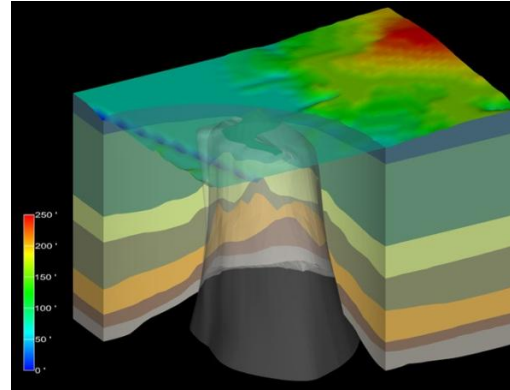


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Deep Borehole Disposal Concept for High-Level Radioactive Waste

Kansas Geological Survey – August 13, 2013

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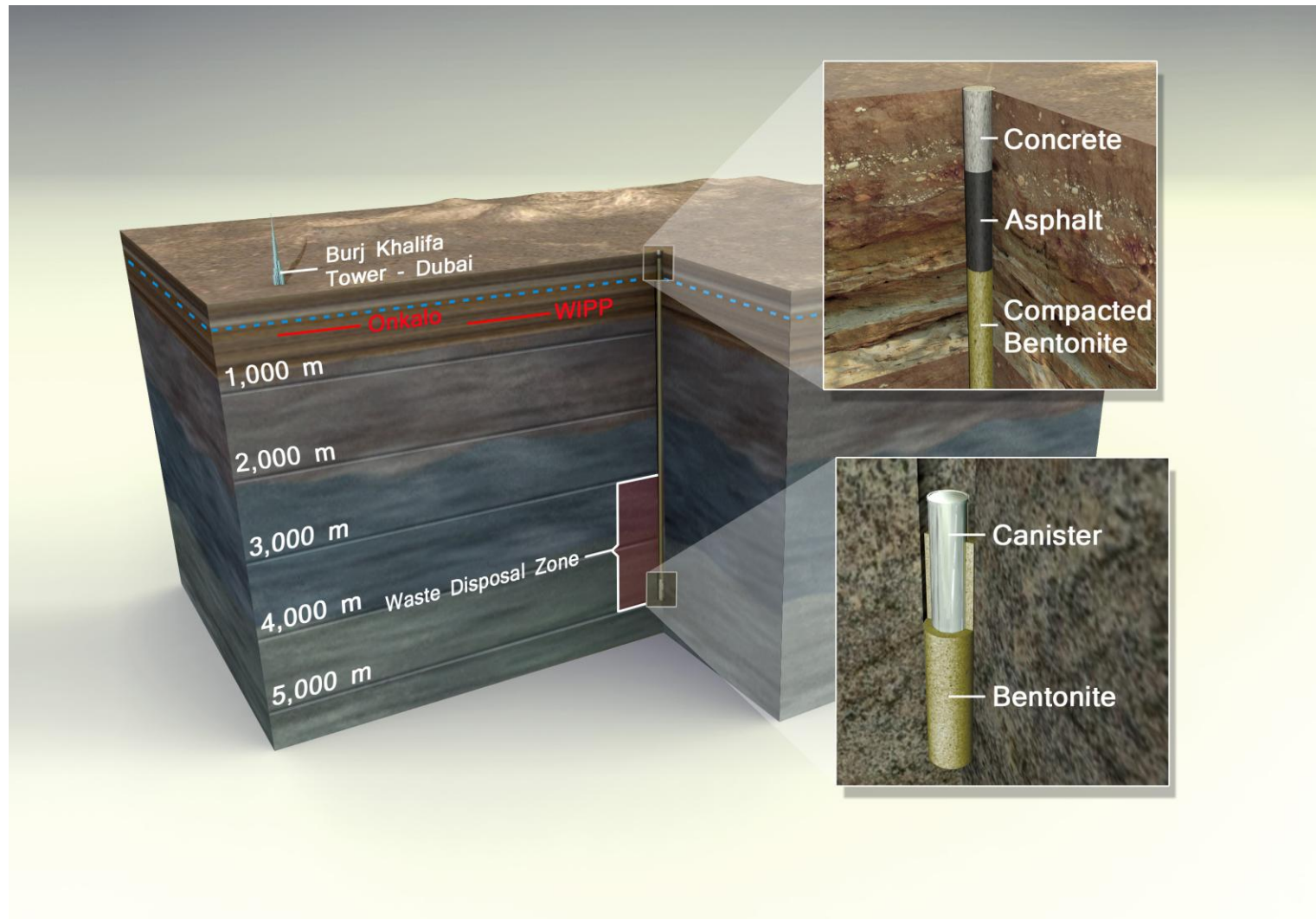
Outline

