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PRELIMINARY PERFORMANCE ASSESSMENT OF DEEP BOREHOLE DISPOSAL OF RADIOACTIVE WASTE

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Abstract: Long-term disposal of high-level radioactive waste (HLW) and spent nuclear fuel (SNF) in deep (3 to 5 km) boreholes has the potential to achieve long-term safety performance at costs competitive with mined repositories. Low permeability, high salinity, and geochemically reducing conditions at many locations in the deep crystalline basement rock limit significant fluid flow and radionuclide transport. For the preliminary performance assessment analysis, 400 spent fuel assemblies were assumed to be vertically stacked inside the lower 2 km segment of 5 km deep borehole. The radionuclide release scenario was assumed to be (1) up the sealed borehole for 1 km in the crystalline basement rock, (2) into the overlying sediments, and (3) eventual capture by a hypothetical water withdrawal well. Coupled thermal-hydrologic analyses indicate that thermal expansion of groundwater would produce an upward pulse of flow. The preliminary performance assessment included the effects of radionuclide solubility, transport up the sealed borehole, sorption, radionuclide decay, and pumping from the withdrawal well, to calculate the dose to a human receptor. The performance assessment calculations indicated a negligible dose to the human receptor. The dose was due solely to the contributions of a single radionuclide (Iodine-129). The negligible long-term dose from a single deep borehole predicted by the preliminary performance assessment underscores the potential viability of deep borehole disposal of radioactive waste.

Keywords: Deep borehole disposal, Radioactive waste, Performance assessment

1. INTRODUCTION

Disposal of high-level radioactive waste, including spent nuclear fuel, in deep boreholes is one of several options that have been considered since geological isolation of these wastes was originally conceived. In 1957 the U.S. National Academy of Sciences Committee on Waste Disposal considered both deep borehole disposal of radioactive waste (in liquid form) and mined storage of radioactive waste in a positive light [1]. Over the last half-century, high-level waste and spent nuclear fuel disposal efforts in the United States and other nations have focused primarily on mined repositories. Nonetheless, the deep borehole disposal concept has been periodically reconsidered in several countries (e.g., [2,3,4,5,6,7]).

The potential technical and cost advantages of deep borehole disposal have become more apparent at the present time. Drilling technology for petroleum and geothermal production has improved, resulting in lower costs and greater reliability for the construction of deep boreholes. Deep borehole construction, characterization and emplacement costs should scale approximately linearly with waste inventory: small inventories require fewer boreholes; large inventories require more boreholes. Not needing a specially engineered waste package would also lower overall borehole disposal costs. Characterization of the near-surface geology and hydrology required for deep borehole disposal should be less extensive and costly than for shallower mined repositories because of the greater isolation of waste in deep boreholes. Conditions favorable for deep borehole disposal exist at many locations, particularly on geologically stable continental cratons. The costs and risks of waste transportation could be significantly lower for a system of regional deep borehole disposal sites, relative to a single national mined repository. These aspects might make borehole disposal attractive for smaller national nuclear power efforts (having an inventory of 10,000 Metric Tons of Heavy Metal (MTHM) or less).

