U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Deep Borehole Disposal (DBD) Performance Assessment

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Sandia National Laboratories

Performance and Risk Assessment Community of Practice

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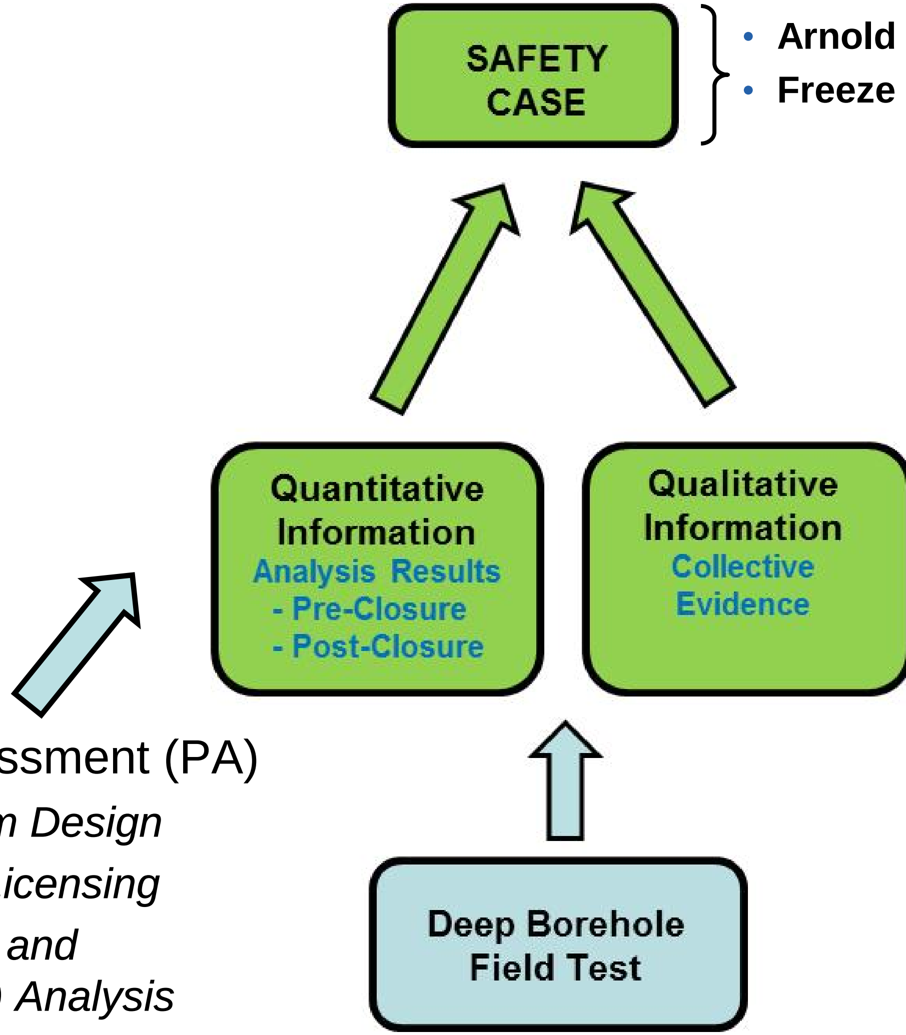
Outline

- **DOE-NE Used Fuel Disposition Campaign (UFDC) Deep Borehole Disposal Scope**
- **Deep Borehole Disposal (DBD) Safety Case**
  - Regulatory and Licensing Considerations
- **DBD Post-Closure System Assessment**
  - Conceptual Model
  - Performance Assessment (PA) Model
    - *PA Model Results*
    - *Sensitivity Analyses*
- **Summary**

DOE-UFDC Deep Borehole Disposal Scope

- **UFDC is performing R&D to provide a sound technical basis for multiple viable radioactive waste disposal options in the US**
  - Mined geologic repositories in crystalline, argillite, and salt rocks
  - Deep borehole disposal in crystalline rock
- **Deep Borehole Disposal R&D**
  - DOE-NE Assessment of Disposal Options (DOE 2014) recommended consideration of deep borehole disposal of smaller DOE-managed waste forms, such as cesium (Cs) and strontium (Sr) capsules
  - UFDC is conducting a planned 5-year **Deep Borehole Field Test (DBFT)** to evaluate the feasibility of siting and operating a deep borehole disposal facility
    - *Safety Case and PA Model analyses support the feasibility evaluation*
    - *DBFT will use surrogate waste packages (no radioactive waste)*
- **Program Participants**
  - DOE, SNL, LANL, LBNL, ORNL, PNNL, INL
- **PA Model Key Contributors (SNL)**
  - Geoff Freeze, Emily Stein, Teklu Hadgu, Glenn Hammond

DBD Safety Case



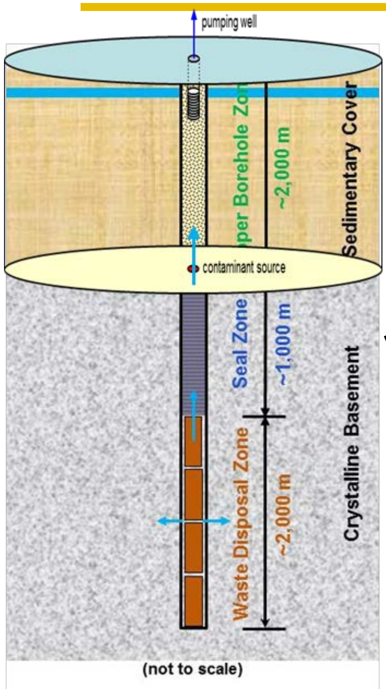
- Arnold et al. (2013, Appendix A)
- Freeze et al. (2013)

- **Pre-Closure**
  - Safety Analysis
- **Post-Closure**
  - Performance Assessment (PA)
    - *Repository System Design*
    - *Regulations and Licensing*
    - *Features, Events, and Processes (FEPs) Analysis*
    - *Scenario Development*
    - *PA Model*

DBD Safety Case – Regulatory and Licensing Considerations

- **Pre-Closure / Operational**
  - Transportation
  - Construction and Operations
  - Decommissioning
- **Post-Closure**
  - Nuclear Waste Policy Act of 1982, as amended (NWPA 1983)
    - *No disposal options for commercial SNF/HLW other than Yucca Mountain are possible without amending the NWPA*
    - *Separate repository for HLW resulting from atomic energy defense activities is possible (NWPA 1983, Section 8(b); DOE 2015)*
  - Licensing (NRC) and Environmental Protection (EPA)
    - *10 CFR 60 and 40 CFR 191 – Existing generic regulations (1981 and later amendments) could, in principle, be applied to other concepts*
      - predate 1987 NWPA amendment, may be revised or replaced in future
    - *10 CFR 63 and 40 CFR 197 – Yucca Mountain specific regulations (2001 and later amendments) could provide inferences to other concepts and/or sites*

