Deep Borehole Disposal Concepts: Preliminary Assessment for the Disposal of Used Fuel Assemblies

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History of Borehole Disposal Concepts

- Deep borehole disposal of High-Level Waste (HLW) has been considered in the US since 1950s
- Shallow and intermediate depth disposal has been done in the US for low-level and transuranic waste
- Deep borehole disposal of used fuel and HLW has been studied in detail since 1970s
  - Recent reconsideration in Sweden, UK
  - Various options have evaluated
    - Disposal of surplus weapons Pu
    - Disposal of vitrified or cemented wastes
    - Disposal of fuel assemblies
    - Melting of host rock to encapsulate waste

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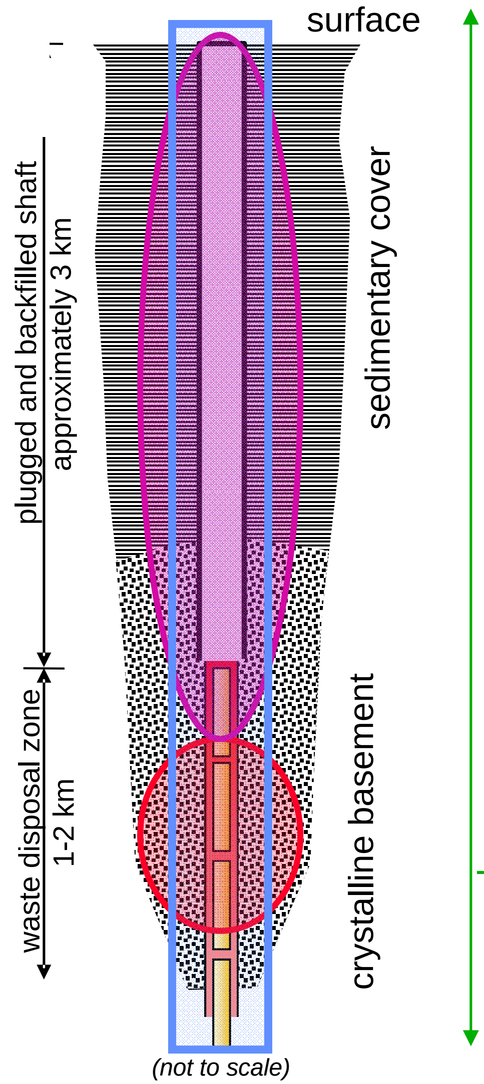
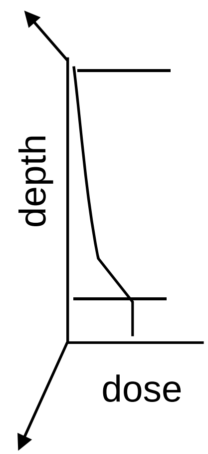
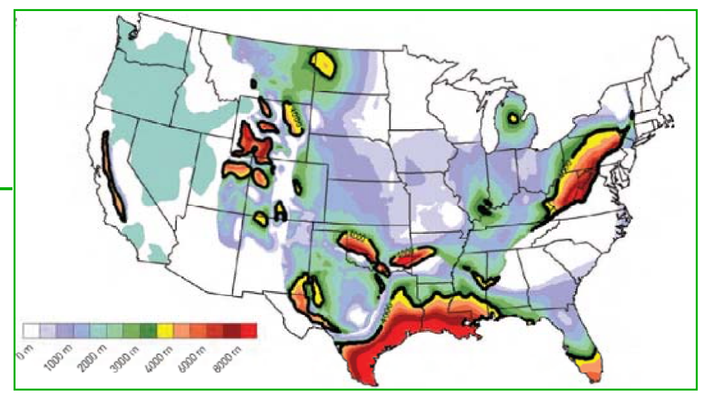


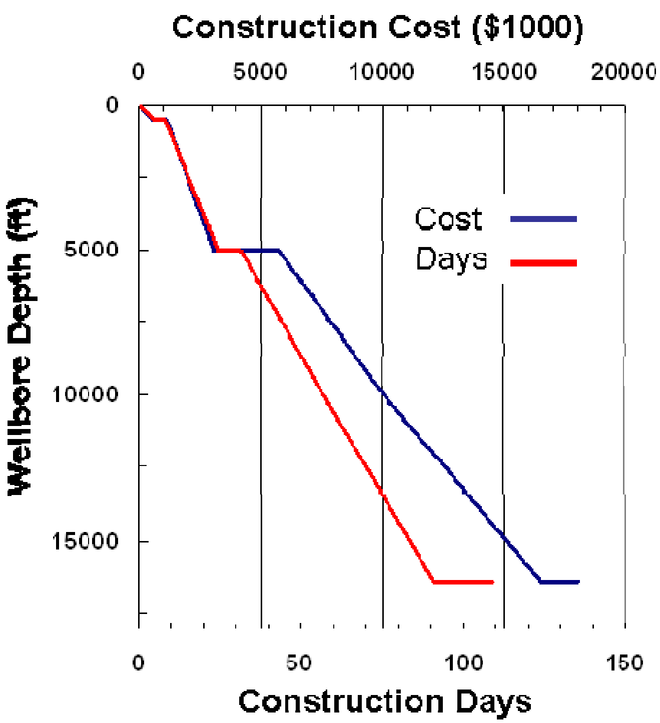


Nominal 5 km borehole

- 45 cm bottom hole diameter
  - 1 PWR assembly or
    3 BWR assemblies
- Lower 3 km in crystalline basement
- 2 km emplacement zone
- 1 km minimum of robust plugs
- Yucca Mountain inventory could be emplaced in ~ 400 holes



