

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

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- **The deep borehole disposal concept**
 - History
 - Overview of design
 - US regulatory framework
- **Preliminary performance assessment**
 - Scenarios for analysis
 - Model configuration
 - Results
- **Multiple papers on this topic at this conference**



History of Borehole Disposal Concepts

- Deep borehole disposal of High-Level Waste (HLW) has been considered in the US since 1950s
- Shallow and intermediate depth disposal has been done in the US for low-level and transuranic waste
- Deep borehole disposal of used fuel and HLW has been studied in detail since 1970s
 - Recent reconsideration in Sweden, UK
 - Various options have evaluated
 - Disposal of surplus weapons Pu
 - Disposal of vitrified or cemented wastes
 - Disposal of fuel assemblies
 - Melting of host rock to encapsulate waste



Concept for Long-Term Isolation

- **Geologic environment and seal systems are the primary barriers**
 - In preliminary analyses described here, no credit taken for waste package
- **Essentially no ground water flow at 3 km and below**
 - Very low permeability of host rock and borehole seals
 - Saline pore water creates density stratification sufficient to limit convective flow from heating
 - Reducing conditions stabilize most radionuclides
 - I-129, Cl-36 remain mobile

The Deep Borehole Disposal Concept

Nominal 5 km borehole

45 cm bottom hole diameter

1 PWR assembly or 3 BWR
assemblies without
consolidation

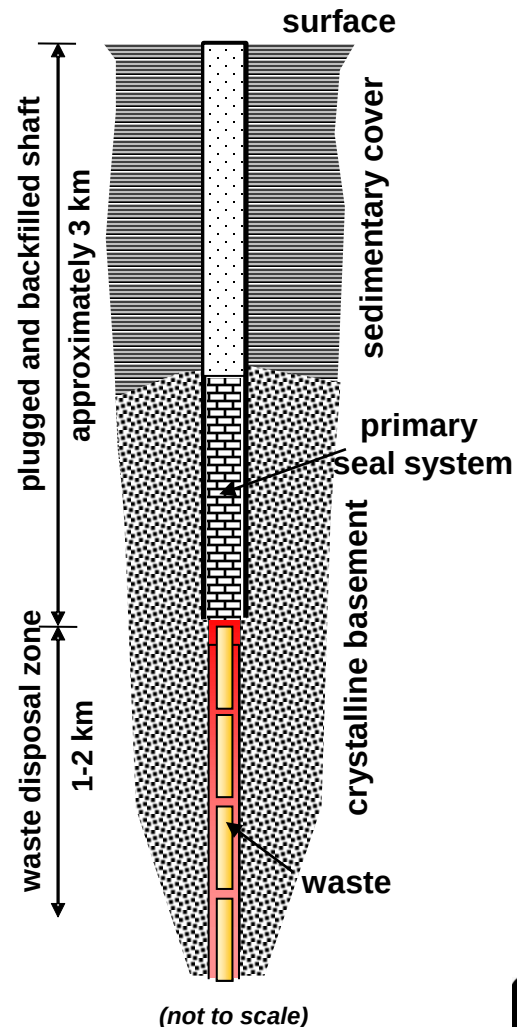
Lower 3 km in crystalline
basement

2 km emplacement zone

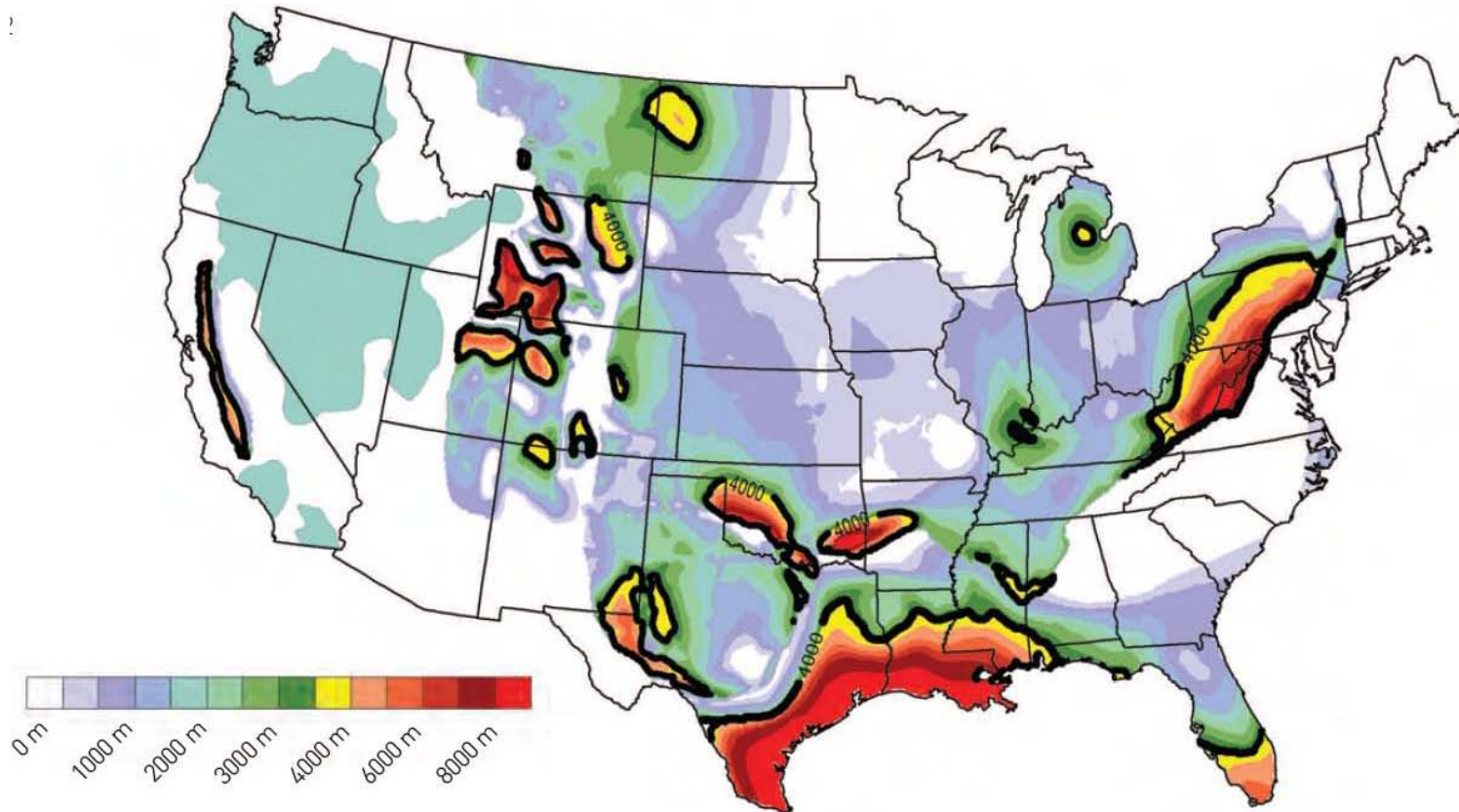
1 km minimum of robust plugs

Yucca Mountain spent fuel
inventory could be emplaced in
~ 600 holes

Source: modified from Brady et al., 2009, Deep
Borehole Disposal of High-Level Radioactive Waste,
SAND2009-4401

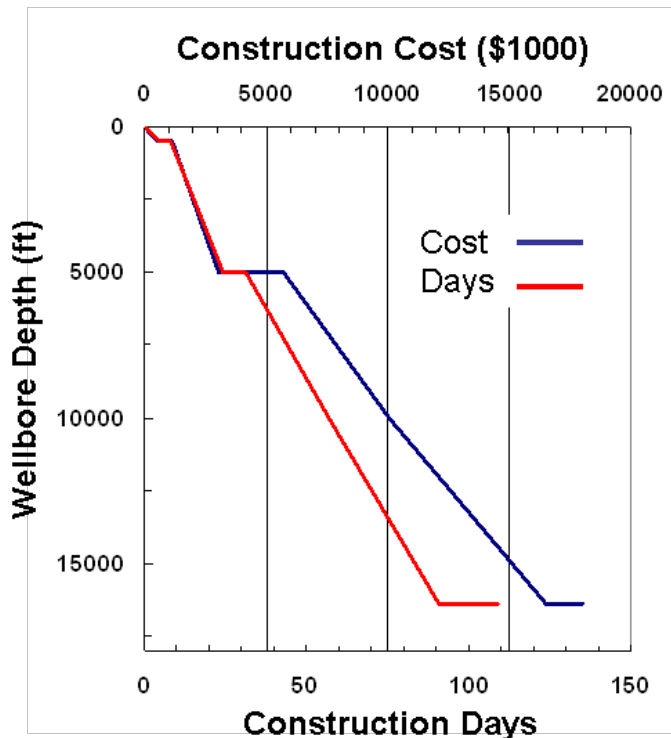


Depth to Crystalline Rock



Source: MIT 2006. *The Future of Geothermal Energy*

Feasibility of Deep Borehole Construction



Source: Polsky, Y., L. Capuano, et al. (2008). *Enhanced Geothermal Systems (EGS) Well Construction Technology Evaluation Report*, SAND2008-7866, Sandia National Laboratories, Albuquerque, NM

