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PRELIMINARY PERFORMANCE ASSESSMENT FOR DEEP BOREHOLE DISPOSAL OF HIGH-LEVEL RADIOACTIVE WASTE

Peter N. Swift[1], Bill W. Arnold[1], Patrick V. Brady[1], Geoff Freeze[1], Teklu Hadgu[1], Joon H . Lee[1], and Yifeng Wang[1]

[1]*Sandia National Laboratories, Albuquerque, New Mexico, USA 87185; pnswift@sandia.gov*

Deep boreholes have been proposed for many decades as an option for permanent disposal of high-level radioactive waste and spent nuclear fuel. Disposal concepts are straightforward, and generally call for drilling boreholes to a depth of three to five kilometers into crystalline basement rocks. Waste is placed in the lower portion of the hole, and the upper several kilometers of the hole are sealed to provide effective isolation from the biosphere. The potential for excellent long-term performance has been recognized in many previous studies. This paper reports updated results of what is believed to be the first quantitative analysis of releases from a hypothetical disposal borehole repository using the same performance assessment methodology applied to mined geologic repositories for high-level radioactive waste. Analyses begin with a preliminary consideration of a comprehensive list of potentially relevant features, events, and processes (FEPs) and the identification of those FEPs that appear to be most likely to affect long-term performance in deep boreholes. Performance assessment model estimates of releases from deep boreholes, and the annual radiation doses to hypothetical future humans associated with those releases, are extremely small, indicating that deep boreholes may be a viable alternative to mined repositories for disposal of both high-level radioactive waste and spent nuclear fuel.

I. INTRODUCTION

The concept of using deep borehole repositories for permanent isolation of radioactive materials has been proposed and investigated intermittently for decades (see Refs. 1 through 15). The earliest proposals for deep borehole disposal considered direct disposal of liquid high-level wastes from reprocessing (e.g., Ref. 1); subsequent analyses have considered disposal of solid wastes of various types, including glass high-level waste, spent nuclear fuel, and surplus weapons-grade plutonium. Although published analyses to date have concluded that the overall concept has the potential to offer excellent isolation, disposal programs worldwide have focused on mined repositories, in part because of the availability of proven mining technologies at the time that national policy decisions were made, and in part because of concerns about the feasibility of retrieving waste from deep boreholes. Advances in drilling technologies over the last several decades suggest that the construction of deep boreholes should no longer be viewed as a greater technical challenge than deep mines, and that retrieval, if required, should not be viewed *a priori* as unachievable. Retrieval of wastes is likely, however, to remain more difficult from deep boreholes than from some mined repository concepts, and if permanent disposal is not intended, deep boreholes may not be a preferred option.

II. ASSUMPTIONS ABOUT A REGULATORY FRAMEWORK FOR DEEP BOREHOLE DISPOSAL

Quantitative assessments of the long-term performance of geologic disposal systems for high-level radioactive wastes are based in part on regulatory specifications that define the goals and scope of the analysis (Ref. 14). Typically, regulations define the overall performance metric (e.g., peak annual dose to a member of the public), the time period of the analysis, the types of scenarios that must be considered, and, in some cases, the methods to be used in estimating performance for the purpose of licensing a disposal site. Recent work at Sandia[12], updated here, provides the first quantitative assessment of deep borehole performance using the methods specified for licensing geologic repositories under regulations of the United States Environmental Protection Agency (US EPA) and United States Nuclear Regulatory Commission (US NRC).

Existing US laws and regulations focus on mined geologic repositories, and, although in principle the generic standards contained in the US EPA's 40 CFR Part 191 [Ref. 16] and the US NRC's 10 CFR part 60 [Ref. 17] could be applied to deep boreholes, it seems more likely that, for any future disposal concept in the US, new regulations would be enacted adopting a peak dose metric similar to that applied to the proposed Yucca Mountain repository. For the purposes of the analyses reported here, we assume a regulatory framework that is essentially the same as that contained in the US NRC's 10 CFR Part 63 (Ref. 18): the primary overall performance metric of interest is mean annual dose to a hypothetical individual, with limits set at 0.15 mSv/yr for 10,000 years following disposal and 1 mSv/yr for the period between

10,000 yr and 1,000,000 yr. (See Ref 12, Section 2 for additional discussion of these assumptions.)

Construction of the initial and boundary conditions for the quantitative performance assessment modeling, including screening criteria for the features, events, and processes (FEPs) that should be included in the performance assessment are assumed to be the same as those in existing regulations. Specifically, the performance assessment does not consider FEPs "that are estimated to have less than one chance in 100,000,000 per year of occurring." Impacts of FEPs that have a higher probability of occurrence need not be evaluated if overall performance in the initial 10,000 years "would not be changed significantly" by their occurrence (40 CFR 197.36(a)(1)) (Ref. 19).

