter of 0.22 m (8.5 in). This design is expected to be achievable in crystalline rocks with currently available commercial drilling technology.

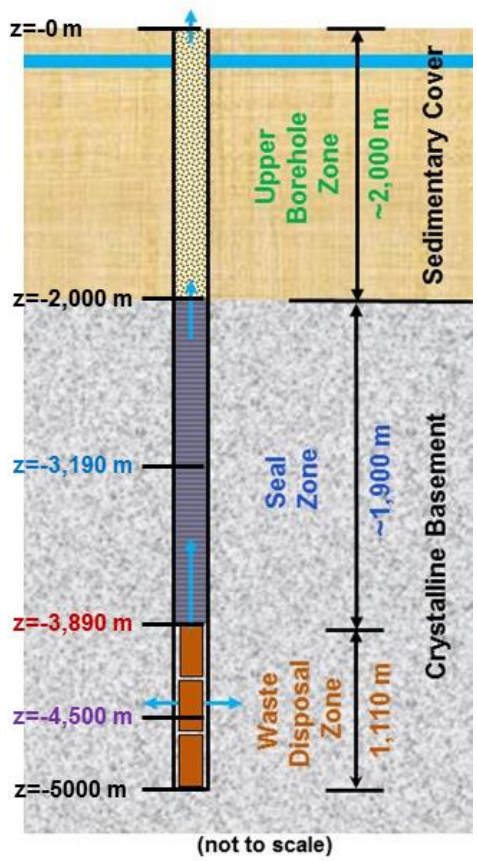


Fig. 2. Baseline deep borehole disposal concept for Cs/Sr capsules.

Waste packages containing the Cs/Sr capsules are emplaced in the lower disposal zone portion of the borehole (between 3,890 m and 5,000 m depth); the upper portion of the borehole is sealed and plugged with alternating layers of bentonite clay, cement, and cement/crushed rock backfill. Each waste package is assumed to contain eight capsules end to end with a total waste package length of 4.34 m, an inside diameter of 0.10 m (4.0 in), and an outside diameter of 0.13 m (5.0 in) [13]. With this

baseline design (other configurations are possible), 242 waste packages would be required to accommodate all of the Cs/Sr capsules, and all of the waste packages would fit in a single borehole with a disposal zone 0.22 m (8.5 in) in diameter and 1,110 m long (this length includes spacing and intermittent bridge plugs between waste packages).

Safety Case Considerations

A safety case includes quantitative (e.g., safety assessments) and qualitative information related to both pre-closure (operational) and post-closure safety [16]. For deep borehole disposal of Cs/Sr capsules, pre-closure safety considers potential hazards associated with waste package surface handling and downhole emplacement activities, which would require radiation shielding and/or remote handling operations; risks include worker safety, accidents, and the potential for operational failures (e.g., waste packages stuck in the borehole above the disposal zone) [13]. Qualitative information relevant to the pre-closure safety case includes [7, 13, 17]:

- Drilling and casing a large diameter borehole to 5,000 m depth in crystalline basement rock is achievable with existing drilling technology.
- Borehole and casing can be designed to provide a high level of assurance that waste packages can be emplaced at the desired depth, with minimal probability of packages becoming stuck during emplacement.
- Waste packages can be engineered to maintain structural integrity and provide a high level of assurance that no leakage of radioactive materials will occur during loading, transportation, handling, and emplacement.
- Emplacement systems can be engineered and operated to provide a high level of assurance the waste packages can be safely surface handled and emplaced.

Post-closure safety considers scenarios for long-term radionuclide transport to the biosphere. For undisturbed post-closure conditions, the low-permeability of the surrounding crystalline host rock is expected to limit radionuclide releases, if they occur, to short-duration (a few hundred years) thermally-induced upward advective transport through the borehole seals and/or disturbed rock zone (DRZ) followed by longer-term slow diffusive transport. Qualitative information relevant to the post-closure safety case includes [7, 13, 17]:

- Waste emplacement is deep – between 3,890 and 5,000 m depth in crystalline basement rock with more than 1,000 m of crystalline rock overlying the waste disposal zone.
- Deep crystalline rocks have low permeability and contain high-salinity fluids at many continental locations, suggesting very limited interaction with shallower sources of useable groundwater [18].
- Geochemically reducing conditions in the deep subsurface stabilize low solubility phases and enhance sorption of many radionuclides, leading to limited mobility in groundwater.
- Density stratification (saline groundwater underlying fresher groundwater) at depth opposes upward groundwater flow and dissolved and colloidal

radionuclide movement, such as from thermally-induced advection due to decay heat from the Cs/Sr capsules.