- **Deep borehole disposal concept**
- **Geological aspects of disposal system safety and borehole siting**
- **Reference design and operations for a deep borehole disposal system**
- **Deep borehole disposal safety analyses**
- **Deep borehole disposal research, development, and demonstration**
- **Conclusions**

Deep Borehole Disposal Concept

- **Deep borehole disposal of high-level radioactive waste has been considered in the U.S. since the 1950s and has been periodically studied since the 1970s**
- **Disposal concept consists of drilling a borehole or array of boreholes into crystalline basement rock to about 5,000 m depth**
- **Borehole casing or liner assures unrestricted emplacement of waste canisters**
- **Waste would consist of spent nuclear fuel, high-level radioactive waste, or other specialized solid waste types**
- **Approximately 400 waste canisters would be emplaced in the lower 2,000 m of the borehole**
- **Upper borehole would be sealed with compacted bentonite clay , cement plugs, and cemented backfill**

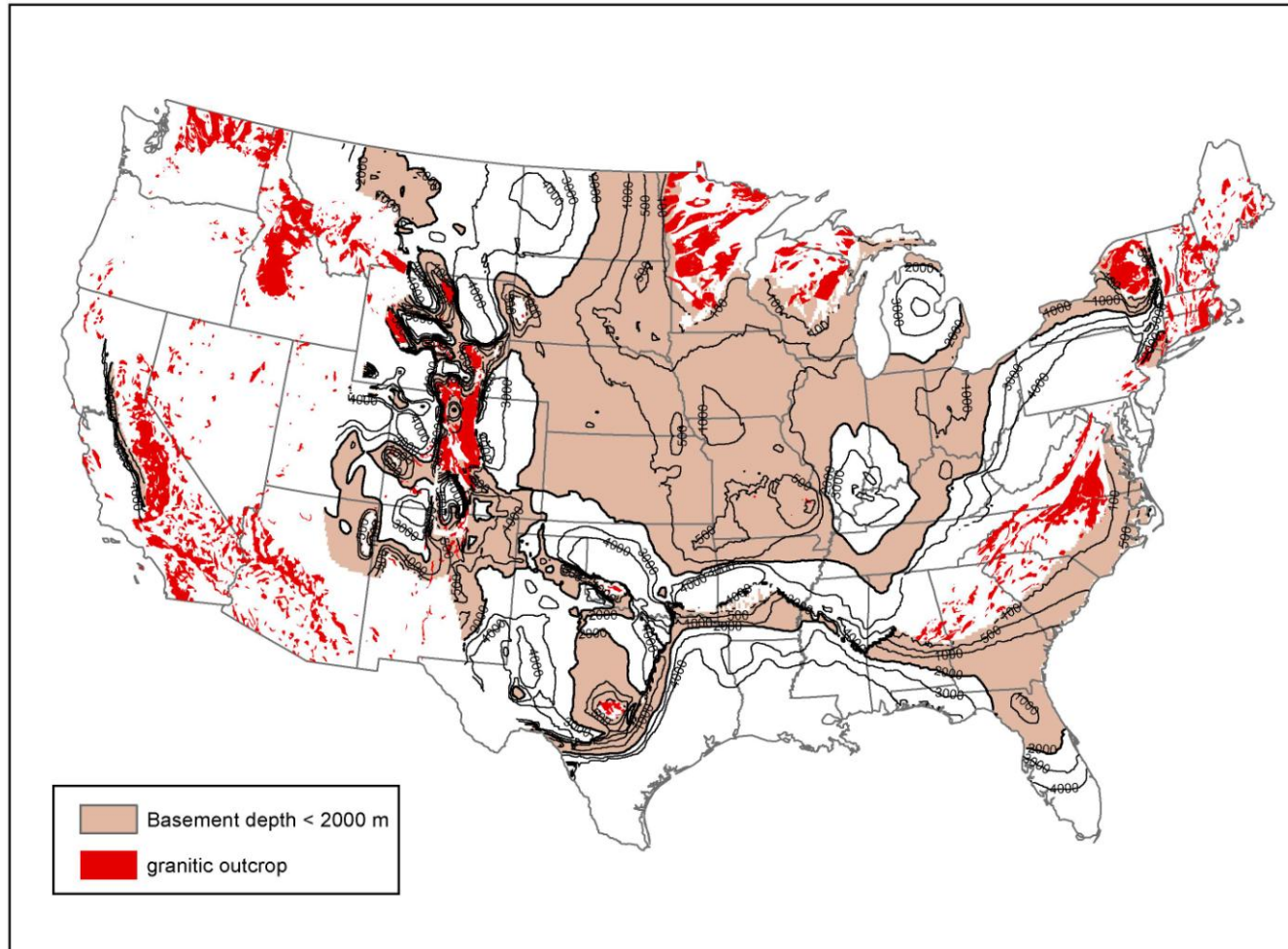
Deep Borehole Disposal Concept



Deep Borehole Disposal Concept: Viability and Safety

- **Crystalline basement rocks are common in many stable continental regions**
- **Existing drilling technology permits reliable construction at acceptable cost**