Feasibility



Source: Polsky, Y., L. Capuano, et al. (2008). *Enhanced Geothermal Systems (EGS) Well Construction Technology Evaluation Report,* SAND2008-7866, Sandia National Laboratories, Albuquerque, NM

Well construction can use existing technology
- **Geothermal operations use large diameter holes in crystalline rock**

Significant challenges may exist for emplacement operations

Robust sealing options
- **Concrete, clay, asphalt**

Overall costs likely to be competitive with repositories

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Concept for Long-Term Isolation

- Geologic environment is the primary barrier
  - In preliminary analyses described here, no credit taken for waste package or waste form
- Essentially no ground water flow at 3 km and below
  - Very low permeability of host rock and borehole seals
  - Saline pore water creates density stratification sufficient to prevent convective flow from heating
  - Reducing conditions stabilize most radionuclides
    - I-129 remains mobile
- Thermal expansion of pore water provides only significant release mechanism

Performance

- **Preliminary analysis suggests excellent long-term performance**
  - **Conservative estimate of deep borehole peak dose to a hypothetical human withdrawing groundwater above the disposal hole is 1.4 x 10^{-10} mrem/yr (1.4 x 10^{-12} mSv/yr**
  - **YMP standard is 15 mrem/yr (< 10,000 yrs) and 100 mrem/yr (peak dose to 1M yrs)**

- **Source: Brady, P.V., B.W. Arnold, G.A. Freeze, P.N. Swift, S.J. Bauer, J.L. Kanney, R.P. Rechard, J.S. Stein, 2009, *Deep Borehole Disposal of High-Level Radioactive Waste,* SAND2009-4401, Sandia National Laboratories, Albuquerque, NM**
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Deep Borehole Disposal: Advantages and Disadvantages

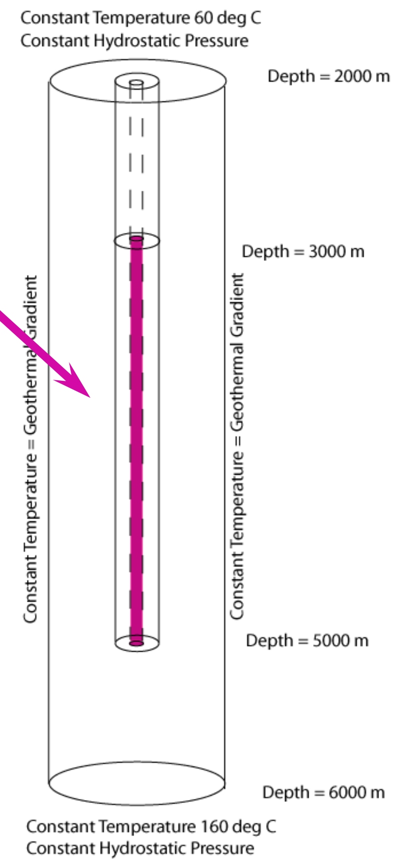
- **Advantages**
  - Excellent prospects for long-term isolation
  - Competitive cost
  - Wide range of suitable locations
  - Readily scales up or down in size
  - Waste is essentially irretrievable

- **Disadvantages**
  - Incompatible with US law and regulations
  - Does not meet US or international expectations for reversibility
    - Waste is essentially irretrievable
  - Operational challenges are untested

BACKUP

Scenario Description - Source

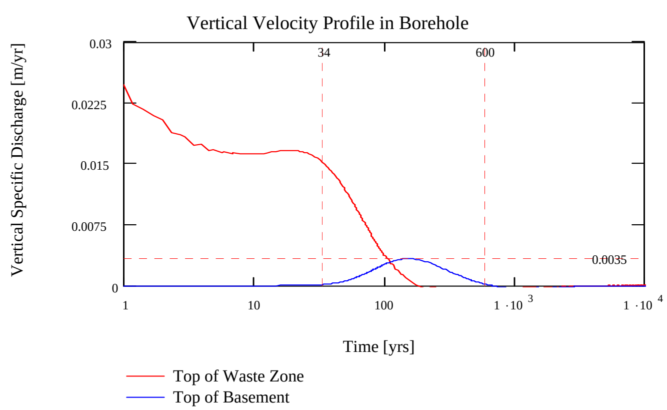
- **Waste Disposal Zone**
  - **Single borehole with 400 PWRs vertically stacked down a 2000 m disposal zone**
  - **No credit for waste package or waste form degradation**
  - **Inventory (31 radionuclides with decay and ingrowth) consistent with YMP PWR assemblies aged to 2117**
  - **Dissolved concentrations subject to solubility limits**

