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Deep Borehole Disposal (DBD): Licensing and Post-Closure Safety Assessment

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U.S. Nuclear Waste Technical Review Board Briefing

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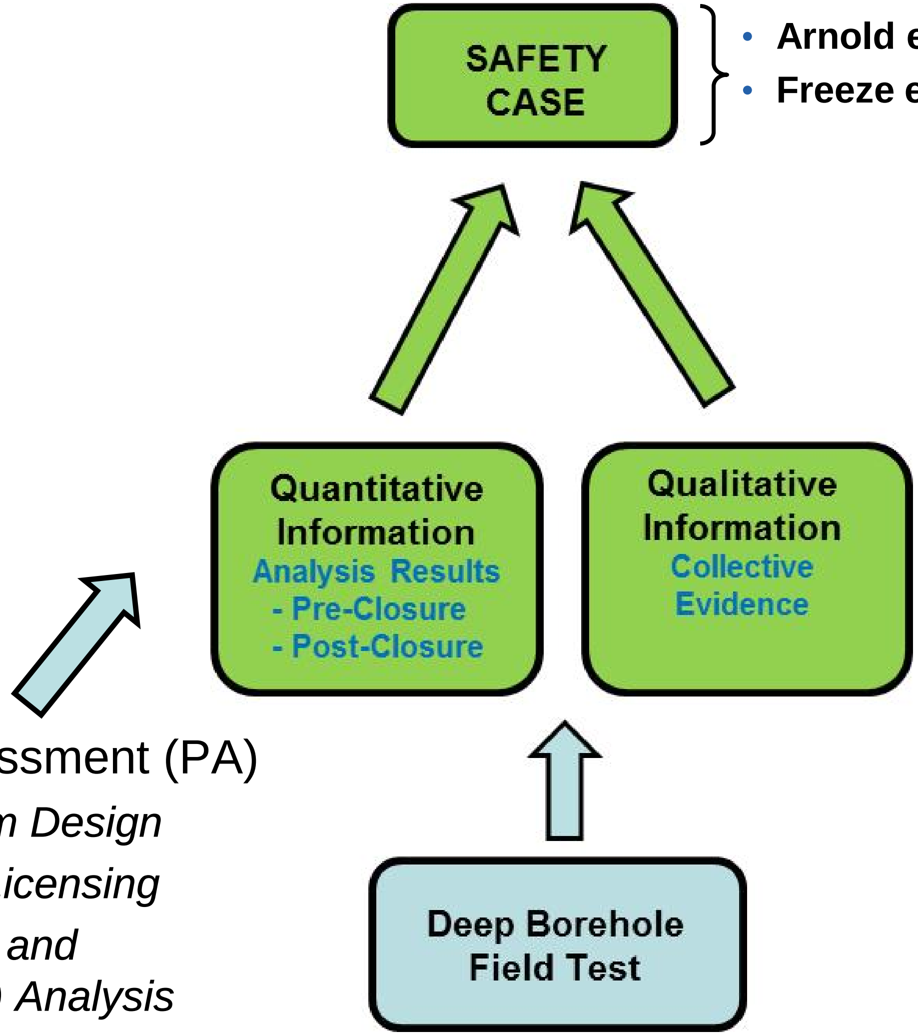
Licensing and Post-Closure Safety Assessment: Outline

- **Basis for Long-Term Isolation**
  - Post-Closure Safety Case
- **Regulatory and Licensing Considerations**
  - Potential Regulatory Topics
- **DBD Post-Closure System Assessment**
  - Conceptual Model
  - Coupled Process Models
  - Performance Assessment (PA) Model
    - *PA Model Results*
    - *Sensitivity Analyses*
- **Summary**

Basis for Long-Term Isolation – 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*

Regulatory and Licensing Considerations

- **Pre-Closure / Operational**
  - Transportation
  - Construction (borehole and surface facilities)
  - Operations (waste storage, handling, and downhole emplacement)
  - Decommissioning
- **Post-Closure**
  - Siting and Site Suitability
    - *Nuclear Waste Policy Act of 1982, as amended (NWPA 1983)*
      - Separate repository for HLW resulting from atomic energy defense activities is possible (NWPA 1983, Section 8(b); DOE 2015)
    - *10 CFR 960 and 963*
  - Licensing (NRC) and Environmental Protection (EPA)
    - *10 CFR 60 and 40 CFR 191 - (Generic – 1981 and later amendments)*
    - *10 CFR 63 and 40 CFR 197 (Yucca Mountain specific – 2001 and later amendments)*
    - *International (e.g., IAEA Guidelines (IAEA 2011))*

Regulatory and Licensing Considerations – Post-Closure

- **Licensing and Environmental Protection:**
  - Existing regulations for disposal of SNF/HLW (10 CFR 60 and 40 CFR 191) could, in principle, be applied to other disposal concepts and/or sites, without revision
    - *10 CFR 60 and 40 CFR 191 predate the 1987 NWPA amendment, may be revised or replaced in the future*
    - *10 CFR 63 and 40 CFR 197 could provide inferences to other concepts and/or sites*
  - Specific regulatory topics that may benefit from clarification for deep borehole disposal include (Arnold et al. 2013, Appendix A; NWTRB 2015; Winterle et al. 2011):
    - *Performance Standards*
      - Containment/Cumulative Release vs. Dose/Risk
      - DBD Reference Biosphere and Receptor for Dose/Risk
    - *Multiple Barriers / Subsystem Performance*
    - *Retrievability*
    - *Human Intrusion*
    - *Licensing (Non-Phased Approach / Multiple Deep Boreholes)*
    - *Underground Injection (40 CFR 144 to 148)*

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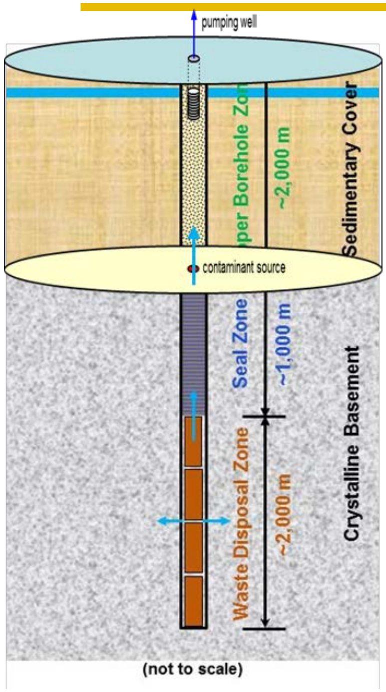
DBD Post-Closure PA Model Development – Chronology

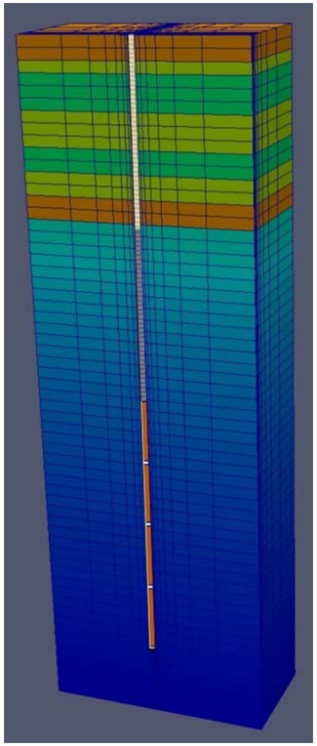


Past PA Work (2009 – 2014)

- **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 – future)