- **Low permeability and long residence time of high-salinity groundwater in deep continental crystalline basement at many locations suggests very limited interaction with shallow fresh groundwater resources**
- **Geochemically reducing conditions at depth limit the solubility and enhance the sorption of many radionuclides in the waste**
- **Density stratification of saline groundwater underlying fresh groundwater would oppose thermally induced groundwater convection**

Geological Aspects of Safety and Siting



from Perry (2013)

Geological Aspects of Safety and Siting

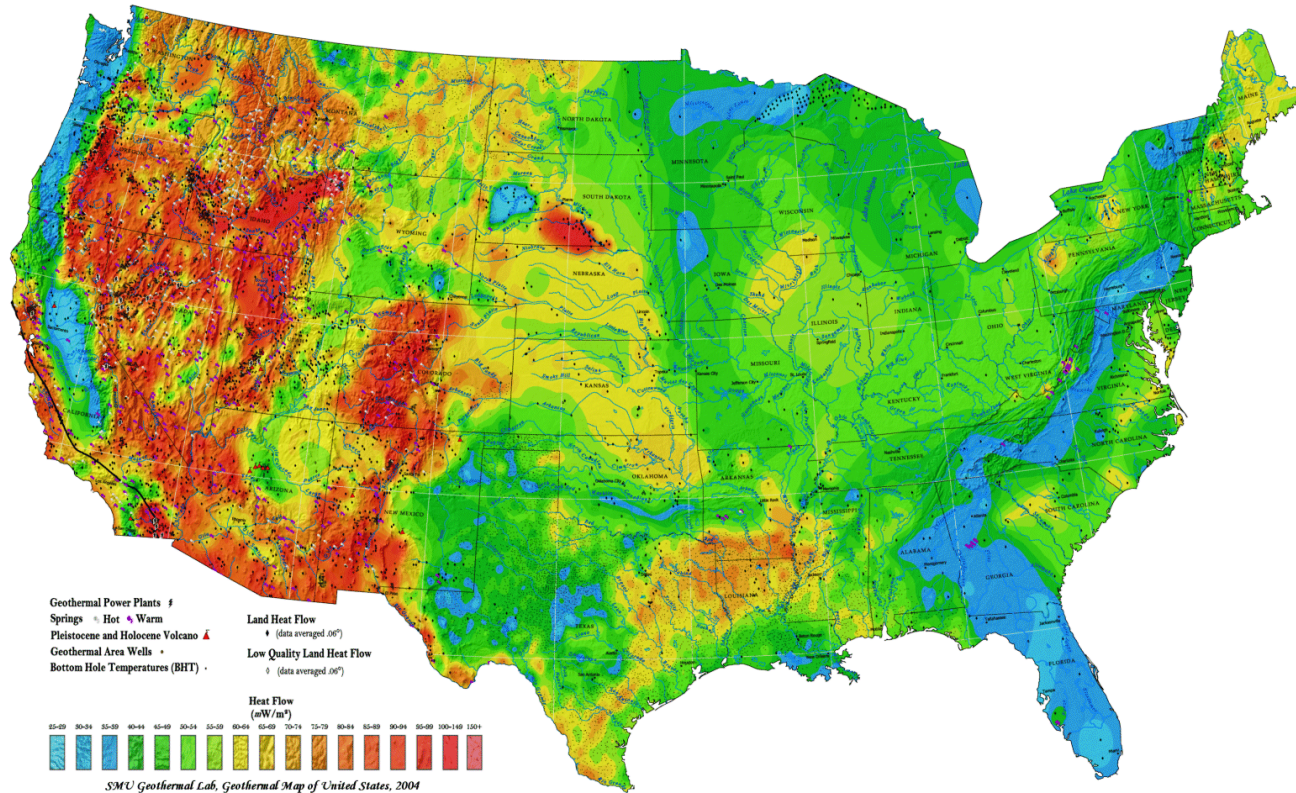
- Geological characterization conditions that are undesirable or not optimal for the deep borehole disposal concept and waste isolation:
 - Young meteoric groundwater at depths of greater than 3 km
 - Low-salinity, oxidizing groundwater at depths of greater than 3 km
 - Economically exploitable natural resources at depths of greater than 3 km depth
 - Significant upward gradient in fluid potential (overpressured conditions) from below 3 km depth
 - Natural interconnected zone of high permeability from the waste disposal zone to the surface or shallow subsurface environment (e.g., fault zone)
 - High geothermal heat flow
 - Significant differential in horizontal stress at depth
 - Tectonically active areas (high topographic relief, Quaternary faulting and volcanism, higher seismic risk)

