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Preliminary Performance Assessment for Deep Borehole Disposal of High-Level Radioactive Waste

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ABSTRACT

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 four to five kilometers (or more) 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. The release pathway selected for preliminary performance assessment modeling is thermally-driven flow and radionuclide transport upwards from the emplacement zone through the borehole seals or the surrounding annulus of disturbed rock. Estimated radionuclide releases from deep borehole disposal of spent nuclear fuel, 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.

INTRODUCTION

The concept of using deep borehole repositories for permanent isolation of radioactive materials has, because of its simplicity, ease of construction, relatively low cost, and safety, been proposed and investigated intermittently for decades (see Refs. 1 through 13). 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 (Ref. 14) 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.

ASSUMPTIONS ABOUT A REGULATORY FRAMEWORK FOR DEEP BOREHOLE DISPOSAL IN THE UNITED STATES

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. 15). 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 National Laboratory (Ref. 12) and by the United States Department of Energy Used Fuel Disposition campaign (Ref. 16) 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. 17) and the US NRC's 10 CFR part 60 (Ref. 18) 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. 19): 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. 20).

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.

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 simply one of many possible configurations.

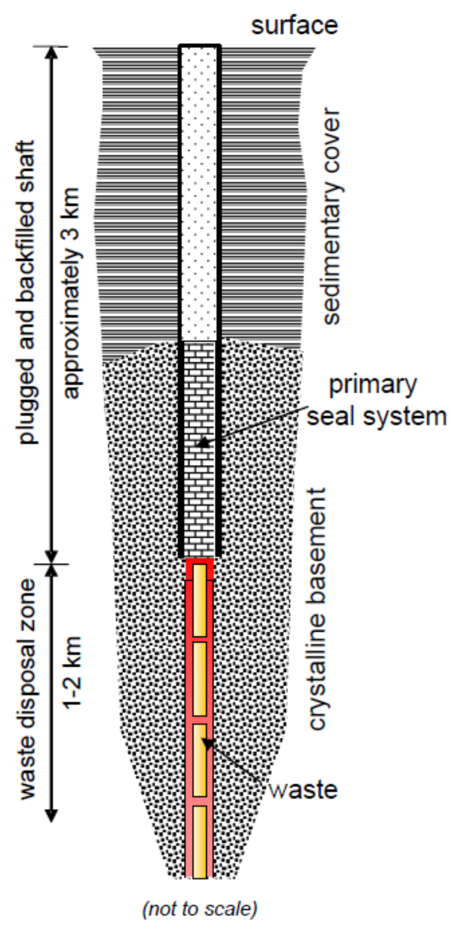

Figure 1. Schematic illustration of deep borehole disposal of high-level radioactive waste or spent nuclear fuel (Adapted from Ref. 12, Figure 1).

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. 14), 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. 21)). The 63,000 metric tons of commercial spent nuclear fuel legislated for disposal at Yucca Mountain contain an estimated 221,000 fuel assemblies (Ref. 22, Table 1.5.1-1); assuming 400 assemblies per borehole, an equivalent amount of spent fuel could be emplaced in approximately 550 deep boreholes. As described in a recent proposal for a simplified reference design for deep borehole disposal (Ref. 23), disposal concepts that include consolidating spent fuel assemblies or recycling fuel and disposing of high-level waste could result in disposal in narrower and/or fewer boreholes.

PRELIMINARY ASSESSMENT OF BOREHOLE PERFORMANCE

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 chemical 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 and bentonite. 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. For this analysis, it is assumed that any radionuclides that are transported out of the sealed section of the deep disposal borehole are released into an aquifer directly overlying the deep borehole and are subsequently captured and transported to the surface by a groundwater withdrawal well. 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 of radionuclides 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.

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. 15, 24, and 25) 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 in mined repositories), 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 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.