DBD Post-Closure PA Model Development – Chronology

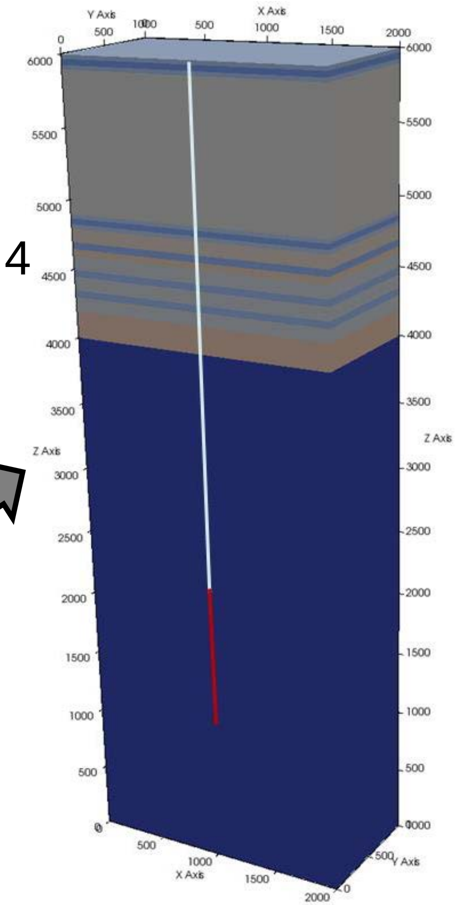


Past PA Work (2009 – 2014)

- **Excel Spreadsheet Model**
  - Brady et al. 2009, Sections 4 and 5
- **GoldSim-based 1-D Model**
  - Wang and Lee 2010, Section 5
  - Clayton et al. 2011, Section 3.4
  - Freeze et al. 2013, Sections 4.3 and 4.4
  - Arnold et al. 2013, Section 4.4

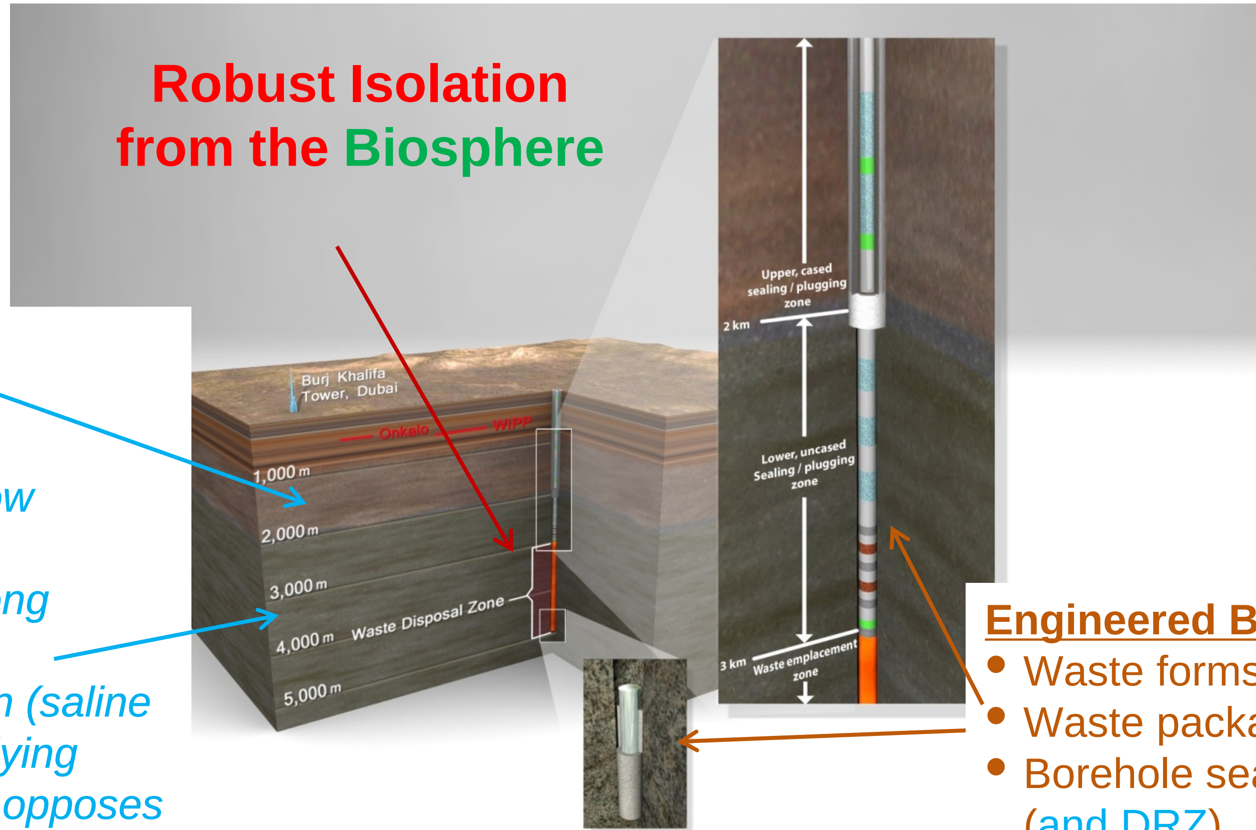
Current/Future PA Work (2015 +)

- **PFLOTRAN-based 3-D Model**
  - Hadgu et al. 2015 (TH only)
  - Stein et al. 2015



DBD Post-Closure Conceptual Model – Components

Robust Isolation from the Biosphere



Natural System

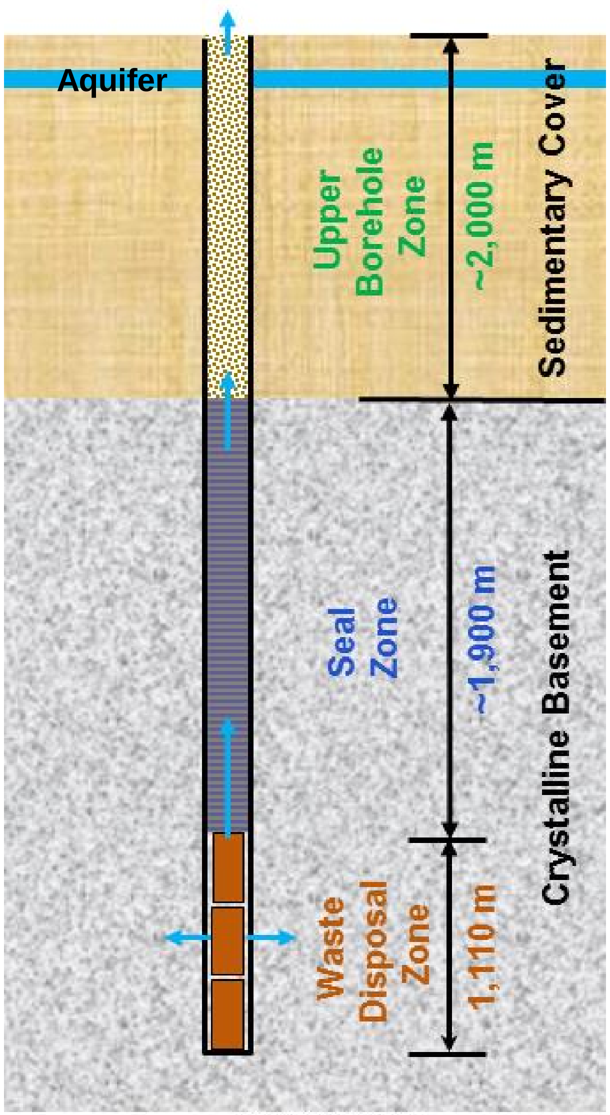
- Overlying Sediments
- Crystalline Basement
  - *Isolated from shallow groundwater (low permeability and long residence time)*
  - *Density stratification (saline groundwater underlying fresh groundwater) opposes upward convection*
  - *Geochemically reducing conditions limit the solubility and enhance the sorption of many radionuclides*