Geological Aspects of Safety and Siting: Aeromagnetic Survey



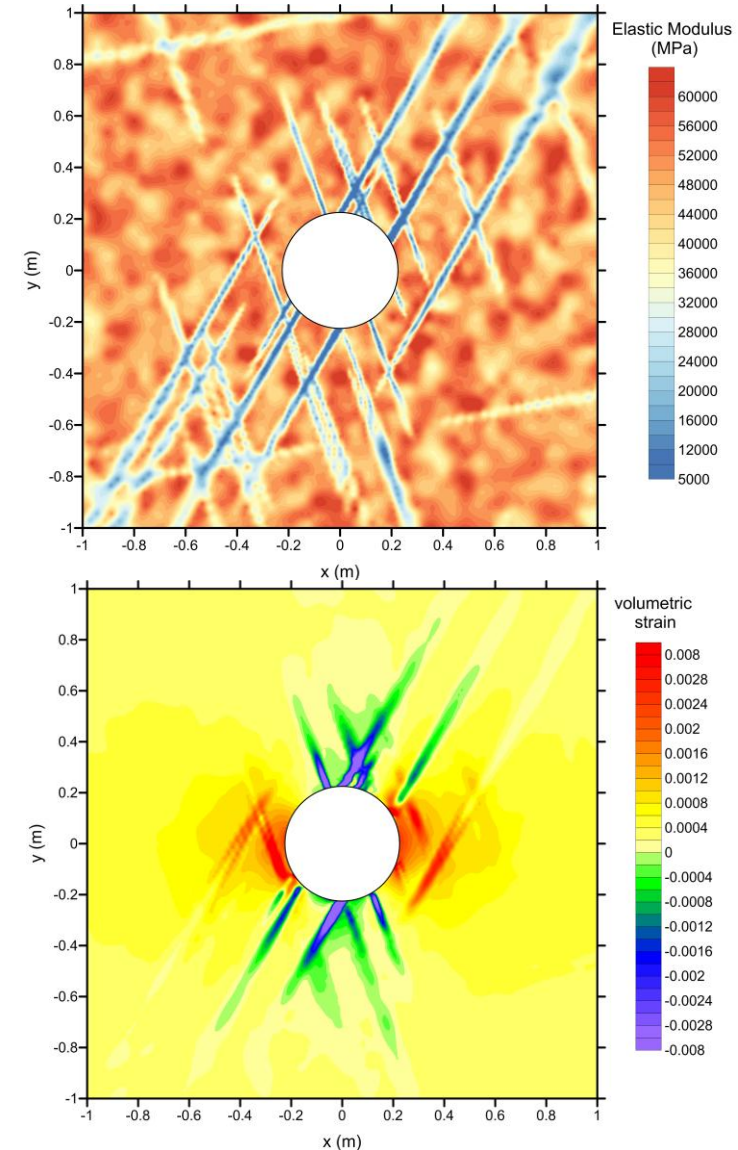
from Sims et al. (2008)