- Borehole seals can be engineered to maintain their physical integrity as permeability barriers, at least over the time scale of thermally-induced upward groundwater flow.

Some of these pre-closure and post-closure safety case considerations, specifically those related to deep drilling, subsurface conditions, and waste package handling and emplacement, will be further assessed as the Deep Borehole Field Test progresses.

Quantitative analyses supporting the safety case are summarized in the following sections. These include preliminary results from pre-closure hazard analyses and post-closure PA calculations.

PRE-CLOSURE HAZARDS ANALYSIS

The pre-closure safety case will be supported by engineering design studies and testing of important components of the deep borehole disposal system; these include surface handling equipment and procedures, waste package integrity during emplacement operations prior to borehole sealing, and the emplacement configuration and procedures [13]. These include consideration of both nominal and off-normal conditions; risks include worker radiation exposure and/or surface contamination caused by waste package breach following an accident such as dropping a waste package or pipe string, or by waste package recovery after one or more packages becomes stuck above the disposal zone [13].

Several options for surface handling and emplacement of waste are under consideration [13]. Waste handling operations are conceptualized to begin with the onsite receipt of a shipping cask that contains a waste package. Emplacement operations begin when the cask is upended over the borehole, locked to a receiving flange or collar. The scope of emplacement includes activities to lower waste packages to total depth, and to retrieve them back to the surface when necessary for any reason during emplacement operations (i.e., prior to sealing). For the baseline concept, it is assumed that waste packages will be lowered, one package at a time, by wireline, as described in [13].

To date, quantitative analyses supporting the pre-closure safety case have been limited to hazard analyses of emplacement operations [13]. A preliminary hazard analysis of wireline emplacement of 242 waste packages down a deep borehole is summarized here. The analysis considers accident hazards and accident event sequences associated with wireline emplacement, based on standard borehole and nuclear materials handling operations. Four top level off-normal events were identified that have the potential to lead to adverse consequences [13]: waste package drops down the borehole from the top; waste package drops during the trip in; waste package gets stuck in borehole during trip in; and wireline and tool string is dropped onto an emplaced package during trip out. Fig. 3 shows an event tree that summarizes the assumed sequence of events that would follow the occurrence of any one of these off-normal top events for wireline emplacement.