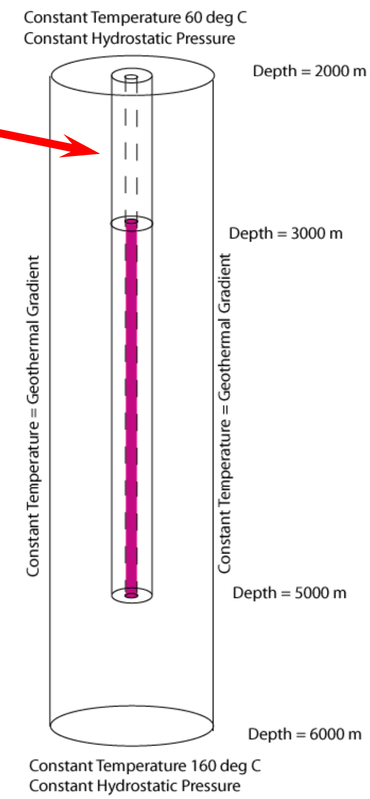


Not to Scale: Domain Radius is 100 m, height is 4 km
Borehole (radius 0.15 m) + Disturbed Zone has a cross-sectional area of 1 square meter

Scenario Description – Borehole Transport

- **Borehole Sealed Zone**
  - **Radionuclide transport up borehole for 1000 m**
  - **Properties are composite of bentonite seal and excavation disturbed zone (EDZ)**
  - **Constant thermally driven flow (pore velocity = 0.5 m/yr) from top of waste disposal zone for 200 yrs**





Not to Scale: Domain Radius is 100 m, height is 4 km
Borehole (radius 0.15 m) + Disturbed Zone has a cross-sectional area of 1 square meter

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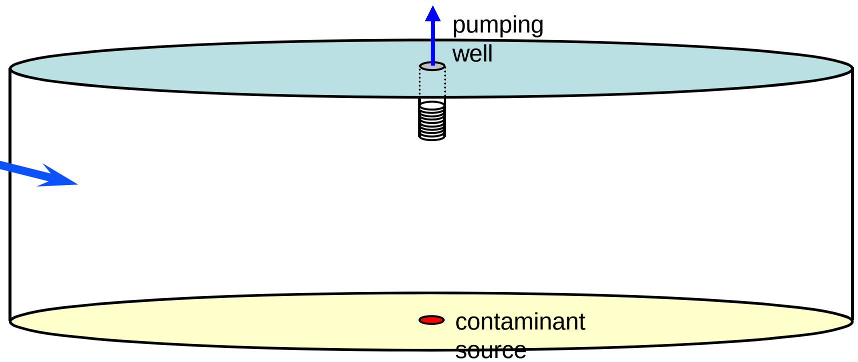
Scenario Description – Geosphere Transport

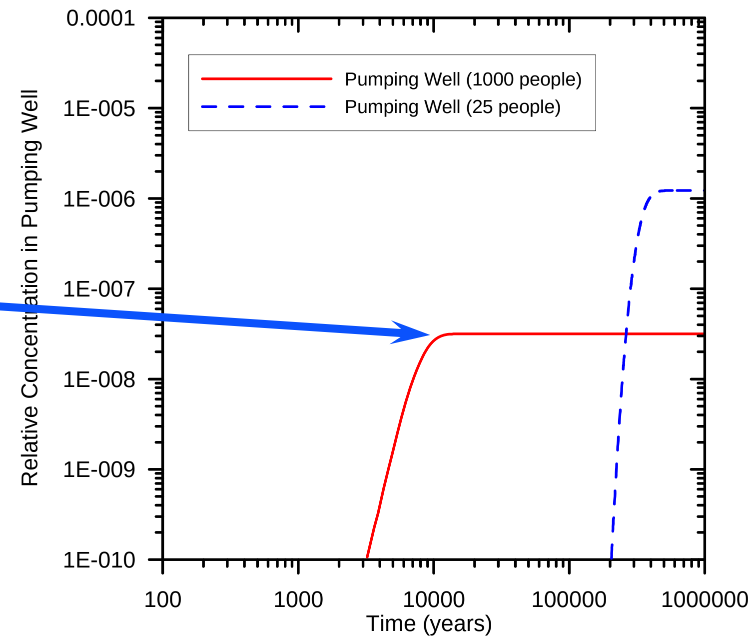
- **Geosphere**



  - **Capture of radionuclides from top of borehole sealed zone**
  - **Transport and dilution of radionuclides in geosphere (properties approximate fractured rock and/or sediments)**
  - **Withdrawal of radionuclides to surface/biosphere via pumping well**

Modeling Approach

- **Source Term**
  - **Continuous radionuclide source**
- **Sealed Borehole Transport**
  - **1-D analytic solution of advection-dispersion equation with sorption and decay through composite bentonite/EDZ**
  - **Transport ceases at 200 yrs**
- **Geosphere Transport**
  - **Assumed travel time (8000 yrs) and dilution factor (3.16 x 10^7)**
- **Dose**
  - **Assumed exposure pathways consistent with YMP**



Preliminary PA Results

- Peak dose to exposed individual is 1.4×10^{-10} mrem/yr at 8200 yrs
- ^{129}I is sole contributor to peak dose
- Peak concentration at top of borehole sealed zone (^{129}I at 200 yrs) is 5.3×10^{-8} mg/L
- Peak is due to leading edge of dispersive front – center of mass of ^{129}I travels ~ 100 m in 200 yrs