For simplicity, the characteristics of the hypothetically exposed individual are assumed to be the same as those defined in 40 CFR Part 197 (Ref. 19) for the proposed Yucca Mountain repository; these characteristics may be appropriate for disposal sites in arid regions, but they should be reconsidered for sites in other regions. The choice of an arid region was made solely to allow the use of existing information about biosphere pathways, and in no way indicates a preference for one environment over another. As shown by the results of the analyses, this assumption has essentially no impact on overall estimates of performance.

Unlike existing US regulations that place the hypothetically exposed individual at some distance from the repository outside a "controlled area," analyses reported here rely on an assumption that exposure occurs directly above the waste. This assumption represents a conservative (although not unrealistic) bound on the possible location of future humans, and allows the analysis to focus on the isolation provided by the deep geologic setting while minimizing the contribution of the near-surface geology.

Analyses reported here do not consider the possible consequences of future human intrusion into a deep borehole repository. Existing US regulatory requirements for consideration of human intrusion events are specific to mined repository concepts, and are not applicable to deep boreholes.

III. CONCEPTUAL DESIGN FOR DEEP BOREHOLE DISPOSAL

The deep borehole disposal concept analyzed here calls for drilling a single borehole five km into crystalline basement rock; emplacing waste in the lower two kilometers of the hole; and installing a robust sealing system at least one km thick above the uppermost waste packages (Figure 1). Other borehole disposal concepts have been proposed, including the construction of multiple emplacement boreholes drilled at an angle from a single vertical hole (e.g., Ref. 13), and the example analyzed here should be considered as a representative starting point for more detailed analyses.

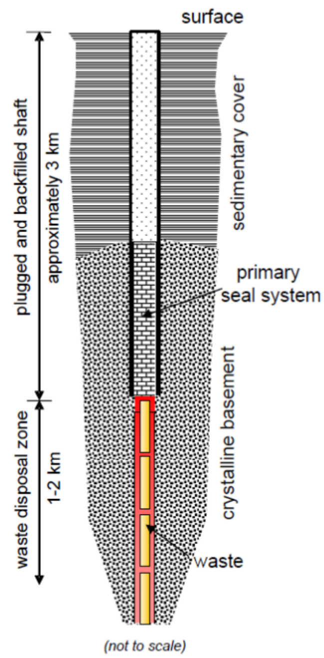

Figure 1. Schematic illustration of deep borehole disposal of high-level radioactive waste or spent nuclear fuel (Adapted from Ref. 12, Figure 1).

A borehole disposal interval of 2,000 m would allow for emplacement of approximately 400 waste canisters each approximately five meters long. Multiple boreholes could be constructed at a single disposal site, with the spacing between boreholes chosen based on thermal considerations. Construction of 4-km-deep boreholes with a bottom-hole diameter of approximately 0.5 m is feasible with current technology (Ref. 15), and extending this technology to 5 km of depth appears reasonable (see also Ref 12, Section 3 for further discussion). A bottom hole diameter of 0.5 m would allow for the possibility of direct disposal of intact spent fuel assemblies (the diagonal width of a standard pressurized water reactor fuel assembly is 0.303 m; boiling water reactor assemblies are smaller (Ref. 20). The 63,000 metric tons of commercial spent nuclear fuel legislated for disposal at Yucca Mountain contain an estimated 221,000 fuel assemblies (Ref. 21, Table 1.5.1-1); assuming 400 assemblies per borehole, an equivalent amount of spent fuel could be emplaced in approximately 550 deep boreholes. Other disposal concepts that include consolidating spent fuel assemblies or recycling fuel and disposing of high-level waste could result in disposal in narrower and significantly fewer boreholes.

IV. CONCEPTUAL DESIGN OF THE MODELED DISPOSAL SYSTEM

The borehole analyzed here is assumed to have been drilled in stages, with a diameter that decreases from 122 cm at the land surface to 44 cm at the disposal interval. Standard drilling industry casing (i.e., steel pipe) is emplaced for the entire depth of the borehole to facilitate emplacement of the waste packages. This casing plays no role in the long-term performance of the disposal system, and is removed from the upper portions of the borehole, above the waste emplacement zone, to ensure good physical contact between the seal system (described below) and the surrounding rock. Waste packages are assumed to be constructed from standard drilling industry steel pipe, and, like the casing, their function is to facilitate waste emplacement. They must be strong enough to provide robust containment for the waste during both handling and emplacement operations and possible retrieval activities prior to final sealing of the hole, but they are not assumed to provide any long-term containment for the waste. The primary containment functions for the disposal concept are provided by the chemical environment in the emplacement zone (high ionic strength brines with strongly reducing conditions) and the long pathway required for transport through the low-permeability seal system.

