



U.S. DEPARTMENT OF  
**ENERGY**

**Nuclear Energy** SAND2015-10776C

# Deep Borehole Disposal (DBD) Performance Assessment

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**Performance and Risk Assessment Community of Practice  
Annual Technical Exchange Meeting  
Richland, WA  
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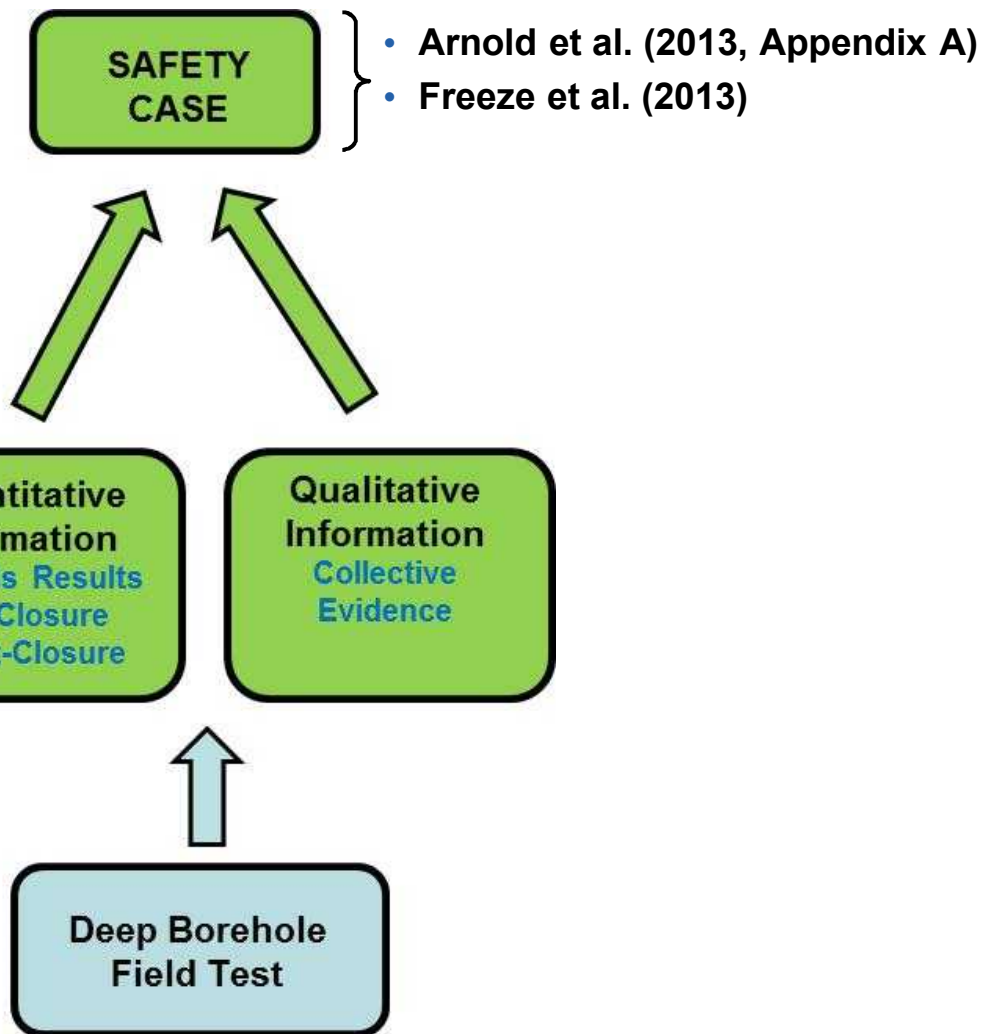
- **DOE-NE Used Fuel Disposition Campaign (UFDC) Deep Borehole Disposal Scope**
- **Deep Borehole Disposal (DBD) Safety Case**
  - Regulatory and Licensing Considerations
- **DBD Post-Closure System Assessment**
  - Conceptual Model
  - Performance Assessment (PA) Model
    - *PA Model Results*
    - *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



## ■ 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 (NWPAA 1983)
  - *No disposal options for commercial SNF/HLW other than Yucca Mountain are possible without amending the NWPAA*
  - *Separate repository for HLW resulting from atomic energy defense activities is possible (NWPAA 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 NWPAA 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

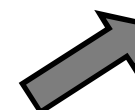
## Past PA Work (2009 – 2014)

### ■ Excel Spreadsheet Model

- Brady et al. 2009, Sections 4 and 5

### ■ GoldSim-based 1-D Model

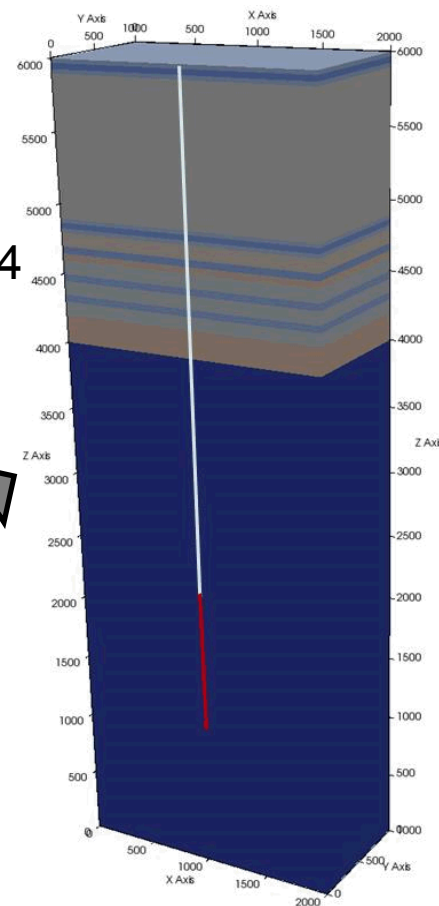
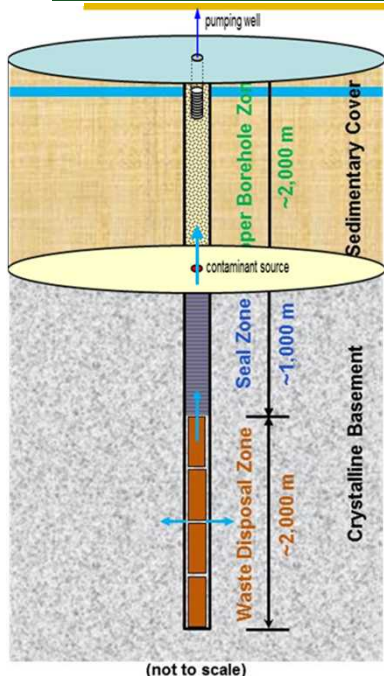
- Wang and Lee 2010, Section 5
- Clayton et al. 2011, Section 3.4
- Freeze et al. 2013, Sections 4.3 and 4.4
- Arnold et al. 2013, Section 4.4



