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

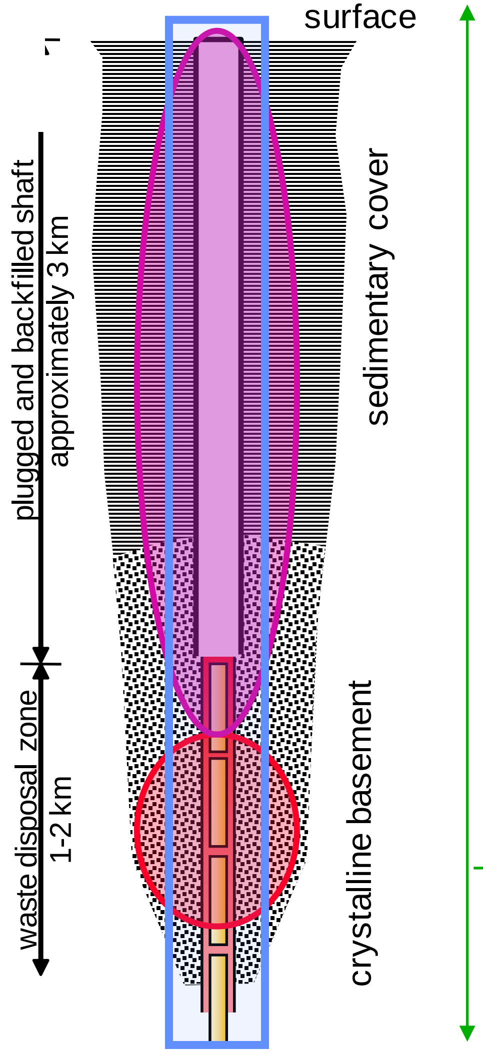
Peter Swift
Pat Brady, Bill Arnold, Geoff Freeze, Steve Bauer
Sandia National Laboratories

DOE Fusion-Fission Hybrid Workshop
Gaithersburg, MD
October 1, 2009

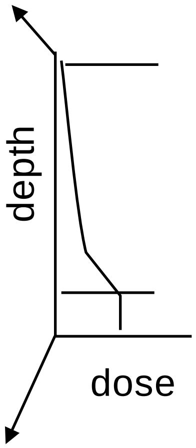
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. The content of this presentation reflects the views of the author and does not necessarily reflect the views or policies of the United States Department of Energy or Sandia National Laboratories

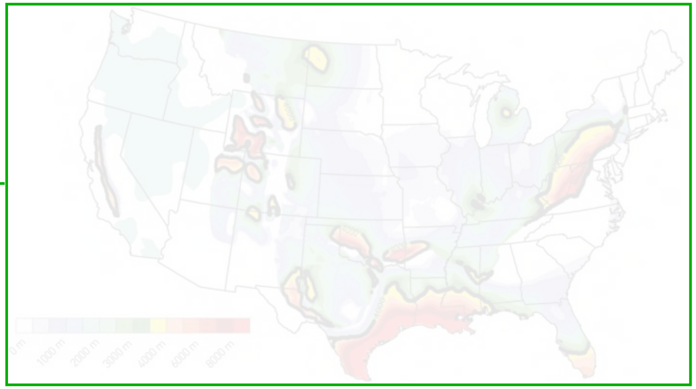
History of Borehole Disposal Concepts

- 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



(not to scale)