Well construction can use existing technology

Geothermal operations use large diameter holes in crystalline rock

Significant challenges may exist for emplacement operations

Robust sealing options

Concrete, clay, asphalt, rock melt

Overall costs likely to be competitive with repositories



US Regulatory Framework Relevant to Deep Borehole Disposal

- Yucca Mountain regulations (40 CFR part 197 and 10 CFR Part 63) apply only to Yucca Mountain
- Existing regulations that predate the 1987 NWPA amendment could, in principle, be applied to other disposal concepts for SNF/HLW without revision
 - EPA 40 CFR part 191 (implemented for the Waste Isolation Pilot Plant)
 - NRC 10 CFR part 60 (never implemented)
- Some aspects of existing regulations may not be appropriate for deep borehole disposal
 - Human intrusion
 - Retrievability
- For the purposes of this analysis, we assume regulations similar to those that apply to Yucca Mountain, without human intrusion



Scenarios for Analysis

- **Preliminary consideration of potentially relevant features, events, and processes (FEPs) identified three potential release scenarios of interest**
 - **Flow and transport through borehole seals**
 - **Flow and transport through an annulus of disturbed rock surrounding the borehole**
 - **Flow and transport through high-permeability zones (for example, faults or fracture zones) in the surrounding rock**
- **For the purposes of this analysis, the first two scenarios are considered with one model treating the borehole and annulus as a cylinder with a single set of properties**

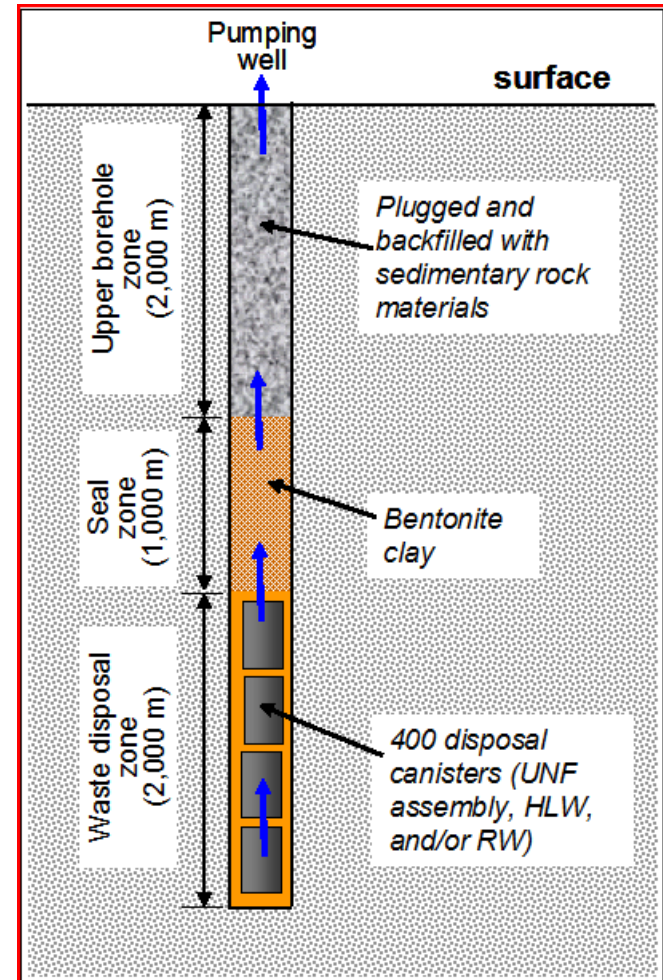


Scenarios for Analysis (cont.)