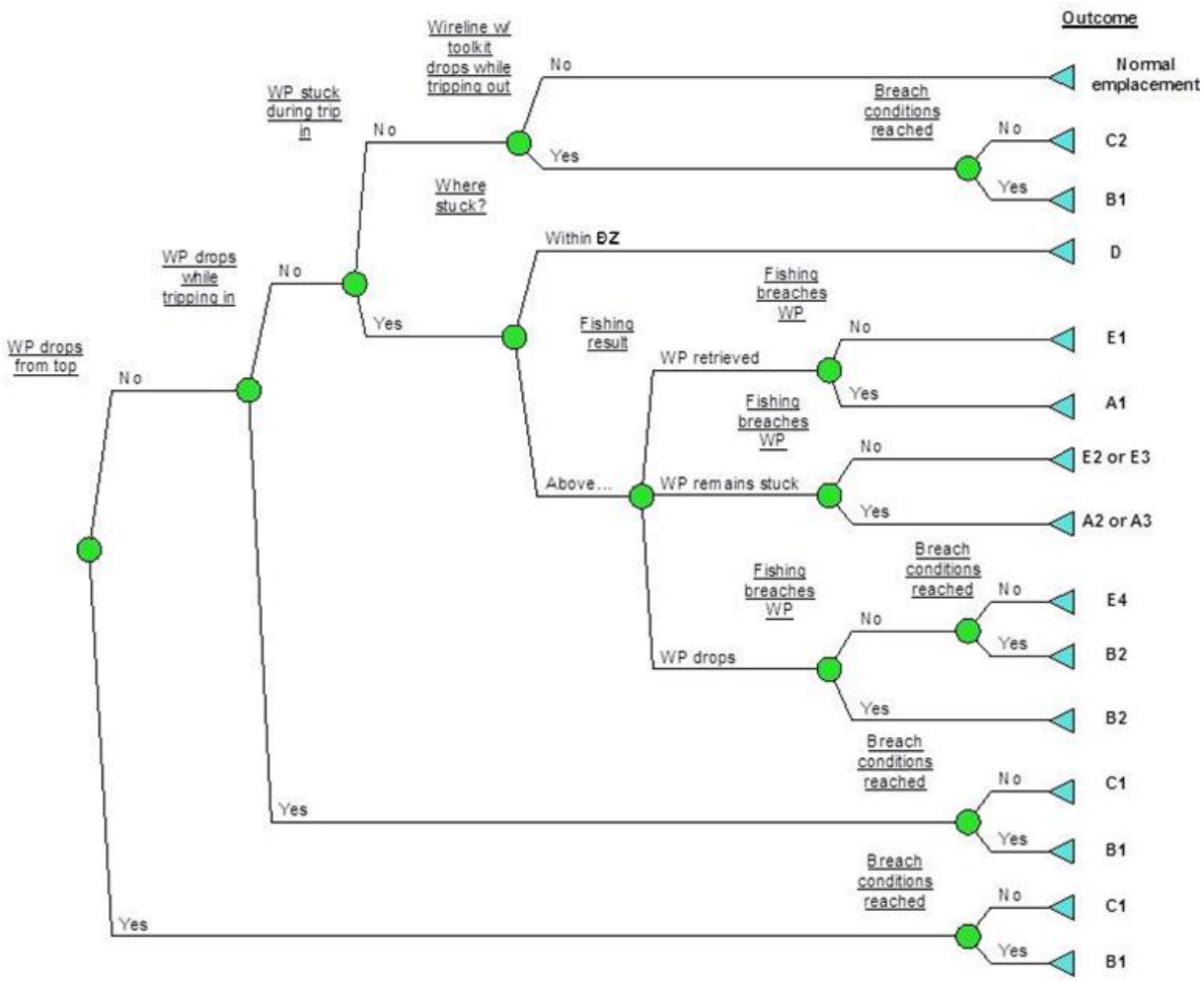


Fig. 3. Event tree for wireline emplacement of waste packages (WPs).

The events along the top of the figure, moving left to right, are the four off-normal top events. For each event, the upper branch indicates a favorable outcome (no drop, not stuck, etc.) and the lower branch indicates the occurrence of the off-normal event. Table I lists the probabilities for each off-normal top event; these were calculated using fault trees that considered various actions (e.g., human error, component failure), informed by expert panel discussion [13].

As shown in the event tree, some of these top events (e.g., package drops) could directly cause a breach of a waste package (Outcome B1), or not (Outcomes C1 and C2). Other top events (e.g., package stuck) could indirectly result in a breach of a waste package if the primary mitigation technique (fishing) is not successful (Outcomes A1, A2, A3, and B2). Calculation of these outcome probabilities required additional event probabilities, as described in Table II. For the purposes of the hazard analysis, outcomes that resulted in a package breach were assumed to result in a radionuclide release, although the duration and magnitude of the release was not estimated.

TABLE I. Summary of top-event probabilities for wireline emplacement [13]

Fault Tree Top Event	Failure Probability	Primary Responsible Events
WP drops from surface	1.12×10^{-7} (per WP)	Over-tension due to winding the wrong way against the stops.
WP drops during trip in	5.50×10^{-5} (per WP)	Wireline break due to dynamic over-tension if the package momentarily hangs up.
WP gets Stuck	2.18×10^{-5} (per WP)	Debris such as residual cement from setting plugs.
Wireline drops during trip out	4.01×10^{-6} (per WP)	Cask door or blind ram shears wireline; wireline damage failure; cable head misassembled and causes release during trip out.

TABLE II. Event probabilities for wireline emplacement event tree

Event	Probability	Basis
WP stuck above DZ	0.77	Conditional probability, given that a WP gets stuck. Based on relative lengths of crystalline rock above and within the disposal zone (DZ) [adapted from Table 5-5 of Ref. 13].
Fishing successful	0.90	Expert panel discussion [Table 5-5 of Ref. 13]. WP retrieved to surface.
Fishing beaches WP	0.03	Expert panel discussion [Table 5-5 of Ref. 13]. Assumes 30 fishing attempts per WP.

The resulting preliminary hazard analysis shows that the probability of incident-free wireline emplacement of 242 waste packages would be 98.07%. The primary potential for incidents arises from waste package drop events due to wireline failure. These drop event incidents were not considered to result in waste package breaches, due in part to the incorporation of impact limiters on the bottom of the waste packages. The probability of an incident leading to a waste package breach and subsequent radiation release (due to fishing damage during attempts to retrieve stuck waste packages) is estimated to be 1.21×10^{-4}.

These hazard analyses, and associated cost-risk analyses [13], can be refined in the future based on experience from the Deep Borehole Field Test. For a future disposal project, additional analyses would also be needed for transportation safety, surface handling, worker exposure, and the effects from low-probability external events such as flooding, extreme weather, seismicity, and sabotage.