Geochemical Constraints over the Source Term

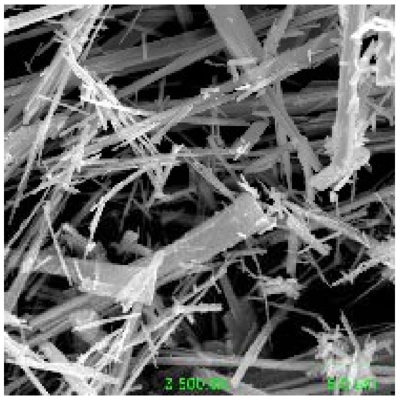
Solubilities; T = 200^oC, pH 8.5,
E_H = -300 mV, 2M NaCl solution

Radioelement	Solubility-limiting phase	Dissolved concentration (moles/L)
Am	Am_2O_3	1×10^{-9}
Ac	Ac_2O_3	1×10^{-9}
C	*	*
Cm	Cm_2O_3	1×10^{-9}
Cs	*	*
I	Metal iodides ?	*
Np	NpO_2	1.1×10^{-18}
Pa	PaO_2	1.1×10^{-18}
Pu	PuO_2	9.1×10^{-12}
Ra	$RaSO_4$	*
Sr	$SrCO_3$, $SrSO_4$?	*
Tc	TcO_2	4.3×10^{-38}
Th	ThO_2	6.0×10^{-15}
U	UO_2	1.0×10^{-8}

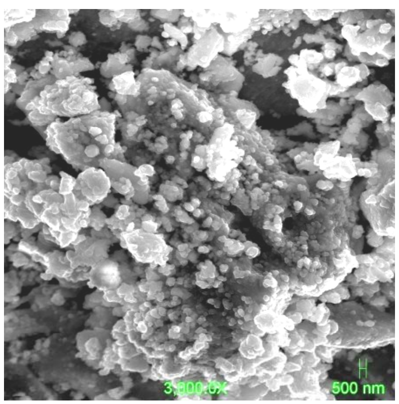
Source term and Borehole K_ds.

Element	$k_{d\ basement}$	$k_{d\ sediment}$	$k_{d\ bentonite}$
Am, Ac, Cm	50-5000	100-100,000	300-29,400
C	0-6	0-2000	5
Cs	50-400	10-10,000	120-1000
Np, Pa	10-5000	10-1000	30-1000
Pu	10-5000	300-100,000	150-16,800
[c]Ra	4-30	5-3000	50-3000
Sr	4-30	5-3000	50-3000
Tc	0-250	0-1000	0-250
Th	30-5000	800-60,000	63-23,500
U	4-5000	20-1700	90-1000
I	0-1	0-100	0-13

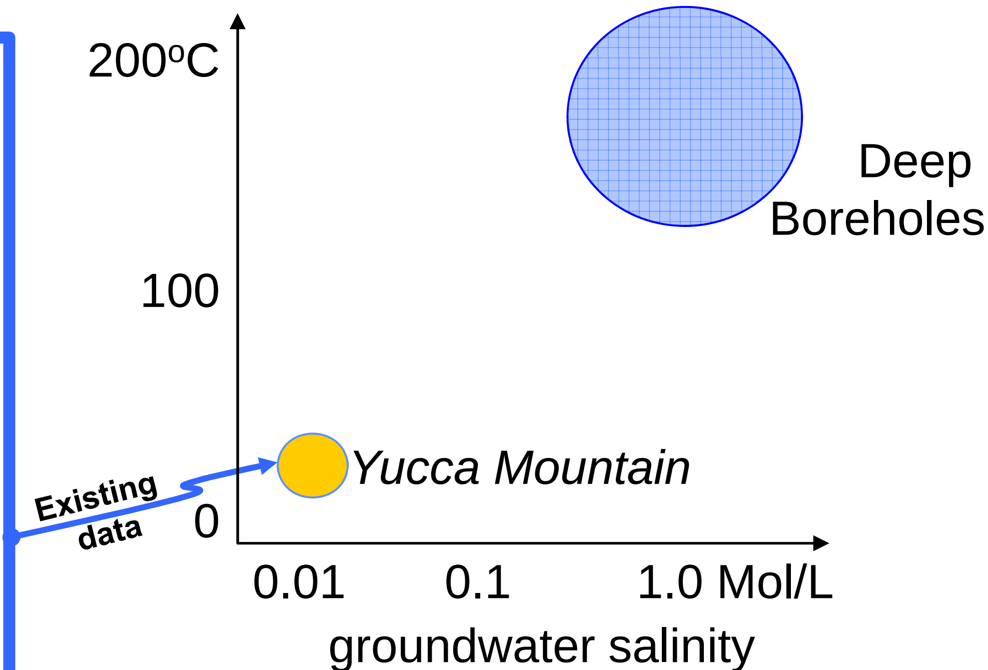
Bismuth-based ^{129}I sorbents



K_d = 720 ml/g



K_d = 2300 ml/g



- Thermal stability of Bi phases
- Effect of anion competition
- Reversibility
- Modification

