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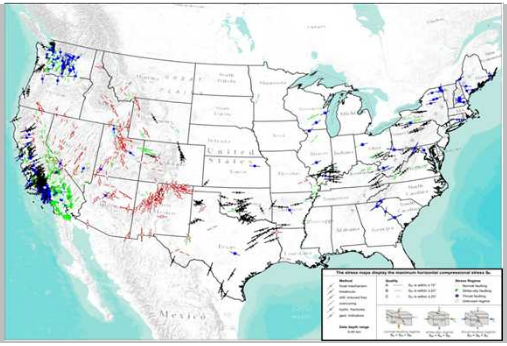

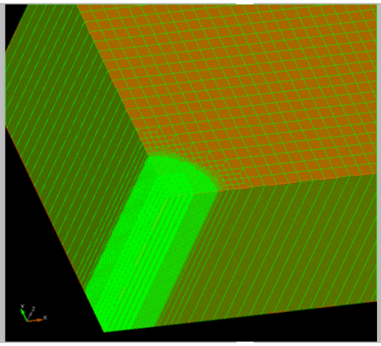

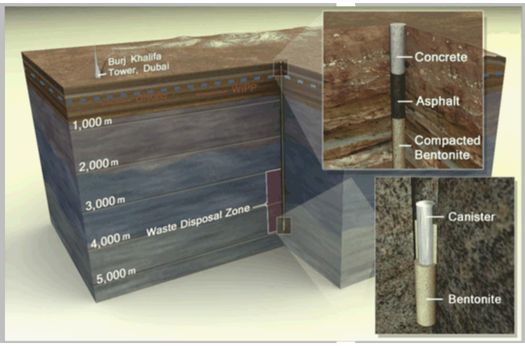

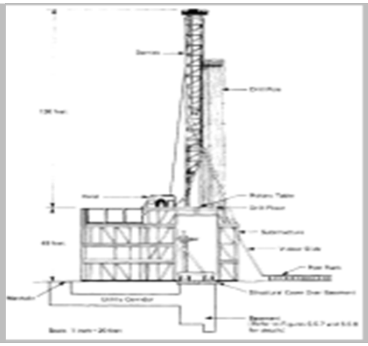

Deep Borehole Demonstration Project Overview

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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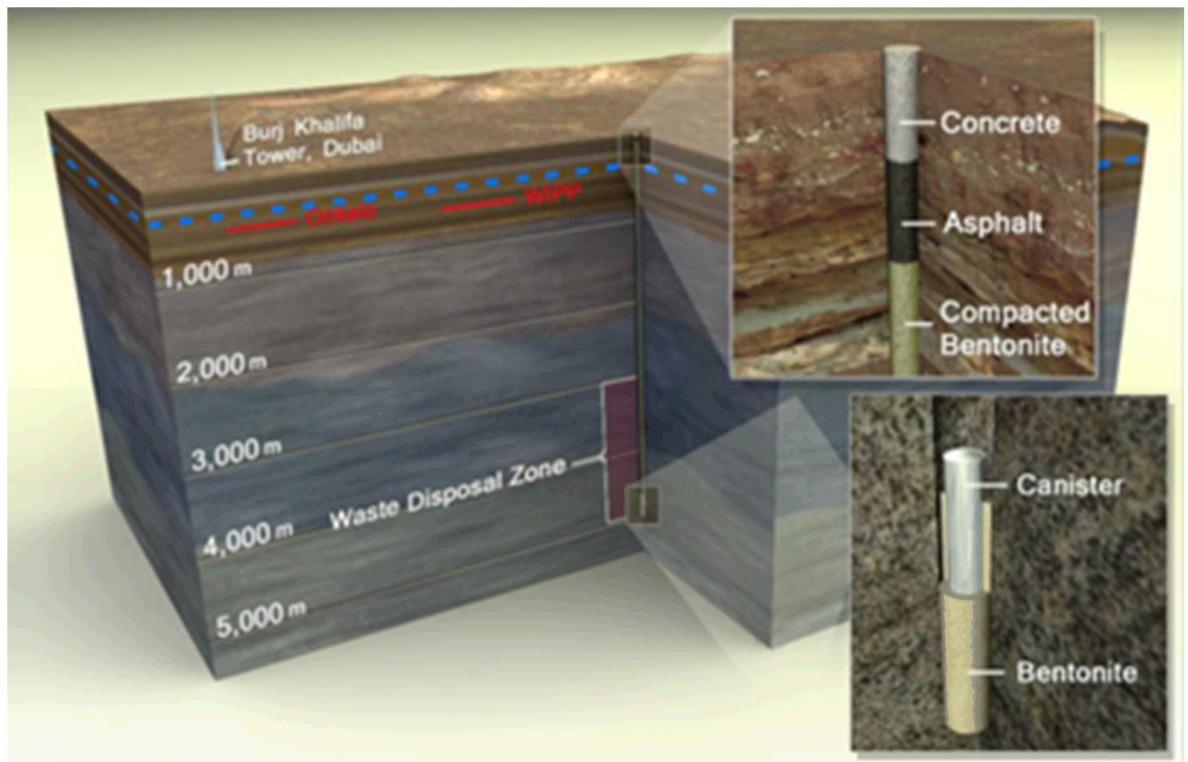
Outline

- Deep borehole disposal concept
- Waste isolation
- Hydrogeology objectives
- Characterization challenges
- Engineering challenges
- Conclusions