POST-CLOSURE PERFORMANCE ASSESSMENT

Results from simplified post-closure PAs for deep borehole disposal of SNF have shown that predicted radionuclide doses under undisturbed conditions are quite low and dominated by non-sorbing, long-lived I-129 [6, 9, 19]. A preliminary PA for Cs/Sr disposal is presented here to examine releases and doses for Sr-90, Cs-135, and Cs-137 under undisturbed conditions.

The baseline undisturbed scenario includes (Fig. 2):

- 242 waste packages (containing 1,335 Cs capsules and 601 Sr capsules) in a 1,110 m waste disposal zone. The waste packages are assumed to maintain structural integrity during surface handling and emplacement, but are assumed to be degraded immediately after sealing and do not perform any function (e.g., gradual corrosion) that would delay radionuclide release or transport.
- The waste forms (solid cesium chloride and strontium fluoride salts) are assumed to degrade immediately after emplacement and do not perform any function (e.g., gradual dissolution) that would delay radionuclide release or transport.
- The crystalline basement rock has low bulk permeability and porosity. For this study, bulk permeability is assumed to decrease with depth as shown in Fig. 4, as observed for metamorphic crystalline rock [20]. An assumption of igneous crystalline rock (e.g., granite) would result in an even lower permeability (Fig. 4). Other crystalline rock properties are shown in Table III. The overlying sedimentary sequence and properties are also shown in Fig. 4 and Table III.
- The DRZ around the borehole is assumed to have a depth-dependent permeability that is a factor-of-10 higher than the adjacent intact basement rock permeability. Other DRZ properties are shown in Table IV.
- Temperature, salinity, and density gradients with depth are assumed. The ambient temperature at the center of the disposal zone is 120°C, based on a surface temperature of 10°C and a thermal gradient of 25°C/km.
- The ~1,900 m seal zone includes bulk permeability and porosity consistent with bentonite clay (Table IV). The upper borehole zone above the seal zone includes bulk permeability and porosity consistent with crushed rock backfill (Table IV).
- Thermal output and radioactivity from the Cs and Sr capsules assumes surface storage/aging until borehole emplacement in 2020 [15, 21].
- Radionuclide mobilization and transport properties are based on geochemically reducing conditions consistent with deep crystalline rock (Table IV).
- Dose calculations are performed using assumptions consistent with a human receptor in the IAEA BIOMASS ERB 1B biosphere [22].

The radial geometry of the near-borehole region is shown schematically in Fig. 5. At disposal zone depth it includes waste packages (containing the Cs and Sr capsules) and an annular region (possibly containing grout) within the borehole, perforated casing, a surrounding DRZ, and the intact crystalline basement rock. The overlying seal zone includes, radially, seal materials (e.g., bentonite) and an annulus (the size of which depends on the efficacy of the seals to the DRZ/host rock) within the borehole, and the surrounding DRZ and intact crystalline rock.

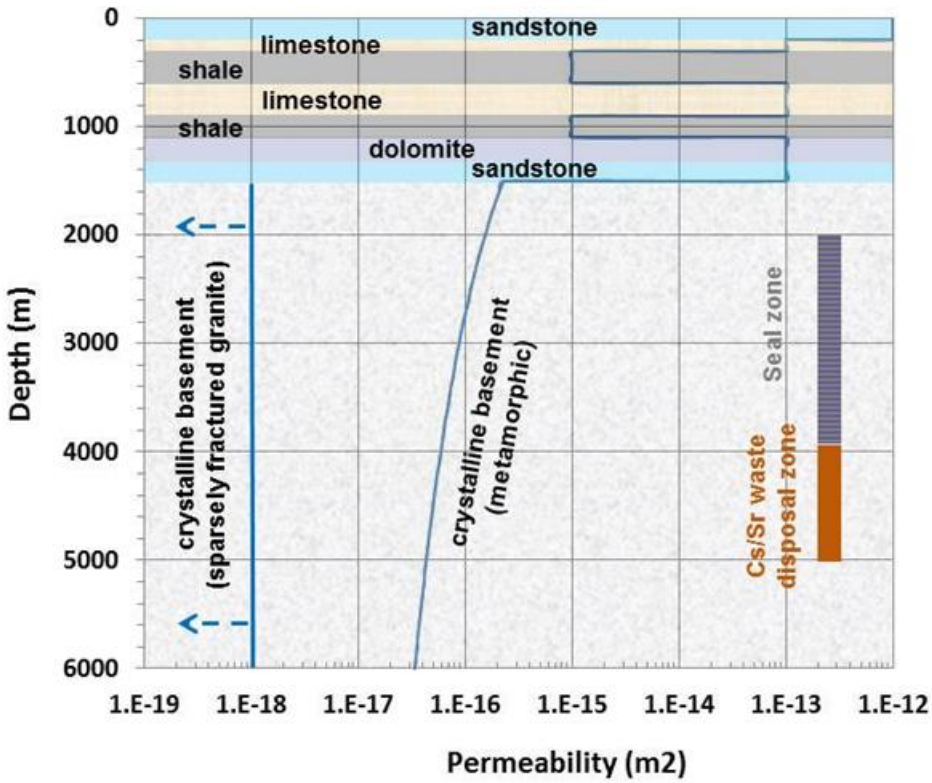


Fig. 4. Baseline scenario sedimentary sequence and permeability.