Engineered Barriers

- Waste forms
- Waste packages
- Borehole seals (and DRZ)

DBD Conceptual Model Overview – Undisturbed Scenario

- **Inventory / Waste Form**
  - DOE-managed HLW (Cs/Sr Capsules)
  - All capsules fit in a single borehole
- **Waste Package**
  - Provides operational protection, assumed to rapidly degrade after emplacement
- **Post-Closure Release Pathways**
  - Undisturbed
    - *Up borehole through seals / DRZ*
    - *To host rock surrounding disposal zone*
      - High-permeability pathway to shallow groundwater
  - Disturbed
    - *Volcanic/igneous*
    - *Human Intrusion*
- **Biosphere (Dose)**
  - Subsurface release to aquifer
    - *Pumping from aquifer to surface receptor*



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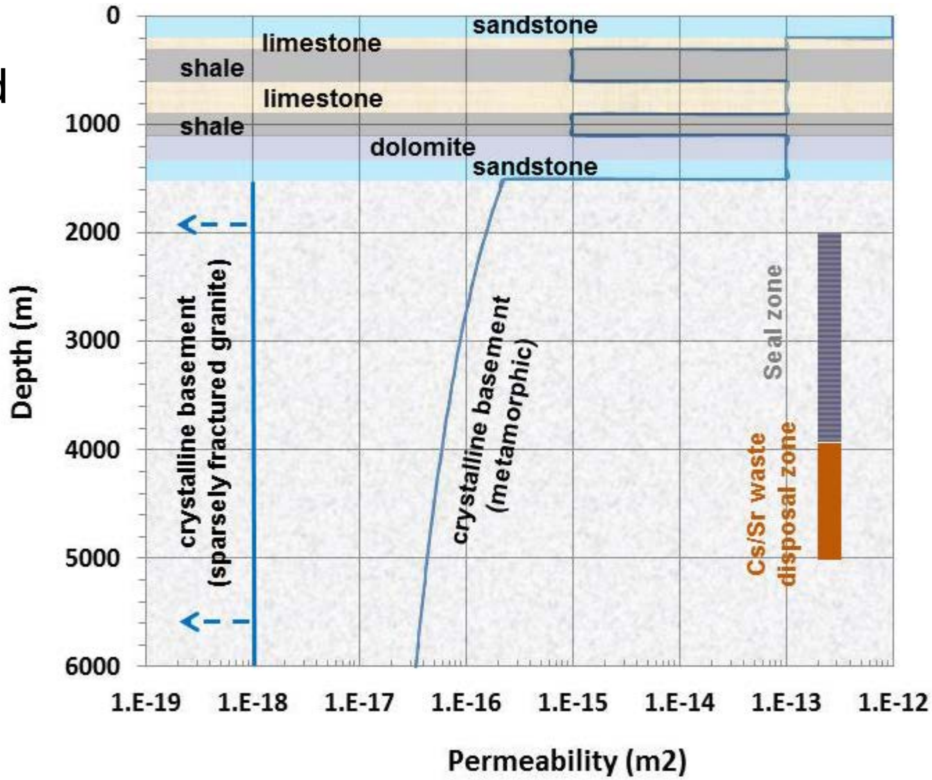
DBD Conceptual Model – Undisturbed Scenario

- **Sediments**
  - Hypothetical alternating units assumed above seal zone
- **Crystalline Basement**
  - Low permeability (k) and porosity (Φ)
    - *$k = 1\times10^{-19}$ to 1×10^{-16} m^2*
    - *$\Phi = 0.01$*
  - Thermal gradient = 25°C/km
    - *Ambient temperature*
      - *10°C at surface*
      - *~120°C at center of disposal zone*
    - *Thermal conductivity = 3.0 W/m°K*
    - *Specific heat = 880 J/kg°K*



  - Ambient reducing geochemical conditions at depth
  - Salinity and density gradients
    - *Salinity ~ 300 g/L TDS at center of disposal zone*
    - *Density ~ 1.2 kg/m3 at center of disposal zone*

DBD Conceptual Model – Undisturbed Scenario

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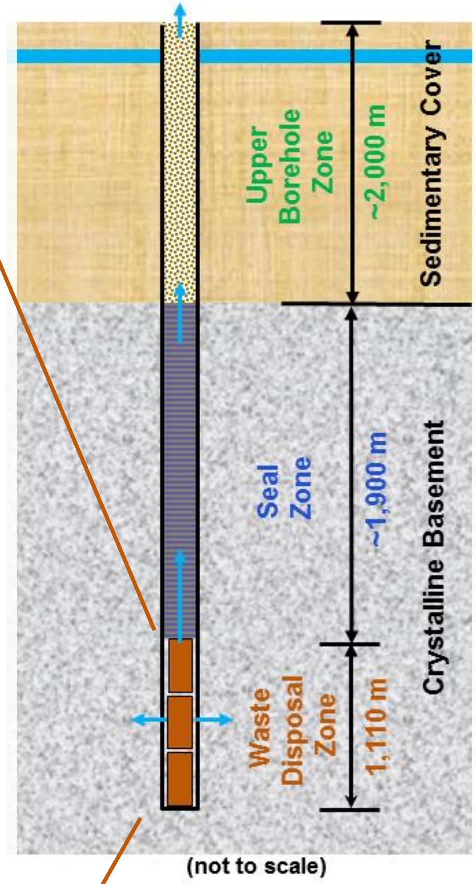
Inventory and Waste Form

- 1936 capsules
  - *1335 CsCl capsules (SNL 2014), per capsule:*
    - Inventory (2017) = ^{137}Cs (278 g), ^{135}Cs (278 g), ^{137m}Ba (0 g)
    - Thermal output (2007) = 144 W
  - *601 SrF_2 capsules (SNL 2014), per capsule*
    - Inventory (2017) = ^{90}Sr (167 g), ^{90}Y (0 g)
    - Thermal output (2007) = 193 W
  - *Waste form degradation assumed to be rapid*
    - Fractional rate = 1.0 yr^{-1}
      - *mass release: 50% by 1 yr ; 100% by 25 yrs*