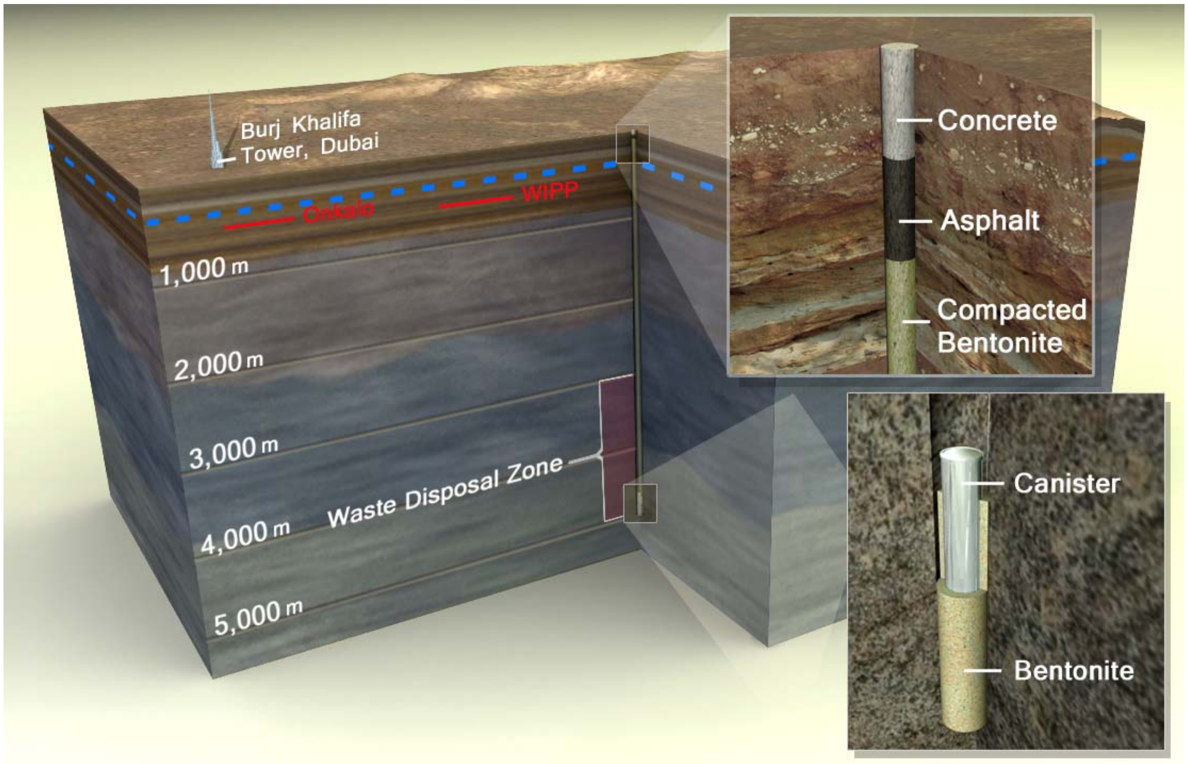
Although previous studies have evaluated individual components of the deep borehole disposal concept, they have not conducted a quantitative risk assessment of the disposal system. This paper presents an updated conceptual evaluation of deep borehole disposal and a summary of the preliminary performance assessment of that concept documented in [8].

2. DEEP BOREHOLE DISPOSAL CONCEPT

The deep borehole disposal concept includes drilling a borehole into crystalline basement rock (typically granite) to a depth of about 5,000 m, emplacing waste canisters containing spent nuclear fuel or vitrified radioactive waste from reprocessing in the lower 2,000 m of the borehole, and sealing the upper 3,000 m of the borehole. The concept is illustrated in Figure 1, showing the borehole disposal depth relative to the typical depth for mined repositories of several hundred meters, such as the Waste Isolation Pilot Plant (WIPP) in New Mexico and the Onkalo facility in Finland. The world's tallest building, the Burj Khalifa Tower in Dubai is also shown for scale. As shown in Figure 1, waste in the deep borehole disposal system is several times deeper than for typical mined repositories, resulting in greater natural isolation from the surface and near-surface environment. A borehole disposal interval of 2,000 m would permit the emplacement of about 400 waste canisters of approximately 5 m length per borehole. Multiple boreholes could be constructed at one disposal site, with the spacing between boreholes determined by the thermal loading of the waste. A borehole seal system consisting of compacted bentonite clay, asphalt, and concrete is proposed to seal the upper part of the borehole.

