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

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NNSA National Nuclear Security Administration

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Outline

- The deep borehole disposal concept
  - History
  - Overview of design
  - US regulatory framework
- Preliminary performance assessment
  - Scenarios for analysis
  - Model configuration
  - Results

History of Borehole Disposal Concepts

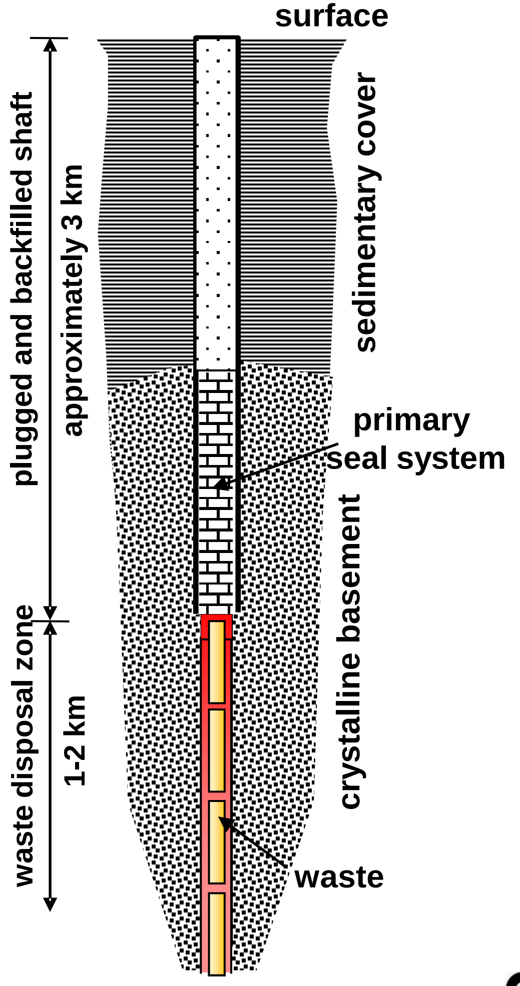
- Deep borehole disposal of High-Level Waste (HLW) has been considered in the US since 1950s
- Shallow and intermediate depth disposal has been done in the US for low-level and transuranic waste
- Deep borehole disposal of used fuel and HLW has been studied in detail since 1970s
  - Recent reconsideration in Sweden, United Kingdom
  - 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

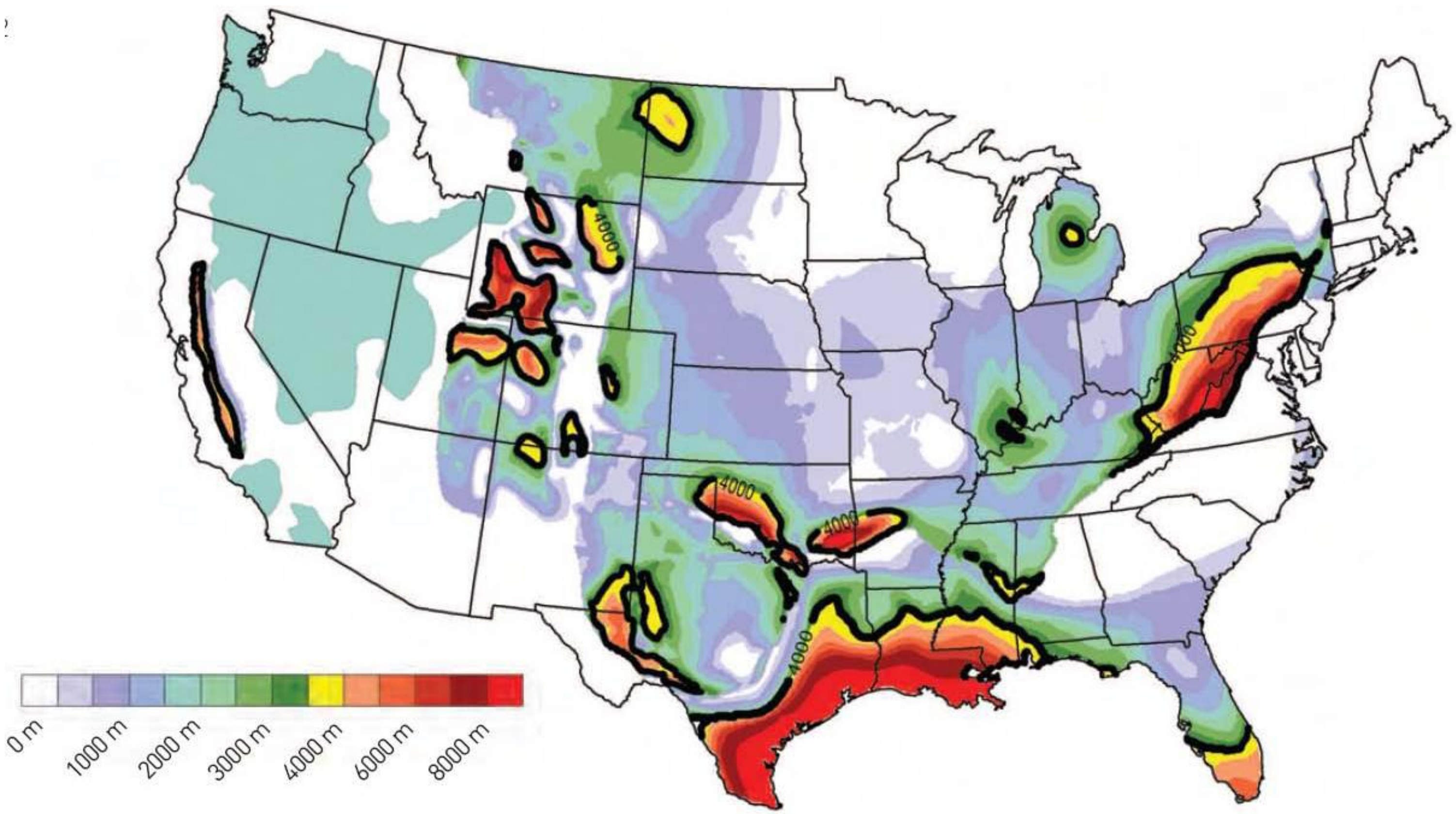
- **Nominal 5 km borehole**
  - **45 cm bottom hole diameter**
    - **1 PWR assembly or 3 BWR assemblies without consolidation**
  - **Lower 3 km in crystalline basement**
  - **2 km emplacement zone**
  - **1 km minimum of robust plugs**
  - **Yucca Mountain spent fuel inventory could be emplaced in ~ 550 holes**