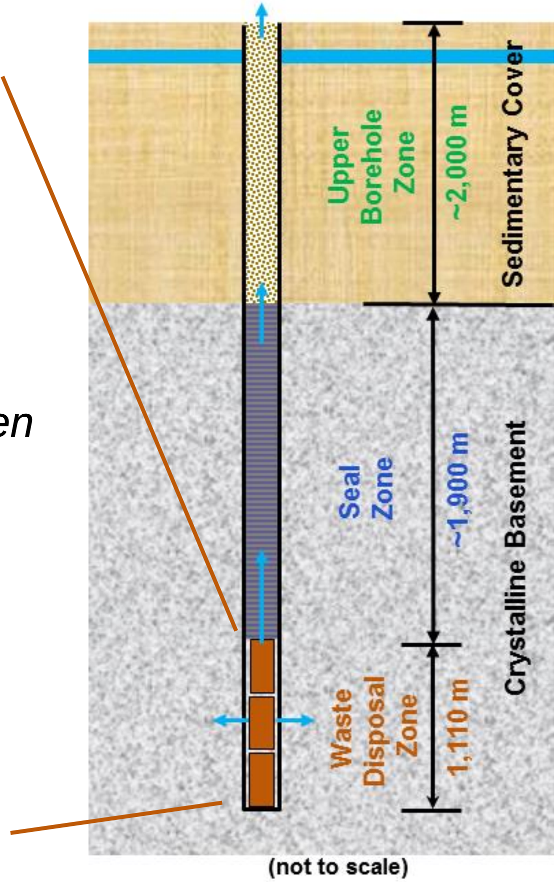
Waste Packages

- 968 waste packages (WPs) in 1,110 m Disposal Zone
  - *2 capsules per package*
  - *WP length = 1.09 m (capsule length ~0.5 m)*
  - *WP diameter ~ 11.5 cm (capsule diameter ~7 cm)*
- Assumed to degrade at time zero (after emplacement)
  - *Mobilization of radionuclides from degraded waste form*

DBD Conceptual Model – Undisturbed Scenario

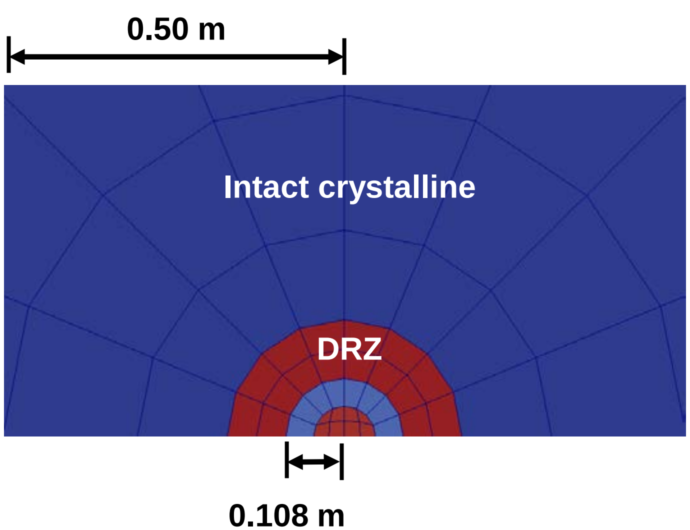
Waste Disposal Zone

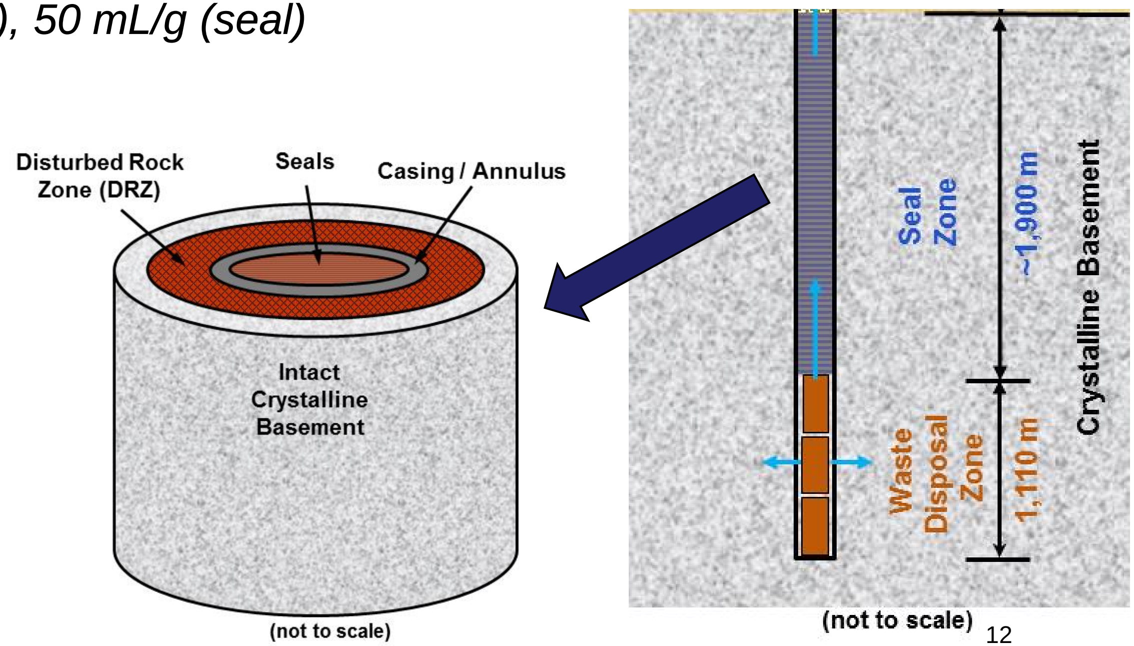
- Borehole bottom-hole (Disposal Zone) diameter =
  - *21.6 cm (8.5 in.)*
- Decay heat effects calculated from regional TH:
  - *Heat conduction in surrounding crystalline basement rock*
  - *Thermal perturbation in borehole produces thermally-driven upward groundwater flow*
- Radionuclide dissolution and transport in groundwater
  - *Advection/Dispersion, Diffusion, Sorption, and Decay*
  - *Based on ambient reducing geochemical conditions*
  - *No sorption (K_d = 0 mL/g for Cs and Sr) in Disposal Zone*



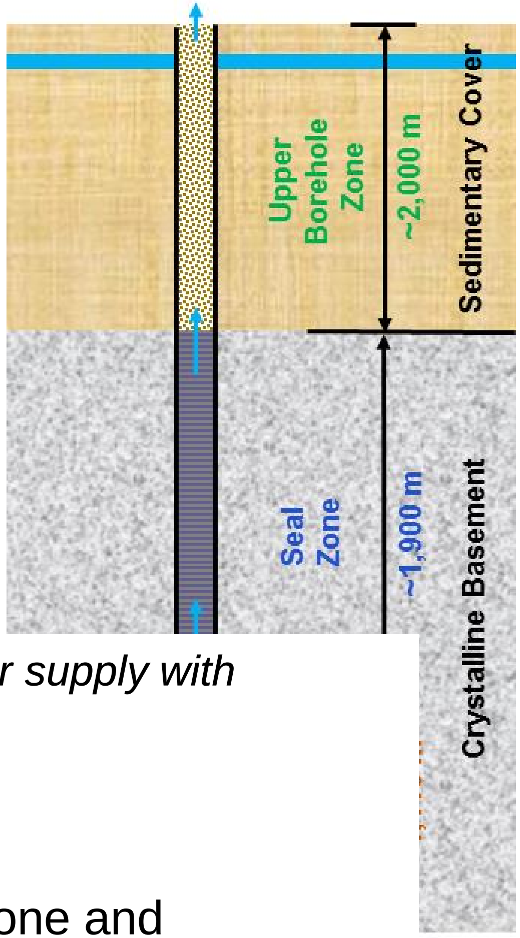
DBD Conceptual Model – Undisturbed Scenario