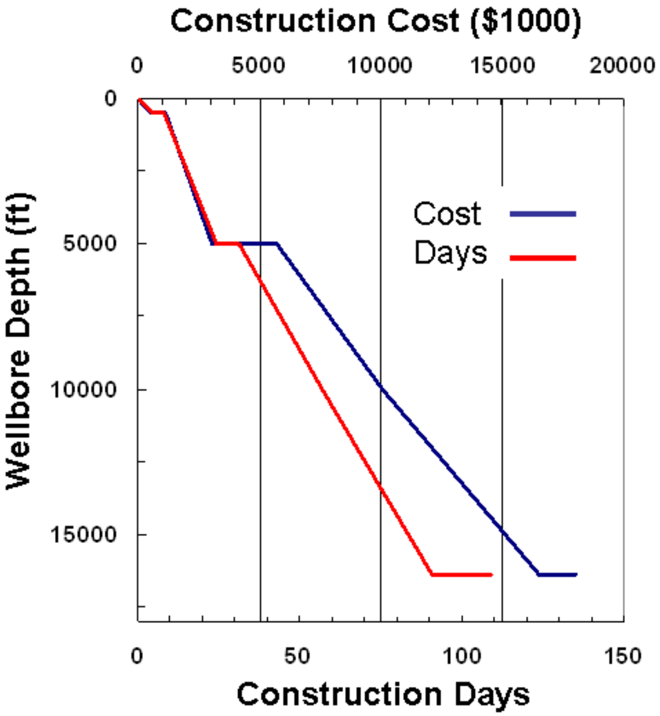




Nominal 5 km borehole

- **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

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**
-

Deep Borehole Disposal: Advantages and Disadvantages

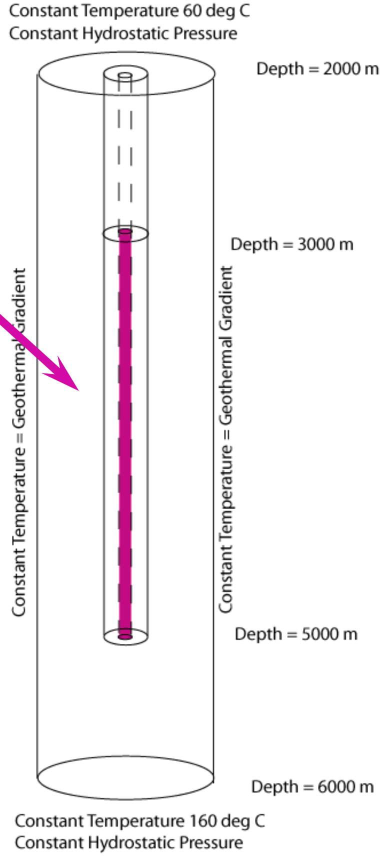
- Advantages
  - Excellent prospects for long-term isolation
  - Competitive cost
  - Wide range of suitable locations
  - Readily scales up or down in size
  - Waste is essentially irretrievable

- 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

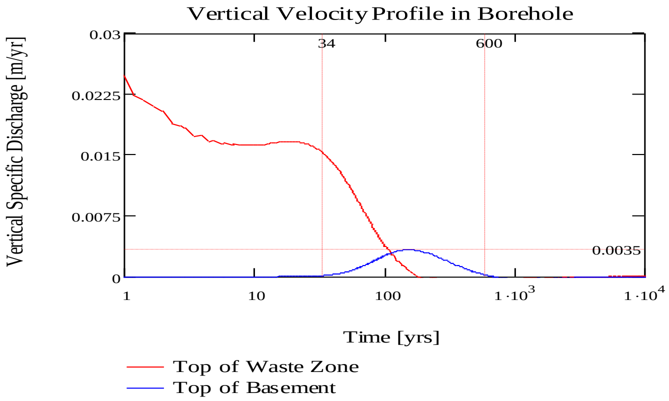
- **Waste Disposal Zone**
  - Single borehole with 400 PWRs vertically stacked down a 2000 m disposal zone
  - No credit for waste package or waste form degradation
  - Inventory (31 radionuclides with decay and ingrowth) consistent with YMP PWR assemblies aged to 2117
  - Dissolved concentrations subject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