Deep Borehole Disposal Concept

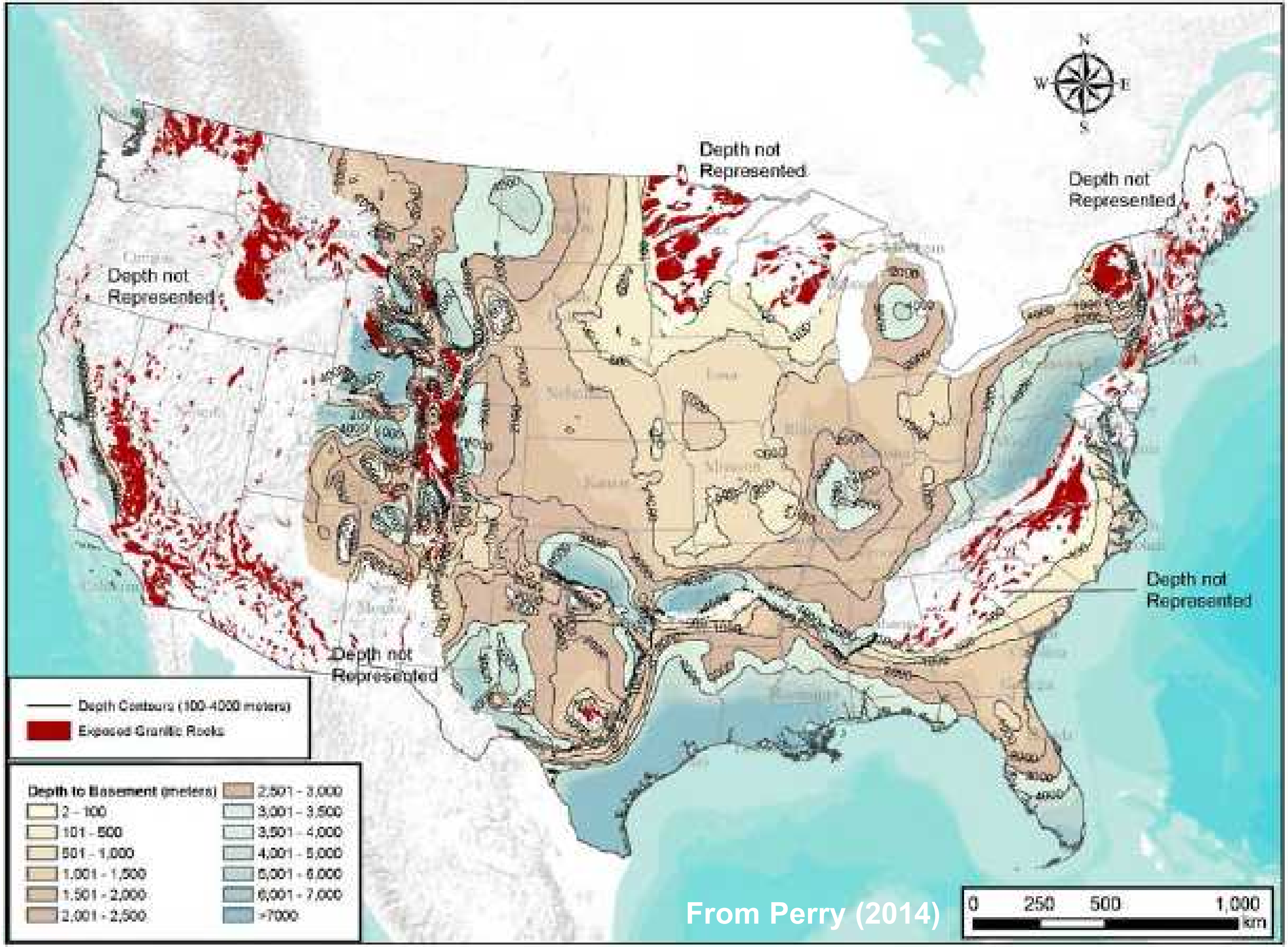
- Array of boreholes into crystalline basement rock to about 5,000 m depth
- Geologically old, saline, immobile groundwater
- Borehole casing assures emplacement of waste canisters
- Upper borehole sealed with compacted bentonite clay , cement, asphalt/ bitumen, concrete
- Borehole diameter 25 to 45 cm; low-alloy steel waste canisters
- Waste forms: DOE-owned waste, HLW, possibly SNF
- Approximately 400 waste canisters could be emplaced in the lower 2,000 m of the borehole



Deep Borehole Disposal Waste Isolation Performance

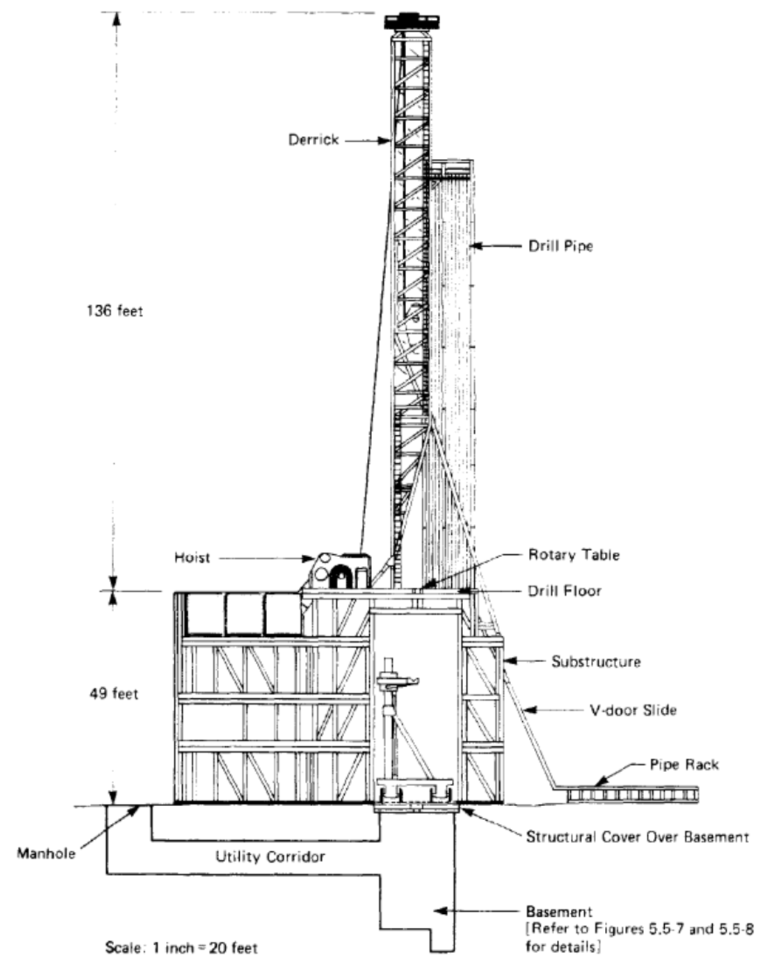
- Crystalline basement within 2,000 m of the surface is common in stable continental regions
- Low permeability, high-salinity ground water, long residence time in deep continental crystalline basement at many locations
- Geochemically reducing conditions at depth
- Density stratification of saline groundwater underlying fresh groundwater would oppose thermally induced groundwater convection
- Start with "specialty" waste forms (e.g., short half-life)

Depth to Crystalline Basement



Deep Borehole Field Test

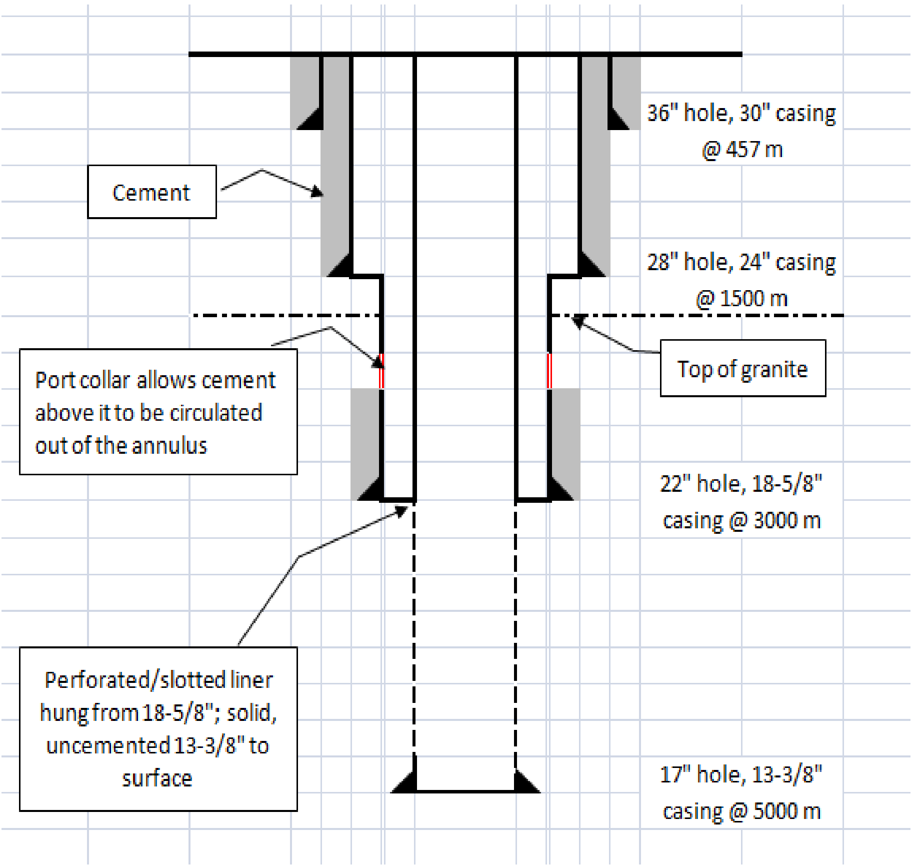
- **Characterization Borehole**
  - Bottom-hole diameter: 25 cm
  - Open-hole testing and core drilling
  - Well logging and geophysical surveys
  - Predictions for field test borehole
  - Downhole underground laboratory
- **Field Test Demonstration Borehole**
  - Bottom-hole diameter: 44.5 cm
  - Drilling method: Rotary tri-cone
  - Fully cased (see casing plan)
  - Emplacement system for mock-up canisters
  - Full-depth emplacement/retrieval, repeated
  - Downhole underground laboratory