TABLE III. Baseline scenario rock properties [21]

Lithology	Permeability (m^2)	Porosity (-)	Thermal Conductivity (W/m/K)	Heat Capacity (J/kg/K)
Sandstone	1×10^{-12}	0.30	3.5	840
Shale	1×10^{-15}	0.02	1.8	840
Limestone	1×10^{-13}	0.05	2.7	840
Dolomite	1×10^{-13}	0.05	4.0	840
Crystalline	see Fig. 4	0.01	3.0	880

TABLE IV. Baseline scenario seal, DRZ, and transport properties

Region	Permeability (m^2)	Porosity (-)	Cs k_d (mL/g)	Sr k_d (mL/g)
DRZ	~ 1×10^{-15} [b]	0.01	5.0	0.4
Seal Zone	1×10^{-16}	0.35	120.0	50.0
Upper Borehole	1×10^{-13}	0.01	10.0	5.0
Composite[a]	~ 1×10^{-15} [b]	0.034	5.0	0.4

[a] Composite is a single region used in modeling that includes seals and the DRZ.
[b] DRZ and Composite region permeabilities are depth-dependent and factor-of-10 higher than depth-dependent crystalline permeability (see Fig. 4).

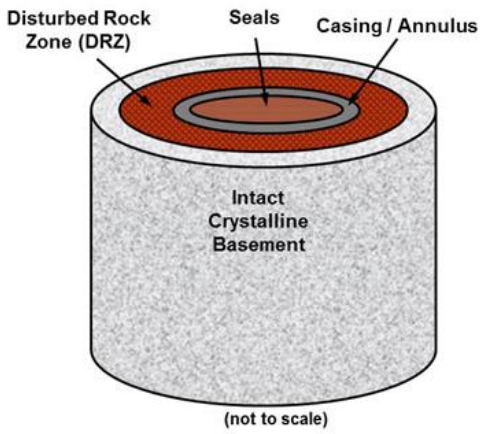


Fig. 5. Schematic representation of the near-borehole radial geometry.

Numerical simulations of thermal-hydrology, radionuclide mobilization and transport, and dose to the receptor for the baseline configuration were carried out for a single deep borehole containing all of the Cs/Sr capsules. Prior simplified post-closure PAs for deep borehole disposal of SNF [9, 19] were run with GoldSim software [23]. The preliminary PA simulations for Cs/Sr disposal described here were implemented with PFLOTRAN, an open source, state-of-the-art massively parallel subsurface flow and reactive transport code [24], in a high-performance computing environment. The use of PFLOTRAN provides a platform for more mechanistic representations of the processes captured in the prior GoldSim-based simulations.

For the PFLOTRAN Cs/Sr disposal simulations, the borehole and regional stratigraphy (Fig. 4) and the associated properties were discretized within 2 km by 2 km model area with a depth of 6 km. The half-symmetry model grid includes 54,000 elements. Within the near-borehole region, the specific materials shown in Fig. 5 were not modeled explicitly. Instead, the near-borehole model geometry includes a higher permeability “borehole” region (with a radius of 0.564 m and of cross-sectional area of 1 m^2) that is a composite representation of the seal materials, annulus, and DRZ (Fig. 6). The borehole region is surrounded by lower permeability host rock region. The model includes realistic representation of the hydrogeological system typical of regions with crystalline bedrock.