- **PFLOTRAN-based 3-D Model**
  - Current iteration of development



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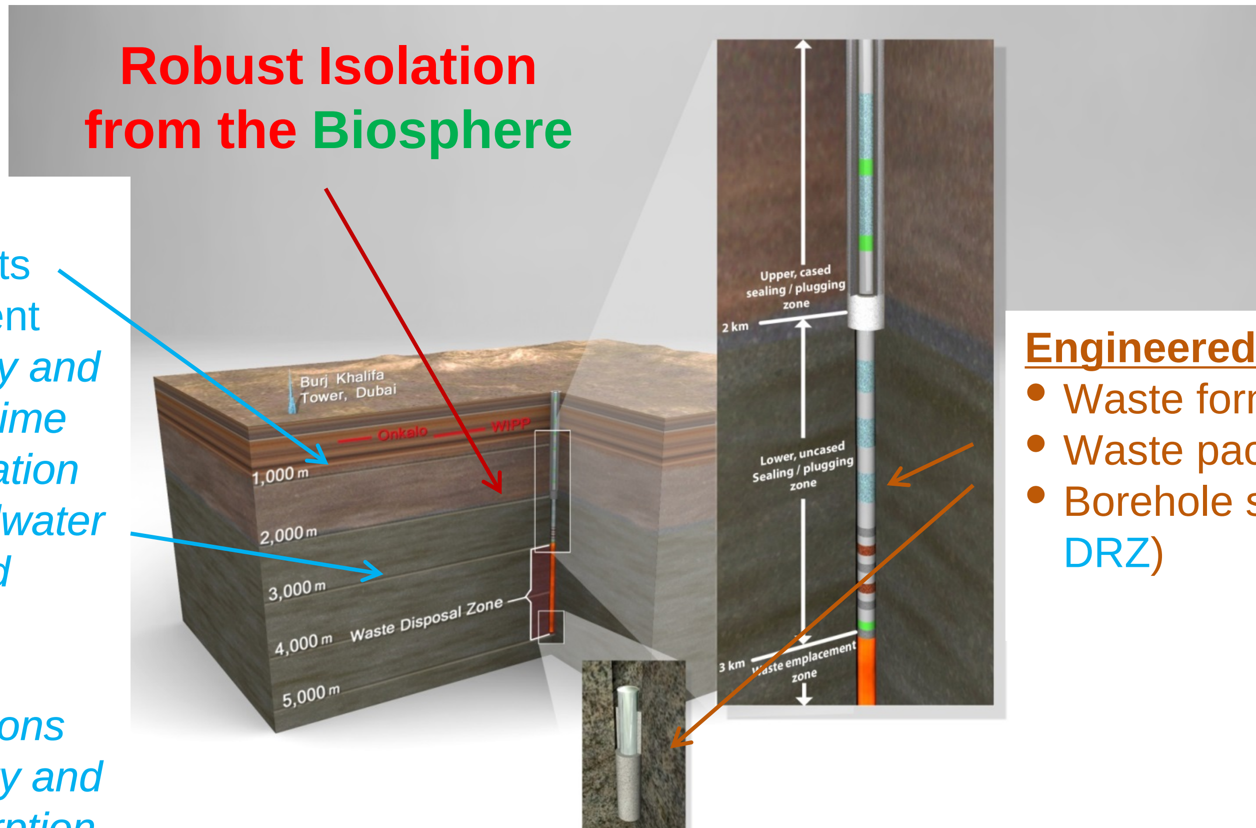
DBD Post-Closure Conceptual Model – Components

Robust Isolation from the Biosphere



Natural System

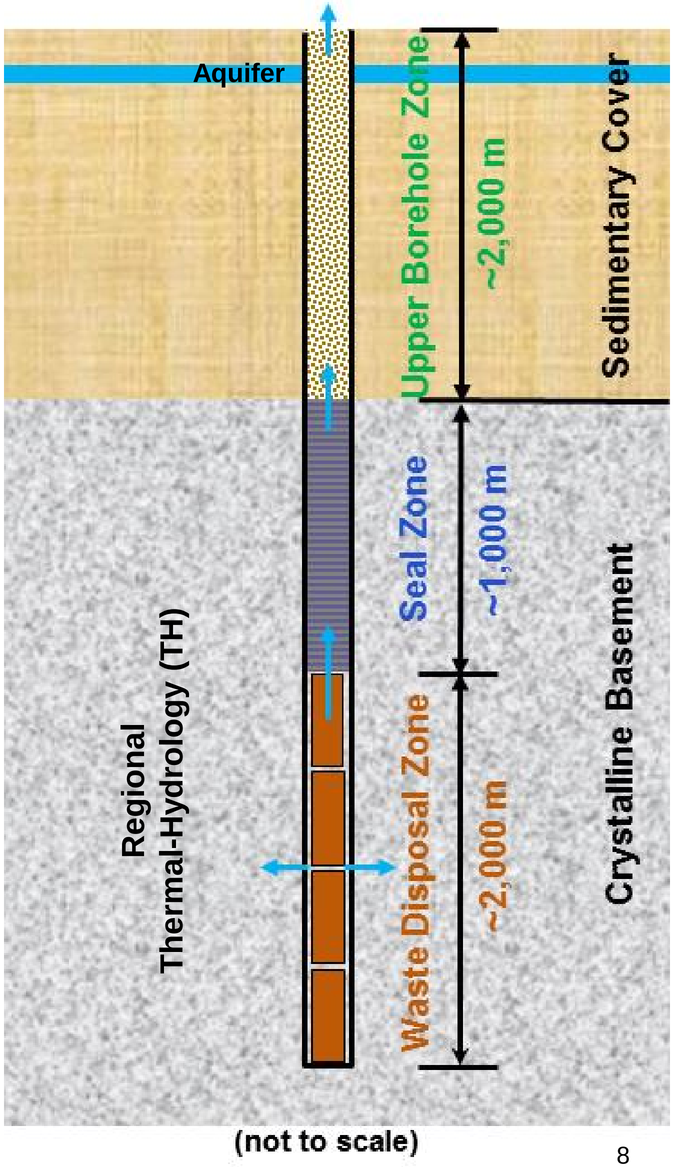
- Overlying Sediments
- Crystalline Basement
  - *Low permeability and long residence time*
  - *Density stratification of saline groundwater opposes upward convection*
  - *Geochemically reducing conditions limit the solubility and enhance the sorption of many radionuclides*

Engineered Barriers

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

DBD Conceptual Model Overview – Single Borehole Undisturbed Scenario

- **Inventory / Waste Form**
  - DOE-managed HLW (Cs/Sr Capsules)
  - Commercial SNF (PWR assemblies)
- **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

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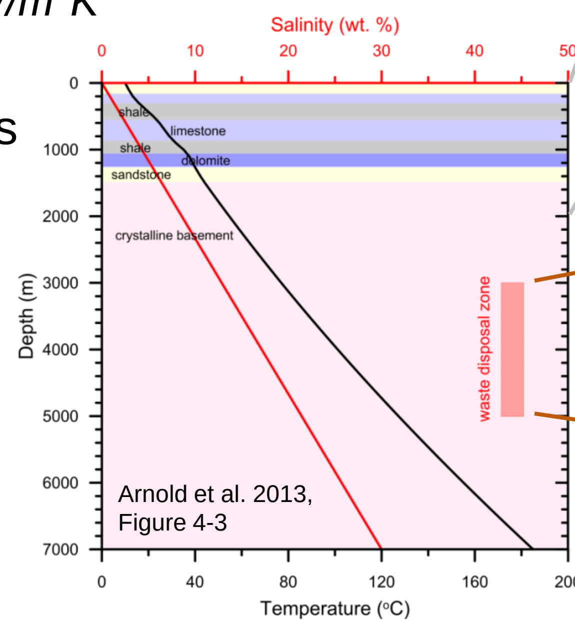
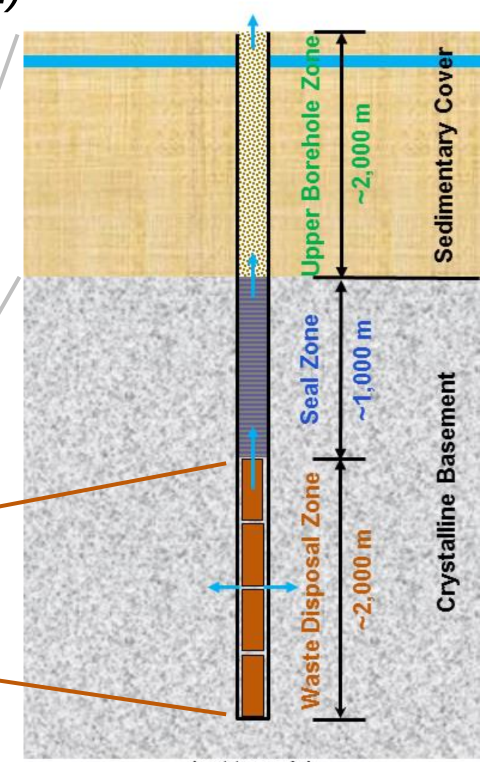
- **Crystalline Basement Host Rock (assumed to be granite):**
  - Low permeability (k) and porosity (Φ)
    - *$k = 1\times10^{-19}$ m^2 (base case), 1×10^{-16} m^2 (high)*
    - *$\Phi = 0.01$*
    - *parameterization ongoing (e.g., permeability variation with depth)*
  - Ambient reducing geochemical conditions at depth
  - Ambient temperature = 10°C at surface
    - *Thermal gradient = 25°C/km (110°C at center of disposal zone)*
    - *Thermal conductivity = 3.0 W/m°K*
    - *Specific heat = 790 J/kg°K*
  - Salinity and density gradients