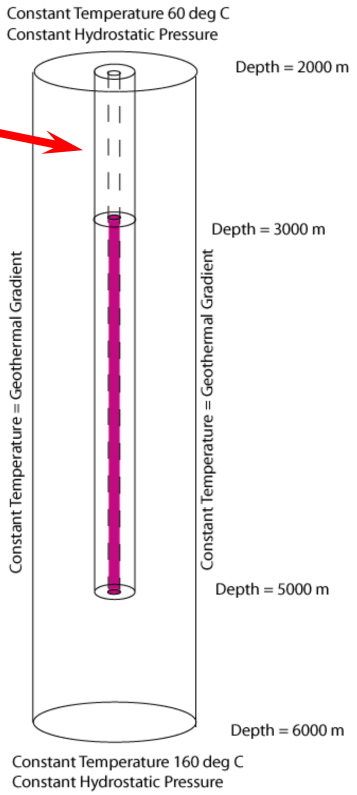


Not to Scale: Domain Radius is 100 m, height is 4 km
Borehole (radius 0.15 m) + Disturbed Zone has a cross-sectional area of 1 square meter

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

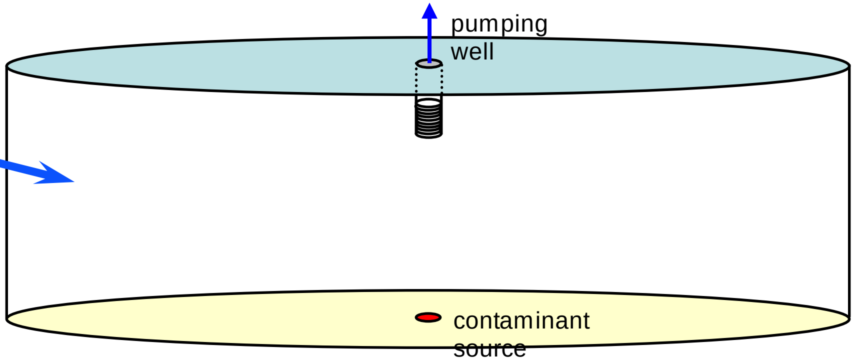




Not to Scale: Domain Radius is 100 m, height is 4 km
Borehole (radius 0.15 m) + Disturbed Zone has a cross-sectional area of 1 square meter

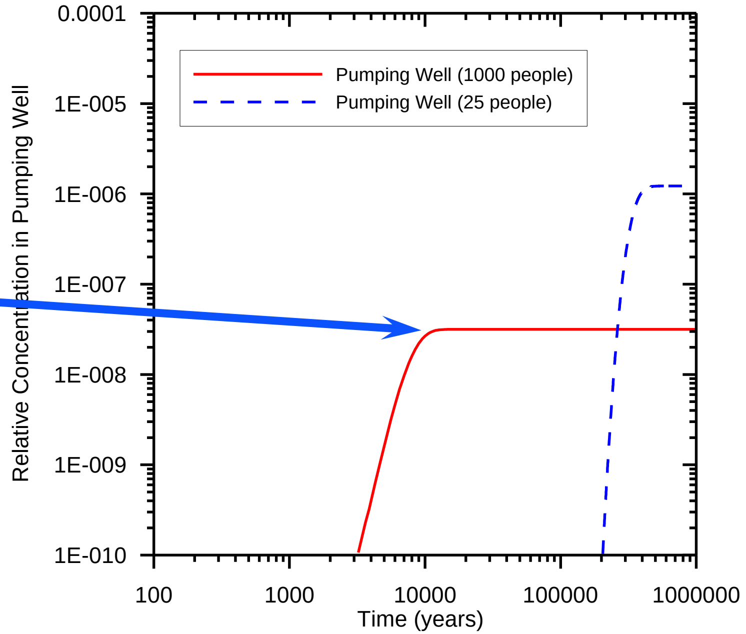
Scenario Description – Geosphere Transport

- **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 x 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 x 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

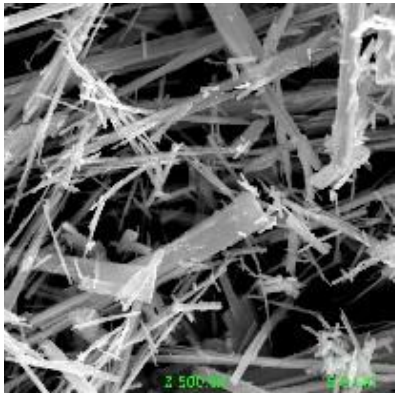
Solubilities; T = 200^{o}C, pH 8.5,
E_H = -300 mV, 2M NaCl solution