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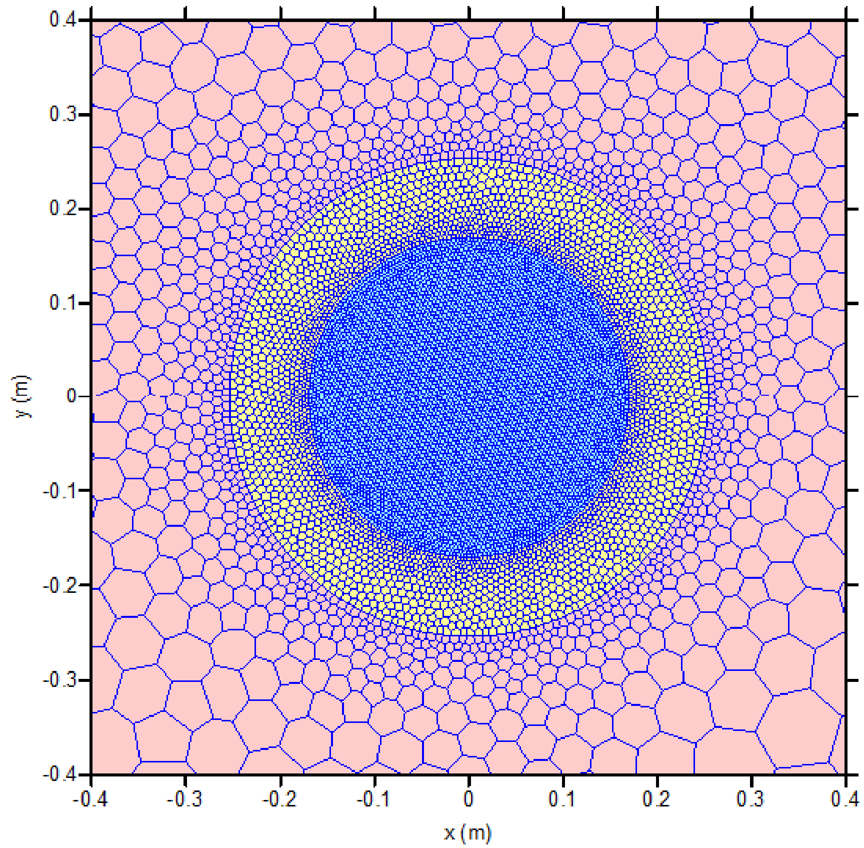
Objectives of Thermal/Hydrologic Analyses

- Quantify temperature changes at the borehole wall and within the host rock as a function of time
  - Disposal of spent nuclear fuel assemblies
  - Disposal of high-level waste from reprocessing
- Simulate thermally induced hydrologic flow within and near the borehole
  - Thermal expansion of water
  - Convective flow
- Examine the potential for hydrofracturing from the thermal expansion of water
- Quantify the dilution and capture time of radionuclides for hypothetical pumping from the shallow groundwater flow system

Thermal Conduction

- **2-D heat conduction simulations performed using the FEHM software code for a single borehole**
- **Initial and boundary conditions assigned for a nominal depth of 4 km and ambient temperature of 110^{o} C**
- **Representative parameter values used:**
  - **3.0 W/m ^{o}K – thermal conductivity of granite**
  - **790 J/kg ^{o}K – specific heat of granite**
  - **0.8 W/m ^{o}K – thermal conductivity of bentonite grout**



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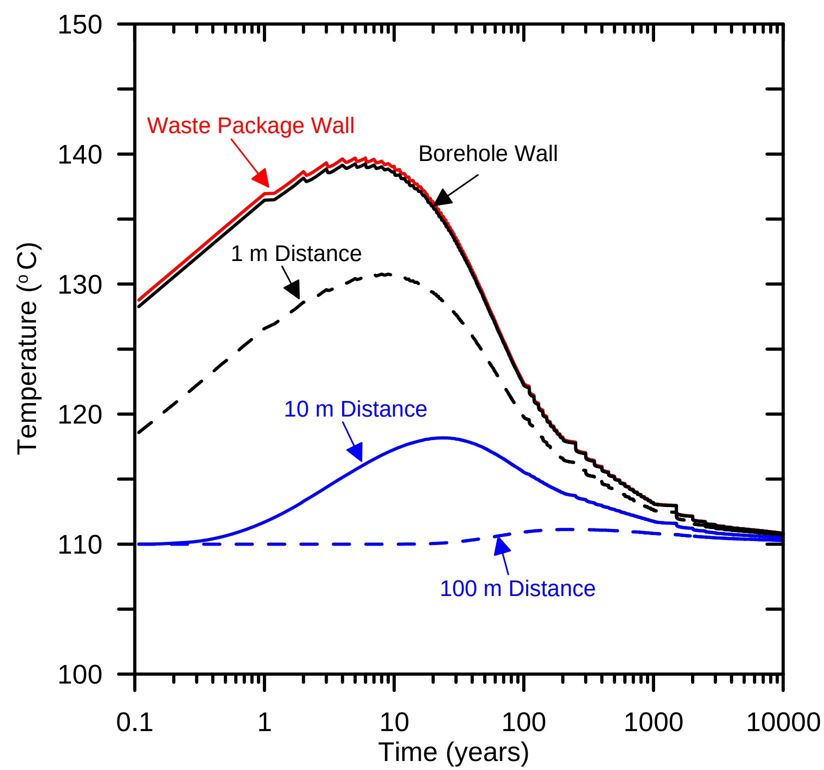
Thermal Conduction