DBD Conceptual Model – Undisturbed Scenario

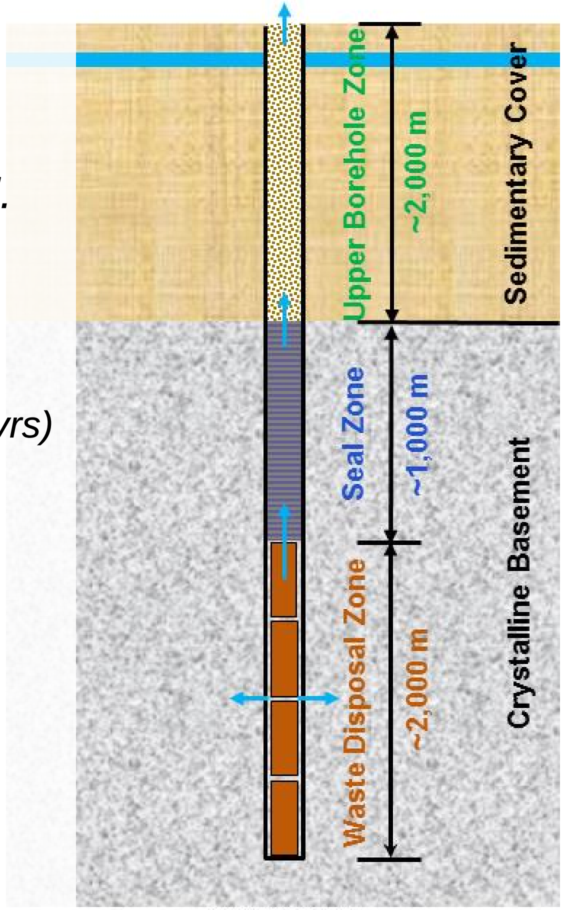
Inventory and Waste Form

Past PA Work

- 400 PWR assemblies stacked in a 2,000 m zone
  - *Radionuclide inventory and thermal output from Carter et al. (2012, Table C-1)*
  - *Waste form degradation = fractional rate*
    - slower = $1\times10^{-7}\ \text{yr}^{-1}$
      - *(mass release: 50% by 4,800,000 yrs; 76% by 10,000,000 yrs)*
    - faster = $2\times10^{-5}\ \text{yr}^{-1}$
      - *(mass release: 50% by 35,000 yrs; 99.9% by 350,000 yrs)*

Current/Future PA Work

- 1936 Cs/Sr capsules stacked in 1,300 m zone
  - *Radionuclide inventory and thermal output from 1335 Cs capsules and 601 Sr capsules (SNL 2014)*
  - *Waste form degradation assumed to be rapid*



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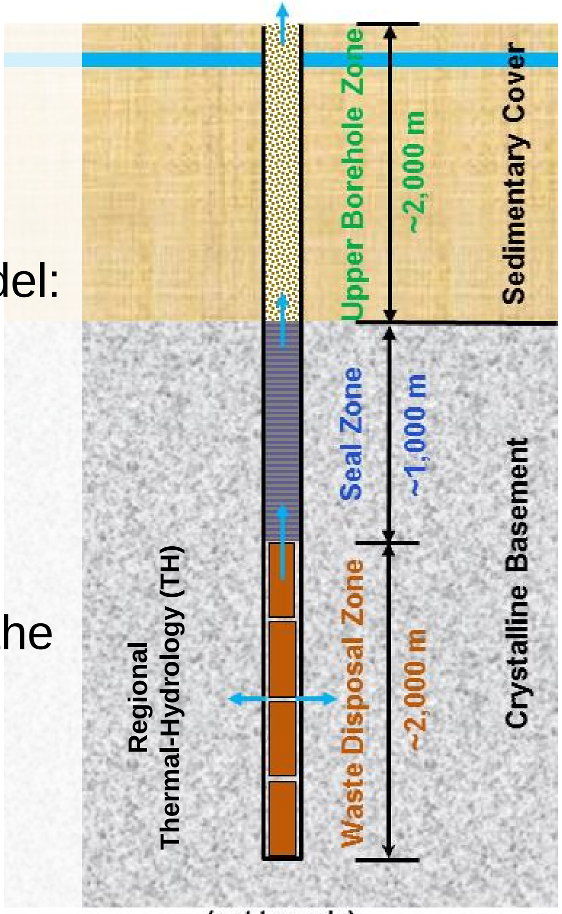
DBD Conceptual Model – Undisturbed Scenario

- **Waste Packages**
  - Assumed to degrade at time zero (after emplacement)
  - Mobilization of radionuclides from degraded waste form
- **Waste Disposal Zone**
  - Decay heat effects calculated with the Regional TH Model:
    - *Heat conduction in surrounding crystalline basement rock (assumed to be granite)*
    - *Thermal perturbation in borehole produces thermally-driven upward groundwater flow*
  - Radionuclide dissolution and transport (advection/dispersion, diffusion, sorption, and decay in the groundwater
    - *Based on ambient reducing geochemical conditions*



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Regional TH Model – Past Work

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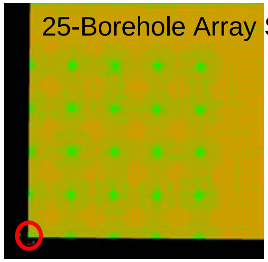
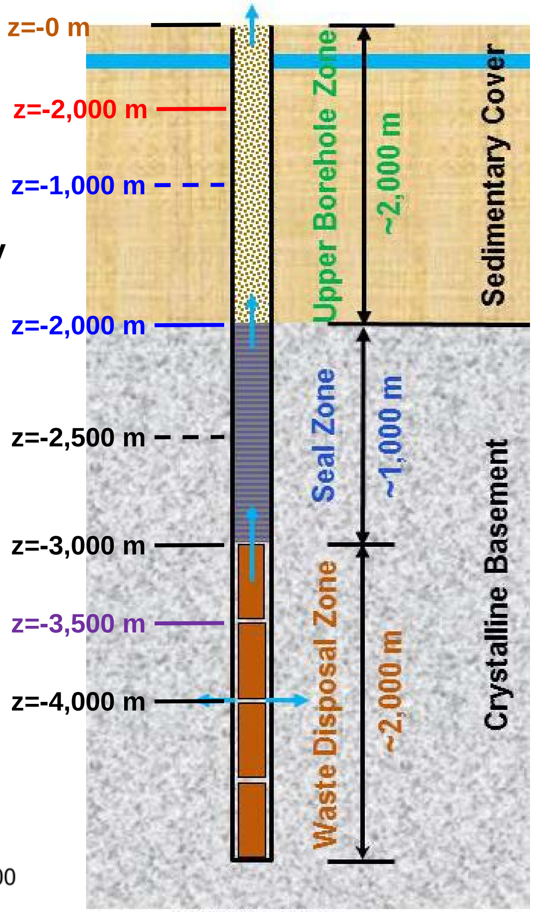
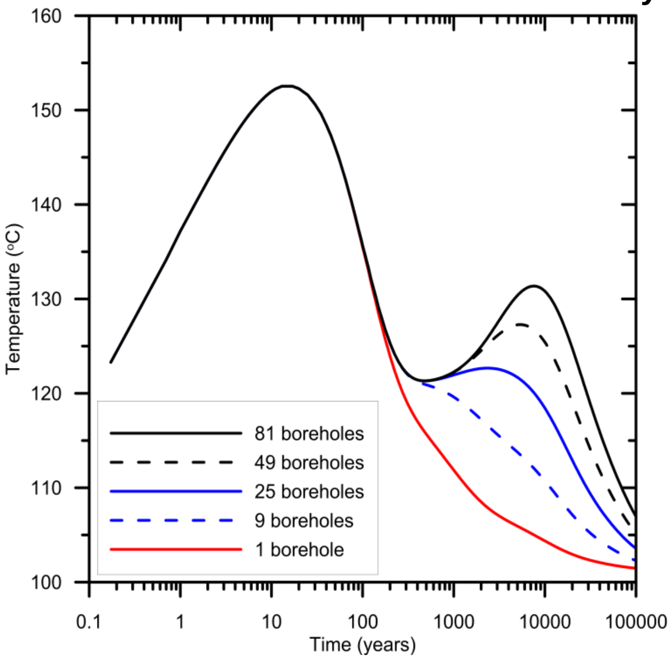
SNF (Arnold et al. 2013, Section 4.2.1) - FEHM