The viability and safety of the deep borehole disposal concept are supported by several factors. Geologically stable crystalline basement rocks are relatively common at depths of 2,000 to 5,000 m in the United States and many other countries, suggesting that numerous appropriate sites exist. Existing drilling technology permits construction of relatively large-diameter boreholes (on the order of 50 cm in diameter) to 5,000 m depth at a cost of about $US 20 million each [8]. Preliminary cost estimates of deep borehole disposal for the projected waste inventory from the current fleet of nuclear reactors in the U. S. in about 950 boreholes indicate that the total costs would be lower than or on the order of a mined repository disposal system at Yucca Mountain. Low permeability and high salinity in the deep continental crystalline basement at many locations suggest very slow groundwater movement and extremely limited interaction with shallow fresh groundwater resources, which is the most likely pathway for human exposure. A typical lower boundary for fresh groundwater is shown by the dashed blue line in Figure 1. The density stratification of groundwater would also oppose thermally induced groundwater convection from the waste to the shallow subsurface. Geochemically reducing conditions in the deep subsurface limit the solubility and enhance the sorption of many radionuclides in the waste, leading to limited mobility.

Figure 1: Concept for Deep Borehole Disposal of High-Level Radioactive Waste



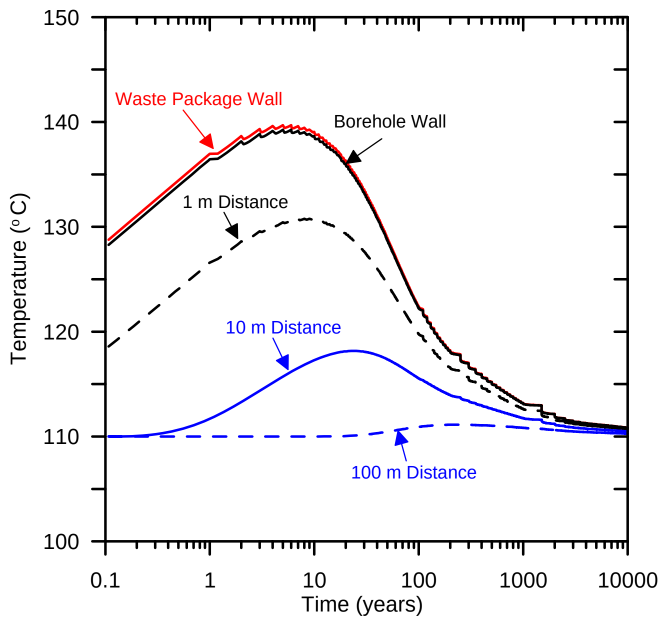
The legal and regulatory framework governing the disposal of high-level radioactive waste in the U. S. and other countries is oriented toward mined geological disposal and likely would need to be revised to implement deep borehole disposal. In particular, regulations specific to the potential retrieval of waste would need to be modified to reflect the more permanent disposal nature of a deep borehole disposal system. Although retrievability would be maintained during emplacement operations, waste may not be fully recoverable once the borehole has been sealed, and deep borehole systems may not be the best choice if permanent and irreversible disposal is not intended.

3. TECHNICAL AND ENGINEERING BASIS

A simple nominal design for the deep borehole disposal system has been evaluated in this study. The borehole would be drilled and cased in stages with the diameter decreasing from about 122 cm at the surface to about 44 cm in the disposal interval. Emplacing intact spent fuel assemblages, without pre-consolidation, is one of the simplest approaches to borehole disposal [9], and is the one evaluated here. A canister made of standard oilfield casing 5 m in length and having an inner diameter of 32 cm and an outside diameter of 34 cm could hold one pressurized water reactor (PWR) fuel assembly. Welded end-caps would seal the canisters after the waste is inserted. The disposal canister must be strong enough to prevent releases and exposure through the waste emplacement phase, including recovery operations for canisters that are stuck or damaged during emplacement. The canisters could be emplaced one at a time or as part of a canister string – a grouping of 10 or 20 canisters. Crushing of underlying canisters during the operational period would be prevented by bridge plugs in the borehole. The canisters would be surrounded by bentonite slurry and the upper 3,000 m of the borehole would be sealed by a combination of compacted bentonite packs, asphalt, and concrete plug, as illustrated in Figure 1.