- **Assumed disposal of a single PWR fuel assembly per waste package**
- **Thermal output for an average fuel assembly that has been aged for 25 years**
- **Results indicate a maximum temperature increase of about 30°C at the borehole wall, similar to the results in the draft report of Sapiie and Driscoll (2009)**
- **Significant temperature increases do not persist beyond 100 to 200 years**



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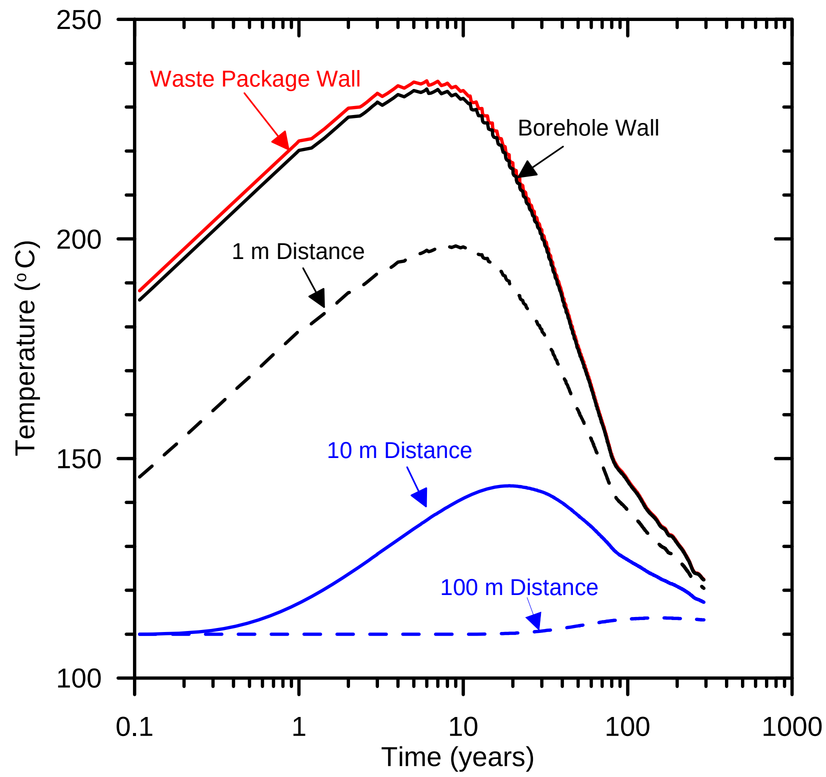
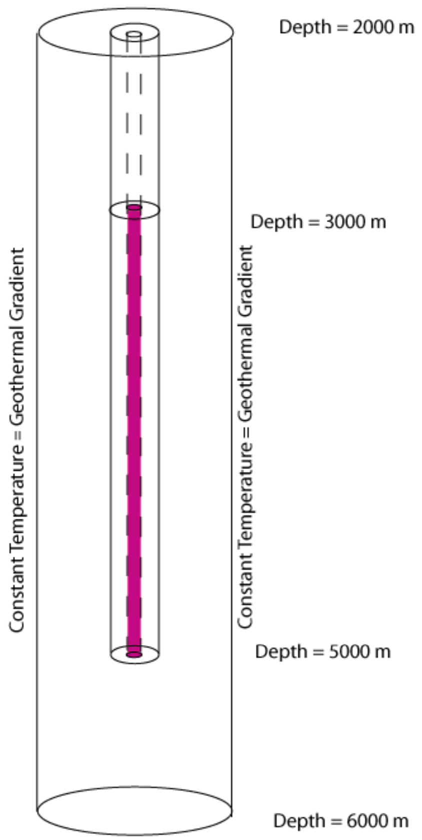
Thermal Conduction

- **Similar analysis performed for vitrified high-level waste**
- **Heat output curves are for the current vitrified waste from reprocessing of commercial spent nuclear fuel in France, aged for 10 years**
- **Results indicate a temperature increase of about 125 ºC at the borehole wall, which is significantly higher than the for disposal of PWR spent nuclear fuel assemblies**



Coupled Thermal-Hydrologic Model



Not to Scale: Domain Radius is 100 m, height is 4 km
Borehole (radius 0.15 m) + Disturbed Zone has a cross-sectional area of 1 square meter

- **Radial 2-D simulations conducted using the FEHM code**
- **Thermal properties were consistent with the thermal conduction modeling**
- **Granite was assigned a permeability of 1 X 10^{-19} m^2**
- **Sealed borehole and disturbed bedrock surrounding the borehole were assigned a value of 1 X 10^{-16} m^2**
- **Hydrostatic fluid pressures were assumed to exist under ambient conditions**