- 3-D multi-borehole configuration
- 400 PWR WPs per borehole (2000 m disposal zone)
  - ~ 240 W/m borehole length



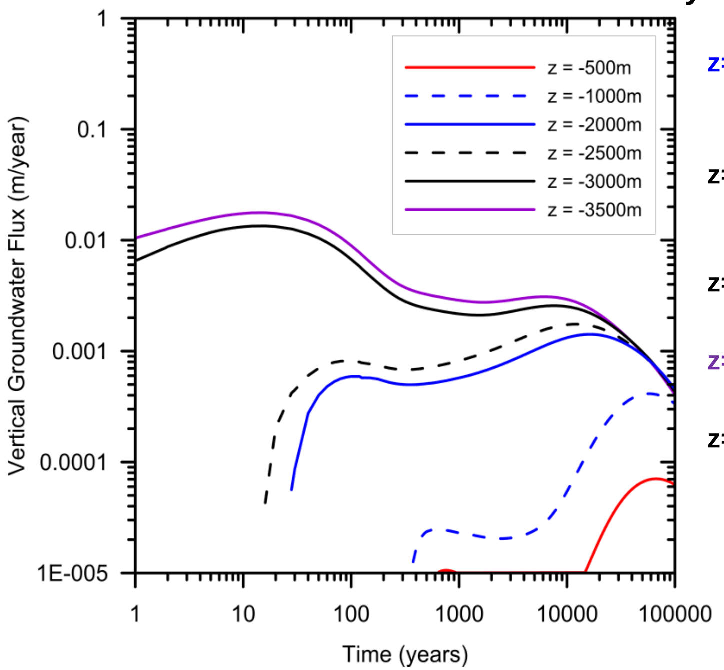


Temperature in Disposal Zone (4,000 m depth, r=0.8 m) of Central Borehole in 81-Borehole Array



Arnold et al. 2013, Figure 4-4

Vertical Groundwater Flux (at various depths) in Central Borehole in 81-Borehole Array



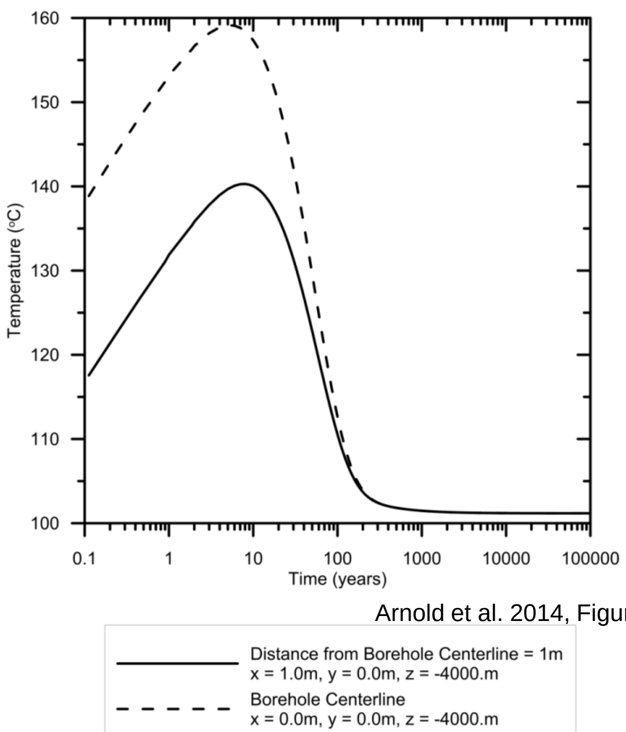
Arnold et al. 2013, Figure 4-5

Regional TH Model – Current/Future Work

HLW (Arnold et al. 2014, Section 3.2.5) – FEHM / PFLOTRAN

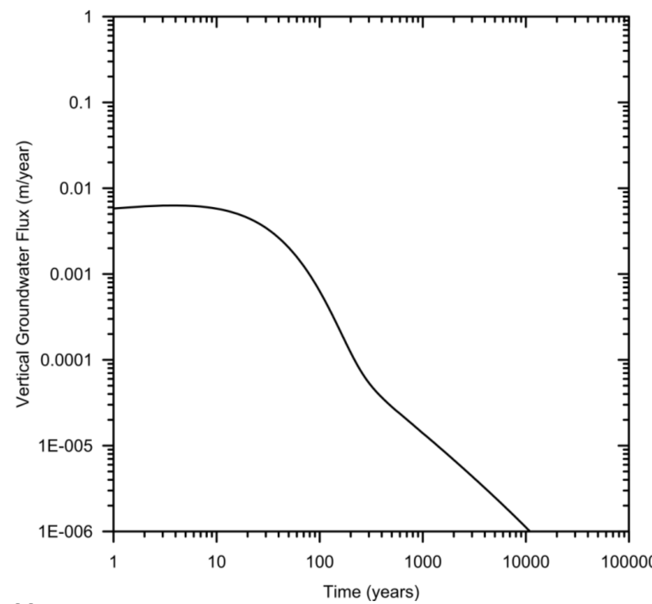
- 3-D single-borehole configuration
- 1936 Cs/Sr capsules in 1 borehole (1,300 m disposal zone)
  - 200–300 W/m borehole length (avg.) (Arnold et al. 2014, Fig 3-2)

Temperature in Disposal Zone (4,000 m depth, r=0.0 and 1.0 m) of Single Borehole

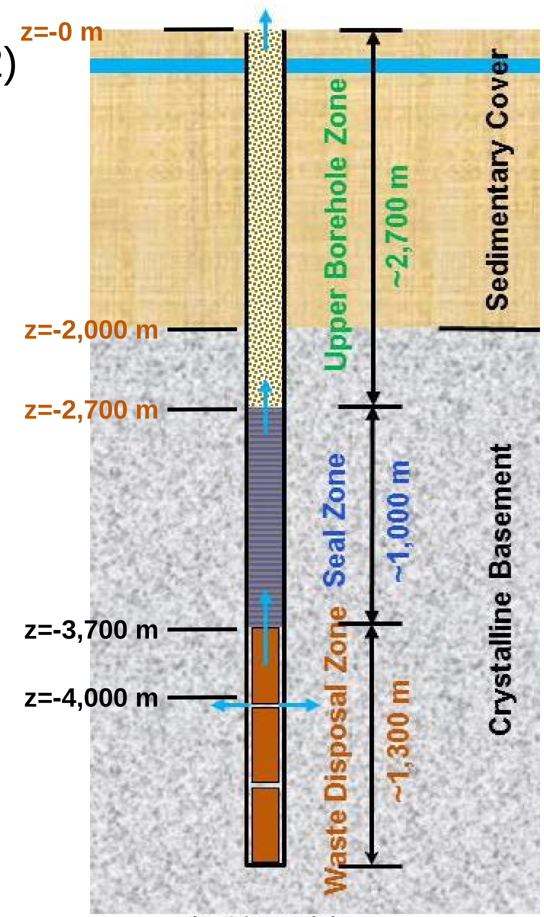


Arnold et al. 2014, Figure 3-23

Vertical Groundwater Flux At Top of Disposal Zone (3,700 m depth) in Single Borehole