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}

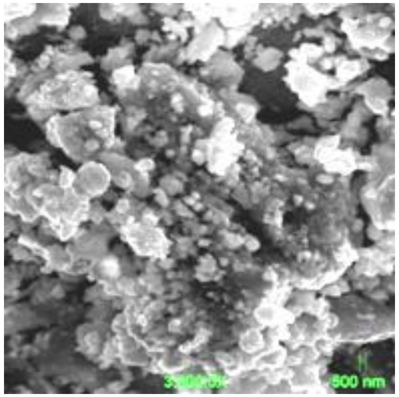
Source term and Borehole K_ds.

Element	**$k_{d\ \text{basement}}$**	**$k_{d\ \text{sediment}}$**	**$k_{d\ \text{bentonite}}$**
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

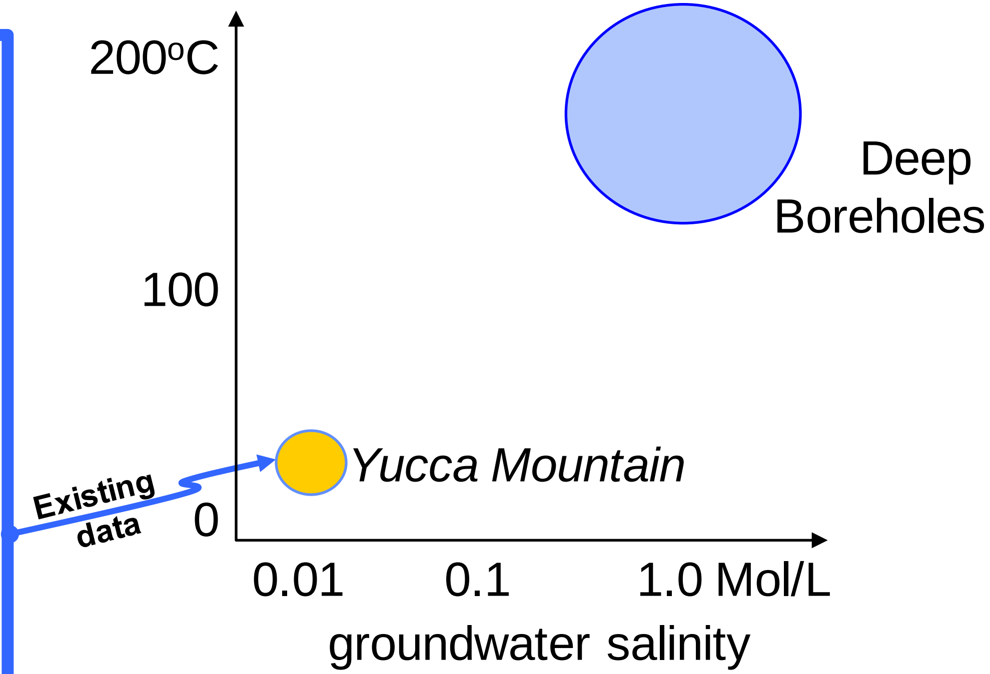
Bismuth-based ^{129}I sorbents



K_d = 720 ml/g



K_d = 2300 ml/g



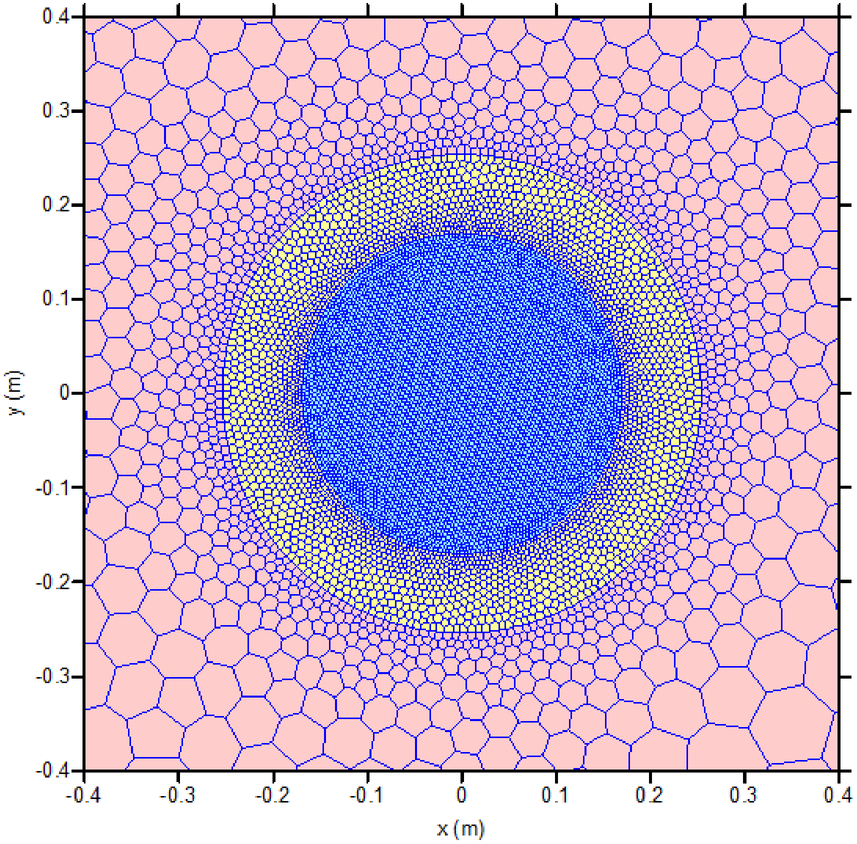
- Thermal stability of Bi phases
- Effect of anion competition
- Reversibility
- Modification