Temperature histories within the borehole and the host rock were simulated using a horizontal, two-dimensional model of thermal conduction. The model uses the heat output curve for a single average PWR spent fuel assembly that has been aged for 25 years and representative values for the thermal conductivity of granite and bentonite. Simulated temperature histories for a single borehole shown in Figure 2 indicate that temperature increases in the vicinity of the borehole are not large, do not persist for long periods of time, and drop off rapidly with distance from the borehole. Temperatures at the borehole wall peak at about 30 ^{o}C higher than the ambient temperature (110^{o}C) of the host rock within about ten years of waste emplacement.

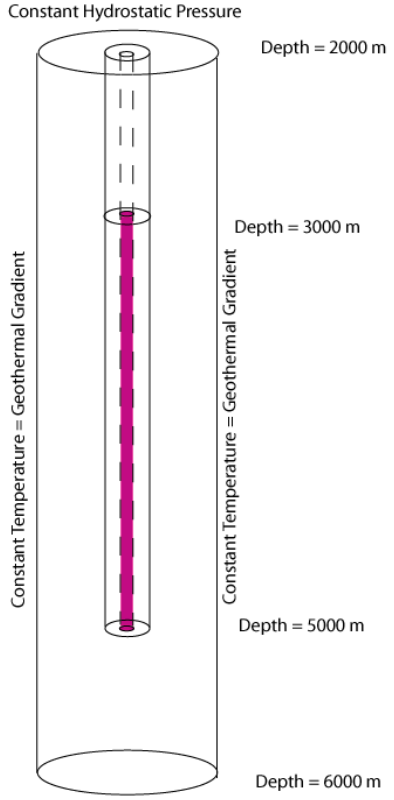
Figure 2: Temperature as a Function of Time and Distance for Deep Borehole Disposal of Spent PWR Fuel Assemblies



A similar analysis of thermal conduction was performed for borehole disposal of vitrified high-level waste from the reprocessing of spent nuclear fuel. The heat output curves used in the analysis are for the current vitrified waste produced by reprocessing of commercial spent nuclear fuel in France [10]. For this analysis it is assumed that the waste is aged for 10 years before disposal and that the vitrified waste fills the waste canister. The simulated temperature increases are significantly higher for the disposal of vitrified high-level waste than those for disposal of spent fuel assemblies, with the temperature increasing by about 125^{o}C at the borehole wall at the time of peak temperature. It should be noted that the thermal impacts of vitrified high-level waste disposal could easily be controlled by reducing the diameter of the waste canisters or by reducing the concentrations of fission products in the waste glass.

Coupled thermal-hydrologic modeling was performed to evaluate the three-dimensional movement of groundwater induced by waste heat from PWR fuel assemblies in a single borehole. These simulations assumed that the disturbed zone in the granite around the borehole would have a higher permeability than the surrounding host rock, forming a "chimney" for potential circulation of fluid, as illustrated in Figure 3. Simulations were conducted using a radially symmetrical model domain centered on the borehole. Results indicate upward vertical flow in the borehole disturbed zone driven primarily by thermal expansion of groundwater, not by significant free convection. The simulation results showed that upward flow of about 1.5 cm/year occurs for about 200 years after emplacement at the top of the waste disposal zone. Lesser upward flow of up to 0.35 cm/year occurs for about 600 years at a location 1,000 m above the waste (still 2,000 m below the ground surface).