Arnold et al. 2014, Figure 3-24



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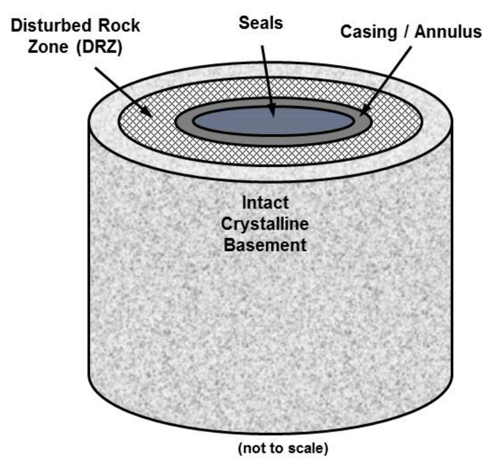
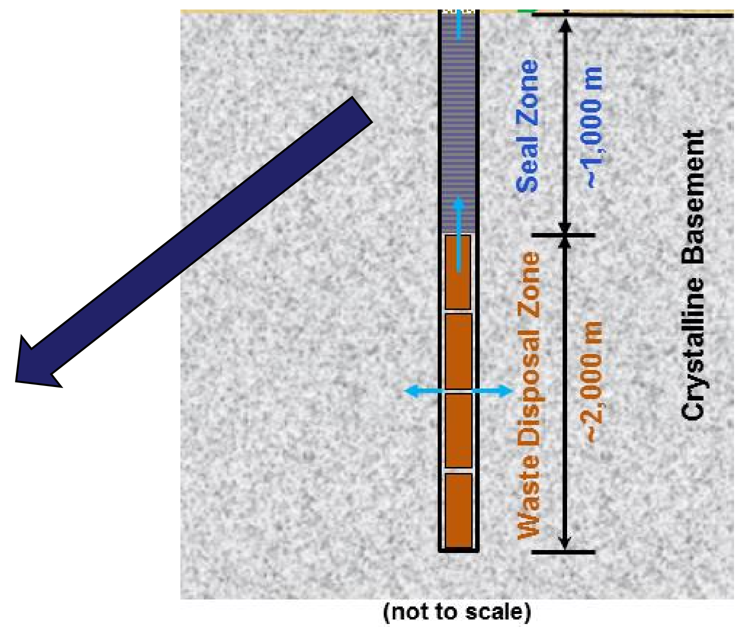
DBD Conceptual Model – Undisturbed Scenario

Seal Zone

- Enhanced permeability (*k*) in the DRZ/sealed borehole
  - *composite k = 1×10^{-16} m^2 (base case), 1×10^{-12} m^2 (high)*
  - *composite porosity (Φ) = 0.034 (bentonite/seal = 0.35, DRZ = 0.01)*
  - *composite tortuosity (T) = 0.324*
  - *parameterization ongoing (e.g., explicit representation of DRZ and seals)*
- Thermally-induced upward groundwater flux
- Transport by advection and diffusion (upward and lateral) with sorption and decay
  - *Advective center of mass moves upward ~ 30 m*
    - (0.01 m/yr)(100 yrs)/(0.034 porosity)





DBD Conceptual Model – Undisturbed Scenario

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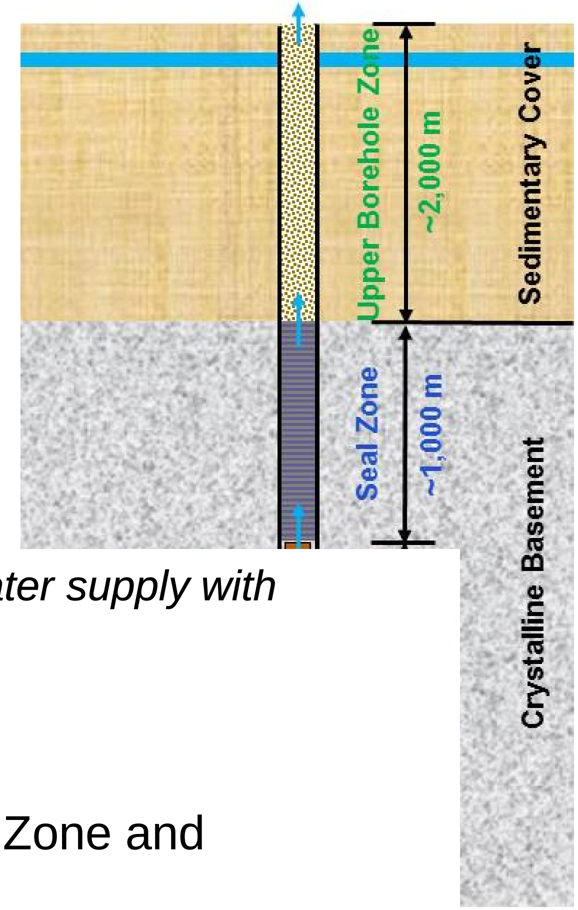
Upper Borehole Zone

- 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

<u>Past PA Work</u>

- 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)*

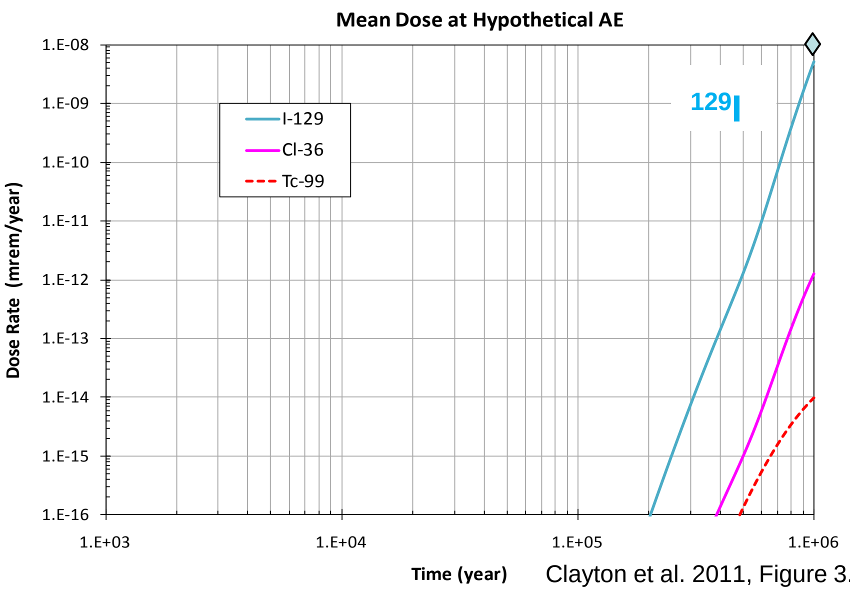
<u>Current/Future PA Work</u>

- 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 – Base Case

(Clayton et al. 2011)