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

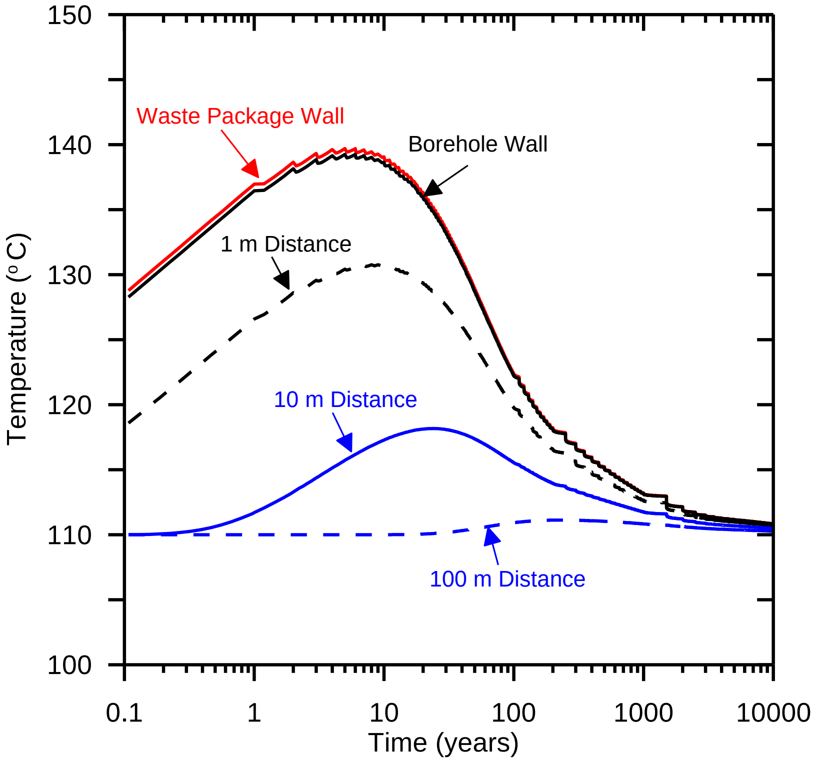
Thermal Conduction

- 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



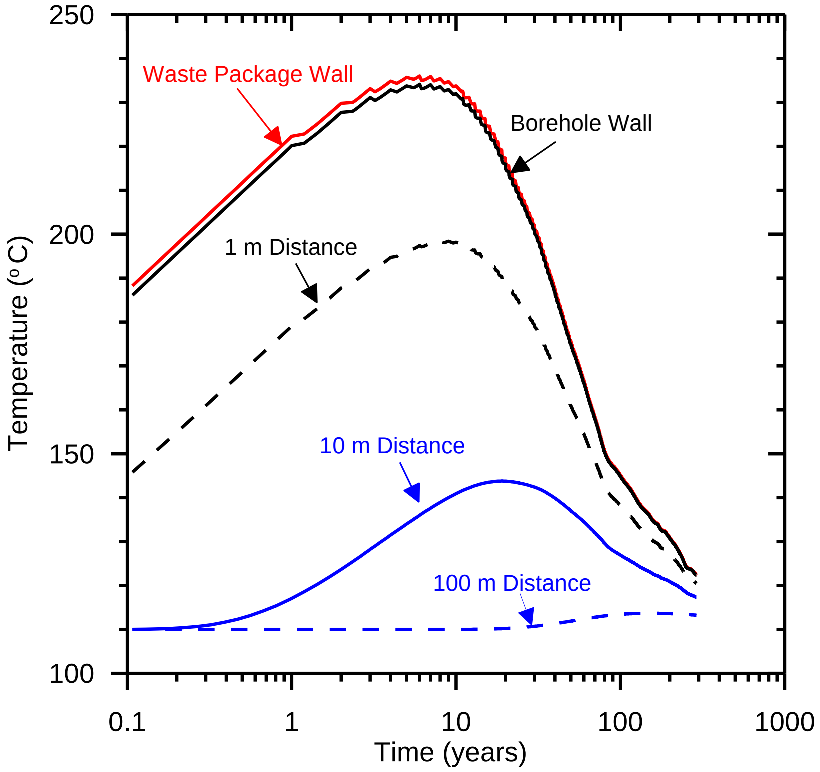
Thermal Conduction

- 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