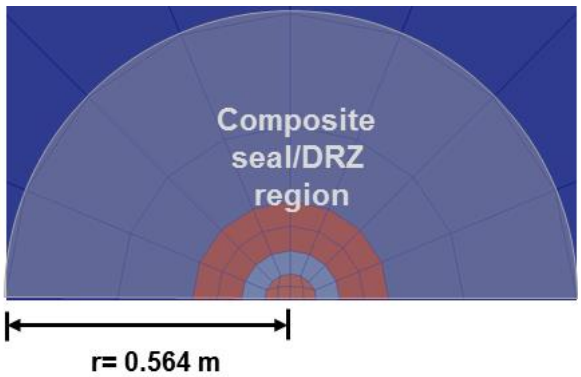
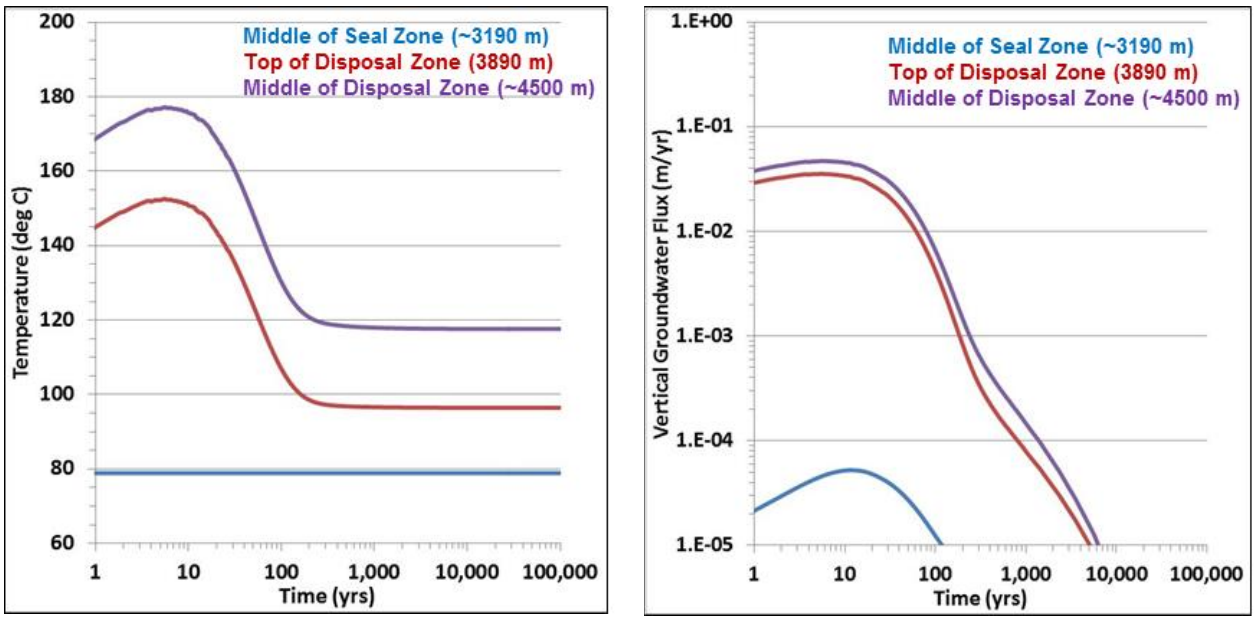


Fig. 6. Composite model representation of near-borehole radial geometry.

For the baseline undisturbed scenario, decay heat from the Cs/Sr capsules produces a post-closure thermal perturbation (Fig. 7a) resulting in a short period of upward groundwater flow (Fig. 7b). The low permeability and low thermal conductivity of the surrounding crystalline host rock focuses the upward flow through the borehole seals and/or the DRZ. The thermal perturbation lasts for about 100 years, with a peak temperature increase of about 60°C in the middle of the disposal zone (Fig. 7a). The resulting thermally-induced vertical groundwater flux (specific discharge or Darcy velocity) from the top of the disposal zone to the seal zone is about 0.03 m/yr for about 100 years (Fig. 7b). The vertical groundwater flux in the middle of the seal zone (~700 m above the top of the disposal zone) is much lower (Fig. 7b).



(a)Temperature **(b) Vertical Groundwater Flux**

Fig. 7. Thermally-induced effects in the borehole from Cs/Sr disposal (adapted from [21]).

The vertical specific discharge at the top of the disposal zone corresponds to a pore velocity of about 0.9 m/yr in the composite seal/DRZ region, which in turn corresponds to a center-of-mass advective distance (without considering sorption) of about 90 m during the approximately 100-year period of thermal perturbation. This advective movement is only a small portion of the ~1,900 m seal zone. Following the period of thermal perturbation, subsequent radionuclide transport to the biosphere is predominately by diffusion up the borehole seal and DRZ. Mass fluxes of Sr-90, Cs-135, and Cs-137 up the borehole at the top of the disposal zone (i.e., at a depth of 3,890 m) are shown in Fig. 8 (advective flux) and Fig. 9 (diffusive flux).