Conceptual drawing of canister handling and emplacement system (drill pipe)

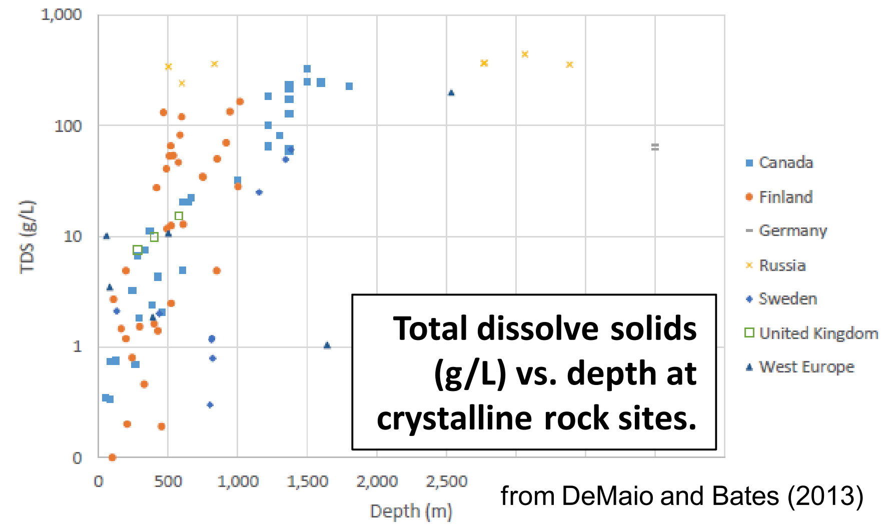
Reference Disposal Borehole Casing Plan

- Liner casing will be in place for the emplacement of waste canisters to assure against stuck canisters and facilitate potential retrieval (until the liner is pulled and seals set)
- The perforated liner will be left in place in the disposal zone, but will be removed in the seal zone, along with most of the intermediate casing
- Testing and logging will be easier in a smaller diameter characterization hole (8.5” bottom-hole)

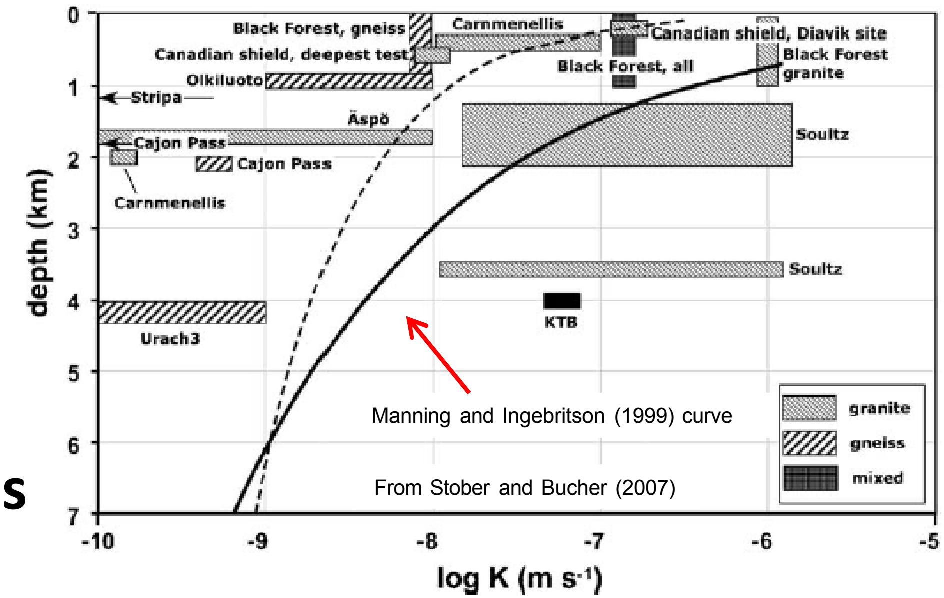


Hydrogeological Characterization

- Groundwater age and source (e.g. Holland et al., 2013)
- Groundwater salinity and geochemistry
- Potentially overpressured conditions
- Permeability in the host rock and disturbed rock zone near the borehole
- Chemical and mineralogical interactions with borehole seals



from DeMaio and Bates (2013)



Depth (km) vs. hydraulic conductivity (m/s)