Geological Aspects of Safety and Siting: Geothermal Heat Flow



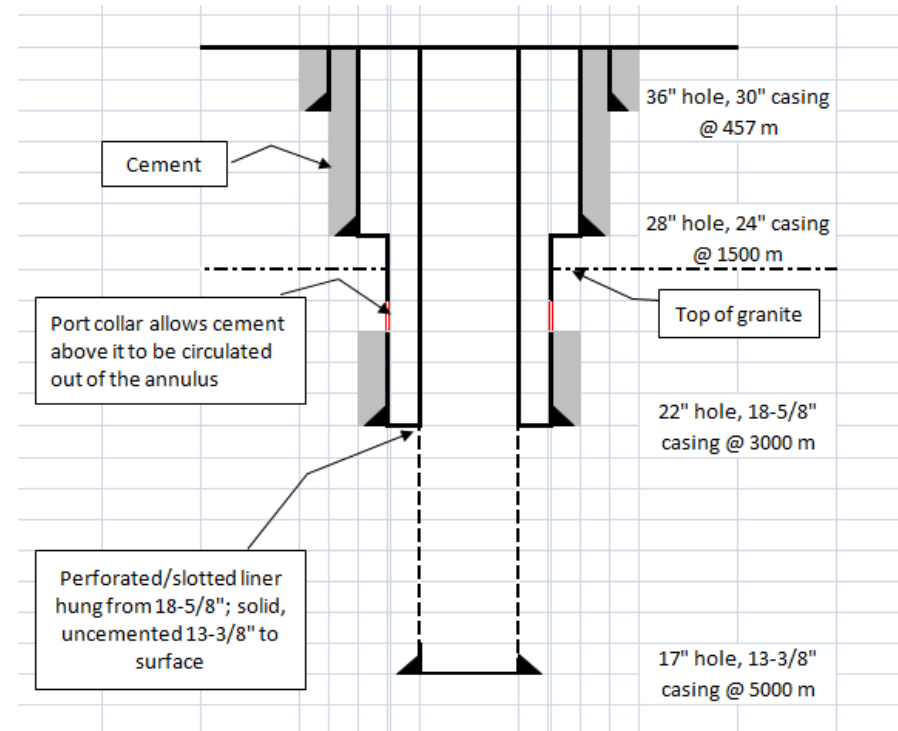
Geological Aspects of Safety: Thermal-Mechanical Modeling

- For differential horizontal stress, the disturbed rock zone near the borehole is placed in extension in the direction of minimum horizontal stress
- Permeability will be increased by extensional strain and decreased by compression
- Coupled thermal-mechanical modeling results for heterogeneous fractured granite and anisotropic horizontal stress shown for disposal of average used pressurized water reactor (PWR) fuel assembly – 5 years after disposal
- Higher temperatures near the borehole and related thermal expansion place much of the host rock in compression
- Some of the fractures in the general direction of the minimum principal horizontal stress remain in extension and would have increased permeability relative to the undisturbed rock