- **Seal Zone**
  - Enhanced permeability (*k*) in the DRZ and seals (assumed degraded bentonite)
    - *$k = 1 \times 10^{-16}$ to 1×10^{-15} m^2 (DRZ), 1×10^{-16} m^2 (seal)*
    - *porosity (Φ) = 0.01 (DRZ), 0.30 (seal)*
    - *tortuosity (T) ~ 0.20 (DRZ), 0.50 (seal)*
  - Transport by advection (thermally-induced upward flux) and diffusion (upward and lateral) with sorption and decay
    - *Cs K_d (min) = 5 mL/g (DRZ), 120 mL/g (seal)*
    - *Sr K_d (min) = 0.4 mL/g (DRZ), 50 mL/g (seal)*





DBD Conceptual Model – Undisturbed Scenario



Upper Borehole Zone

- Release of radionuclides upward in the borehole from the Seal Zone to Upper Borehole Zone
- Transport by diffusion (upward and lateral) with sorption and decay to aquifer and/or surface

Biosphere

Current PA Work

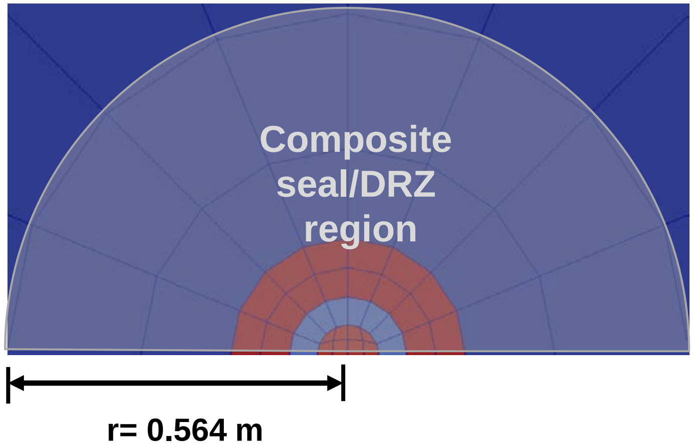
- IAEA BIOMASS ERB 1B Biosphere (IAEA 2003)
  - *Pumping of groundwater from Upper Borehole Zone for water supply with specified dilution rate and individual consumption rate*
  - *IAEA Dose Conversion Factors (DCFs)*

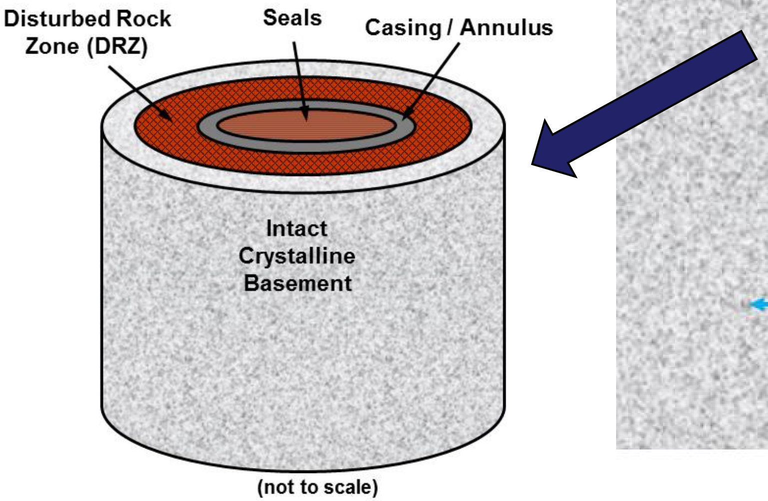
Future PA Work

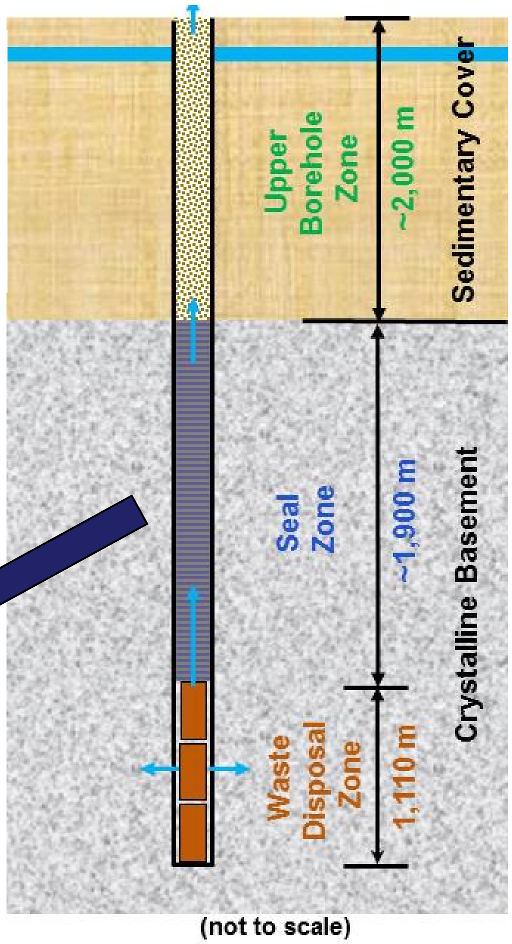
- Explicit flow and transport modeling in Upper Borehole Zone and sedimentary units, including aquifer
  - *Pumping of the groundwater from the aquifer for water supply*
  - *IAEA Dose Conversion Factors (DCFs)*

DBD PA Model Results – Thermally-Induced Upward Flow

- **3-D PFLOTRAN TH simulation (Hadgu et al. (2015)**
  - Borehole represented by uniform region with cross-sectional area of 1 m^2 (r=0.564 m) and composite seal/DRZ properties
    - *composite k = 1×10^{-16} m^2 (degraded seal and DRZ)*
    - *composite porosity (Φ) = 0.034 (DRZ=0.01, seal = 0.30)*
    - *composite tortuosity (T) = 0.324 (DRZ=0.20, seal = 0.50)*







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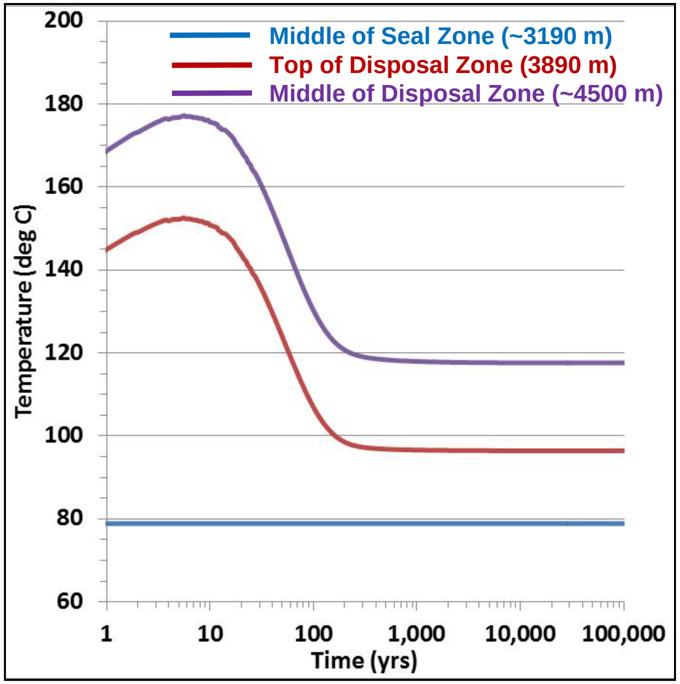
DBD PA Model Results – Thermally-Induced Upward Flow