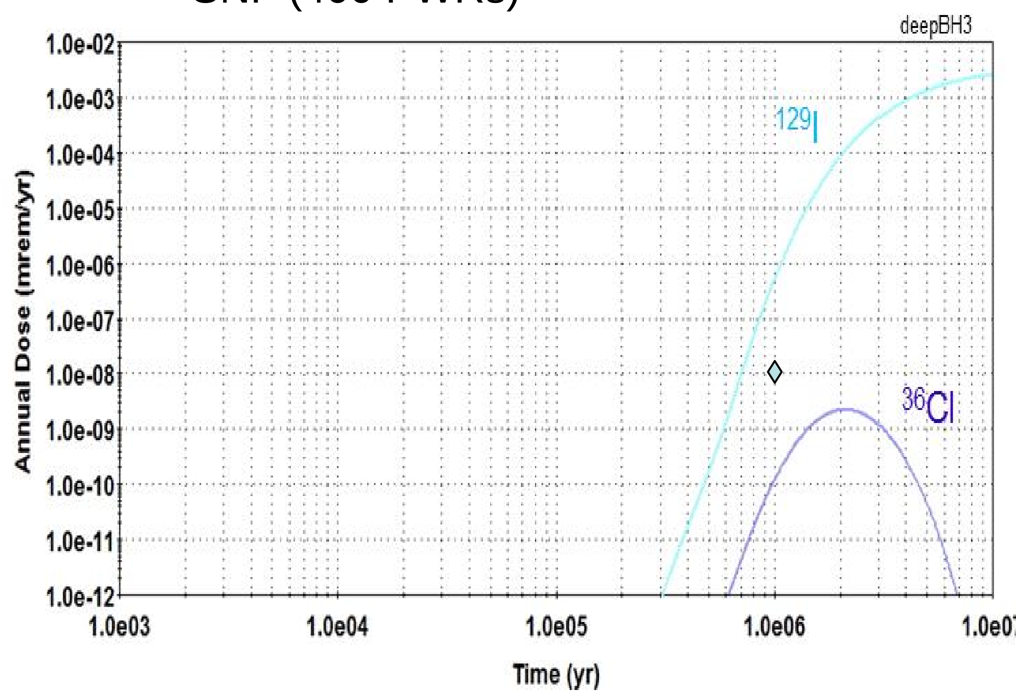
- Probabilistic (^{129}I k_d = 0-13 ml/g)
- Slower WF degradation (1×10^{-7} yr^{-1})
- Granite $k=10^{-19}$ m^2, Seal/DRZ $k=10^{-16}$ m^2
- SNF (400 PWRs)



Clayton et al. 2011, Figure 3.4-9

(Freeze et al. 2013)

- Deterministic (^{129}I k_d = 0 ml/g)
- Faster WF degradation (2×10^{-5} yr^{-1})
- Granite $k=10^{-19}$ m^2, Seal/DRZ $k=10^{-16}$ m^2
- SNF (400 PWRs)

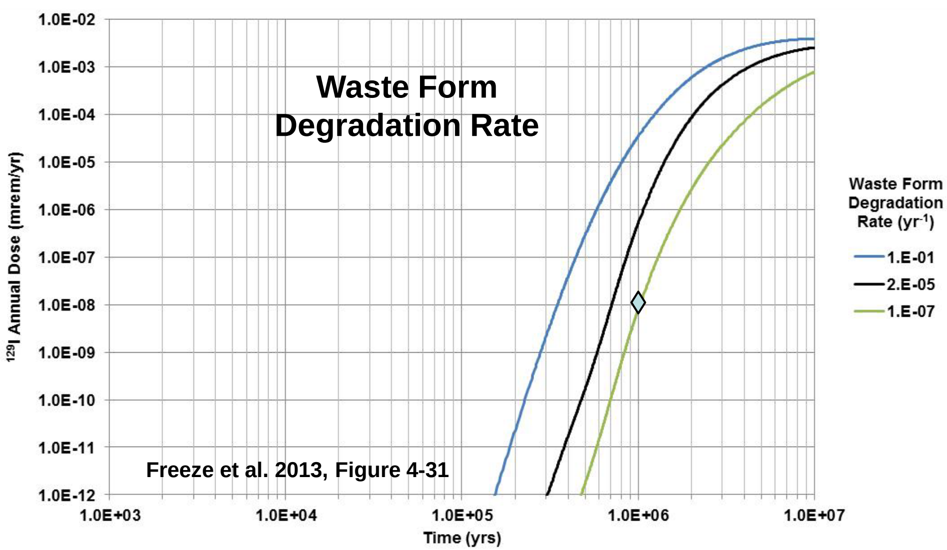


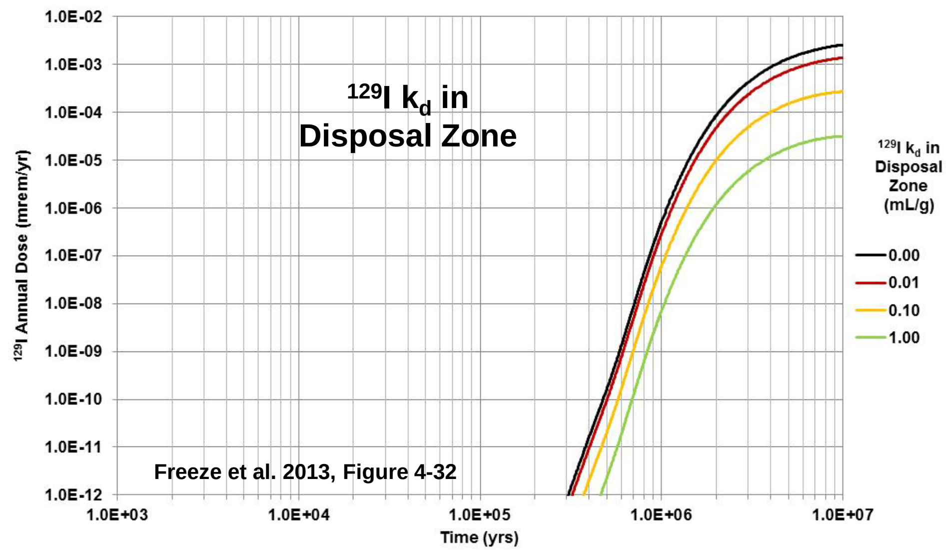
Freeze et al. 2013, Figure 4-8

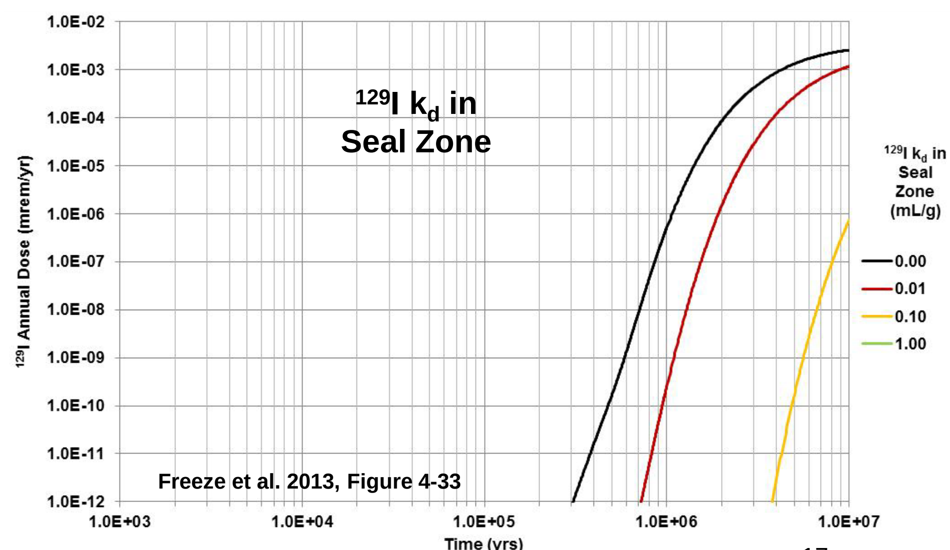
DBD PA Model Results – Sensitivity

(Freeze et al. 2013)

- Sensitivity of ^{129}I Annual Dose
  - Faster transport than ^{135}Cs, ^{137}Cs, or ^{90}Sr