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, or that are potential resource extraction targets, 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 affect borehole disposal (Ref 12, Section 4.3). For example, molecular diffusion alone is shown to be slow enough to limit maximum transport to approximately 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 the volume required for critical configurations at the isotopic enrichments found in spent fuel.

Model configuration and parameters

Based on the conceptual design described above, a preliminary deep borehole performance assessment was performed for a simplified and conservative representation of the release scenarios identified following preliminary FEP screening. The conceptual model is as follows:

- 400 fuel assemblies (~150 metric tons) are vertically stacked down the length of the waste disposal zone (~ 2 km) in a borehole that is 5 km deep.
- The initial radionuclide inventory is representative of pressurized water reactor (PWR) fuel assemblies aged to year 2117 (Ref. 16, Table 3.4-1).
- Dissolved concentrations in the waste disposal zone are limited by thermal-chemical conditions (radionuclide solubilities from Ref. 16, Table 3.4-4).
- Waste packages are assumed to fail at the time the borehole is sealed. The waste form (used fuel) degrades at a fractional rate between 10^{-6}/yr and 10^{-8}/yr, consistent with the strongly reducing conditions anticipated in the borehole (Ref. 16, Section 3.1.2.5). The possible rapid release of a gap fraction of mobile radionuclides is not included in the analysis.
- Thermally driven hydrologic flow within the waste disposal zone and upward through 1000 m of a bentonite-sealed borehole and surrounding fractured rock annulus is calculated using a nine-well array in a three-dimensional flow model (Ref. 26) implemented in the FEHM software code (Ref. 27). Flow rates vary as a function of time and depth.
- Radionuclide transport in a single borehole (the center borehole in the array used in the thermal hydrology model) is calculated using the contaminant transport module of the GoldSim software (Ref. 28). Modeled processes include advection, dispersion, diffusion, sorption, decay, and ingrowth. Sorption coefficients are given in Ref. 16(Table 3.4-3).
- Water is pumped to the surface from an aquifer intersecting the deep borehole at a depth of 2,000 m with a withdrawal well assumed to be located directly above the deep borehole. This is represented using a one-dimensional GoldSim transport model, with a constant volumetric groundwater rate of 0.00235 m^3/year. The rate was obtained as a result of an analysis to match the breakthrough curve (of pumping well for 1000 people) in Ref. 12 (Figure 11) using the one-dimensional transport model.
- The International Atomic Energy Agency's (IAEA) BIOMASS Example Reference Biosphere 1B (ERB 1B) dose model (Ref. 29) is used to convert the dissolved radionuclide concentrations in groundwater to an estimate of annual dose to a receptor based on drinking well water consumption. The model assumes a dilution rate of 1×10^4 m^3/year in the aquifer and an individual water consumption rate of 1.2 m^3/year (Ref. 29).

Model Results

Thermally-driven groundwater flow in the sealed borehole is calculated for three separate cases: a base case representing the reasonably anticipated properties of an effective borehole seal system; a degraded case representing the properties of a fully-failed seal system; and a third case representing the permeability of an extremely effective seal system. For the base case and the lower seal permeability case, the host rock surrounding the seal system is assigned a permeability of 10^{-19} m^2, consistent with the properties of crystalline rock at depths greater than 3 km. For the degraded case, the host rock permeability is set at 10^{-16} m^2. Permeability of the borehole is treated as a lumped parameter for a cylindrical volume representing both the seal and the surrounding annulus of disturbed rock, and is assigned values of 10^{-16} m^2 for the base case, 10^{-12} m^2 for the fully degraded case (roughly representing a seal system that is no more effective than fine sand), and 10^{-19} m^2 for the lower seal permeability case. Calculated groundwater flux at the base of the seal system (3000 m) for each case is shown in Figure 2. The downward groundwater flow that is simulated to occur between approximately 1000 and 10,000 years for the base case and the lower seal permeability case results from cooling within the waste disposal zone and the corresponding thermal contraction of groundwater within this zone. For the degraded case, this effect is overcome by the broader pattern of upward thermal convection that occurs in the higher-permeability host rock and borehole.