## Current/Future PA Work (2015 +)

### ■ PFLOTRAN-based 3-D Model

- Hadgu et al. 2015 (TH only)
- Stein et al. 2015



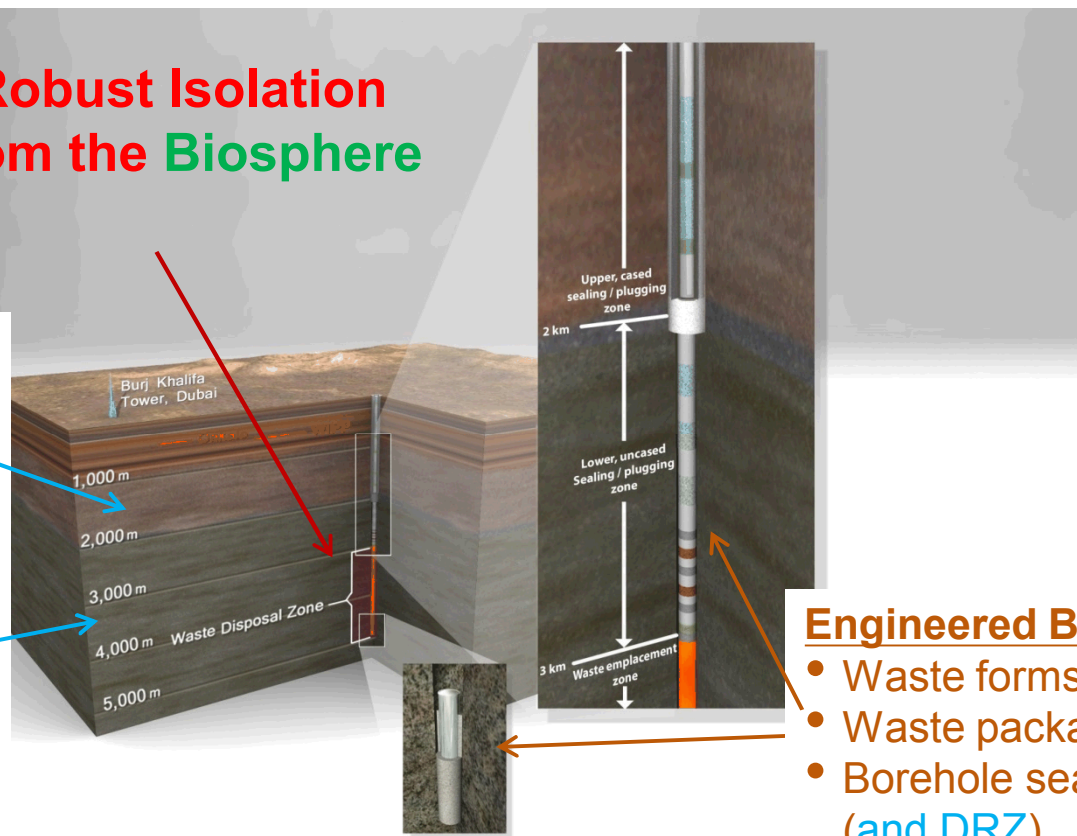


# DBD Post-Closure Conceptual Model – Components

## 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

## Robust Isolation from the Biosphere



## 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

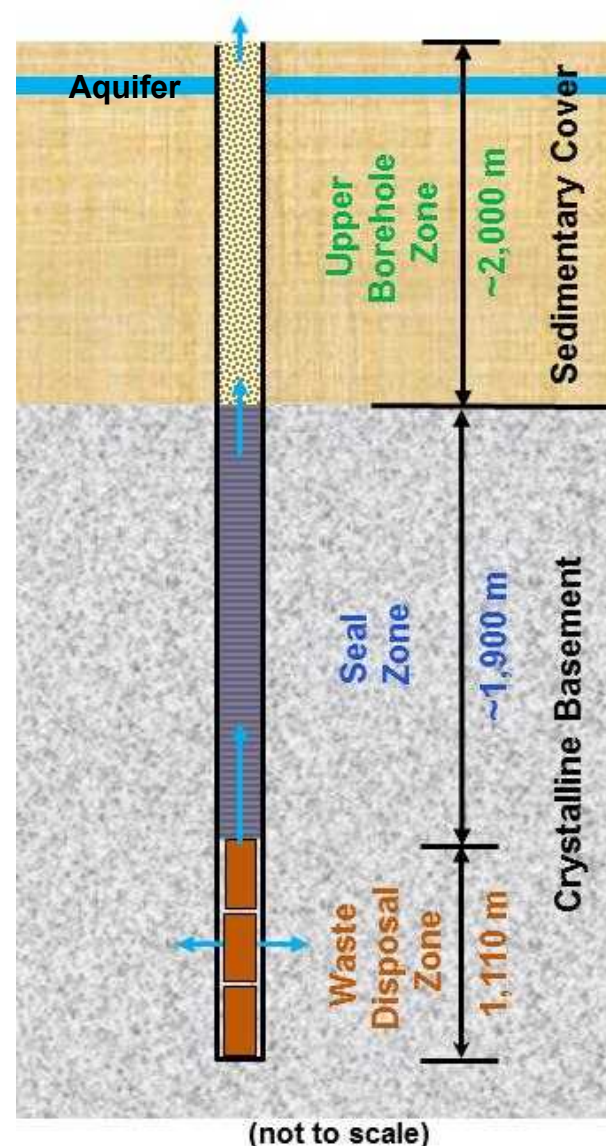
- Provides operational protection, assumed to rapidly degrade after emplacement