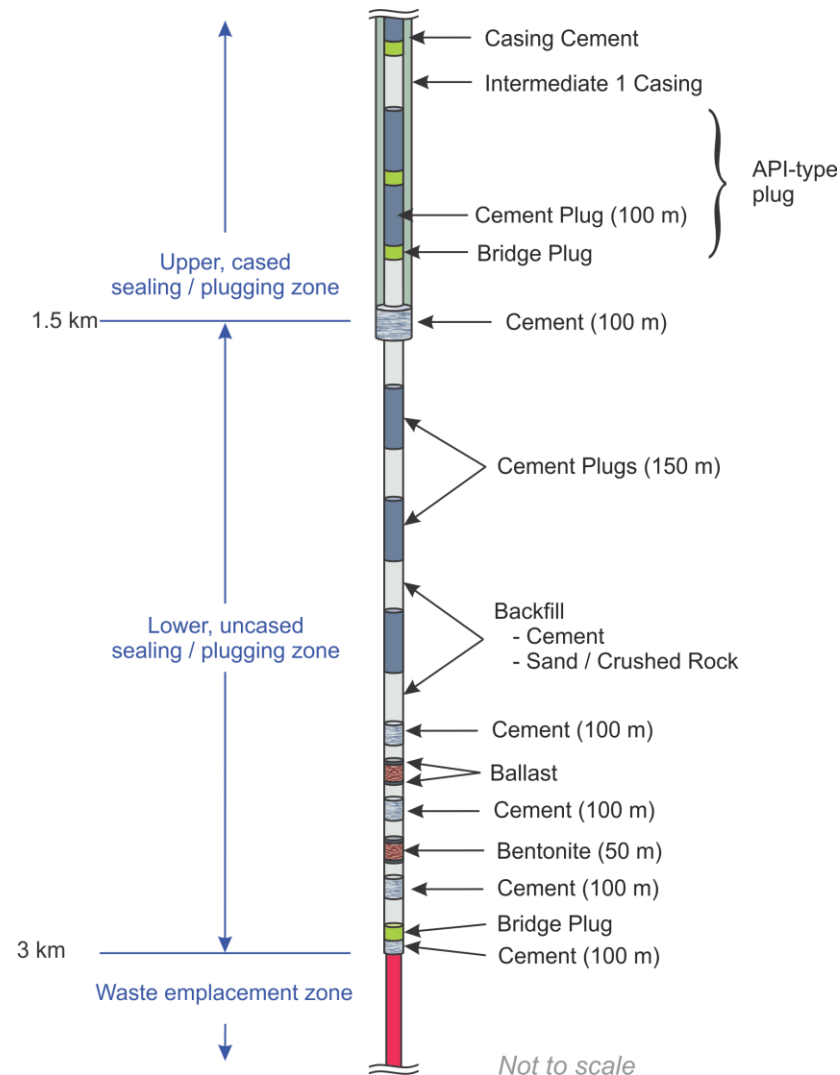
Reference Design and Operations: Borehole Design

- Drilling to 5 km depth is not exceptional for geothermal development and 17 inches diameter should be feasible with current technology
- The perforated liner will be left in place in the disposal zone, but may be removed in the seal zone, along with most of the intermediate casing
- Canisters are designed to withstand projected hydrostatic pressure and mechanical load of overlying canisters
- Emplacement option: Strings of up to 40 canisters (about 200 m) may be attached to the pipe string with a J-slot assembly and lowered to the disposal zone



Reference Design and Operations: Seals Design

- After the waste canisters have been emplaced and the immediately overlying plugs have been set, the guide casing will be removed and the intermediate casing in the seal zone (1.5 to 3.0 km depth) will be cut and removed
- Seals and plugs in the seal zone will be seated in contact with the rock of the borehole walls
- Compacted bentonite seals that swell by the uptake of water would be set by extrusion from a container or emplacement of a perforated tube
- Cement seals, alternating with sand/crushed rock/cement backfill, would fill the remainder of the seal zone



Deep Borehole Disposal Costs

- **Costs are dominated by borehole drilling and construction**
- **There is significant uncertainty about drill rig time and cost associated with testing and logging of the borehole**
- **The estimated \$27M cost shown here is for boreholes following the more intensively characterized initial borehole at a site**
- **Aside from transportation costs, estimated disposal costs are \$158/kg heavy metal (HM) (compared to the U.S. nuclear waste fund fee of roughly \$400/kg HM (Gibbs, 2010))**
- **Estimated time for drilling, borehole completion, waste emplacement, and sealing is about 186 days**

	Cost per Borehole
Drilling, Casing, and Borehole Completion	\$27,296,587
Waste Canisters and Loading	\$7,629,600
Waste Canister Emplacement	\$2,775,000
Borehole Sealing	\$2,450,146
Total	\$40,151,333

Note: All costs are in 2011 \$US and approximately for 2011 expenses.

from Arnold et al. (2011)