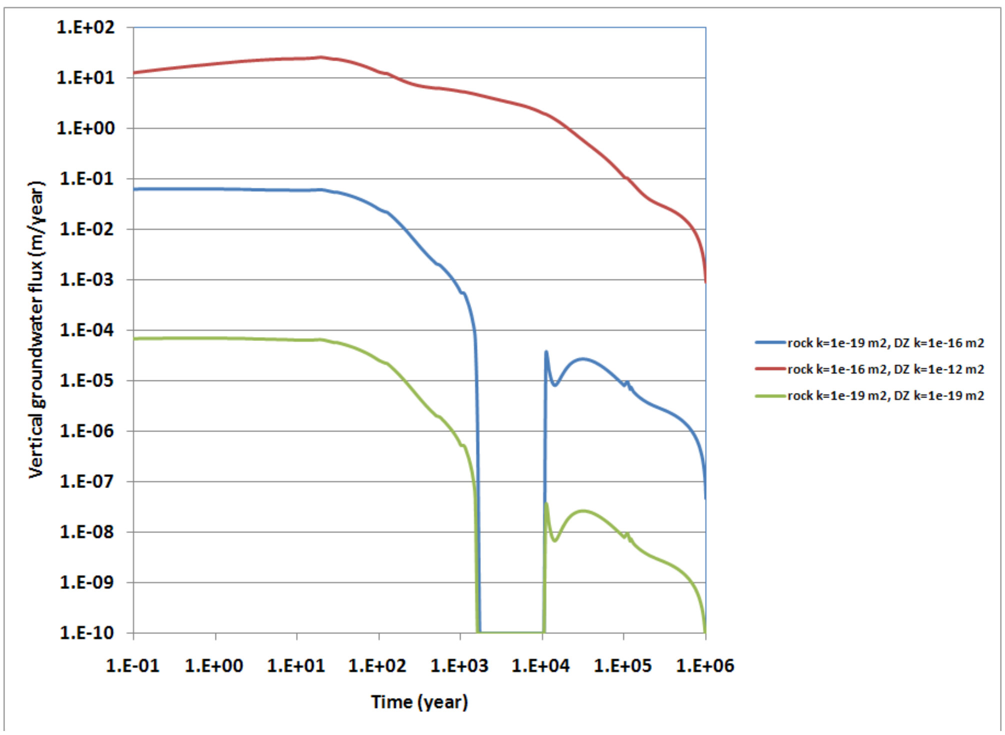

Figure 2. Upward groundwater flux (borehole center, 3000 m depth) versus time. Note that flow is downward for the base case and the lower-permeability seal case between approximately 1000 and 10,000 years (Ref. 16, Figure 3.4-3).

Radionuclide transport in the borehole was calculated only for the base case and the fully degraded properties cases, because vertical groundwater fluxes were extremely low for the lower permeability seals, indicating there would be effectively no radionuclide release for that case.

Transport calculations treated waste form degradation rates, radionuclide solubility limits, and sorption coefficients as uncertain parameters, and results are presented as mean values based on 100 realizations for each case. Estimated mean annual dose to the hypothetical receptor is shown in Figure 3 for the base case groundwater flux shown in Figure 2 and in Figure 4 for the case using degraded rock and seal properties. Results are shown in Figures 3 and 4 for a single borehole borehole disposal; concepts that call for an array of multiple holes could result in proportionally larger dose estimates.