Figure 3: Model Domain for Coupled Heat and Fluid Flow Simulation



The geochemical behavior (solubility, sorption, colloidal behavior, etc.) of the projected waste inventory in the deep borehole environment sets limits on the stability of the uranium spent fuel matrix and on radionuclide transport to the biosphere. Fluids recovered from deep boreholes tend to be rich in sodium, calcium, and chloride. Lesser amounts of sulfate and carbonate are likely to be present. For the purposes of estimating radionuclide solubilities and sorption coefficients, a reasonable salinity is ~ 2-3 M/L, pH values are 8-9 and the system Eh is ~ -300 mV [11]. At depth oxygen tends to be scavenged from groundwater, and the low redox state anchored, by the presence of reduced Fe and Mn in the basement rocks. The relatively low solubility of UO_2 under deep borehole conditions, estimated to be on the order of $1x10^{-8}$ M/L, will favor stabilization of spent fuel rods. The solubilities of isotopes of Am, Ac, Cm, Np, Pa, Pu, Tc, and Th are even lower than that of uranium – sometimes several orders of magnitude lower – suggesting that aqueous releases of these radionuclides would be small. Table 1 identifies likely solubility-limiting phases and provides estimates of dissolved radioelement concentrations at depth, based on chemical equilibrium modeling with the PHREEQC software code.

Table 1: Radionuclide Solubilities in Deep Boreholes

Radioelement	Solubility-limiting phase	Dissolved concentration (M/L)	Notes
Am	Am_2O_3	1×10^{-9}	$AmOH(CO_3)$ would control Am solubilities if carbonate present.
Ac	Ac_2O_3	1×10^{-9}	Am solubility is used as proxy for chemically similar Ac.
C	*	*	No solubility limiting phase
Cm	Cm_2O_3	1×10^{-9}	Am solubility is used as proxy for chemically similar Cm.
Cs	*	*	No solubility limiting phase
I	Metal iodides ?	*	Possible
Np	NpO_2	1.1×10^{-18}	
Pa	PaO_2	1.1×10^{-18}	Np solubility is used as proxy for chemically similar Pa.
Pu.	PuO_2	9.1×10^{-12}	
Ra	$RaSO_4$	*	Possible
Sr	$SrCO_3$, $SrSO_4$?	*	Possible
Tc	TcO_2	4.3×10^{-38}	
Th	ThO_2	6.0×10^{-15}	
U	UO_2	1.0×10^{-8}	

Additional geochemically appealing features of deep boreholes are that the elevated temperatures of deep boreholes should stabilize the less soluble crystalline forms of radioelement oxide minerals, while high temperatures and high salinities will both favor the less soluble anhydrous forms of the oxide phases. Note though that the relatively high temperatures and salinities of deep fluids should accelerate the corrosion of steel pipes, fuel assemblies, and the waste itself. The scarcity of oxygen might slow the oxidation of spent fuel.

Most radionuclides released from the waste in deep boreholes adsorb to basement rocks, to overlying sediments, and to the bentonite used to seal the borehole. Sorbing radionuclides would move hundreds to thousands of times more slowly than any groundwater movement. Notable exceptions are ^{129}I and ^{14}C, which would be highly soluble and experience little or no sorption onto the host rock. Estimated values of sorption coefficients for radionuclides were taken from literature review [12]. Colloids do not remain suspended in groundwater at high salinity and would not be a significant factor in radionuclide transport.

4. PRELIMINARY PERFORMANCE ASSESSMENT

Analysis in the deep borehole disposal performance assessment is based on the assumption that regulatory requirements for deep borehole disposal will be essentially the same as those currently extant in 10 CFR 63. Specifically, the performance measure of interest is assumed to be the mean annual dose to a hypothetical member of the public (the "reasonably maximally exposed individual" of 40 CFR 197.21) who lives in the accessible environment near the disposal site.

The list from the Yucca Mountain license application (see Appendix B, Table B-1) was adopted as a reasonable starting point for evaluation of features, events, and processes (FEPs) potentially relevant to performance of the deep borehole disposal system. Each of the 374 FEPs on this list has been considered (screened) for potential relevance to deep borehole disposal; FEPs that may be unique to deep borehole disposal have been considered and compared to the list to identify existing FEPs that capture the processes of interest and concern for boreholes. No new FEPs were identified in this process, confirming that, although the Yucca Mountain list was specifically tailored for a mined repository, it remains a useful starting point for this preliminary analysis.