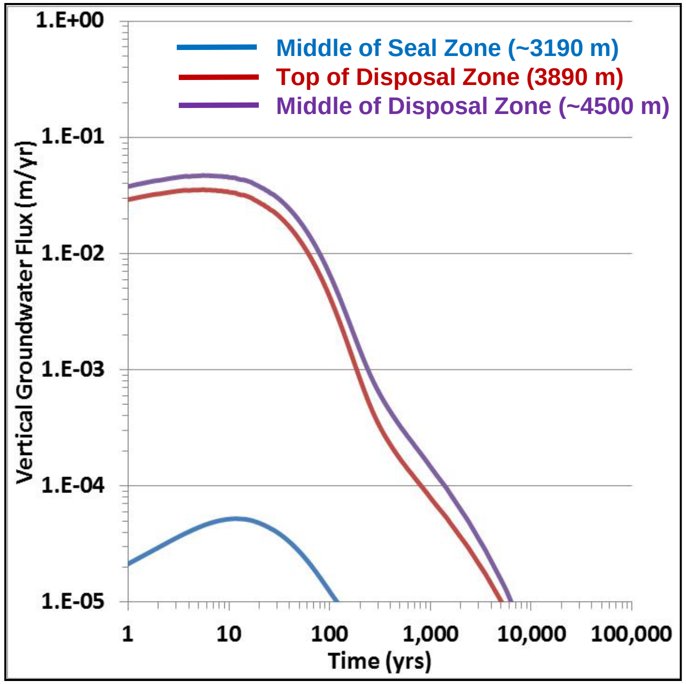
- 1936 Cs/Sr capsules in 1 borehole (1,110 m disposal zone)
  - ~300W (CsCl) or ~400W (SrF_2) per waste package (from decay of ^{137}Cs and ^{90}Sr)
- Advective center of mass upward movement
  - *(0.03 m/yr)(100 yrs)/(0.034 porosity) ~ 90 m*
  - *advection is even less with sorption*

Temperature in Borehole

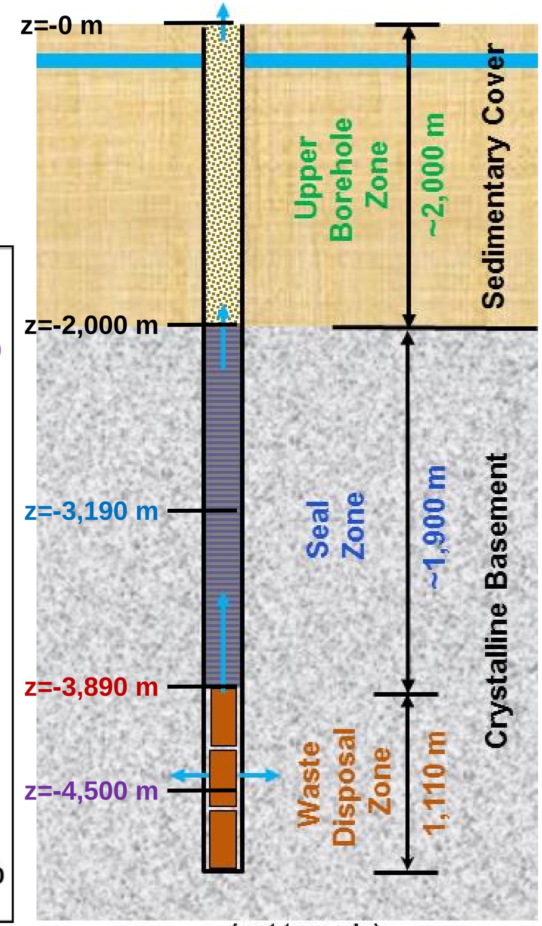


adapted from Hadgu et al. (2015), Figure 7

Vertical Groundwater Flux (Specific Discharge) in Borehole



adapted from Hadgu et al. (2015), Figure 8

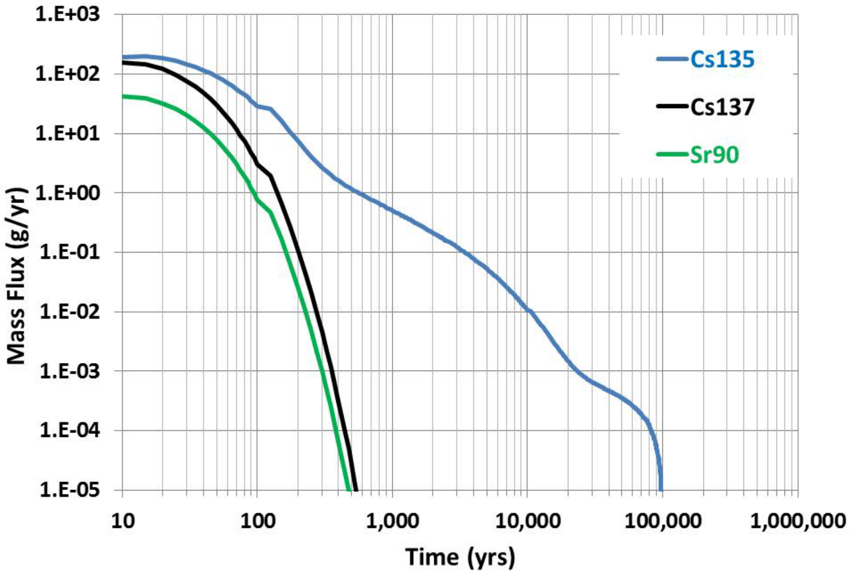


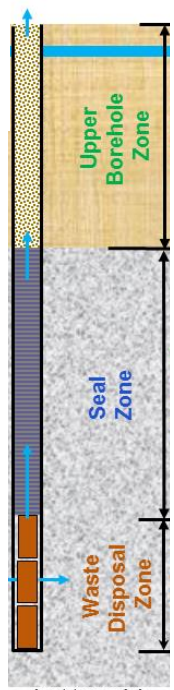
(not to scale)

DBD PA Model Results – Undisturbed Scenario

- **Mass flux - no radionuclide releases above seal zone**
  - ^{135}Cs
    - *Short duration of thermally-induced upward advection (~ 100 years)*
    - *Slow upward diffusion and sorption in seal zone/DRZ*
  - ^{90}Sr and ^{137}Cs
    - *Decay in <1,000 years due to short half-lives*