## ■ 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*







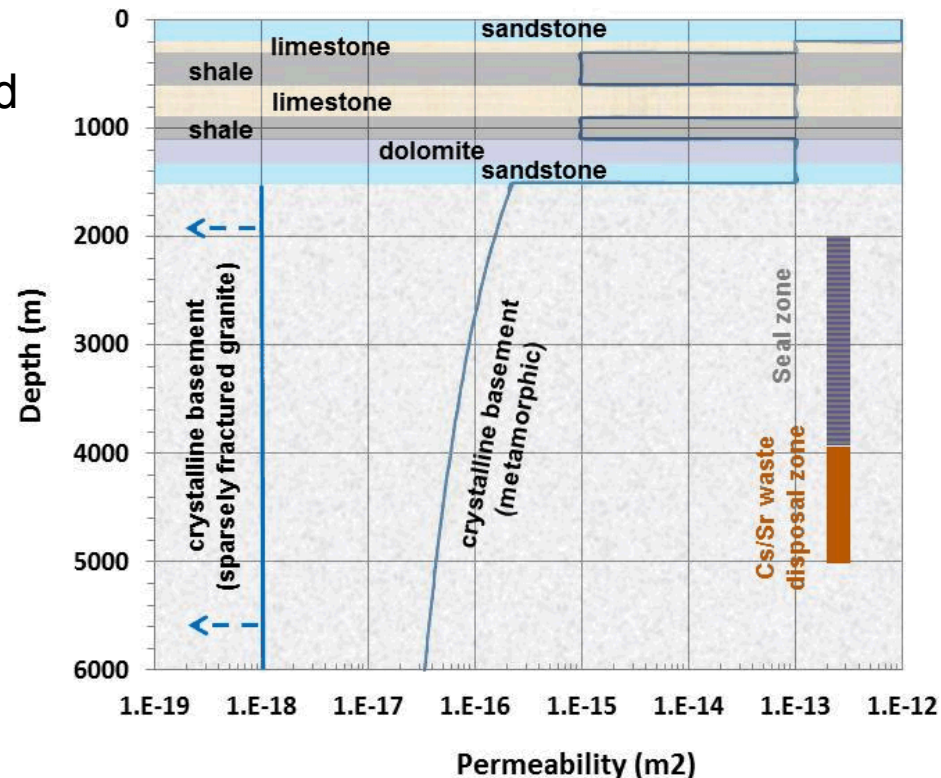
# DBD Conceptual Model – Undisturbed Scenario

## ■ Sediments

- Hypothetical alternating units assumed above seal zone

## ■ Crystalline Basement

- Low permeability ( $k$ ) and porosity ( $\Phi$ )
  - $k = 1 \times 10^{-19}$  to  $1 \times 10^{-16} \text{ m}^2$
  - $\Phi = 0.01$
- Thermal gradient =  $25^\circ\text{C}/\text{km}$ 
  - *Ambient temperature*
    - $10^\circ\text{C}$  at surface
    - $\sim 120^\circ\text{C}$  at center of disposal zone
  - *Thermal conductivity* =  $3.0 \text{ W}/\text{m}^\circ\text{K}$
  - *Specific heat* =  $880 \text{ J}/\text{kg}^\circ\text{K}$
- Ambient reducing geochemical conditions at depth
- Salinity and density gradients
  - *Salinity*  $\sim 300 \text{ g/L TDS}$  at center of disposal zone
  - *Density*  $\sim 1.2 \text{ kg}/\text{m}^3$  at center of disposal zone





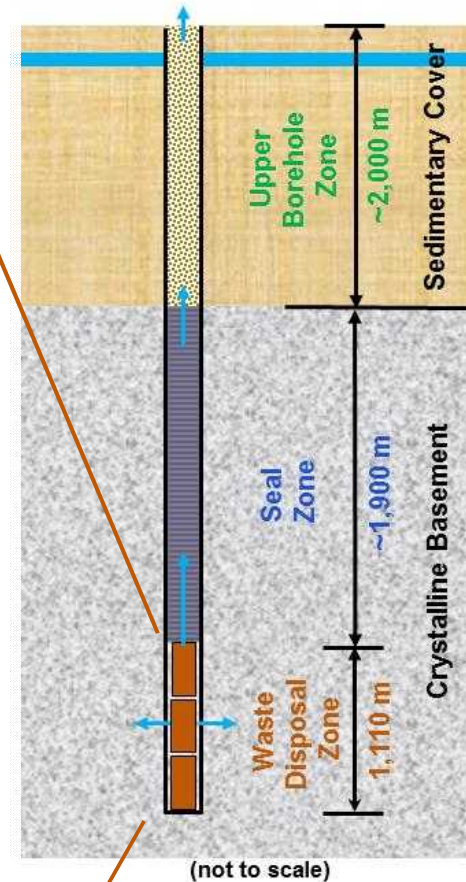
# DBD Conceptual Model – Undisturbed Scenario

## ■ Inventory and Waste Form

- 1936 capsules
  - 1335 *CsCl capsules (SNL 2014), per capsule:*
    - Inventory (2017) =  $^{137}\text{Cs}$  (278 g),  $^{135}\text{Cs}$  (278 g),  $^{137\text{m}}\text{Ba}$  (0 g)
    - Thermal output (2007) = 144 W
  - 601 *SrF<sub>2</sub> capsules (SNL 2014), per capsule*
    - Inventory (2017) =  $^{90}\text{Sr}$  (167 g),  $^{90}\text{Y}$  (0 g)
    - Thermal output (2007) = 193 W
  - *Waste form degradation assumed to be rapid*
    - Fractional rate =  $1.0 \text{ yr}^{-1}$ 
      - *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*