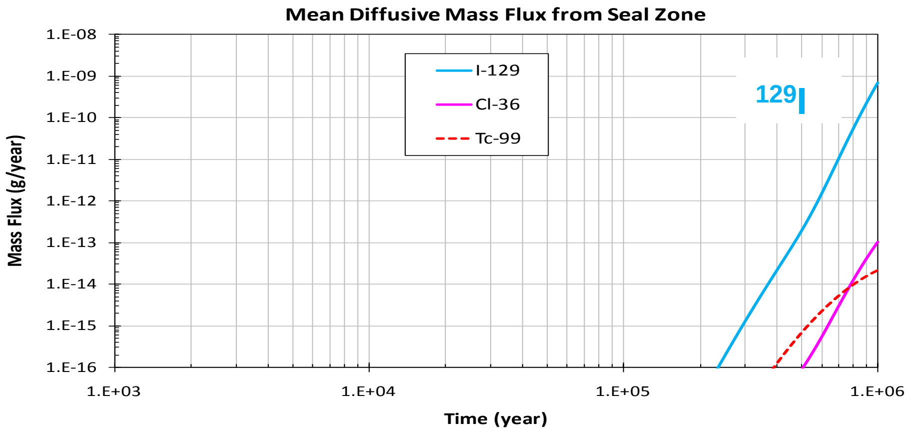






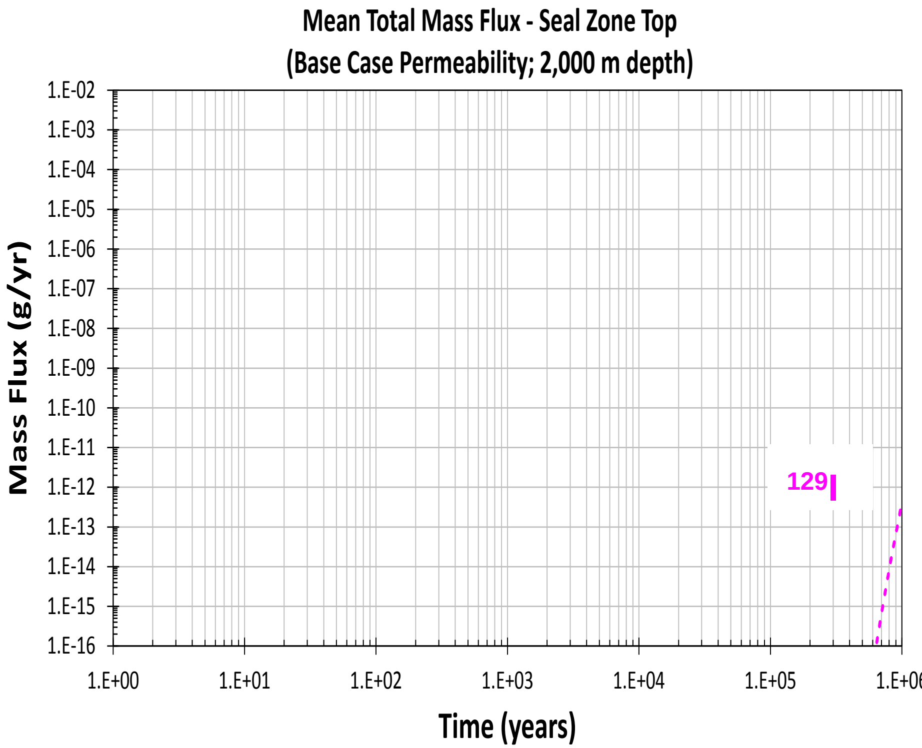
DBD PA Model Sensitivity –

Base-Case (Clayton et al. 2011)
No lateral diffusion into granite



Clayton et al. 2011, Figure 3.4-9

Base-Case (Arnold et al. 2013)
Lateral diffusion into granite



Arnold et al. 2013, Figure 4-19

Summary

- **Past PA Model results suggest minimal radionuclide releases/dose**
  - Results are sensitive to:
    - *waste form degradation rate*
    - *radionuclide sorption (k_d)*
    - *granite and seal permeability*
    - *thermally-induced upward flow (waste thermal characteristics)*
    - *waste package degradation*
- **Future PA Model enhancements**
  - Full consideration of features, events, and processes relevant to potential release pathways and scenarios (e.g., PFLOTRAN implementation)
  - Incorporation of more detailed modeling, including coupled processes
    - *Seal and DRZ conceptualization*
    - *Coupled thermal-hydrologic-mechanical-chemical behavior near the borehole*
  - Refinement of parameter values
    - *Cs/Sr capsule waste form*
    - *Data from DBFT*

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Backup Slides

Regulatory and Licensing Considerations – Post-Closure

- **Siting**
  - No disposal options for commercial SNF/HLW other than Yucca Mountain are possible without amending the Nuclear Waste Policy Act (NWPA 1983)
  - Separate repository for HLW resulting from atomic energy defense activities is possible (NWPA 1983, Section 8(b); DOE 2015)
  - NWPA (1983, Sec. 112-120) and 10 CFR 963 provide technical and administrative guidance on site suitability and site characterization activities specific to Yucca Mountain
    - *Could, in principle, provide insights to siting for other SNF/HLW disposal concepts and/or sites*

Potential Regulatory Topics

- **10,000-Yr Performance Standards (10 CFR 60 and 40 CFR 191)**
  - 40 CFR 191.13 Containment Standard
    - *cumulative releases of radionuclides to the accessible environment*
      - Release limits normalized to initial inventory (no benefit for smaller repositories)
      - Cumulative limits remove uncertainty associated with exposure pathways and future human lifestyles
    - *includes consideration of human intrusion*
  - 40 CFR 191.15 Individual Protection Standard (undisturbed only)
  - 40 CFR 191.24 Groundwater Protection Standard (undisturbed only)
- **1,000,000-yr Performance Standards (10 CFR 63 and 40 CFR 197)**
  - 40 CFR 197.20 Annual Dose Standard for Individual Protection
    - *10,000-yr (15 mrem/yr) and 1,000,000-yr (100 mrem/yr) limits*
  - 40 CFR 197.25 Human Intrusion Standard (separate standard)
  - 40 CFR 197.30 Groundwater Protection Standard (10,000-yr only)
- **New standards are likely to be Dose/Risk-based to 1,000,000 yrs**
  - Consistent with IAEA guidelines (IAEA 2011) and the National Academy of Sciences (1995) recommendations on Yucca Mountain standards

Dose vs. Cumulative Release Standards

- **Dose**
  - Emphasis on low annual dose/risk
  - Can be open-ended in time (or to peak dose)
  - Uncertainty in human behavior (e.g., water use and diet) is large
  - Encourages dilution and gradual release as well as isolation
  - Encourages smaller initial inventories
- **Cumulative Release**
  - Emphasis on isolation
  - Meaningful only for specified time period
  - Allowable limit is a function of time
  - Focuses on uncertainty in barrier system performance
  - No benefit for dilution
  - Normalization to initial inventory (as in 40 CFR 191) removes incentive for smaller repositories

Potential Regulatory Topics

- **Multiple Barriers / Subsystem Performance**
  - 10 CFR 60.113(a)
    - *Substantially complete containment in waste packages for not less than 300 years*
    - *Release rate of any radionuclide from the engineered barrier system shall not exceed one part in 100,000 per year of the inventory of that radionuclide at 1000 years*
    - *Groundwater travel time to the accessible environment along the fastest path shall be at least 1,000 years*
  - 10 CFR 63.113(a)
    - *"The geologic repository must include multiple barriers, consisting of both natural barriers and an engineered barrier system."*
  - A deep borehole disposal system includes engineered barriers (waste form, waste package, seals, liner/casing)
    - *Current design (waste package does not provide any post-closure isolation) may be satisfy engineered subsystem requirements in 10 CFR 60.113(a)*
    - *10 CFR 60.113(b) states "On a case-by-case basis, the Commission may approve or specify some other radionuclide release rate, designed containment period or pre-waste-emplacement groundwater travel time, provided that the overall system performance objective, as it relates to anticipated processes and events, is satisfied."*

Potential Regulatory Topics

- **Retrievability**
  - 40 CFR 191.14(f)
    - *"Disposal systems shall be selected so that removal of most of the wastes is not precluded for a reasonable period of time after disposal."*
  - 10 CFR 60.111 (and 10 CFR 63.111)
    - *"(1) The geologic repository operations area shall be designed to preserve the option of waste retrieval throughout the period during which wastes are being emplaced and, thereafter, until the completion of a performance confirmation program … To satisfy this objective, the geologic repository operations area shall be designed so that any or all of the emplaced waste could be retrieved on a reasonable schedule starting at any time up to 50 years after the waste emplacement operations are initiated, unless a different time period is approved or specified by the Commission."*
  - 10 CFR 60.46(a) "… an amendment shall be required …"
    - *"[for any] action which would make emplaced high-level radioactive waste irretrievable or which would substantially increase the difficulty of retrieving such emplaced waste"*