Advective Flux (g/yr) in Borehole from Top of Waste Disposal Zone





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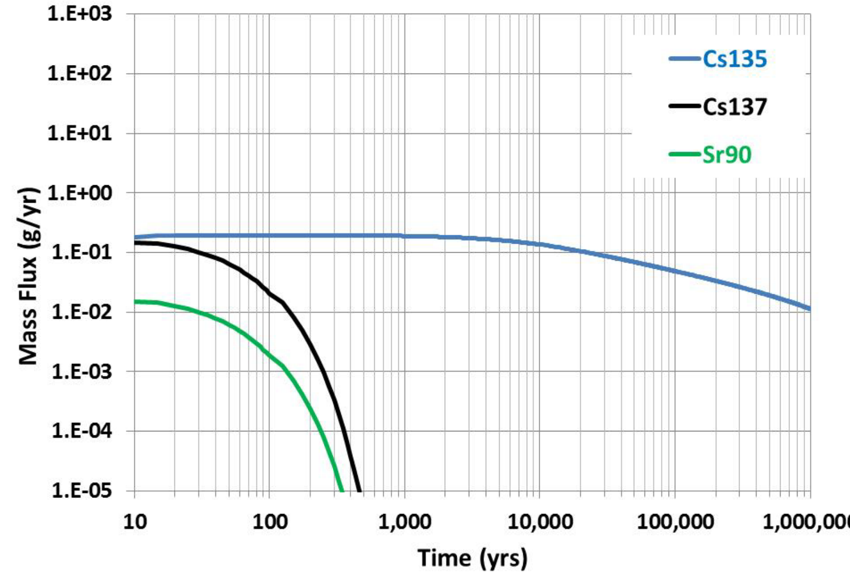
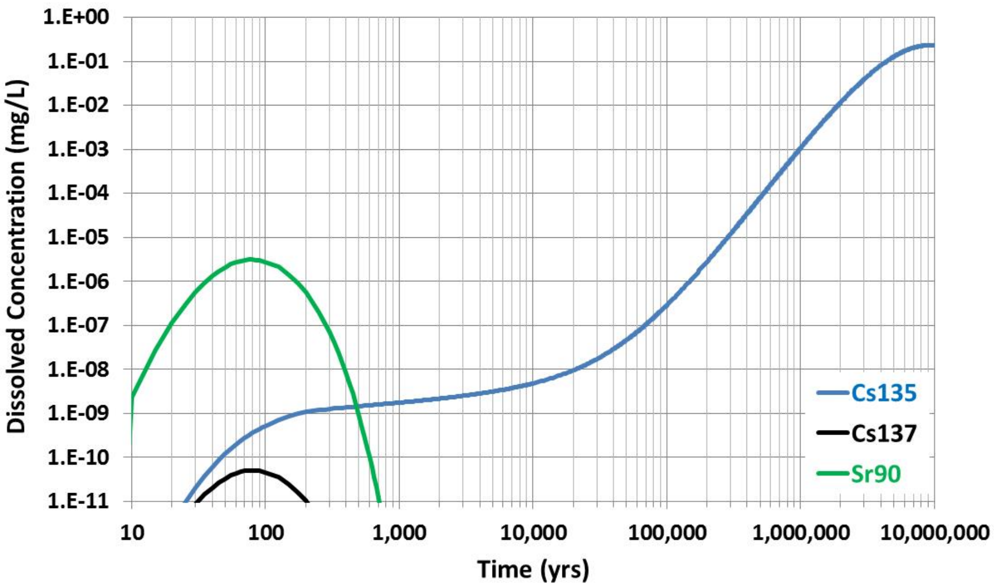
Diffusive Flux (g/yr) in Borehole from Top of Waste Disposal Zone



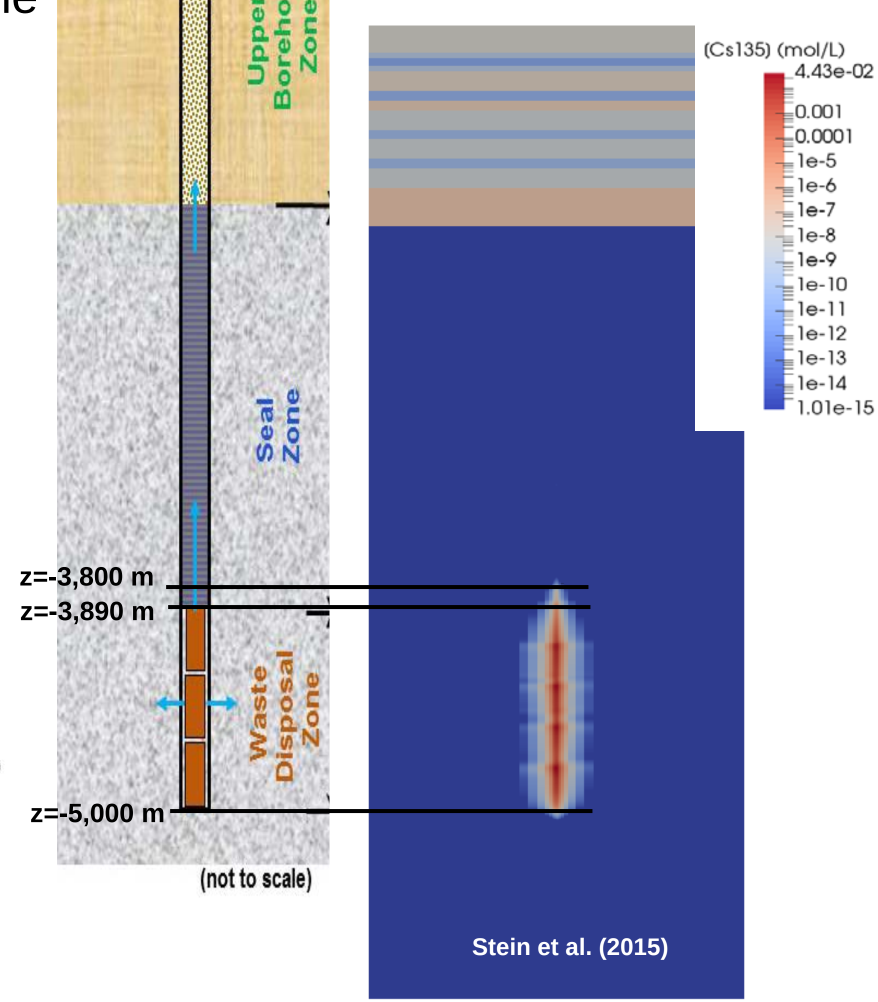
DBD PA Model Results – Undisturbed Scenario

- **Dissolved Concentrations**
  - Minimal migration beyond disposal zone

Dissolved Concentration (mg/L) in Borehole in Seal Zone (~3,800 m depth)