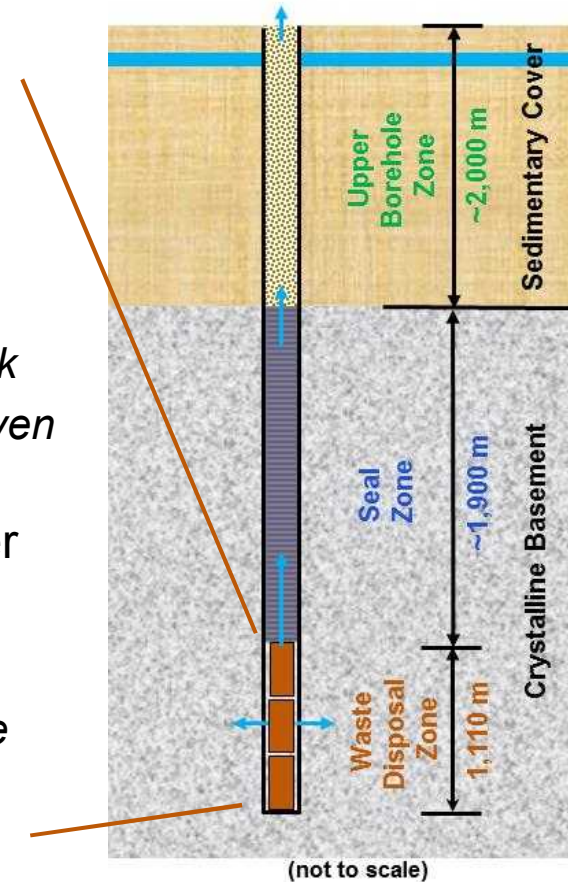




# DBD Conceptual Model – Undisturbed Scenario

## ■ Waste Disposal Zone

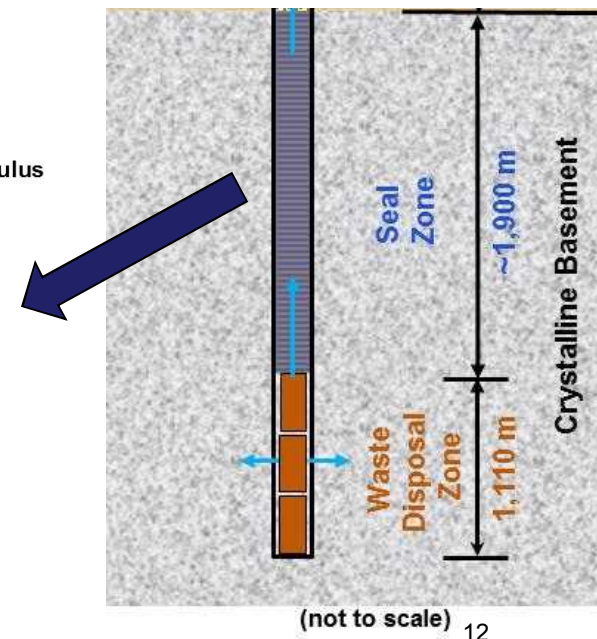
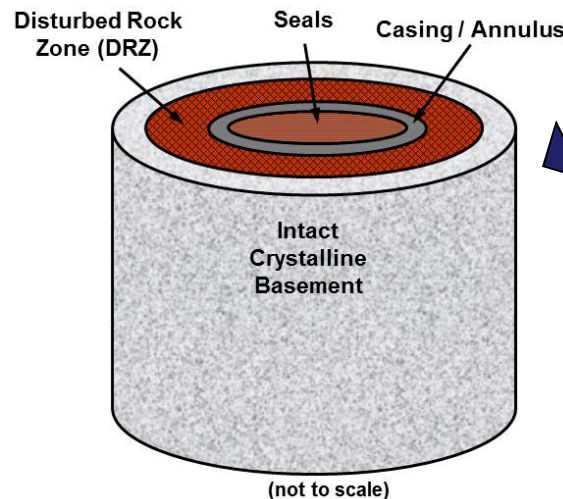
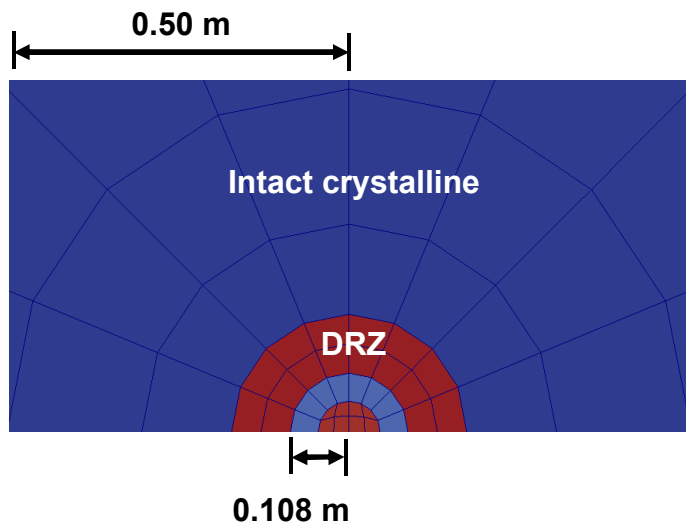
- Borehole bottom-hole (Disposal Zone) diameter =
  - 21.6 cm (8.5 in.)
- Decay heat effects calculated from regional TH:
  - *Heat conduction in surrounding crystalline basement rock*
  - *Thermal perturbation in borehole produces thermally-driven upward groundwater flow*
- Radionuclide dissolution and transport in groundwater
  - *Advection/Dispersion, Diffusion, Sorption, and Decay*
  - *Based on ambient reducing geochemical conditions*
  - *No sorption ( $K_d = 0$  mg/L 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  $1 \times 10^{-15} \text{ m}^2$  (DRZ),  $1 \times 10^{-16} \text{ m}^2$  (seal)
  - porosity ( $\Phi$ ) = 0.01 (DRZ), 0.30 (seal)
  - tortuosity ( $T$ )  $\sim$  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 mg/L (DRZ), 120 mg/L (seal)
  - Sr  $K_d$  (min) = 0.4 mg/L (DRZ), 50 mg/L (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