- Preliminary scenario analysis suggests that some site characteristics could become *de facto* site selection criteria, for example:
 - Flow and transport through high-permeability pathways in the host rock is not modeled explicitly in this analysis, but if such features are detected during drilling the hole could be abandoned prior to waste emplacement
 - Regions with anomalously high heat flow, high fluid pressures at depth, or low salinity at depth may also be inappropriate
- The potential for rock and fluid properties at depth to change with time (e.g., as a result of future tectonic activity or glaciation) should be considered

Performance Assessment Conceptual Model for a Single Disposal Borehole

- Model domain consists of three components:
 - Waste-disposal zone
 - Seal zone
 - Upper-borehole zone and aquifer
- Groundwater flow driven by thermal-hydrologic effects (thermal expansion and thermal buoyancy) – no ambient gradient in fluid potential
- Groundwater flow in the upper-borehole zone driven by 3D radial flow to a water supply well (Brady et al., 2009)
- Flow and radionuclide transport in waste-disposal and seal zones occurs in 1 m^2 cross-sectional area consisting of the borehole, borehole seals or canisters plus grout, and disturbed rock zone (DRZ) surrounding borehole





Performance Assessment Conceptual Model (cont.)

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- Waste canister failure occurs immediately after emplacement
 - Constant fractional waste-form degradation rate
 - Radionuclide solubility limits representative of reducing conditions in brine (Brady et al., 2009)
 - Linear sorption coefficients representative of reducing conditions are used for radionuclide retardation (Brady et al., 2009)
 - Radionuclide transport processes of advection, dispersion, diffusion, sorption, decay and ingrowth are included
 - Groundwater flow rates vary with depth and time in the waste-disposal and seal zones (derived from separate 3D thermal-hydrologic modeling of a 9-borehole array, Arnold et al. 2011, this conference)
 - Groundwater flow rates are constant in the upper borehole zone and surrounding aquifer
 - Radionuclide releases to the biosphere diluted in 10,000 m³/year water supply (IAEA 2003, Example Reference Biosphere 1B)
 - Numerical model is implemented with the GoldSim software code