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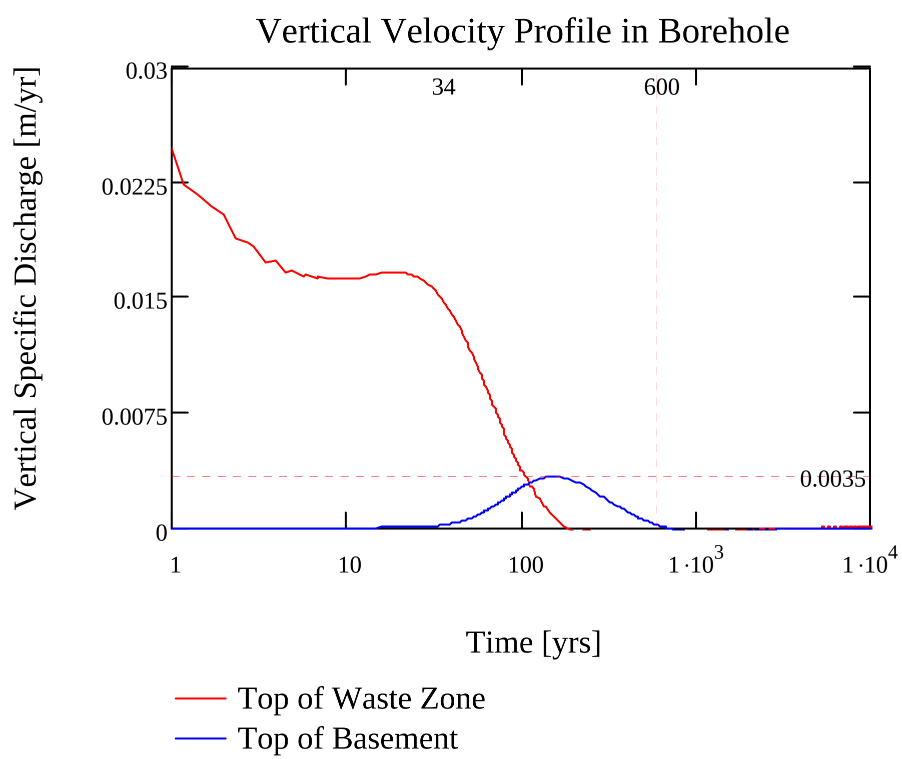
Coupled Thermal-Hydrologic Model

- **Results indicate upward vertical flow in the borehole driven primarily by thermal expansion, and not by free convection**
- **Significant upward flow persists for about 200 years at the top of the waste disposal zone**
- **Lesser upward flow occurs for about 600 years in the borehole at a location 1000 m above the waste**



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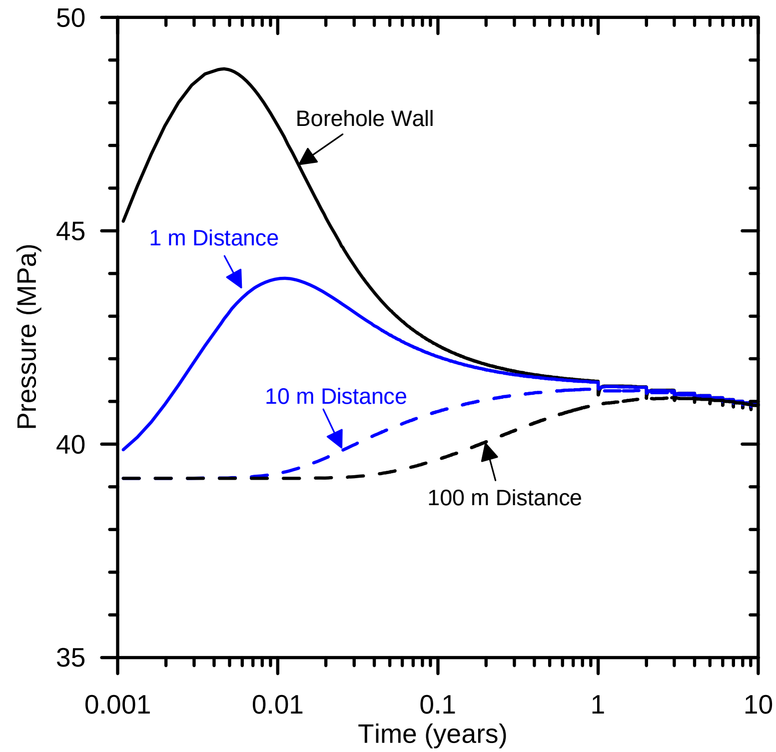
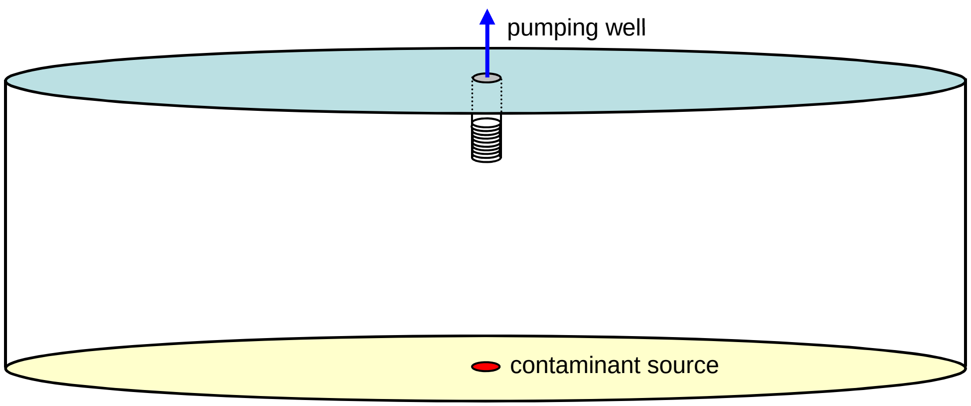
Potential for Thermal Hydrofracturing