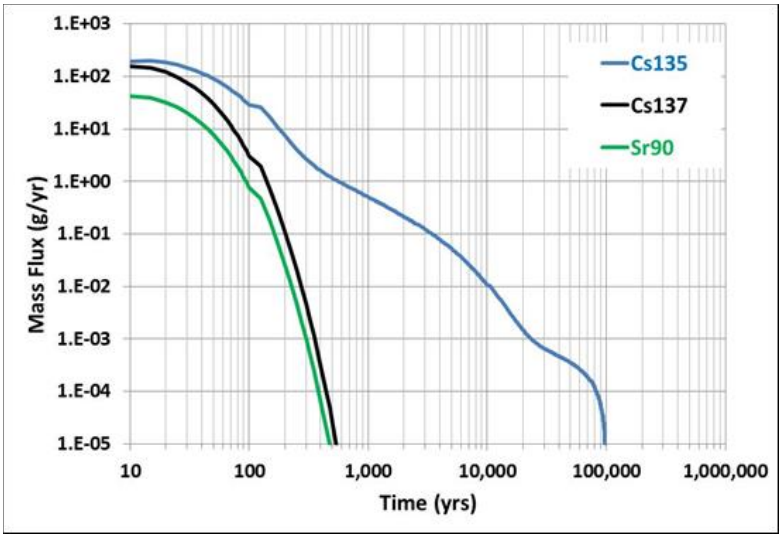


Fig. 8. Advective mass flux up the borehole from the top of the disposal zone.

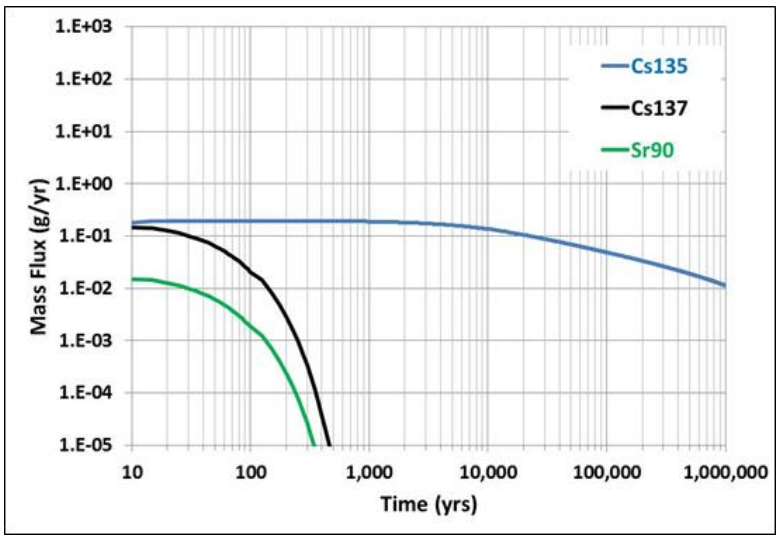


Fig. 9. Diffusive mass flux up the borehole from the top of the disposal zone.

The model results for mass flux further demonstrate that advective flux is the dominant radionuclide transport mechanism at the top of the disposal zone during the early, thermally-perturbed, portion of the post-closure period. The mass flux from the top of the disposal zone does not move very far into the seal zone; thermally-induced advective flux decreases with height above the disposal zone, diffusive flux is small; and much of the radionuclide mass is sorbed in the DRZ and bentonite seal material. Furthermore, the mass of short-lived Sr-90 and Cs-137 decline significantly after a few hundred years. Fig. 10 shows the radionuclide dissolved concentrations with time in the seal zone, just 90 m above the top of the disposal zone (i.e., at a depth of ~3,800 m).

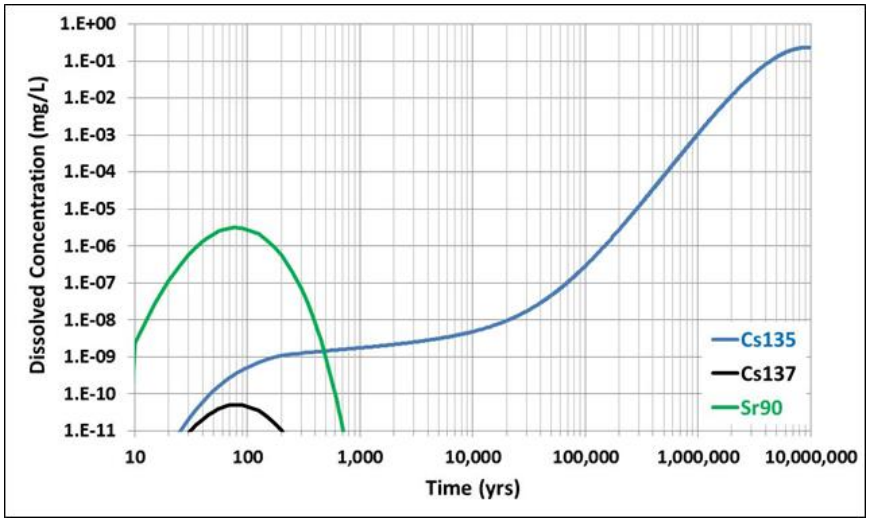


Fig. 10. Dissolved concentrations in the seal zone of the borehole (~3,800 m depth).