Potential Regulatory Topics

- **Retrievability (cont.)**
  - EPA noted when promulgating 10 CFR 191 in 1985:
    - *"The intent of this provision was not to make recovery of waste easy or cheap, but merely possible… ."*
  - NEA (2001) noted:
    - *"The introduction of provisions for retrievability must not be detrimental to long-term safety. Thus, for example, locating a repository at a depth that is less than optimum from a long-term safety perspective in order to facilitate retrieval is unlikely to be acceptable…."*
  - Prior to sealing, intact waste packages could potentially be retrieved from a cased borehole
  - After sealing, large-diameter core drilling has the potential for "waste recovery", at least for relatively narrower-diameter boreholes.
  - "… deep borehole systems may not be the best choice if permanent and irreversible disposal is not intended." (Brady et al. 2009)

Potential Regulatory Topics

- **Human Intrusion**
  - 40 CFR 191 and 197 are specific to mined repositories
    - *Single borehole – may be reasonable to assume low probability of intrusion*
    - *Multiple boreholes – may require further analysis*
- **Licensing**
  - Existing regulations contain an implicit assumption that a repository system will be licensed and constructed as a single unit
  - Need to consider approaches to licensing multiple boreholes
    - *License full multi-borehole system prior to waste emplacement?*
    - *Follow licensing approach for reactors?*
  - Phased licensing may not be applicable because emplacement may take place in months/years rather than decades (Winterle et al. 2011)
    - *Single license application (e.g., construct and operate)?*

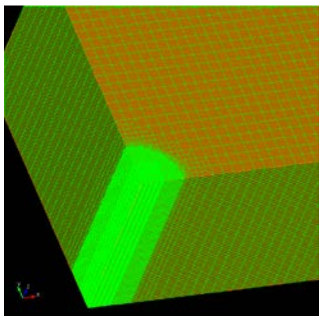
Potential Regulatory Topics

- **Underground Injection (40 CFR 144 to 148)**
  - EPA requirements for the Underground Injection Control (UIC) program promulgated under the Safe Drinking Water Act
  - Focus is on subsurface injection of fluids, but may apply to deep borehole disposal
  - 40 CFR 144.6(a) includes as a Class I injection well:
    - *"(3) Radioactive waste disposal wells which inject fluids below the lowermost formation containing an underground source of drinking water within one quarter mile of the well bore"*
  - Permitting authority varies from state to state
  - In its 1993 repromulgation of 40 CFR 191, EPA determined
    - *"that nuclear waste disposal systems should not be considered underground injection" (58 FR 66407).*
  - Compliance with 40 CFR part 144 was considered for WIPP
    - *DOE concluded that emplacement in WIPP did not constitute "injection" (DOE 1996, BECR Section 8.1)*
  - Need further guidance from EPA to determine whether canistered solid or granular HLW can be excluded from UIC

DBD PA Computational Model – Past Work (GoldSim)

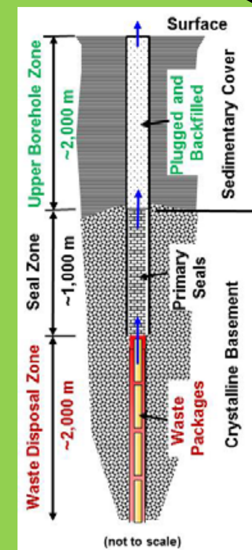
[FEHM]

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

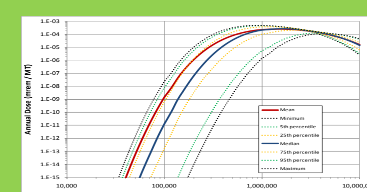


Input Parameter Distributions

- **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)

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Input Parameter Distributions

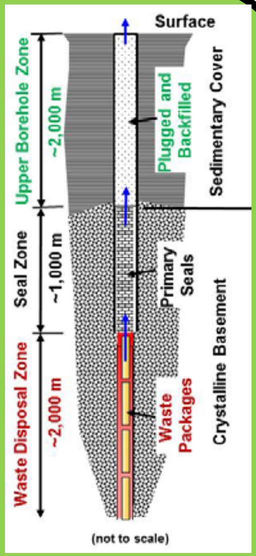
Sensitivity Analysis and Uncertainty Quantification

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



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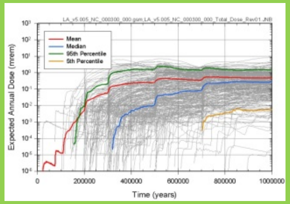
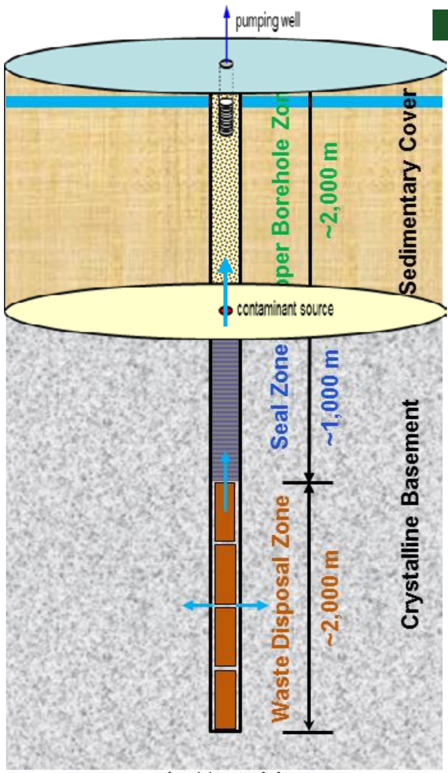


DBD Conceptual Model – Undisturbed Scenario



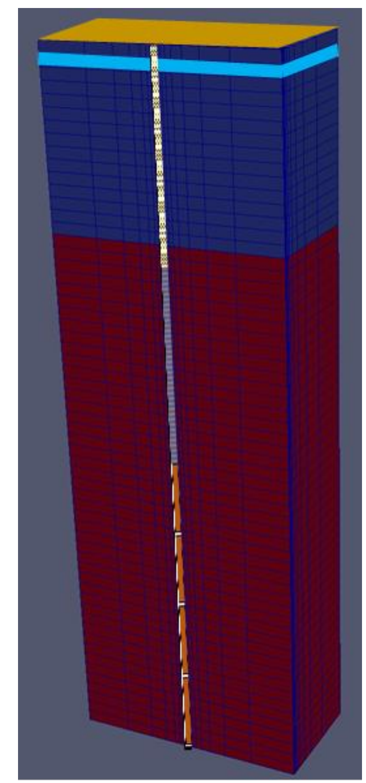
(not to scale)

Biosphere (Past Work)

- Assume IAEA BIOMASS ERB 1B Biosphere
  - *Potentially contaminated water from Seal Zone mixes in Upper Zone and surrounding permeable sediments*
  - *Pumping of the groundwater from Upper Zone for water supply*
    - Dilution rate = 10,000 m^3/yr
    - Individual consumption rate = 1.2 m^3/yr
  - *IAEA Dose Conversion Factors (DCFs)*

Biosphere (Current/Future Work)

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



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Additional References for Backup Slides

- 40 CFR Part 191. *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes*. 58 FR 66407, Readily available.
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- NAS (National Academy of Sciences) 1995. *Technical Bases for Yucca Mountain Standards.* National Research Council, Board on Radioactive Waste Management. National Academy Press. Washington, DC.
- NEA (Nuclear Energy Agency) 2001. *Reversibility and Retrievability in Geologic Disposal of Radioactive Waste: Reflections at the International Level*. NEA Report No. 6923. Nuclear Energy Agency Organization for Economic Cooperation and Development, Paris, France.