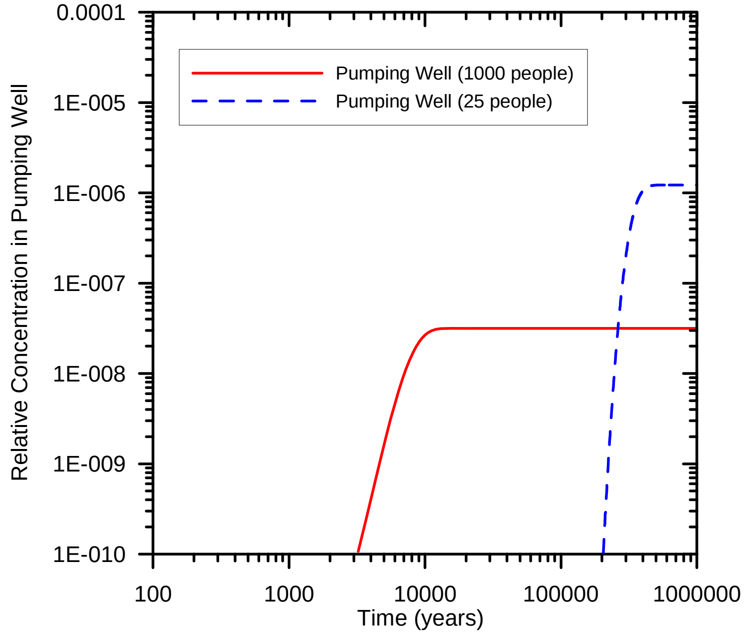
A preliminary quantitative performance assessment was conducted for the deep borehole disposal of spent nuclear fuel assemblies using a simplified and conservative representation of the system [8]. The single release scenario analyzed in this performance assessment involved transport of dissolved radionuclides by thermally driven hydrologic flow up the zone of enhanced permeability associated with the borehole and into a shallow fresh water aquifer from which they are pumped to the biosphere via a water supply well. Several features, events, and processes (including nuclear criticality, molecular diffusion, and hydrofracturing of the host rock by thermal expansion of water) were excluded from consideration in the performance assessment based on separate preliminary analyses.

The performance assessment analysis is for a single borehole containing 400 PWR assemblies (~150 MTHM) stacked in a 2,000 m waste disposal zone between 3,000 to 5,000 m below the surface. It is assumed that the waste canisters corrode quickly and that dissolved concentrations of radionuclides within the borehole are governed by solubility limits of solid oxide phases. Radionuclides that experience sorption onto the host rock and bentonite seals are subject to retardation within the zone of enhanced permeability around and within the borehole. Thermally driven flow within and above the waste disposal zone was applied for 200 years after emplacement, based on the coupled thermal-hydrologic modeling described above. The performance assessment included 31 key radionuclides.

Radionuclide transport up the borehole from the source (waste disposal) zone occurs for 200 years, corresponding to the duration of the thermally driven flow in the coupled thermal-hydrologic modeling. 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 PWR 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 determined for expected geochemical conditions at depth as the source concentration.

Radionuclide transport for 1,000 m up the borehole from the top of the waste disposal zone was calculated using the one-dimensional Ogata-Banks analytical solution [13], including the effects of advection, dispersion, decay, and sorption. It was conservatively assumed that the upper 2,000 m of the subsurface contains fresh groundwater and that a water supply well for 1,000 people was pumped directly above the disposal zone. A dilution factor of $3x10^7$ and delay time of about 8,000 years for radionuclide transport associated with the well pumping was calculated in a separate three-dimensional model simulation and applied in the performance assessment calculation. The simulated radionuclide breakthrough curves for a non-sorbing contaminant are shown for two alternative pumping scenarios in Figure 4. Although pumping from a lower capacity well for 25 people results in a significantly smaller dilution factor, the delay time is much greater and exceeds 200,000 years.