(not to scale)

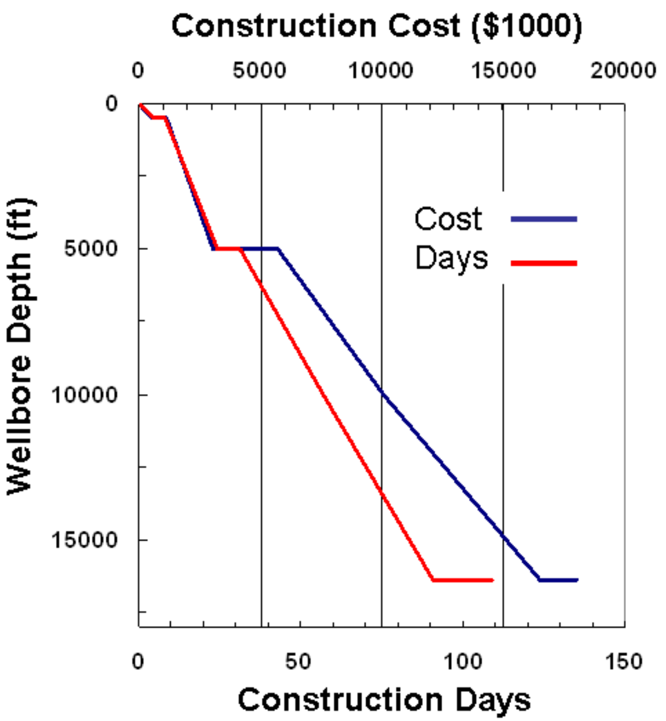
Source: modified from Brady et al., 2009, Deep Borehole Disposal of High-Level Radioactive Waste, SAND2009-4401

Depth to Crystalline Rock in the United States



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

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US Regulatory Framework Relevant to Deep Borehole Disposal

- Yucca Mountain regulations (40 CFR part 197 and 10 CFR Part 63) apply only to the proposed Yucca Mountain repository
- 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