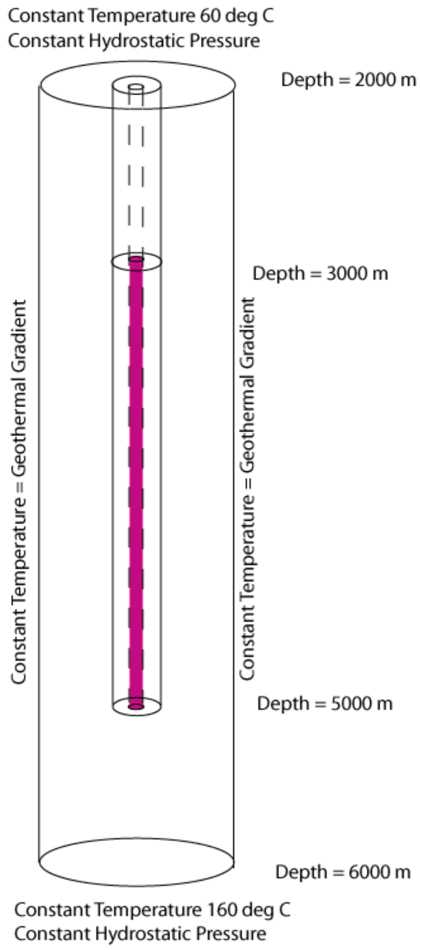


Thermal Conduction

- **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 ^{o}C at the borehole wall, which is significantly higher than the for disposal of PWR spent nuclear fuel assemblies**