Figure 4: Simulated Contaminant Breakthrough Curves for Two Groundwater Pumping Scenarios



Radiological dose to a hypothetical person using water from the pumping well was calculated using biosphere dose conversion factors from the Yucca Mountain Project. These biosphere dose conversion factors account for effective dose to an individual based on the concentrations of radionuclides in well water that is used for drinking, irrigation of crops, and multiple other pathways in the biosphere. Although the values of biosphere dose conversion factors from the Yucca Mountain Project are specific to the lifestyle of the population in Amargosa Farms, Nevada, these provide a reasonable estimate of the total dose to a reasonably maximally exposed individual at a generic location exposed to groundwater contaminated with radionuclides from spent nuclear fuel.

Results of the preliminary performance assessment indicated a peak dose to an individual using the contaminated groundwater of $1.4x10^{-10}$ mrem/year ($1.4x10^{-12}$ mSv/year). This calculated dose is for a single borehole; however, the result should scale approximately linearly for multiple boreholes. The only radionuclide contributing to the calculated dose was ^{129}I, which has high solubility and is nonsorbing. None of the other radionuclides, all of which experience some amount of sorption, are transported through the entire 1,000 m of sealed borehole above the waste disposal zone during the simulation. The peak dose was calculated to occur about 8,200 years after waste emplacement. For comparison, the IAEA recommends a postclosure dose limit of 0.3 mSv/year (30 mrem/year) for geological disposal facilities [14]. Although uncertainty in these results was not formally evaluated, the preliminary performance assessment used reasonable parameter values for the calculations and several conservative assumptions in the conceptual model of the disposal system.

5. CONCLUSIONS

Deep borehole disposal of high-level radioactive waste, including spent nuclear fuel, appears to be a viable and safe alternative to geological disposal in mined repositories. As established in previous studies, conditions favorable for disposal, including crystalline basement rocks, low permeability, high salinity, and geochemically reducing conditions, occur at depth in many locations. The modular nature of deep borehole disposal is advantageous with regard to flexibility in siting, reduced transportation costs, and for countries with small spent fuel inventories. Advances in drilling technology have made construction of deep boreholes less expensive and more reliable. Preliminary performance assessment of deep borehole disposal of spent nuclear fuel indicates that postclosure radiological dose and associated risks to human health are negligible.

Deep boreholes exhibit substantial potential for the disposal of spent nuclear fuel and other high-level radioactive waste and warrant additional study in several areas. A more comprehensive and detailed cost analysis would provide a firmer basis for quantitative comparisons with other disposal system options. Specific criteria for site selection and characterization requirements of deep boreholes for suitability should be identified. More detailed analyses of operational and engineered systems for waste emplacement are required. Borehole seals are clearly important barriers for waste isolation and their long-term behavior needs to be more fully assessed. Modeling of coupled thermal-hydrologic-mechanical-chemical behavior near boreholes with emplaced waste is needed to better understand borehole stability and alterations to the host rock in the disturbed zone. Compounds that sequester radionuclides, particularly radioactive iodine, should be evaluated as additives in the borehole and seals. Performance assessment analyses should be extended to consider a complete list of relevant features, events and processes, to incorporate more detailed process modeling, and to be scaled up from a single borehole to multiple boreholes. In addition, performance assessment analyses should include a comprehensive evaluation of conceptual model and parameter uncertainty. These evaluations of uncertainty should then be applied to a fully probabilistic assessment of deep borehole disposal performance.

It is recommended that ultimately a full-scale pilot project be undertaken, perhaps with surrogate waste, in order to fully explore the viability of a borehole disposal concept. The scientific and engineering advances gained from a single pilot project, and the applicability to subsequent borehole disposal implementations, are in contrast to site-specific mined repositories and their unique site characterization demands with relatively little transferable knowledge to subsequent repositories. Given the potential for standardizing the borehole design, and thus the ready extension to multiple borehole facilities, a single pilot project could provide significant gains on the scientific and engineering issues needing to be resolved, enable the development of international standards, and accelerate the evaluation of the viability of deep borehole disposal of spent nuclear fuel and high-level radioactive waste.

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