The concentration of long-lived Cs-135 in the lower seal zone is shown to slowly increase over time, primarily due to slow upward diffusion from the disposal zone (see Fig. 9). The simulation was run out to 10,000,000 years to ensure that the behavior of long-lived Cs-135 (half-life = 2,300,000 years) was fully captured; peak concentration is reached at about 8,000,000 years. The spatial distribution of Cs-135 around the disposal zone is shown in Fig. 11 (note that concentration units in Fig. 11 (mol/L) are different from Fig. 10 (mg/L), but the concentrations are the same).

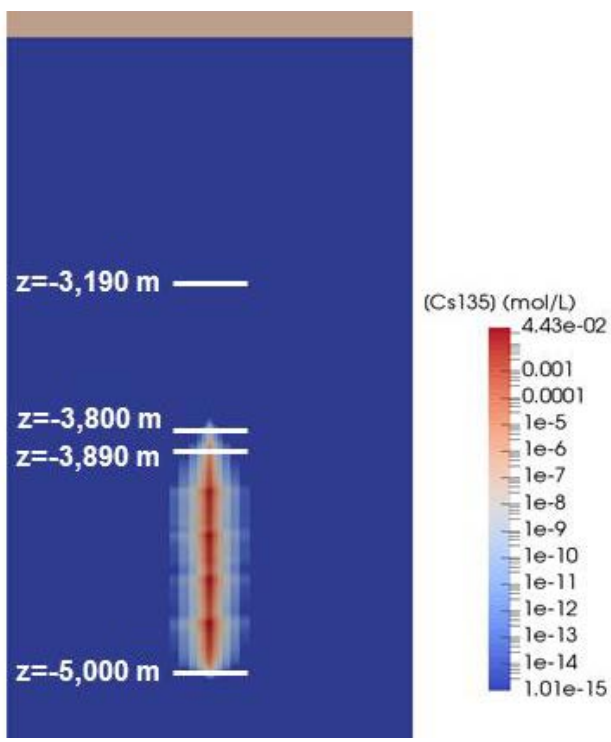


Fig. 11. Dissolved concentration of Cs-135 at 100,000 years [25].

Fig. 11 shows that Cs-135 does not migrate very far above the disposal in the seal/DRZ nor does it migrate very far into the surrounding host rock. No Cs-135 reaches the biosphere, so there is no dose.

These preliminary undisturbed scenario results suggest that there is minimal radionuclide migration and zero dose from deep borehole disposal of Cs/Sr capsules, even without any performance credit from the waste forms or waste packages. Future simulations will examine processes and parameters in more detail, and will consider additional scenarios (e.g., high-permeability fault intersects borehole).

SUMMARY AND CONCLUSIONS

This paper describes qualitative and quantitative safety case considerations to assess the feasibility of the deep borehole disposal concept for Cs/Sr capsules.

Qualitative information relevant to the pre-closure safety case includes:

- Drilling and casing a large diameter borehole to 5,000 m depth in crystalline basement rock is achievable with existing drilling technology.
- Borehole and casing, waste packages, and emplacement systems can be engineered to provide a high level of assurance that waste packages can be safely surface handled and emplaced at the desired depth with minimal probability of packages becoming stuck and/or breached during emplacement.

Qualitative information relevant to the post-closure safety case includes:

- Waste emplacement is deep; between 3,890 and 5,000 m depth in low-permeability crystalline basement rock with limited interaction with shallower groundwater.
- Radionuclide mobility is limited due to geochemically reducing conditions in the deep subsurface that enhances solubility and sorption and thermohaline stratification at depth that opposes upward advection.
- Borehole seals can be engineered to maintain their physical integrity as permeability barriers, at least over the approximately 100-year time period of thermally-induced upward groundwater flow from decay heat.

Some of these pre-closure and post-closure safety case considerations, specifically those related to deep drilling, subsurface conditions, and waste package handling and emplacement, will be further assessed as part of the Deep Borehole Field Test.

Finally, preliminary quantitative results from pre-closure hazard analyses and post-closure performance assessment (PA) calculations further suggest that a favorable safety case can be developed for deep borehole disposal of Cs/Sr capsules.

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