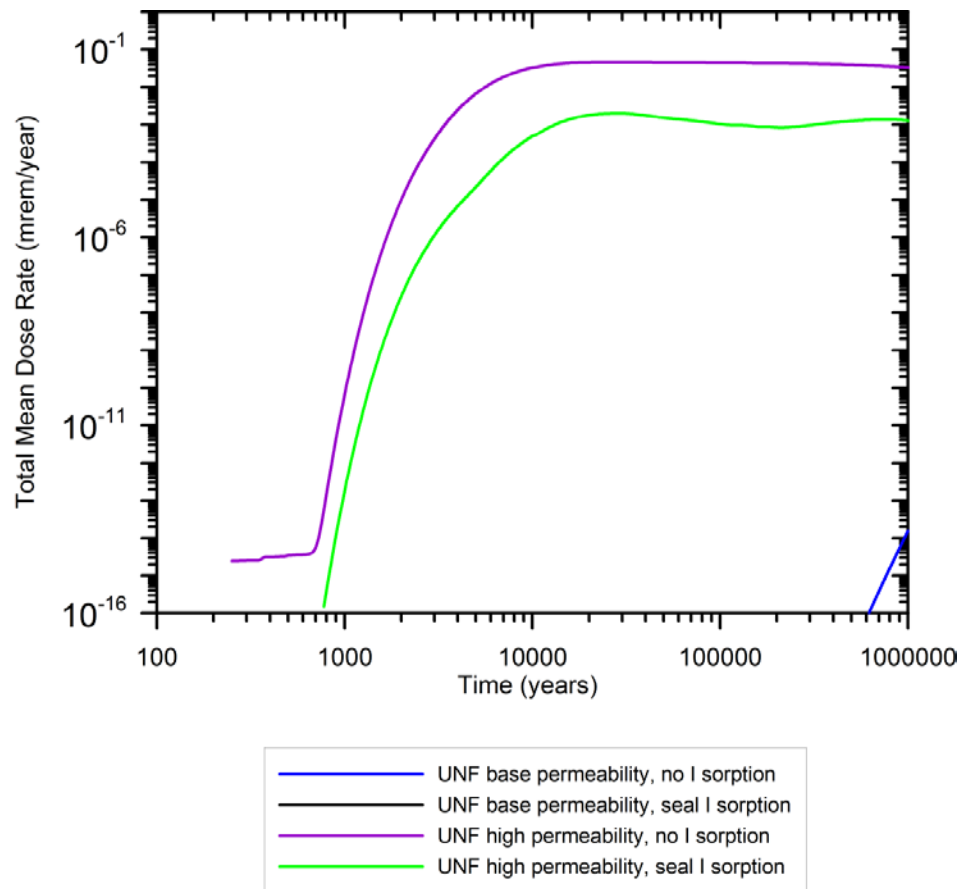


Performance Assessment Model Cases and Parameters

- Direct disposal of US Commercial Used Nuclear Fuel (UNF)
- Radionuclide inventory and thermal output consistent with Yucca Mountain data
- Sampled values for UNF fractional dissolution rate
 - log triangular: min = $10^{-8}/\text{yr}$, mode = $10^{-7}/\text{yr}$, max = $10^{-6}/\text{yr}$
 - “Instantaneous” release of gap fraction not modeled
- Radionuclide solubility limits and sorption coefficients from Brady et al., 2009
- Two flow cases considered from Arnold et al., 2011
 - Base case: rock permeability = 10^{-19} m^2 and borehole/DRZ permeability = 10^{-16} m^2
 - High-permeability case: rock permeability = 10^{-16} m^2 and borehole/DRZ permeability = 10^{-12} m^2 (equivalent to fine sand, conceptually intended to provide a conservative representation of a fully-failed seal system)
- Base case assumes no sorption of I-129 or Cl-36
 - Sensitivity analysis considers hypothetical gettering of I in seals system, k_d for I varies uniformly from 0.1 to 100

Performance Assessment Preliminary Model Results

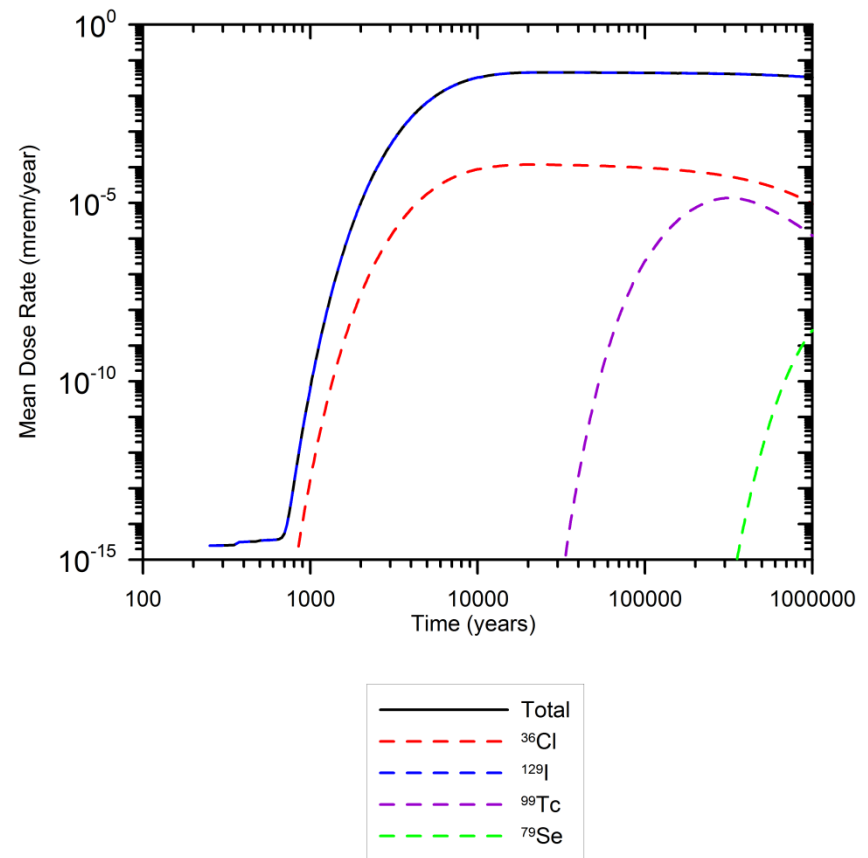
- **Results shown for a single disposal borehole**
 - Performance of multiple disposal holes in a single array could scale approximately linearly with the number of holes
- **For reasonably achievable seal permeabilities, estimated doses are extremely small**
- **For a fully failed seal system (approximate permeability of fine sand, corresponding to fully degraded or fully bypassed seals), estimated doses are well below regulatory limits**
- **Estimated dose is dominated by I-129; sorption of I by hypothetical getters in seals would provide defense in depth**



Performance Assessment Preliminary Model Results (cont.)

Contributors to the estimated dose for the high-permeability case

- Advective flow and transport in borehole from thermal effects
- Diffusive transport also contributes
- I-129 is the primary radionuclide, Cl-36, Tc-99, and Se-79 also contribute
- Peak dose rate limited by the fractional dissolution of the used fuel





References

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