A Prototype Performance Assessment Model for Generic Deep Borehole Repository for High-Level Nuclear Waste

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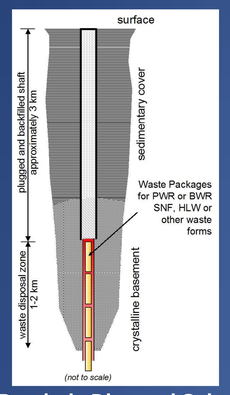
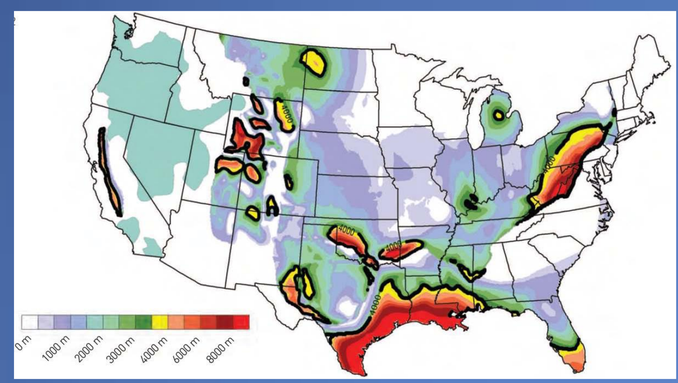
ABSTRACT:

A deep borehole repository is one of the four geologic media currently under study by the U.S. DOE to support the development of a long-term strategy for geologic disposal of high-level nuclear waste. The immediate goal of the generic deep borehole repository study is to develop the necessary modeling tools to evaluate and improve the understanding of the repository system response and processes relevant to long-term disposal of the waste in a deep borehole. A prototype performance assessment (PA) model for disposal in a generic deep borehole has been developed using the approach for a mined geological repository. The preliminary PA results indicate that soluble, non-sorbing (or weakly sorbing) fission product radionuclides, such as I-129 and Cl-36, are the likely major dose contributors, and the annual radiation doses to hypothetical future humans may be extremely small. While much work needs to be done to validate the model assumptions and parameters, the 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 high-level nuclear waste.

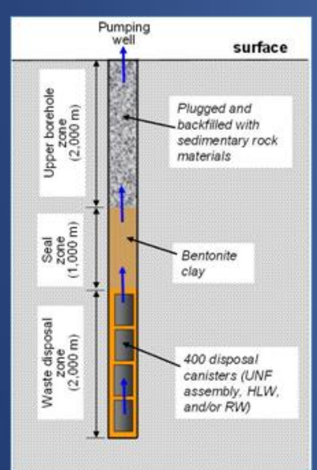


Deep Borehole Disposal Schematic Diagram (Swift et al 2011)



Depth to Crystalline Rock in the US (Brady et al 2009)

CONCEPTUAL MODEL:



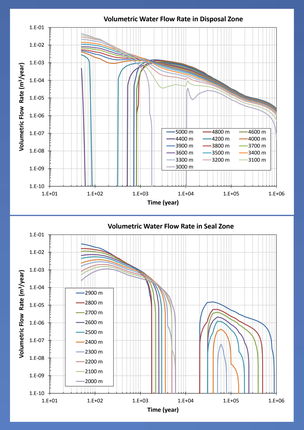
A Schematic of the Conceptual Model for Performance Assessment of a Generic Single Deep Borehole

- Model domain consists of three components: 1) Waste-disposal zone, 2) Seal zone, and 3) Upper-borehole zone and aquifer
- Groundwater flow driven by thermal-hydrologic effects (thermal expansion and thermal buoyancy) – no ambient gradient in fluid potential (Arnold et al., 2009)
- 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
- Waste canister failure occurs immediately after emplacement
- Constant fractional waste-form degradation rate
- Radionuclide solubility limits representative of chemically reducing conditions in brine for the disposal and seal zones, and less reducing (or slightly oxidizing) conditions for the upper zone
- 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 framework

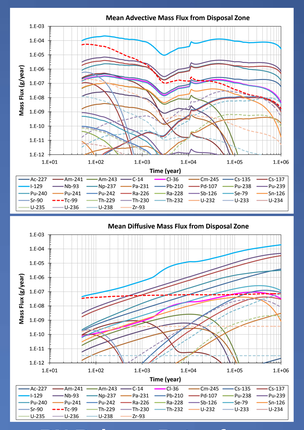
PERFORMANCE ASSESSMENT MODEL CASES AND PARAMETERS:

- 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
- 400 disposal canisters stacked vertically down the length of the disposal zone (~2 km), each containing one PWR assembly
- 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
- 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)
- Analysis performed probabilistically, with 100 realizations for each case and for a time period of one million years

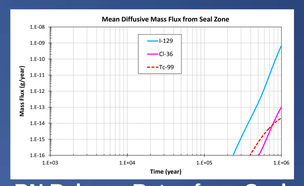
PRELIMINARY PERFORMANCE ASSESSMENT RESULTS: Base Permeability Case



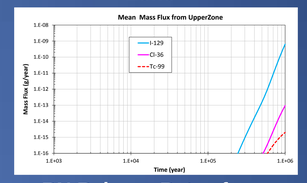
Water Flow Rate Histories



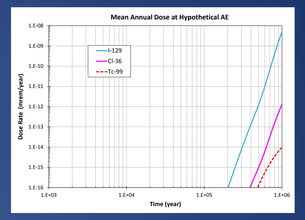
RN Release Rates from Disposal Zone



RN Release Rates from Seal Zone



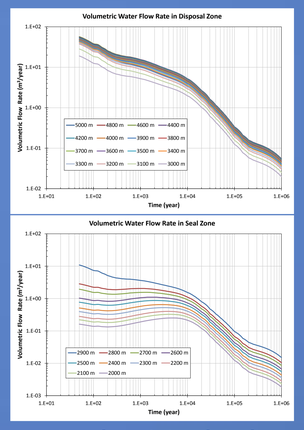
RN Release Rates from Upper Borehole Zone



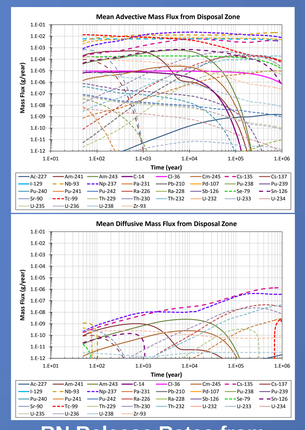
Mean Annual Dose by RNs

- **Downward flux between ~1000 and ~10,000 yr for lower permeability cases results from thermal contraction of water during cooling**
- **Base case permeability results in an estimated peak mean annual dose less than 10^{-8} mrem/yr**
- **I-129 is primary contributor, lesser contributions from Cl-36 and Tc-99**

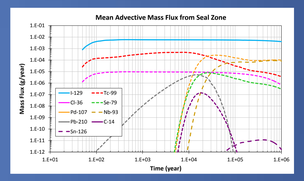
PRELIMINARY PERFORMANCE ASSESSMENT RESULTS: High Permeability Case

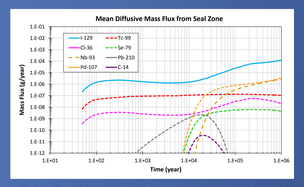


Water Flow Rate Histories

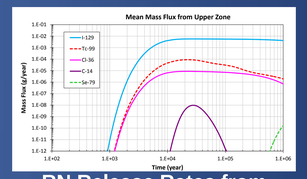


RN Release Rates from Disposal Zone

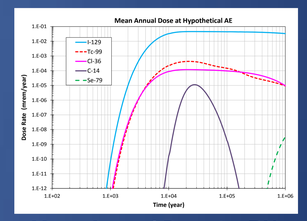




RN Release Rates from Seal Zone



RN Release Rates from Upper Borehole Zone



Mean Annual Dose by RNs

- **High permeability case (fully degraded seals) results in an estimated peak mean annual dose less than 0.1 mrem/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**

SUMMARY AND CONCLUSIONS:

- **A prototype PA model for a single deep borehole has been developed using the approach for modeling the performance of a minded geological repository**
- **Preliminary results indicate that deep boreholes have the potential to effectively isolate UNF and HLW 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**

FUTURE WORK:

- **Improve conceptual models for the RN release pathways and scenarios that are representative of a deep borehole GDS**
- **Additional studies and experimental work to better characterize and quantify important geochemical processes in deep borehole environments (e.g., solubility, sorption, etc.)**
- **Additional studies to characterize and quantify the degradation process of candidate waste forms in generic deep borehole repository environments, including possible rapid release of a gap fraction of mobile RNs in the waste form**
- **Improved analyses to better define and quantify the waste stream type and inventory, particularly reprocessing HLW of commercial UNF**

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