Fluid Age and History: Environmental Tracers

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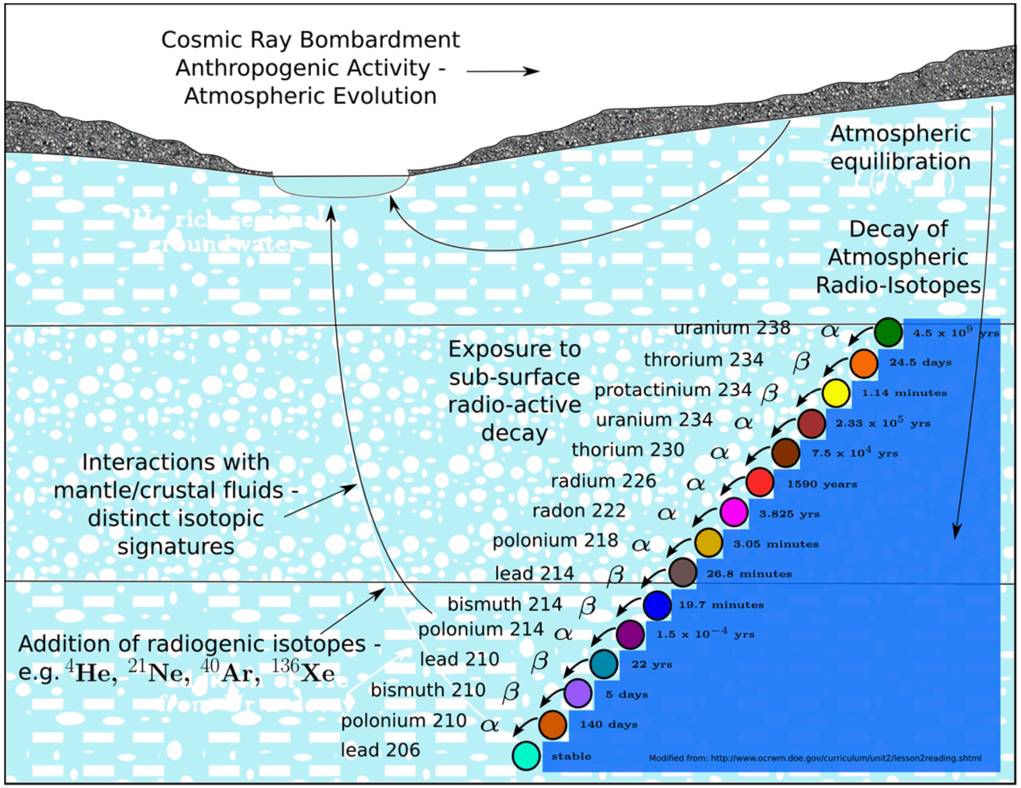
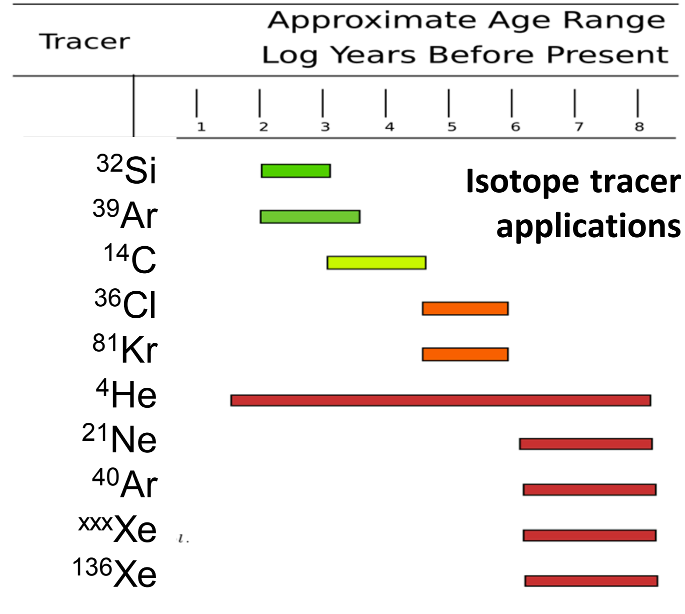
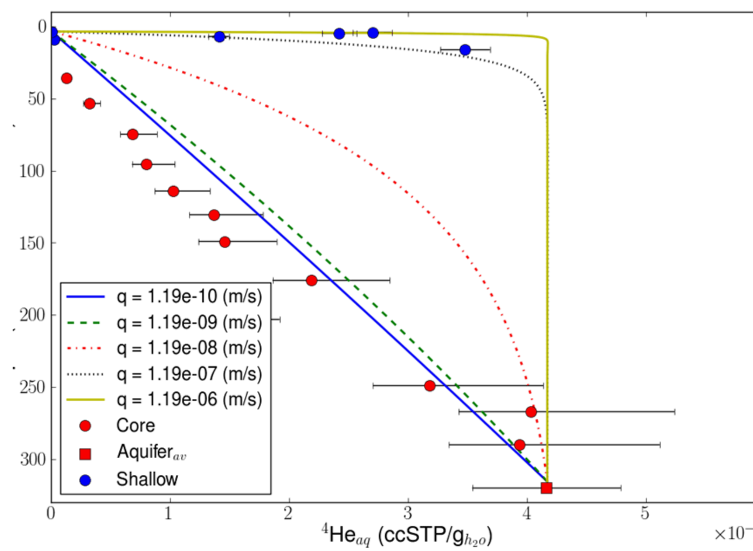


↑ **U-series and isotope tracers**

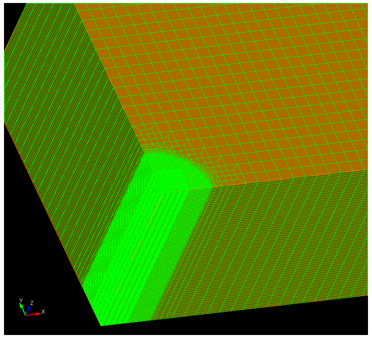


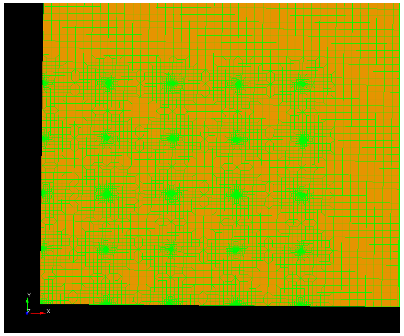
^{4}He abundance data compared to calculated responses, vs. depth →