- **Coupled thermal-hydrologic simulations were performed using 2-D model domain from thermal conduction calculations**
- **A low value of permeability was assumed for the granite (1 X 10^{-20} m^2) to maximize fluid pressure buildup**
- **Assuming an average vertical gradient in horizontal stress of 24 MPa/km, the simulated peak fluid pressure is well below the estimated horizontal stress of 96 MPa at a 4-km depth**



Groundwater Pumping and Dilution

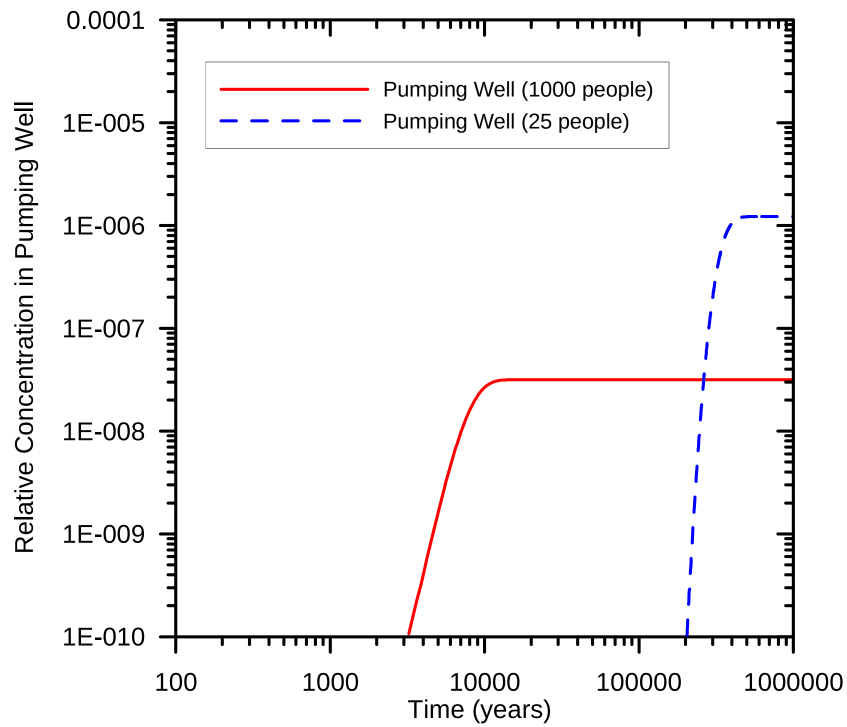
- **Radial 2-D model of groundwater pumping and contaminant transport was constructed for the fresh water system in the upper 2000 m of the geosphere**
- **Two pumping scenarios were used for water supply to 25 people and to 1000 people**
- **Contaminant source has a continuous specified flow rate equal to the peak value from the thermal-hydrologic simulations at 1000 m above the waste**



Not to Scale: Model domain has a radius of 10 km and depth of 2 km.
Contaminant source has a cross-sectional area of approximately 1 m^2.

Groundwater Pumping and Dilution

- **Results indicate significant delay in the transport of radionuclides to the pumping well and large amounts of dilution**
- **Radionuclide mass would arrive more quickly to the higher-capacity pumping well, but dilution would be greater**
- **Quantitative estimates of delay and dilution were incorporated into the performance assessment calculations**



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Summary and Conclusions

- **Peak temperature increases of about 30 ^{o}C and 125 ^{o}C at the borehole wall are predicted to occur for borehole disposal of PWR spent fuel assemblies and vitrified high-level waste from reprocessing, respectively**
- **Coupled thermal-hydrologic simulations indicate small volumetric flow rates for several hundred years, primarily from thermal expansion of fluid**
- **Modeling indicates limited potential for hydrofracturing of the host rock from thermal expansion of fluid**
- **Simulations of groundwater pumping and radionuclide transport in the shallow groundwater system show significant delays in transport to a pumping well and large amounts of dilution**

Scenario Selection

- Evaluated comprehensive list of FEPs from Yucca Mountain Project (YMP) and geologic disposal programs in other countries
- Formed three scenarios from retained (screened in) FEPs
  - Transport up borehole
  - Transport up DRZ/annulus around the borehole
  - Transport away from borehole in surrounding rock

Conclusions from the Preliminary PA

- **Deep borehole peak dose is 1.4 x 10^{-10} mrem/yr even with bounding assumptions**
- **YMP standard is 15 mrem/yr (< 10,000 yrs) and 100 mrem/yr (peak dose/1M yrs)**
- **Deep borehole peak dose only considers postclosure, does not consider emplacement/operations releases**

Conclusions and Recommendations

- **Preliminary evaluation suggests excellent long-term performance and competitive costs**
- **Open questions**
  - **Technical issues associated with reliably assured well construction, waste emplacement, and operations**
  - **Full consideration of potentially relevant features, events and processes**
  - **Full consideration of potential release mechanisms and pathways**

Conclusions and recommendations (cont.)

- Topics for further study
  - Coupled thermal-hydrologic-chemical-mechanical behavior of borehole environment during thermal pulse
  - Site selection/considerations based on in situ conditions
  - Seal design (materials and placement) and testing
  - Sequestration/sorbing of I-129
  - Scale-up from single-hole models to array
  - Borehole design
  - Operations
  - Cost analysis
  - Engineering system analysis
  - Legal and regulatory analysis
    - Retrievability
- Pilot project

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