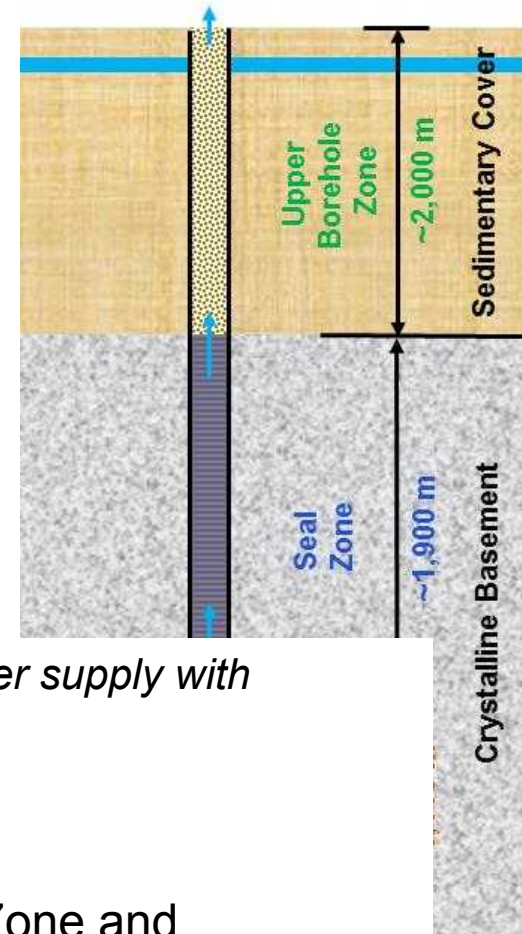
## ■ Biosphere

### 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

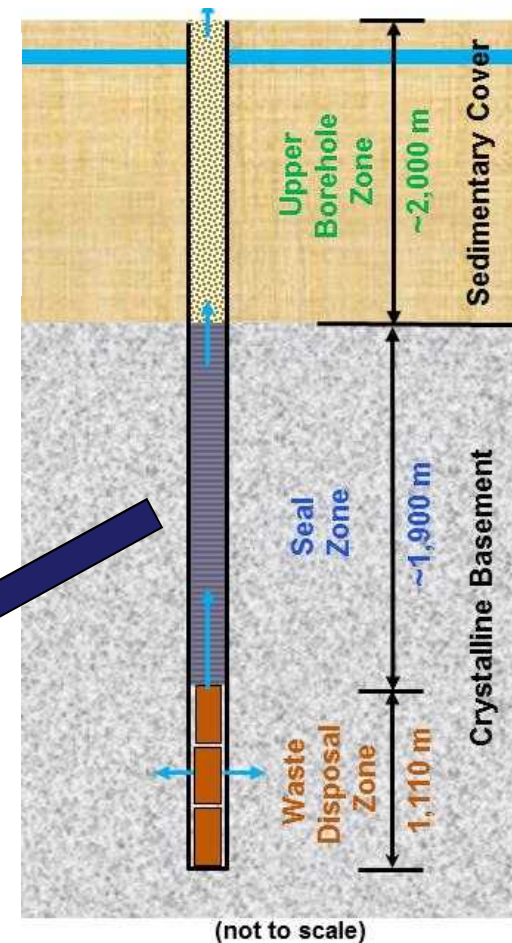
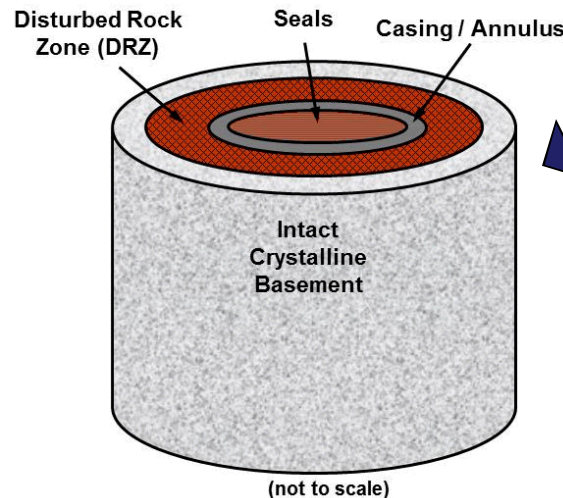
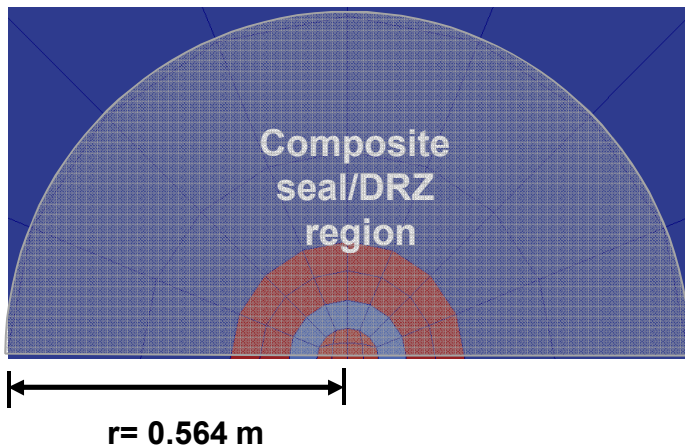
- Explicit flow and transport modeling in Upper Borehole Zone and sedimentary units, including aquifer
  - *Pumping of the groundwater from the aquifer for water supply*
  - *IAEA Dose Conversion Factors (DCFs)*



# 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  $1 \text{ m}^2$  ( $r=0.564 \text{ m}$ ) and composite seal/DRZ properties
  - composite  $k = 1 \times 10^{-16} \text{ m}^2$  (degraded seal and DRZ)
  - composite porosity ( $\Phi$ ) = 0.034 (DRZ=0.01, seal = 0.30)
  - composite tortuosity ( $T$ ) = 0.324 (DRZ=0.20, seal = 0.50)