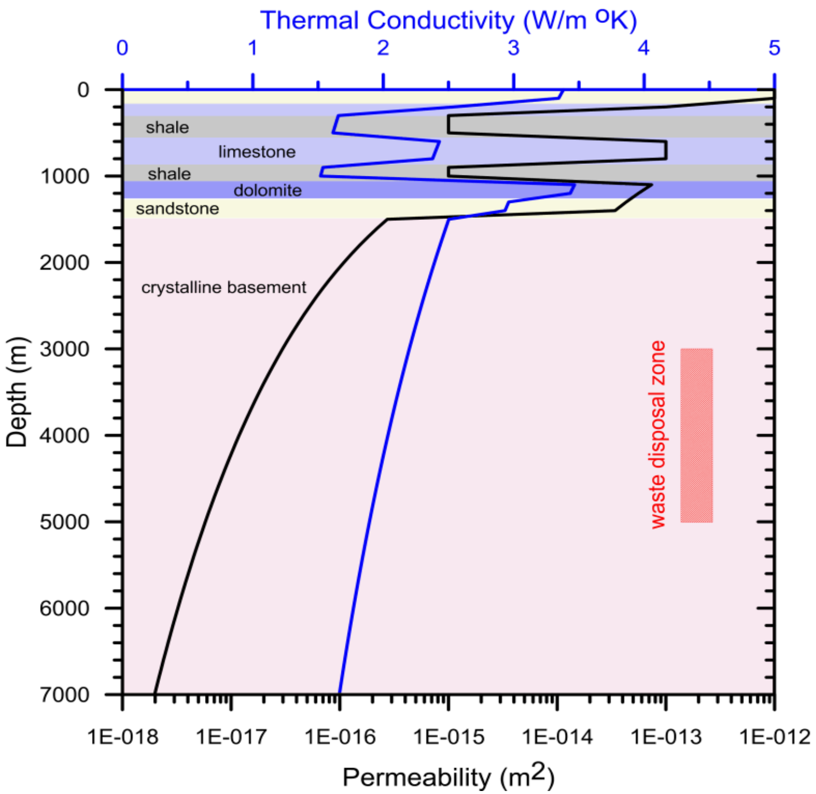


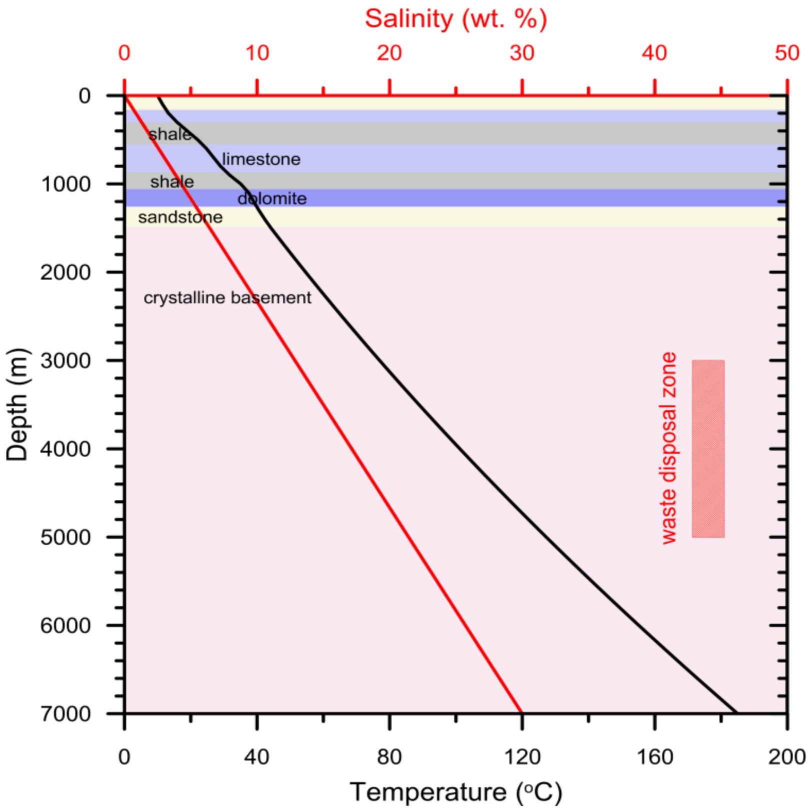
Thermal-Hydrologic Model

- **81-borehole 3D quarter-symmetry**
- **Finite element (FEHM) code coupling thermal, Dardy flow, and fluid density effects**









Thermal-Hydrologic Model Results

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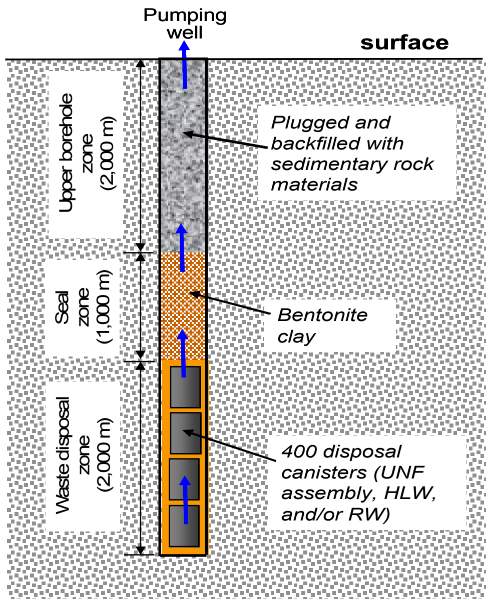
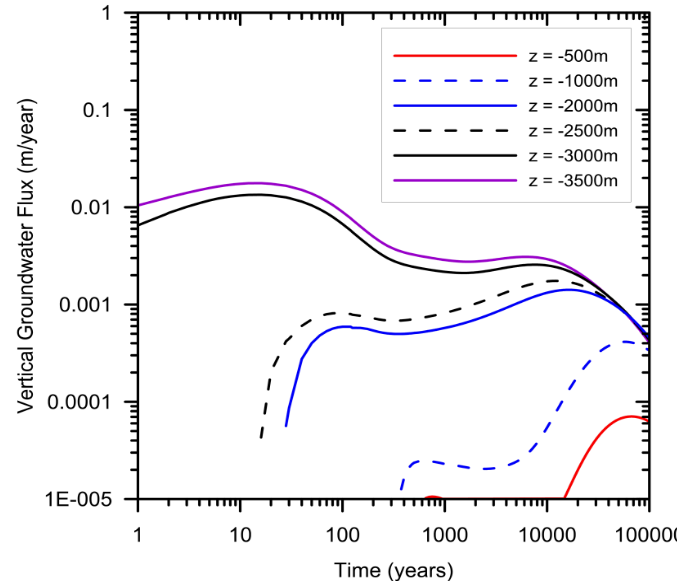
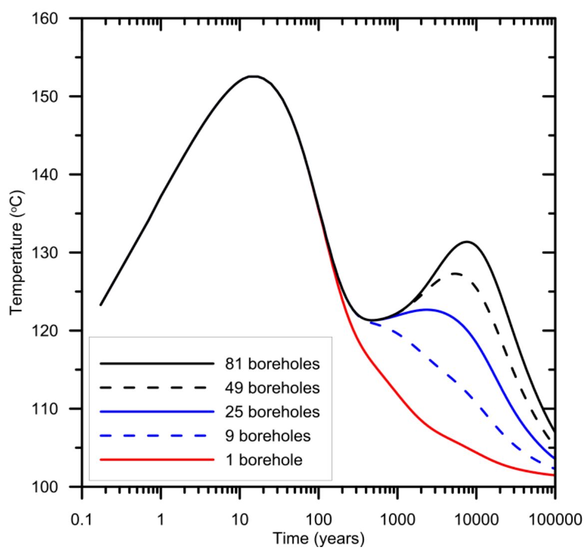
Model schematic



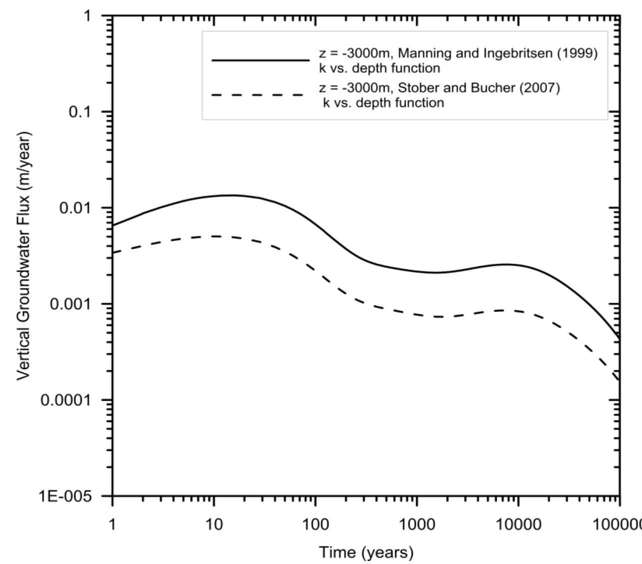
Flux (m/yr) vs. time (upper disposal zone and seal zone)



Temperature vs. time (vary # of boreholes)