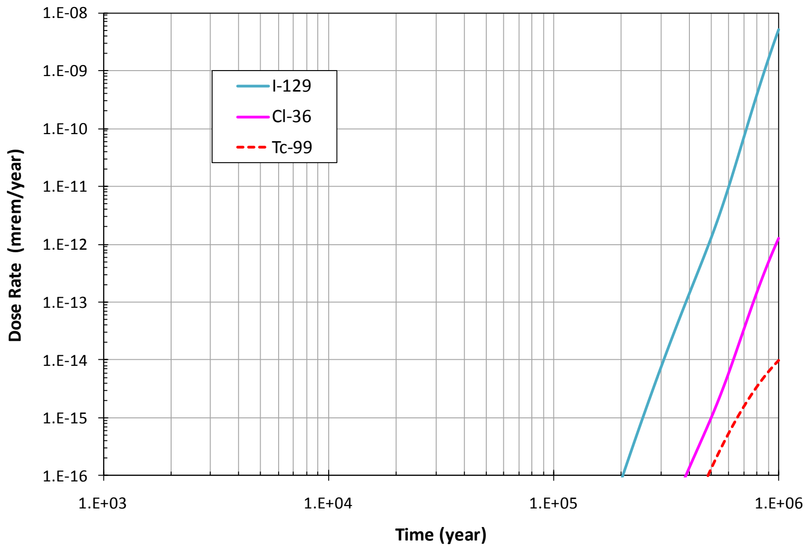

Figure 3. Estimated mean annual dose to a hypothetical receptor located above a borehole repository, base case material properties for the host rock and seal system.

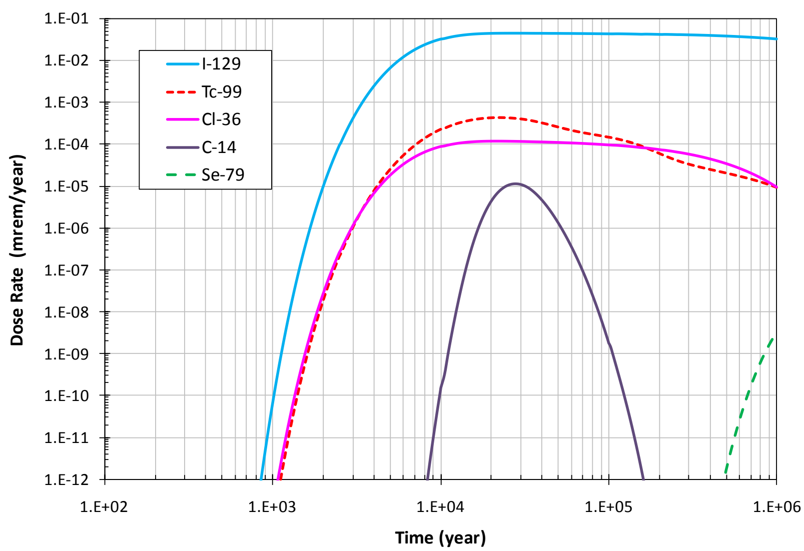

Figure 4. Estimated mean annual dose to a hypothetical receptor located above a borehole repository, fully degraded material properties for the host rock and seal system (seal permeability equivalent to fine sand).

Results shown in Figures 3 and 4 indicate that for boreholes in which seals perform as expected, radionuclide releases and associated doses to humans in the surface environment may be extremely small. Modeled mean annual doses for the base case (Figure 3) are dominated by ^{129}I, which is highly mobile in essentially all chemical environments, with the peak mean annual dose at 1 million years estimated to be less than 10^{-8} mrem/yr (10^{-10} mSv/yr). Estimated doses due to ^{36}Cl and ^{99}Tc are orders of magnitude smaller. Modeled mean annual doses for the case considering a fully degraded seal system (Figure 4) are larger, indicating the importance of a robust seal design for a borehole repository concept, but the peak mean annual dose is still below 0.1 mrem/yr (0.001 mSv/yr).

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 performance assessment indicate that radionuclide releases from a hypothetical deep borehole repository, and the annual radiation doses to hypothetical future humans associated with those releases, may be extremely small. These preliminary results highlight the importance of a robust seal design in assuring long-term isolation, and 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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