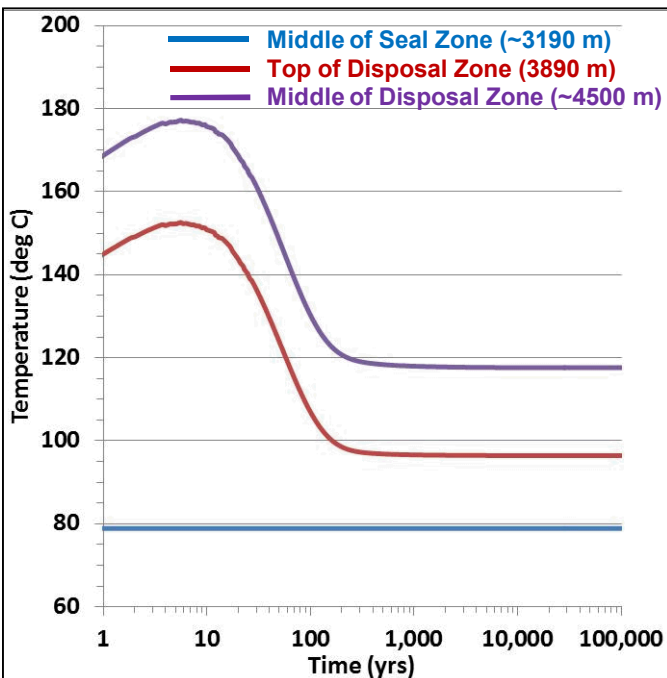




# DBD PA Model Results – Thermally-Induced Upward Flow

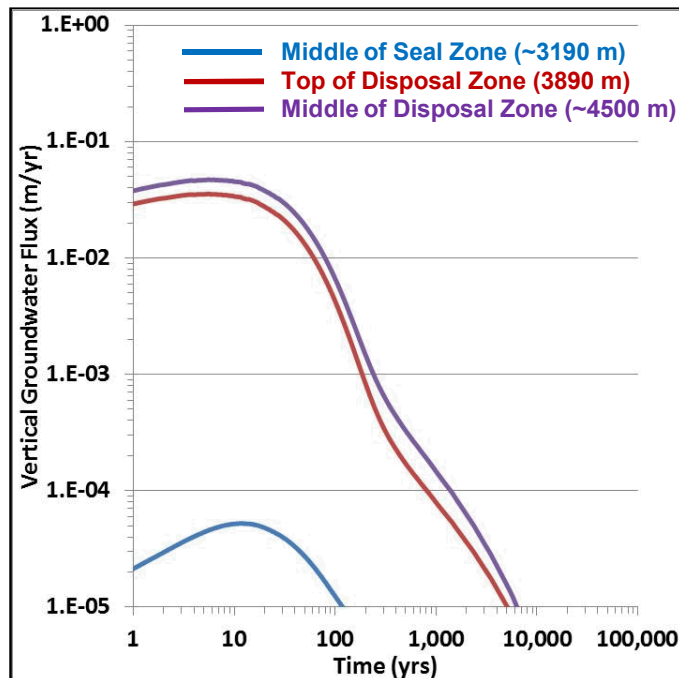
- 1936 Cs/Sr capsules in 1 borehole (1,110 m disposal zone)
  - ~300W (CsCl) or ~400W (SrF<sub>2</sub>) per waste package (from decay of <sup>137</sup>Cs and <sup>90</sup>Sr)
- Advective center of mass upward movement
  - $(0.03 \text{ m/yr})(100 \text{ yrs})/(0.034 \text{ porosity}) \sim 90 \text{ m}$
  - *advection is even less with sorption*