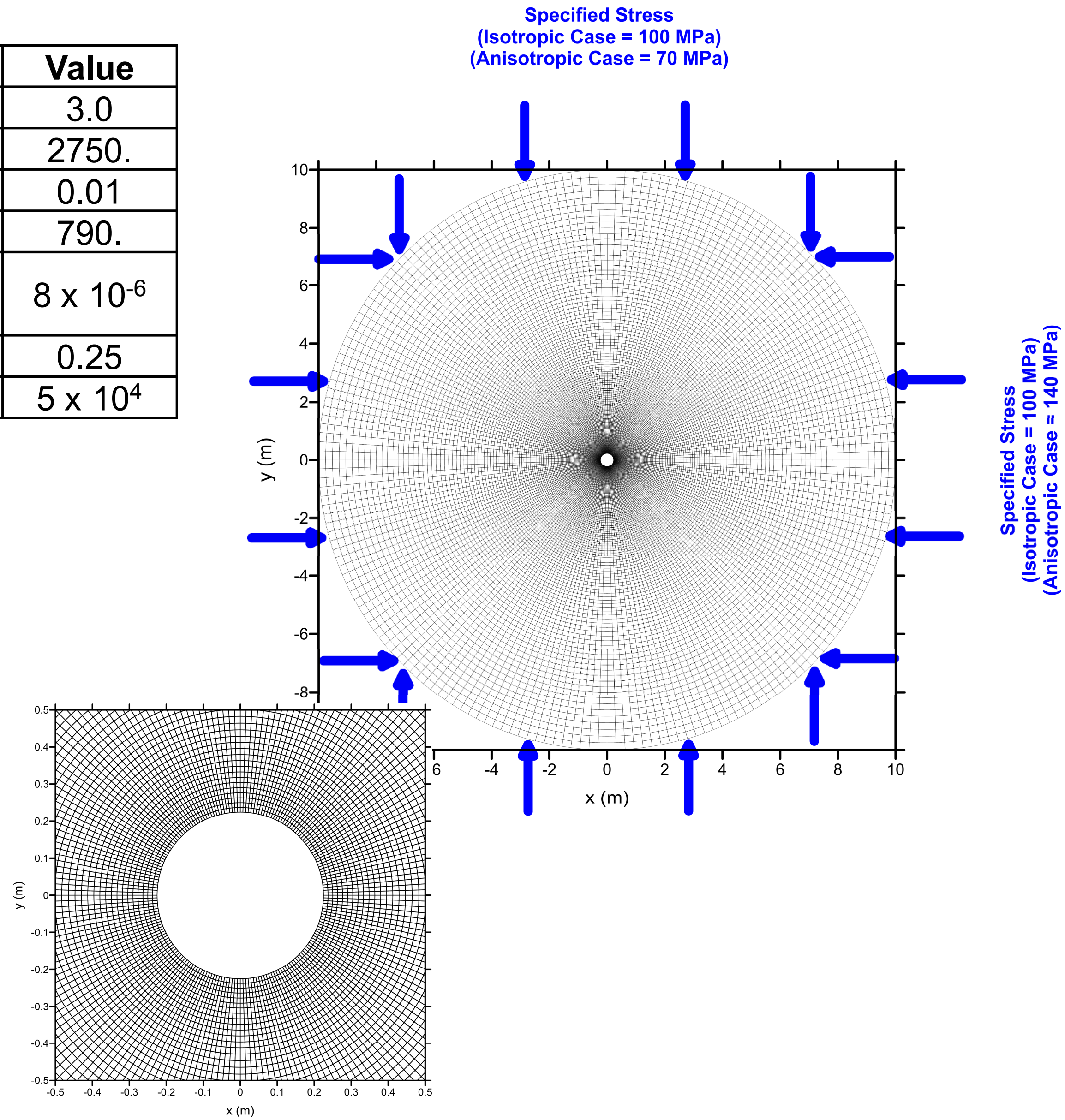
Flux (m/yr) vs. time (top of disposal zone) comparing permeability models



2D Mechanical Modeling

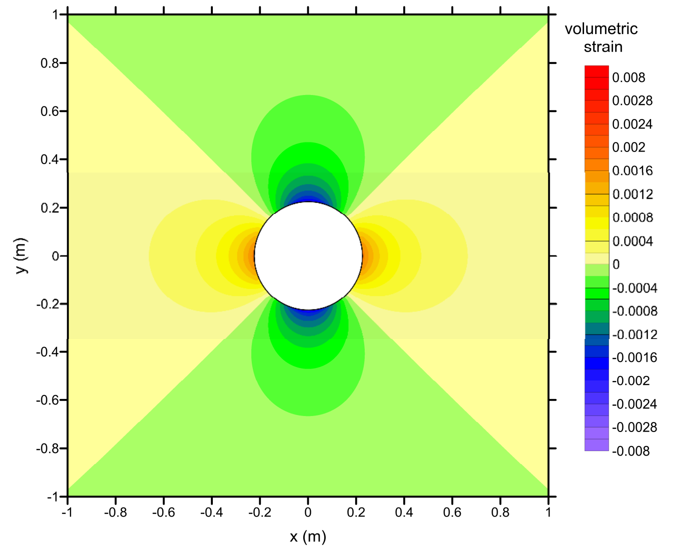
Parameter	Value
thermal conductivity (W/m °K)	3.0
density (kg/m^3)	2750.
porosity (-)	0.01
specific heat (J/kg °K)	790.
linear coefficient of thermal expansion (°K^{-1})	8 x 10^{-6}
Poisson ratio (-)	0.25
elastic modulus (MPa)	5 x 10^4

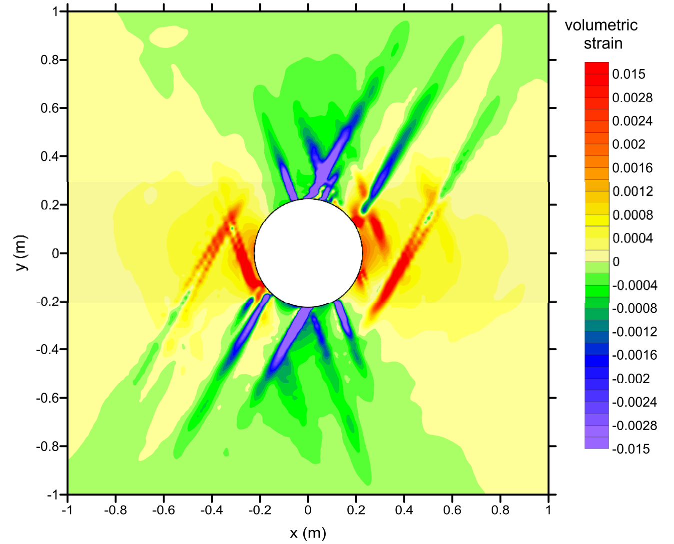
- 2D model of linear elastic and thermo-elastic processes implemented with the FEHM code (Zyvoloski et al., 1997)
- Boundary and initial conditions consistent with a nominal depth of 4,000 m
- Parameter values representative of granite