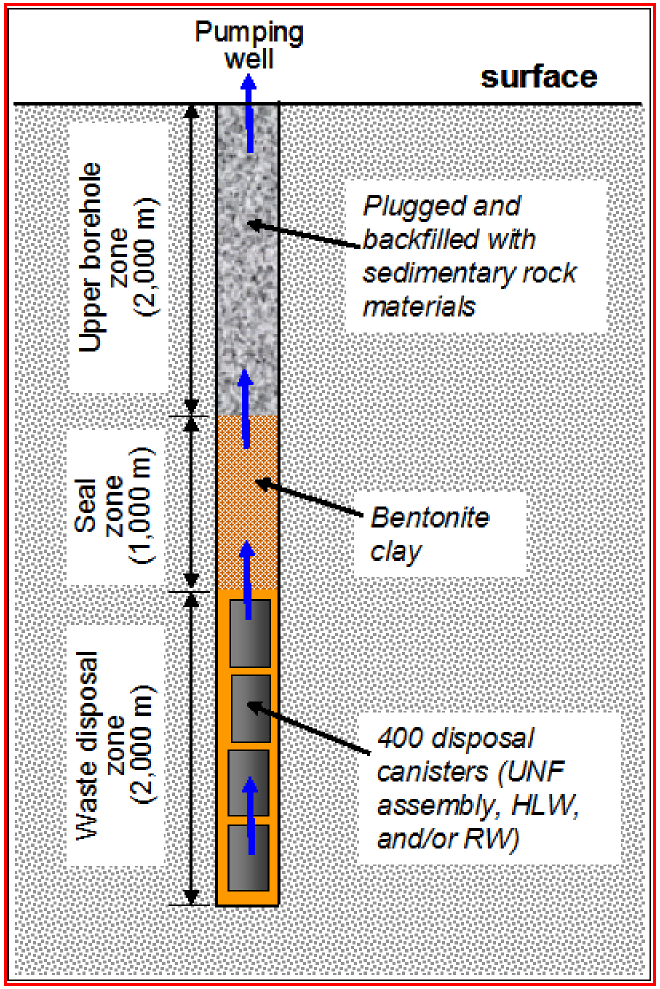
- Preliminary consideration of potentially relevant features, events, and processes (FEPs) identified three potential release scenarios of interest
  - Flow and transport through borehole seals
  - Flow and transport through an annulus of disturbed rock surrounding the borehole
  - Flow and transport 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, low salinity at depth, or potential natural resource targets 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 m² 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.)

- 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)
- Groundwater flow rates are constant in the upper borehole zone and surrounding aquifer
- Radionuclide releases to the biosphere diluted in 10,000 m^3/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 based on PWR (pressurized water reactor) fuel
  - 60 GWd/MTHM burnup, 30 year cooling period after reactor discharge
- Sampled values for UNF fractional dissolution rate
  - log triangular: min = 10^{-8}/yr, mode = 10^{-7}/yr, max = 10^{-6}/yr
    - "Instantaneous" release of gap fraction not modeled
- Radionuclide solubility limits and sorption coefficients from Brady et al., 2009
  - Essentially unlimited solubility and no sorption for I-129 and Cl-36
- Three flow cases considered from Arnold et al., 2011
  - Base case: rock permeability = 10^{-19} m^2 and borehole/DRZ permeability = 10^{-16} m^2
  - Low permeability case: rock permeability = 10^{-19} m^2 and borehole/DRZ permeability = 10^{-19} m^2 (corresponds conceptually to a highly-effective seal system)
  - 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)