Coupled Thermal-Hydrologic Model

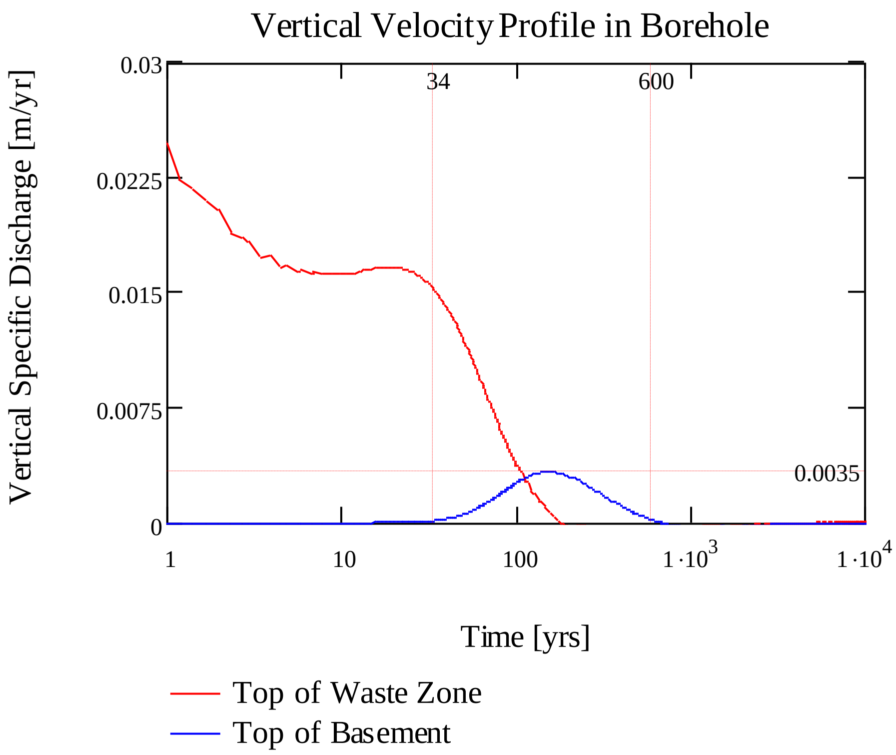


Not to Scale: Domain Radius is 100 m, height is 4 km
Borehole (radius 0.15 m) + Disturbed Zone has a cross-sectional area of 1 square meter