Hydrogeological Characterization: Disturbed Rock Zone

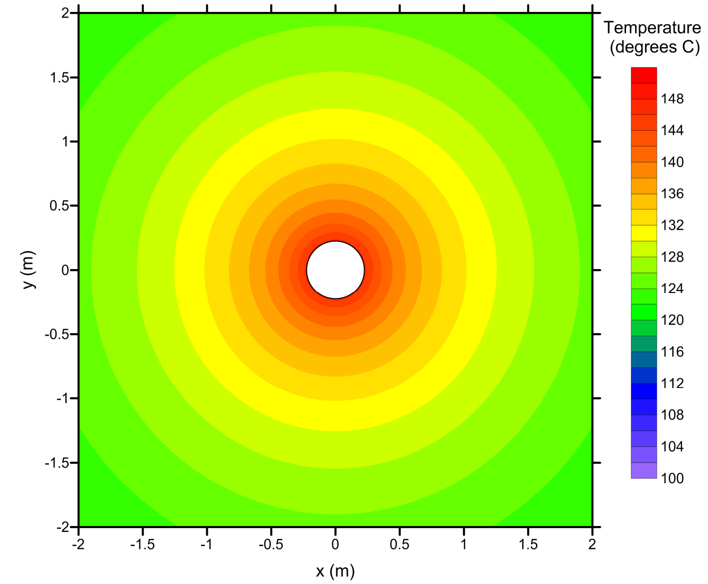
- Disturbed rock zone near the borehole wall may have enhanced permeability relative to the host rock
- Preliminary modeling of mechanical response under anisotropic horizontal stress suggests potential preferential permeability increase in some fractures
- Vertical dipole pumping and tracer tests can be used to evaluate the flow and transport characteristics of the disturbed rock zone

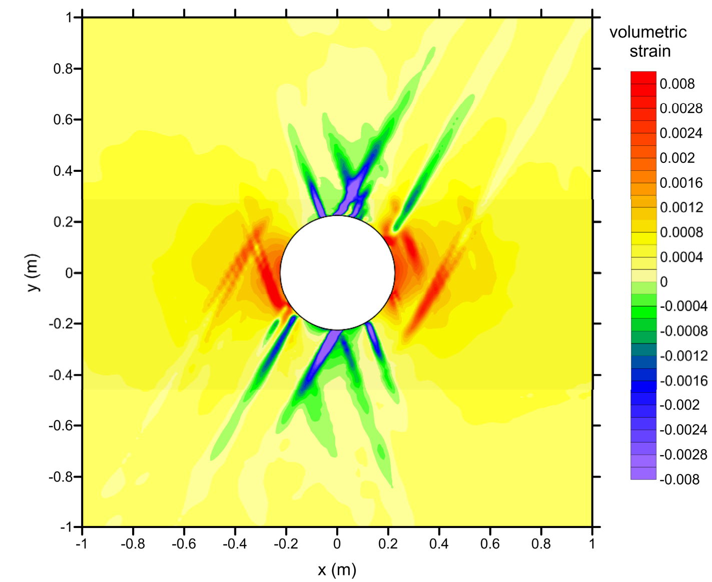




2D Thermal-Mechanical Modeling

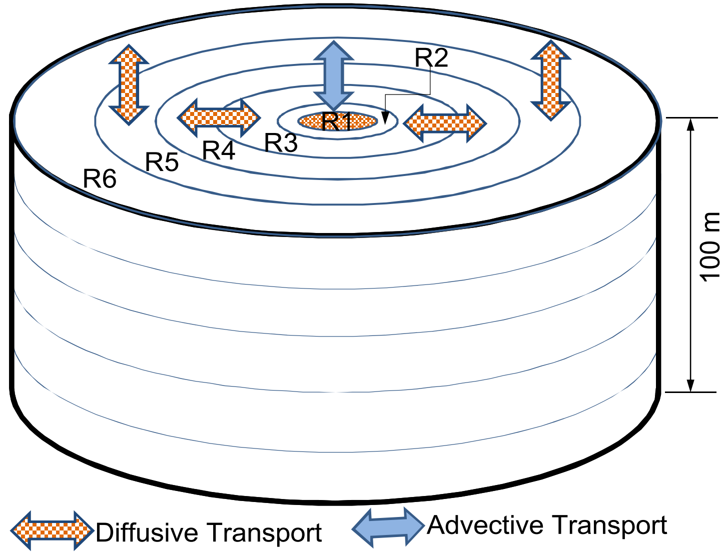
- Coupled T-M FEHM results for heterogeneous fractured granite and anisotropic (2:1) horizontal stress
- Disposal of average 1 average PWR fuel assembly – 5 years after discharge
- Stress/strain magnitudes are similar to in situ stress mechanical effect
- Fractures oriented toward σ_h could be in extension with increased permeability





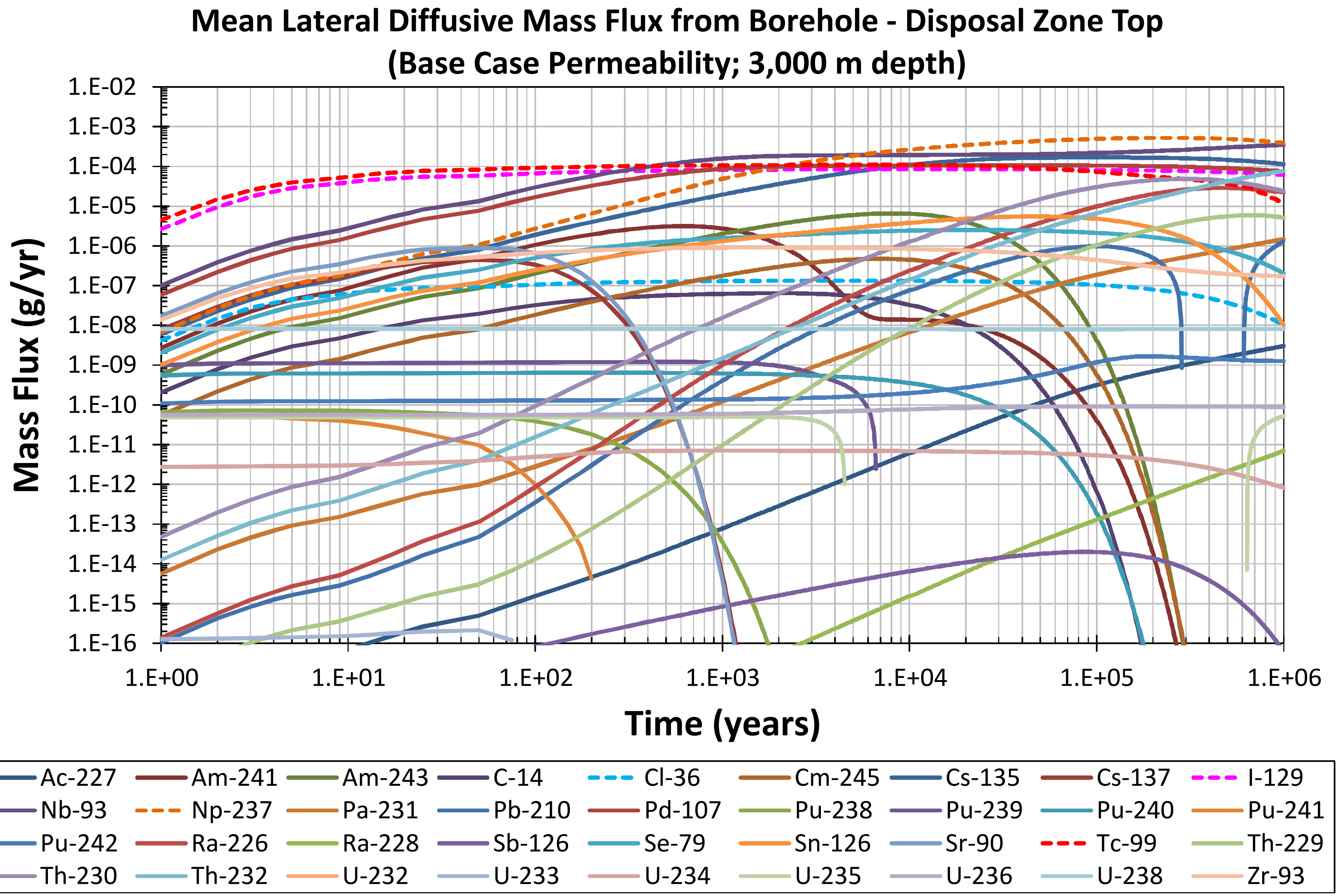
Radionuclide Release and Transport Model (performance assessment)