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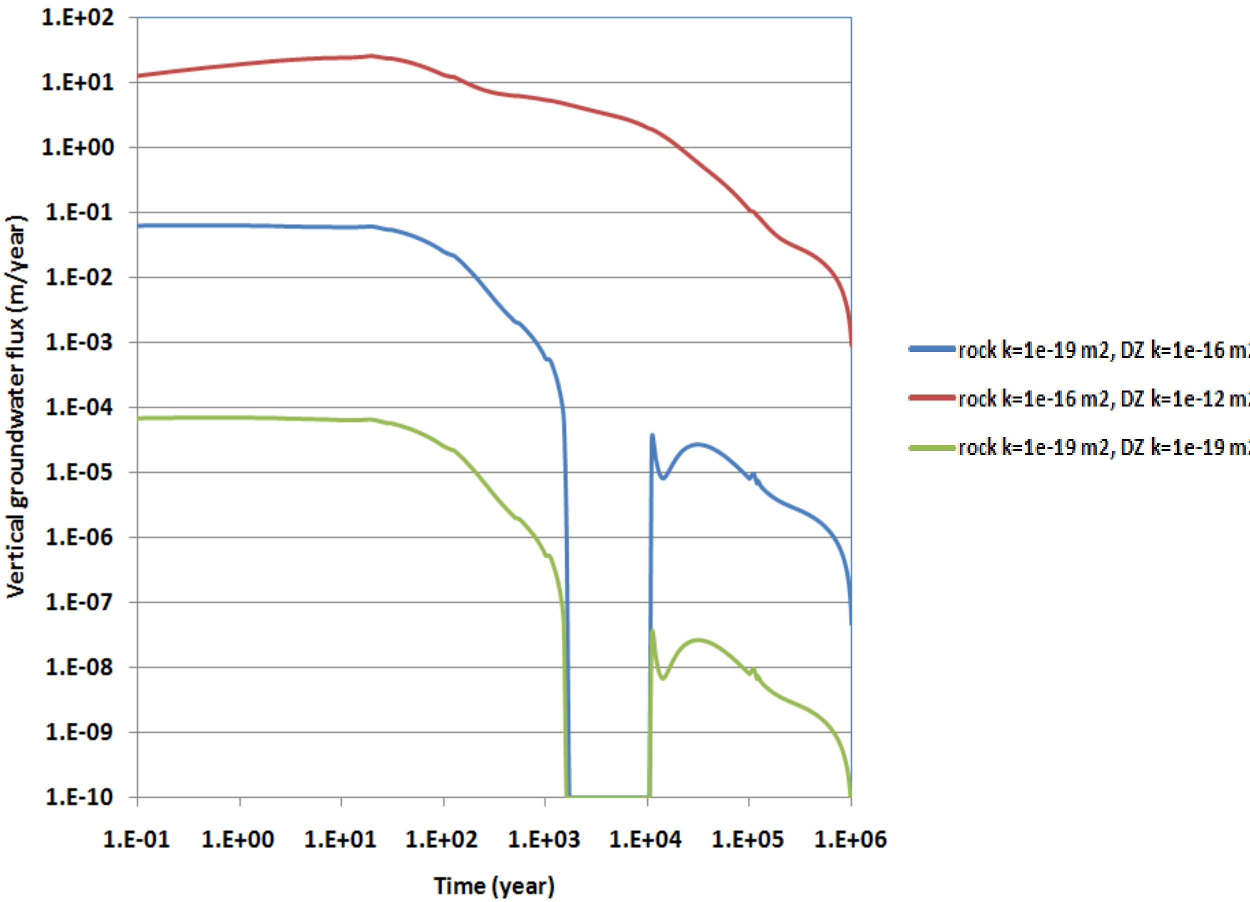
Preliminary Model Results: Groundwater Flow in the Borehole

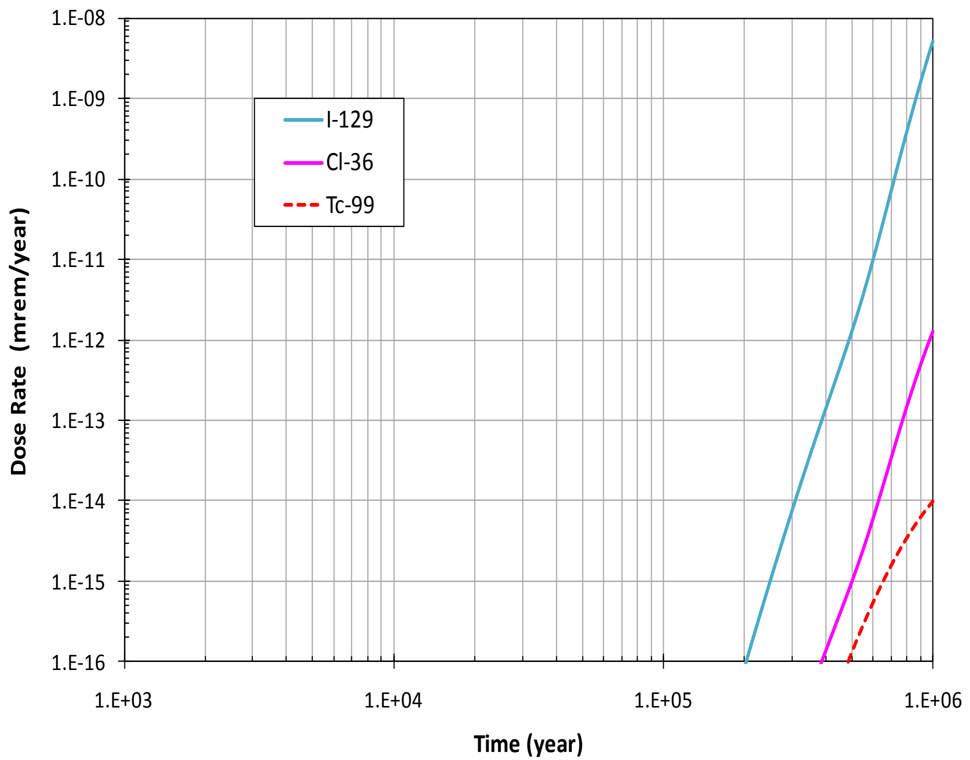
- Upward flux at 3000 m depth (top of waste disposal zone) calculated for the central borehole in a nine-hole array, 200-m spacing
- Downward flux between ~1000 and ~10,000 yrs for lower permeability cases results from thermal contraction of water during cooling