Temperature in Borehole

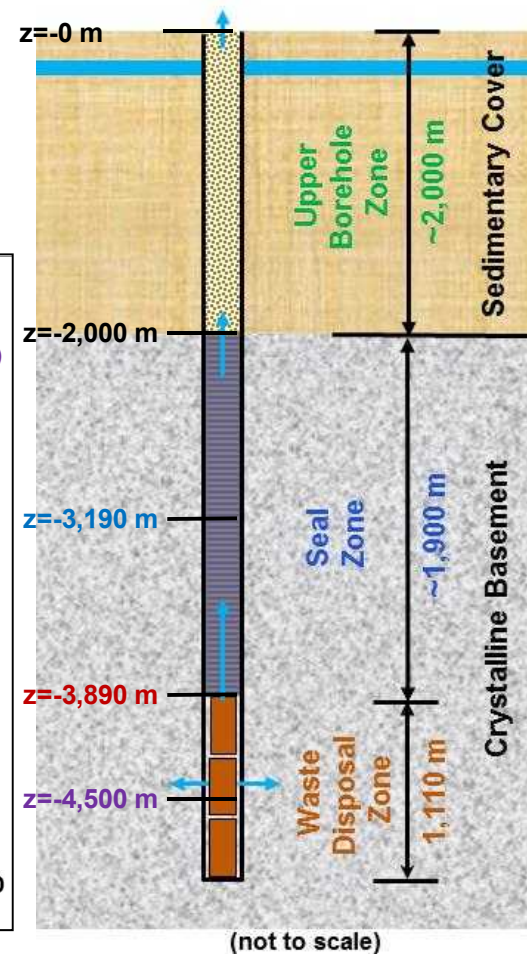


adapted from Hadgu et al. (2015), Figure 7

Vertical Groundwater Flux  
(Specific Discharge) in Borehole



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

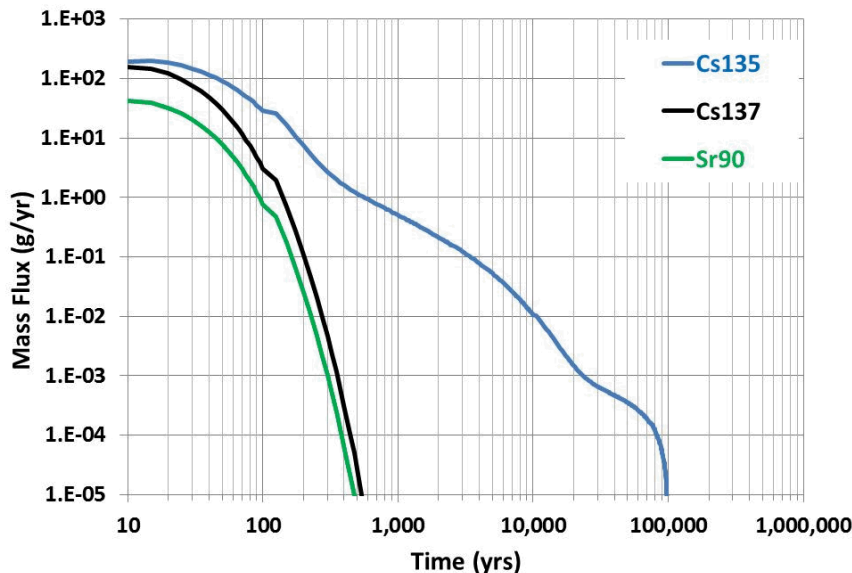


# DBD PA Model Results – Undisturbed Scenario

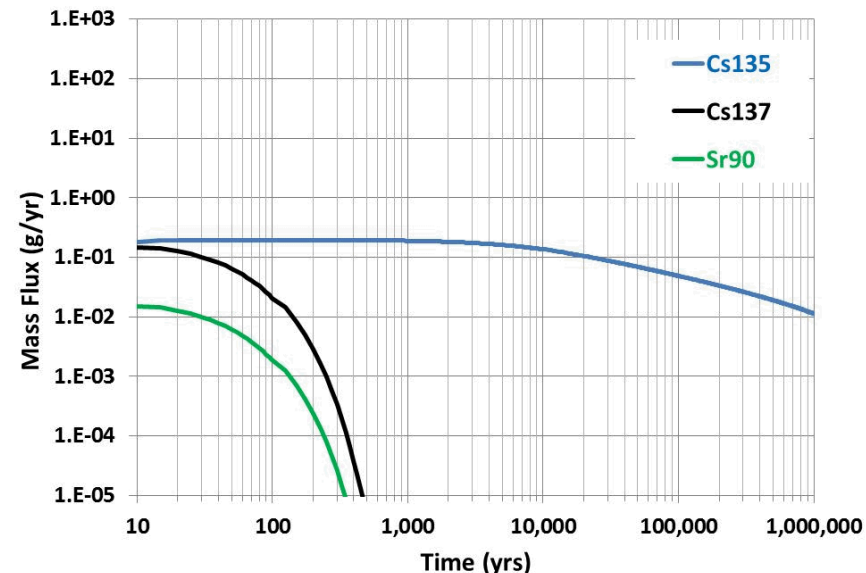
## ■ Mass flux - no radionuclide releases above seal zone

- $^{135}\text{Cs}$ 
  - Short duration of thermally-induced upward advection ( $\sim 100$  years)
  - Slow upward diffusion and sorption in seal zone/DRZ
- $^{90}\text{Sr}$  and  $^{137}\text{Cs}$ 
  - Decay in  $<1,000$  years due to short half-lives

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



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



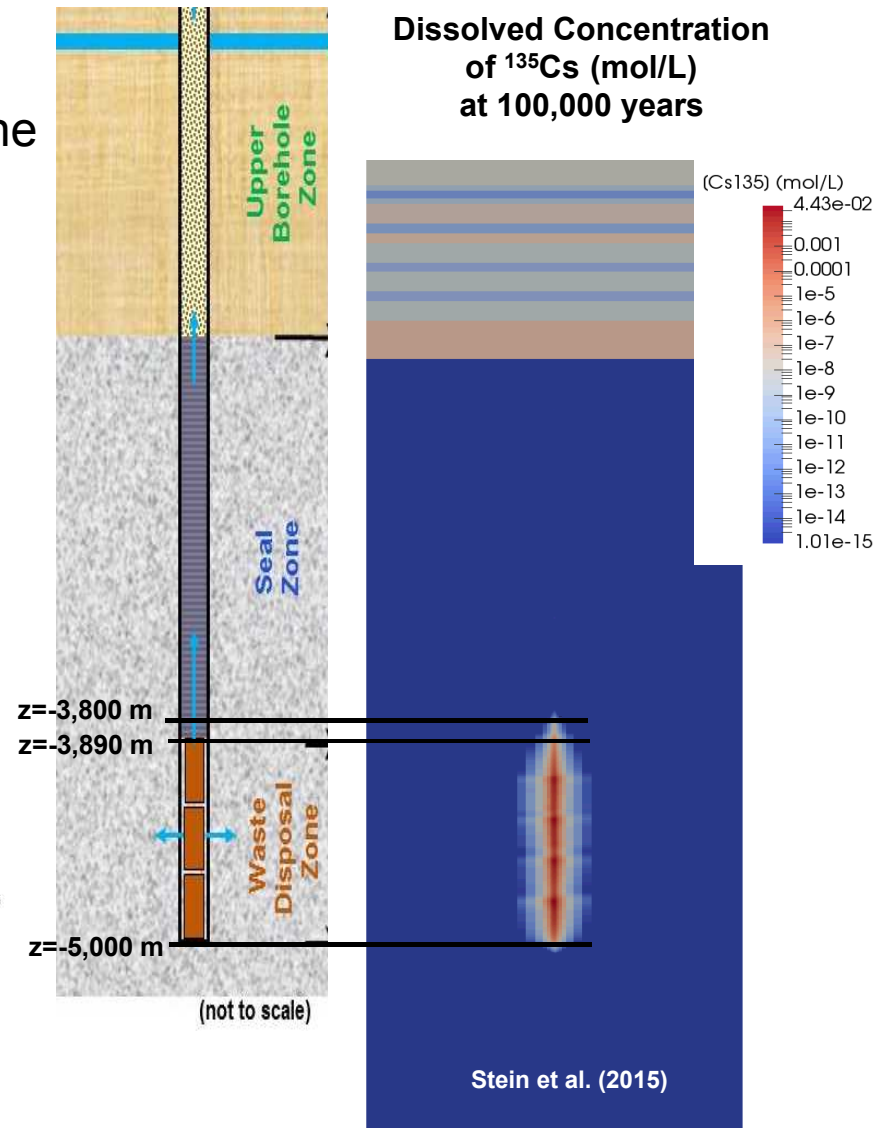
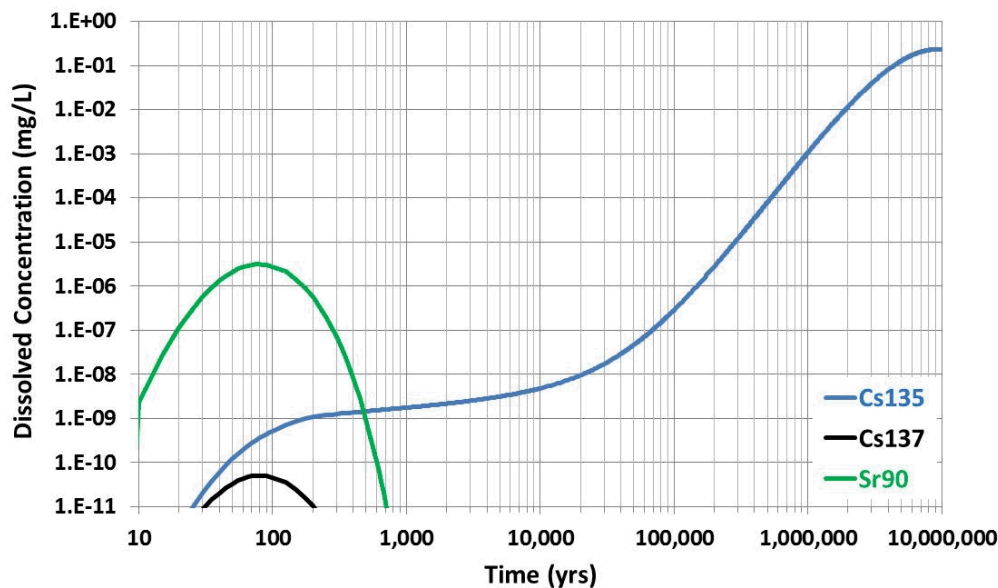