Borehole seals are conceptualized to be constructed using currently available technology with sequences of concrete, bentonite, and, at higher levels in the borehole, asphalt. Details of borehole seal design remain an important topic for future research, but given present understanding of physical properties of the major components and the length of the hole available for seal emplacement, low permeability seals appear to be achievable.

As discussed further in Ref. 12, Section 3.2.3, modeling radionuclide exposure to humans requires assumptions about future groundwater use in the surrounding region and the potential for mixing and dilution of contaminated waters in higher-permeability aquifers near the land surface. Unavoidable uncertainty about future groundwater use can have a potentially significant impact on dose estimates; high pumping rates for groundwater can capture contaminants from greater depths and result in radionuclides reaching the withdrawal well sooner, but will also cause greater dilution, lowering the peak concentrations reaching humans. Smaller pumping rates could, in theory, delay the arrival of radionuclides in the biosphere, but could also result in somewhat higher concentrations in well water.

V. SCREENING OF RELEVANT FEATURES, EVENTS, AND PROCESSES

The method used in performance assessments for mined repositories for identifying a comprehensive set of the potentially relevant features, events, and processes and screening them to select those that warrant full inclusion in system-level modeling (e.g., Refs. 14, 22, and 23) can be applied equally well to deep borehole disposal. Preliminary analyses began by considering the potential relevance for borehole disposal of each of the 374 FEPs evaluated for the proposed Yucca Mountain repository (Ref. 12, Section 4). Fundamental differences in design mean that some FEPs have different applications in boreholes (e.g., the vertical emplacement interval in the borehole is functionally equivalent to the horizontal emplacement drifts at Yucca Mountain), but no new FEPs were identified in this work that are specific only to boreholes, and the list remains a suitable starting point for evaluation.

Preliminary analyses identified three potential release scenarios of interest. In the first scenario, higher-than-anticipated permeability in the borehole seals allows groundwater flow and radionuclide transport directly up the borehole. In the second scenario, flow and transport occur through a high-permeability annulus of fractured rock surrounding the borehole seals. The third scenario postulates groundwater flow and radionuclide transport transport away from the borehole through high permeability zones (e.g., faults or fractures) in the surrounding rock. For the purposes of modeling, the first two scenarios are combined by treating the borehole seal and the annulus of fractured rock surrounding the hole as a single cylindrical element with an effective permeability reflecting properties of both the seal and the disturbed rock. The third scenario is not modeled in these preliminary analyses because features with a high-enough permeability to cause releases greater than those that might occur through the borehole are assumed to be detectable by downhole testing, allowing the hole to be plugged and abandoned before waste emplacement occurs. Further analyses are needed to confirm that this scenario does not present a greater risk.

Preliminary screening evaluations identified some FEPs for which the current technical basis for screening is incomplete but for which there is reasonable confidence that more detailed analysis will confirm that they will not result in significant impacts on long-term performance if borehole locations and engineered systems are chosen appropriately. The presence or absence of some features may eventually become a de facto site selection criterion for deep borehole disposal. For example, as noted above, boreholes that intersect high-permeability zones at depth are likely to be unsuitable. Similarly, regions with anomalously high heat flow or high fluid pressures at depth may be less desirable. The potential for changes in fluid and rock properties at depth, such as might occur with future tectonic activity or glaciation of the land surface above, should be considered.

Preliminary screening evaluations indicate that some FEPs of potential interest for other disposal concepts are unlikely to effect borehole disposal (Ref 12, Section 4.3). For example, molecular diffusion alone is shown to be slow enough to result in a maximum transport distance on the order of 200 m in 1,000,000 years; this is substantially less than the one km of transport required to move through the seal system. The potential for criticality events, which can be difficult to analyze despite being unlikely in any disposal environment, is essentially precluded in deep boreholes by geometric constraints: the borehole diameter is smaller than volume required for critical configurations at the isotopic enrichments found in spent fuel.

VI. MODEL CONFIGURATION AND PARAMETERS

Based on the conceptual design described in Section IV, a preliminary deep borehole performance assessment was performed for a simplified and conservative representation of the release scenarios described in Section V. The conceptual model is as follows:

- 400 fuel assemblies (~150 metric tons) vertically stacked down the length of the waste disposal zone (~ 2 km).
- Initial radionuclide inventory representative of pressurized water reactor (PWR) fuel assemblies aged to year 2117 (Ref. 12, Appendix A).
- Dissolved concentrations in the waste disposal zone limited by thermal-chemical conditions (radionuclide solubilities from Ref. 12, Table 4).
- Thermally driven hydrologic flow from the top of the waste disposal zone upward through 1000 m of a bentonite sealed borehole and surrounding fractured rock annulus with a specific discharge of 0.017 m/yr for 200 years (based on thermal analyses in Ref. 12, Section 3.2.2 and Figure 8).
- Radionuclide transport up the borehole calculated using a 1-dimensional solution to the advection-dispersion equation that includes decay and sorption (Ref. 24, Equation 10.3.4).
- Pumping of borehole water (from the location 1000 m above the top of the waste disposal zone) to the surface (biosphere) via a withdrawal well. No credit is taken for sorption or decay along the saturated zone transport pathway from the borehole to the withdrawal well.
- A dilution factor of 3.16×10^7 (based on analyses in Ref. 12, Section 3.2.3 and Figure 11) is applied to account for the fact that the borehole water would mix with water in an existing aquifer before it would be captured by the withdrawal well (assumed to supply 1,000 people).
- A transport time of 8,000 years (Ref. 12, Figure 11) is applied to account for the time taken for the bulk of the dissolved radionuclide mass to be captured by the withdrawal well (at a constant pumping rate necessary to supply 1,000 people).
- Doses to a hypothetical person living near the withdrawal well are based on biosphere dose conversion factors (BDCFs) consistent with the lifestyle of the Yucca Mountain reasonably maximally exposed individual (RMEI), as specified by the EPA in 40 CFR 197.

The conceptual model was implemented numerically using GoldSim software (Ref. 25) with the Contaminant Transport module. GoldSim provides a numerical solution to the advection-dispersion equation for dissolved radionuclide concentration in the sealed borehole, C (in mg/L), as a function of time, *t*, and distance, *x*, from a continuous source having concentration C_0.

Radionuclide transport up the borehole from the source (waste disposal) zone occurs for 200 years, corresponding to the duration of the thermally driven flow (Ref. 12, Figure 8). Subsequent to the thermal period, ambient conditions are not expected to provide any upward gradient, and upward radionuclide transport was assumed to cease.

The source concentration at the top of the waste disposal zone was determined by (a) calculating a maximum potential concentration based on dissolving the entire initial mass inventory in a fuel assembly into the void volume (i.e., the potential volume of water) of a waste canister, and (b) selecting the lower of the maximum potential concentration and the solubility limits (Ref. 12, Table 4) as the source concentration.

Sealed borehole properties were selected to be representative of combined bentonite and fractured rock annulus (effective diameter of 1.1 m, permeability of 1×10^{-16} m^2, porosity of 0.034, and bulk density of 2450 kg/m^3). A thermally-induced driving pressure was specified, in conjunction with these sealed borehole properties, to produce a specific discharge of 0.017 m/yr. This specific discharge corresponds to a hydrologic pore velocity of 0.502 m/yr and a travel time through the 1000 m sealed borehole zone ((for an unretarded radionuclide) of 1991.3 years.

VI. MODEL RESULTS

Because the period of thermally driven flow (200 years) is short relative to the hydrologic travel time up the sealed borehole (1991.3 yrs), the only radionuclide with a non-zero concentration 1000 m above the waste disposal zone in the sealed borehole is ^{129}I, which is the only radionuclide that has no retardation. The non-zero ^{129}I concentration (which is only 1.0 x 10^{-7} mg/L) represents the leading edge of the dispersive transport front. However, the center of mass for ^{129}I advection moves only 100.4 m, and therefore does reach the top of the 1000 m sealed section of the borehole because there is no further movement after 200 years. ^{79}Se, with a center of mass advective distance of 1.4 m, is the only other radionuclide with center of mass advection of greater than a few tens of centimeters.

Accounting for the 8,000-year travel time for the radionuclides to reach the withdrawal well from the top of the sealed borehole zone, results in a peak dose to the RMEI at 8,200 years. The total dose to the RMEI for all radionuclides at 8,200 years is 2.7 x 10^{-10} mrem/yr. The only contributor to the dose is ^{129}I.

These simplified performance assessment model results are based on several bounding and conservative assumptions, such as: all waste is assumed to instantly degrade and dissolve inside the waste canisters; all waste is assumed to be PWR assemblies; and no credit is taken for sorption or decay along the saturated zone transport pathway from the sealed borehole to the withdrawal well. More refined performance assessments may indicate lower, and/or later, peak doses than established here.

VI. CONCLUSIONS

Deep (3-5 km) boreholes have the potential to effectively isolate high-level radioactive waste and spent nuclear fuel from the biosphere. Quantitative results from a simplified, bounding performance assessment estimated radionuclide releases from a hypothetical deep borehole repository, and the annual radiation doses to hypothetical future humans associated with those releases, to be extremely small. These preliminary results suggest that deep boreholes may be a viable alternative to mined repositories for disposal of both high-level radioactive waste and spent nuclear fuel.

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