- Implemented in GoldSim® software
- Commercial SNF source term

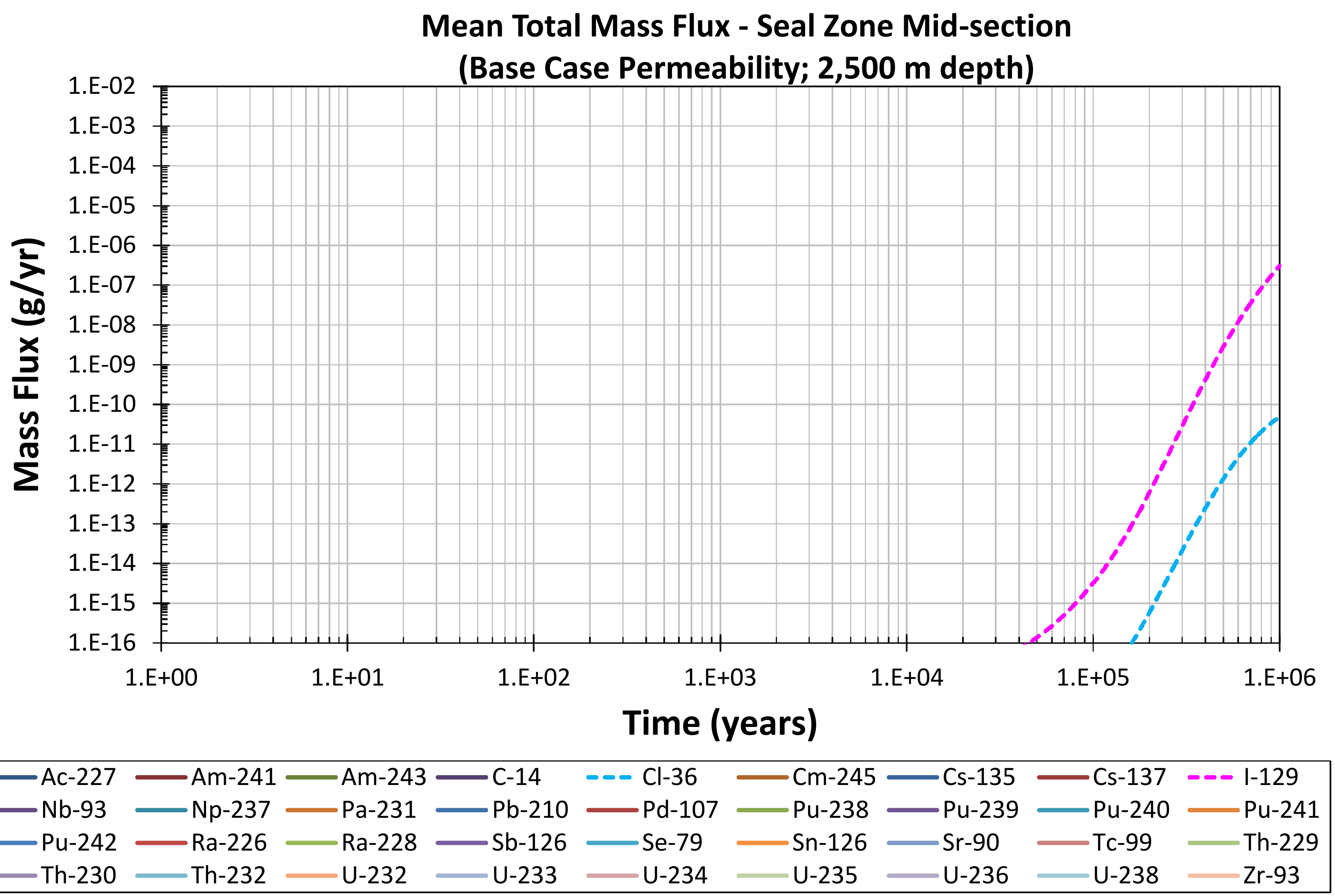


Shell Region	Description	Medium	Shell Radius (m)	Shell Layer Thickness (m)	Porosity
R1	Borehole Disposal zone	Compacted clay and WP & WF degradation products	0.564 (whole cylinder)	0.564 (whole cylinder)	0.034
	Borehole Seal zone	Compacted bentonite clay			0.034
	Borehole Upper zone	Sedimentary rock backfill and seals			0.01
R2	Disturbed rock zone	Granite	1.0	0.436	0.01 – 0.05
R3	Bedrock	Granite	3.0	2.0	0.01
R4	Bedrock	Granite	9.0	6.0	0.01
R5	Bedrock	Granite	34.0	25.0	0.01
R6	Bedrock	Granite	100.0	66.0	0.01

Example PA Results: Total Radionuclide Upward Mass Flux, Bottom of Seal Zone



Example PA Results: Total Radionuclide Upward Mass Flux, Seal Zone Mid-Section



Characterization Challenges

- **Identifying and sampling uncontaminated, representative ground water in fractured, low-permeability crystalline rocks**
- **Accurately determining fluid potential as a function of depth to assess potentially overpressured conditions**
  - Salinity gradient
  - Mud weight
- **Characterizing the disturbed rock zone near the borehole**
- **Determining long-term interactions between groundwater and borehole seals, and assessing the impacts on sealing integrity**

Engineering Challenges

- **Borehole stability and breakouts**
  - Stress and diameter dependence
- **Packer testing and wireline coring**
- **Well logging and testing in large-diameter boreholes (17.5" diameter reference design)**
- **Canister lowering system**
  - Wireline, coiled tubing, or drill pipe
  - Integration with existing canister transport, shielding
- **Canister instrumentation**
- **Canister retrieval**

Conclusions

- **Multiple qualitative and calculated indications that deep borehole disposal would be safe and feasible**
- **Borehole field test planned (no radioactive waste) and siting is underway**
- **Field test site selection guidelines indicate that large areas with favorable geological characteristics exist in the U.S.**
- **Characterization will focus on aspects of the system critical to demonstrating safety of the deep borehole disposal system:**
  - Groundwater age and history
  - Salinity and geochemistry
  - Potential for vertical fluid movement
  - Permeability in the host rock and disturbed rock zone
  - Borehole seals integrity and durability

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