# DBD PA Model Results – Undisturbed Scenario

## ■ Dissolved Concentrations

- Minimal migration beyond disposal zone

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



# DBD PA Model Results – Sensitivity

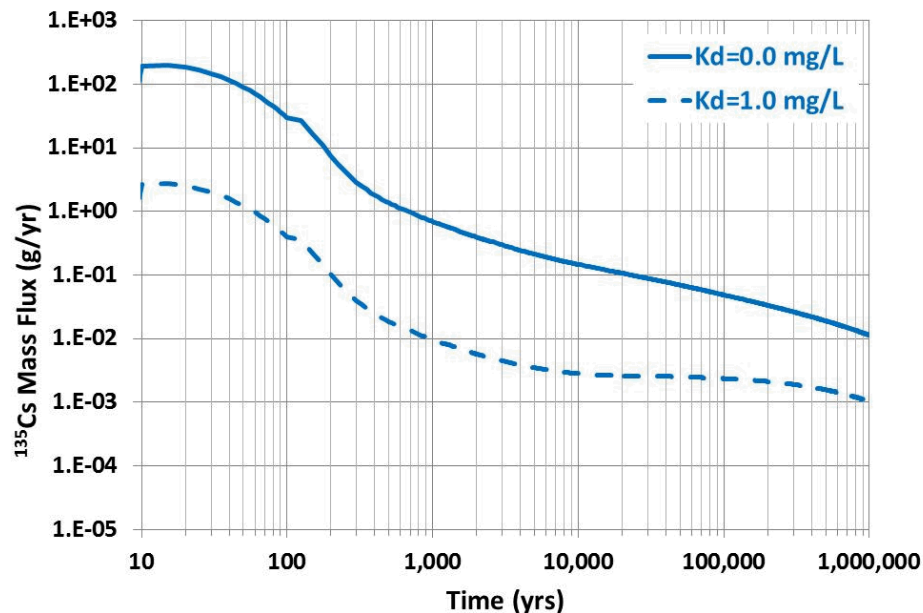
## ■ Sorption ( $K_d$ ) in Disposal Zone

- Increase  $K_d$
- Reduce Mass Flux from Top of Disposal Zone

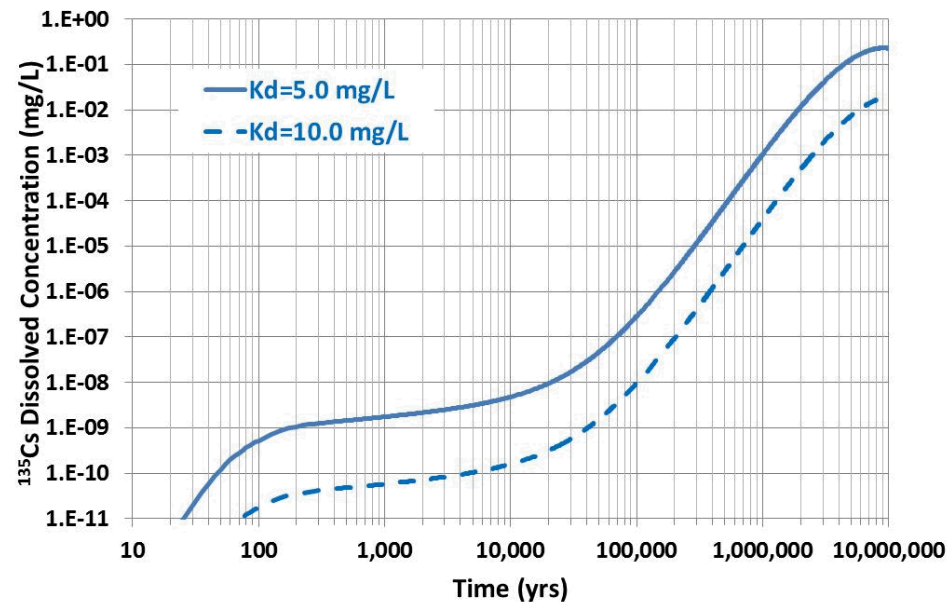
## ■ Sorption ( $K_d$ ) in Seal Zone

- Increase  $K_d$
- Reduce Dissolved Concentration in Seal Zone

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



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





- **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*





# References

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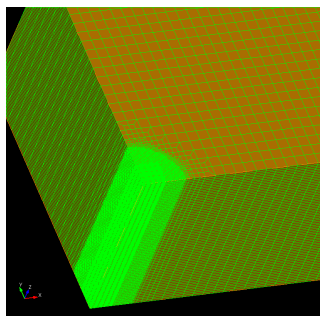
# Backup Slides



# DBD PA Computational Model – Past Work (GoldSim)

## [FEHM]

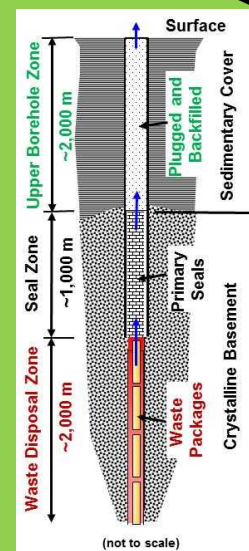
- Thermal energy from decay heat
- Heat conduction
- Multiphase flow



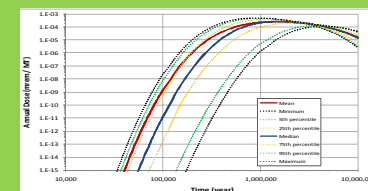
## Input Parameter Distributions



- **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)