Preliminary Model Results: Estimated Mean Annual Dose

- **Low permeability seal case not illustrated: estimated million-year dose is zero**
- **Base case permeability results in an estimated peak mean annual dose less than 10^{-10} mSv/yr**
  - **I-129 is primary contributor, lesser contributions from Cl-36 and Tc-99**

Results shown for a single borehole

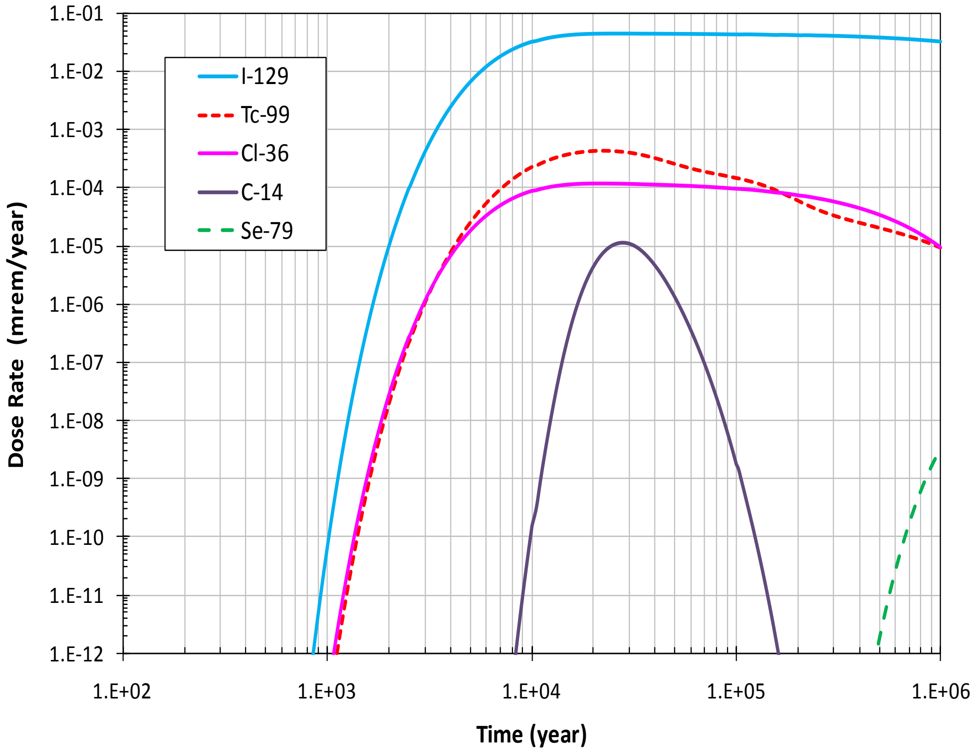


Base case: rock permeability = 10^{-19} m^2 and borehole/DRZ permeability = 10^{-16} m^2

Preliminary Model Results: Estimated Mean Annual Dose (cont.)

- **High permeability case (fully degraded seals) results in an estimated peak mean annual dose less than 0.001 mSv/yr**
  - **I-129 is primary contributor, lesser contributions from Cl-36,Tc-99, C-14, and Se-79**
  - **Peak dose rate limited by the fractional dissolution of the used fuel**
- **Relatively higher (but still small) estimated doses for high permeability case indicate the importance of a robust seal design**

Results shown for a single borehole



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)

Conclusions

- Preliminary results indicate that deep boreholes have the potential to effectively isolate high-level radioactive wastes and spent nuclear fuel from the biosphere
- Estimated radiation doses to hypothetical future humans in the far future are extremely small (and potentially zero) if borehole seals are effective
- Borehole performance remains relatively robust even with an assumption that seals fail completely
- The US Department of Energy and Sandia National Laboratories are continuing to study deep borehole disposal options

References

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