- **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**

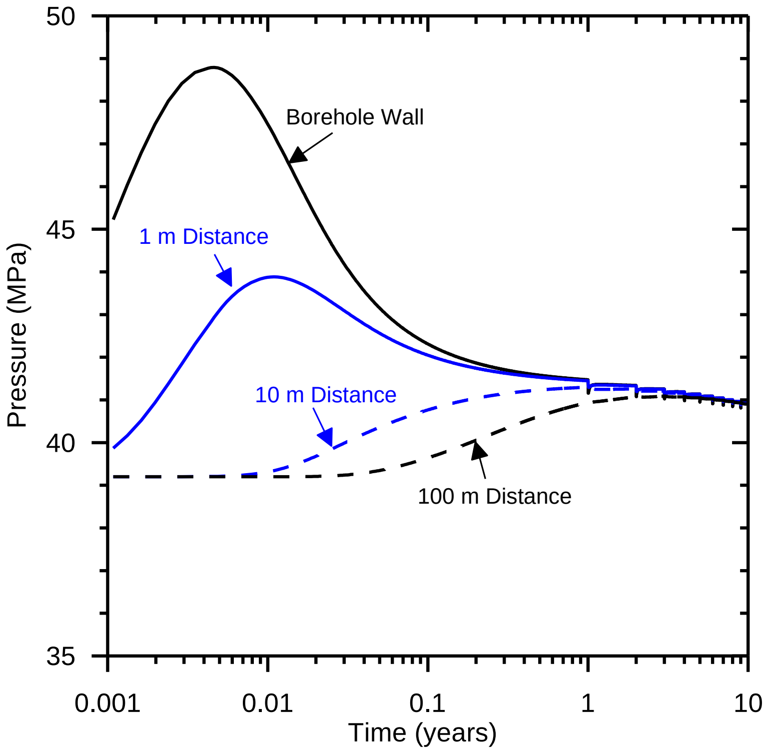
Coupled Thermal-Hydrologic Model

- **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**



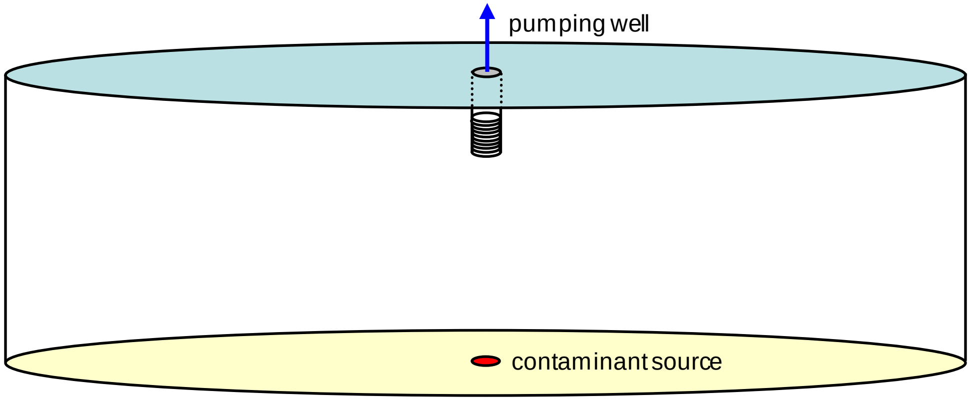
Potential for Thermal Hydrofracturing

- **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

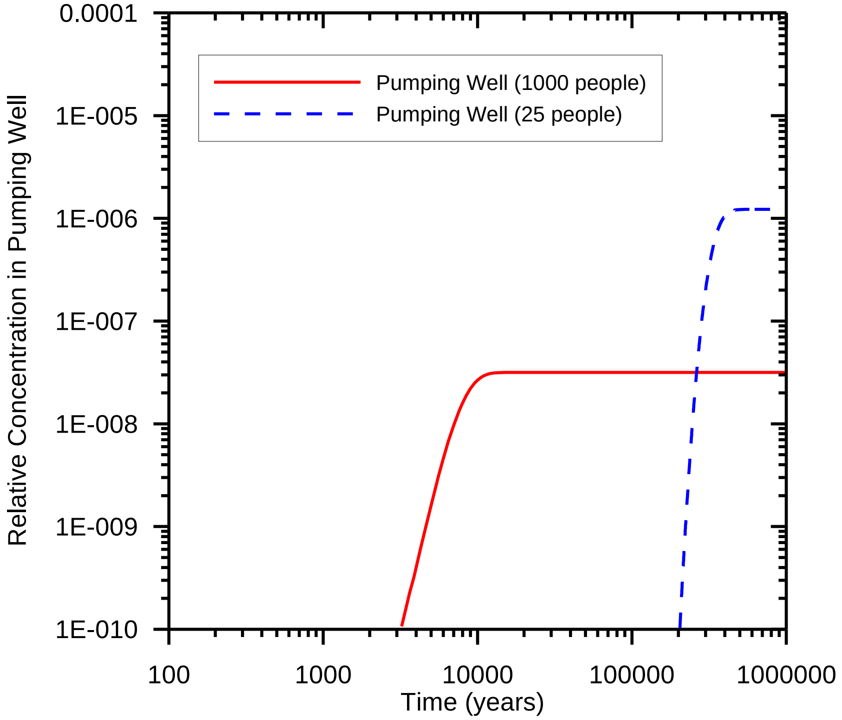
- **Radial 2-D model of groundwater pumping and contaminant transport was constructed for the fresh water system in the upper 2000 m of the geosphere**
- **Two pumping scenarios were used for water supply to 25 people and to 1000 people**
- **Contaminant source has a continuous specified flow rate equal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



Summary and Conclusions

- Peak temperature increases of about 30 °C and 125 °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**