Dissolved Concentration of ^{135}Cs (mol/L) at 100,000 years

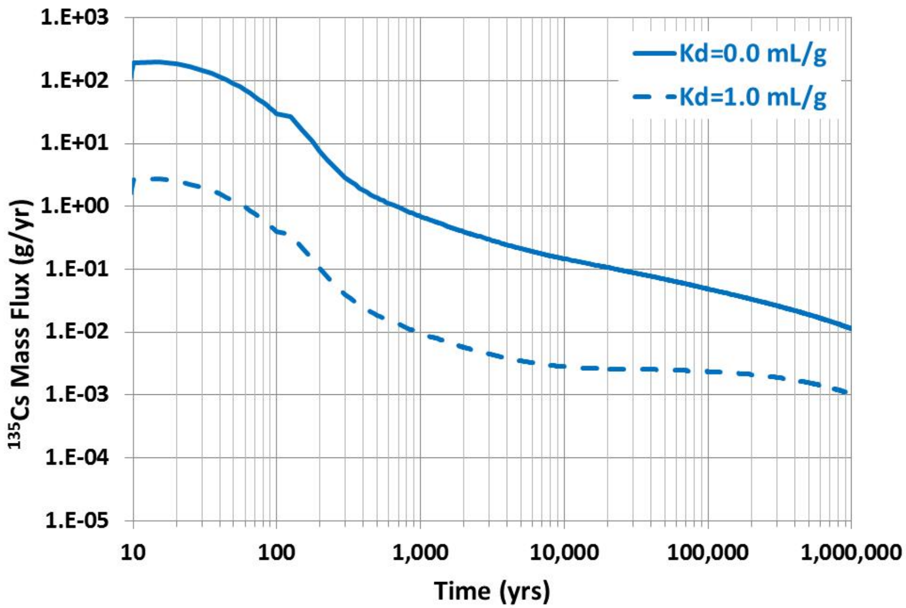


DBD PA Model Results – Sensitivity

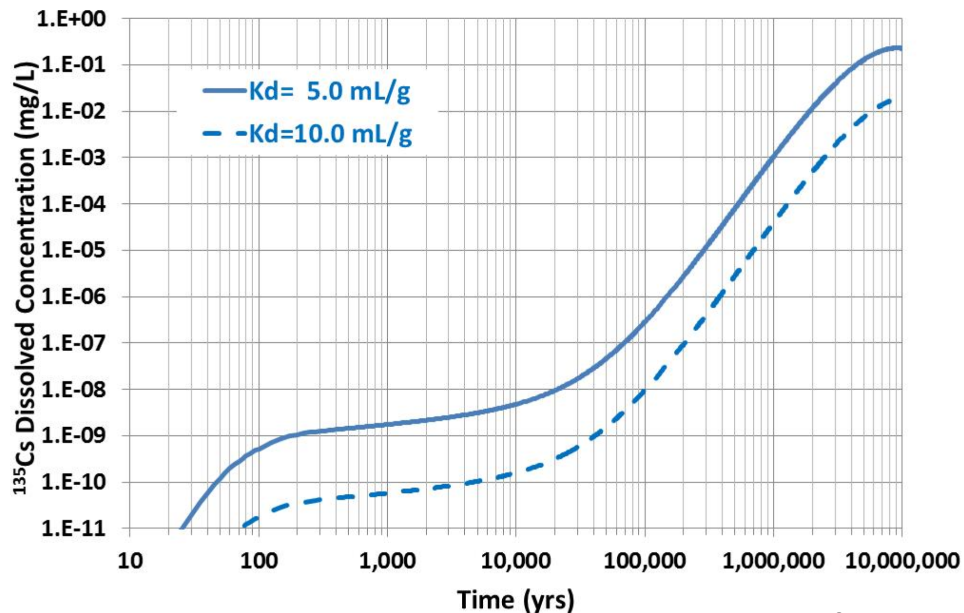
- **Sorption (K_d) in Disposal Zone**
  - Increase in K_d leads to reduced mass flux from top of disposal zone

- **Sorption (K_d) in Seal Zone**
  - Increase in K_d leads to reduced dissolved concentration in seal zone

Total (Advective+Diffusive) ^{135}Cs Flux (g/yr) in Borehole from Top of Waste Disposal Zone



^{135}Cs Dissolved Concentration (mg/L) in Borehole in Seal Zone (~3,800 m depth)



Summary

- **PA Model results suggest minimal post-closure radionuclide releases/dose**

- **Future PA Model enhancements**
  - Full consideration of features, events, and processes (FEPs) relevant to potential release pathways and scenarios
    - *e.g., borehole is intersected by significant fracture*
  - Incorporation of more detailed modeling, including coupled processes
    - *Explicit seal and DRZ conceptualization*
    - *Coupled thermal-hydrologic-mechanical-chemical behavior near the borehole*
  - Refinement of parameter values
    - *Data from Deep Borehole Field Test*

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Backup Slides

DBD PA Computational Model – Past Work (GoldSim)

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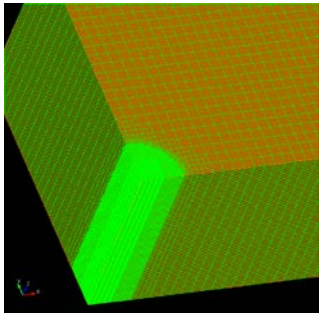
[FEHM]

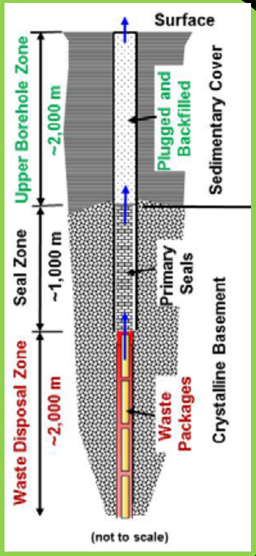
- Thermal energy from decay heat
- Heat conduction
- Multiphase flow



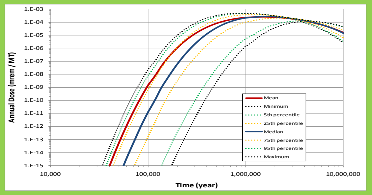
Input Parameter Distributions

GoldSim

- **Radionuclide Source Term**
  - Waste Form Degradation
  - Radionuclide Solubility
- **1-D Flow and Transport**
  - Advection and Diffusion
  - Sorption and Decay
- **Biosphere**
  - Aquifer dilution
  - Pumping and Individual Uptake
- **LHS Sampling, Sensitivity Analysis**



Results



DBD PA Computational Model – Current/Future Work (PFLOTRAN)

Input Parameter Distributions

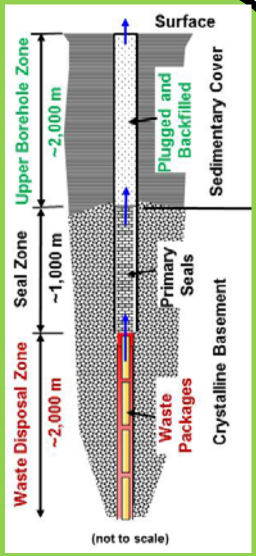
Sensitivity Analysis and Uncertainty Quantification

DAKOTA

Computational Support
- Mesh Generation - Cubit
- Visualization – ParaView, VisIt
- Parameter Database

PFLOTRAN

- **Radionuclide Source Term**
  - Waste Form Degradation
  - Radionuclide Solubility
- **3-D Thermal-Hydro-Chemistry**
  - Thermal Effects
  - Advection and Diffusion
  - Sorption and Decay
- **Biosphere**
  - Aquifer flow and transport
  - Pumping and Individual Uptake



Results