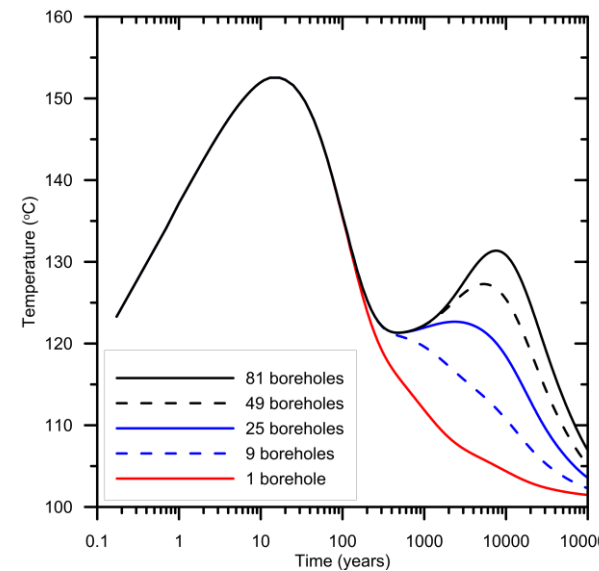
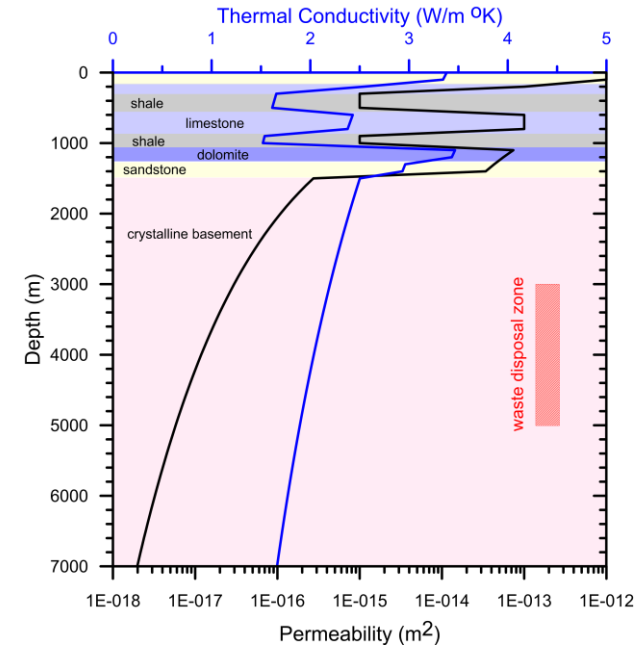
Deep Borehole Disposal Capacity

- **Current commercial used fuel inventory could be disposed in 273 boreholes using the reference design and rod consolidation of all waste in canisters (disposal of about 240 metric tons of uranium per borehole)**
- **The slowed replacement scenario assumes half the rate of new plant construction between the no replacement and the maintain current capacity scenarios**

Scenario				Number of Boreholes Needed		
	PWR MTU	BWR MTU	Total MTU	0% Rod Consolidation	100% Rod Consolidation	PWR Only 100% Rod Consolidation
2010 Current Inventory	42300	23000	65300	568	273	499
No Replacement – end in 2055	91000	49000	140000	1215	585	1067
Maintain Current – through 2100	175000	95000	270000	2346	1127	2062
Slowed Replacement – through 2100	133000	72000	205000	1780	856	1564
Maintain - 40K MTU – through 2100	149500	80500	230000	1995	960	1752
Slowed Replacement - 40K MTU – through 2100	107250	57750	165000	1431	689	1257

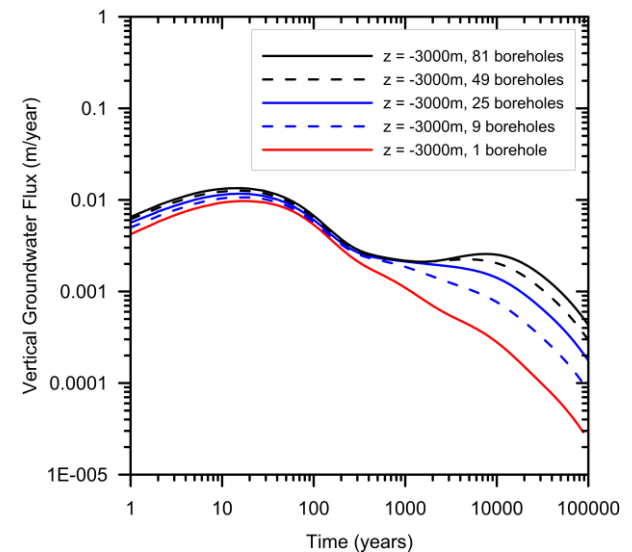
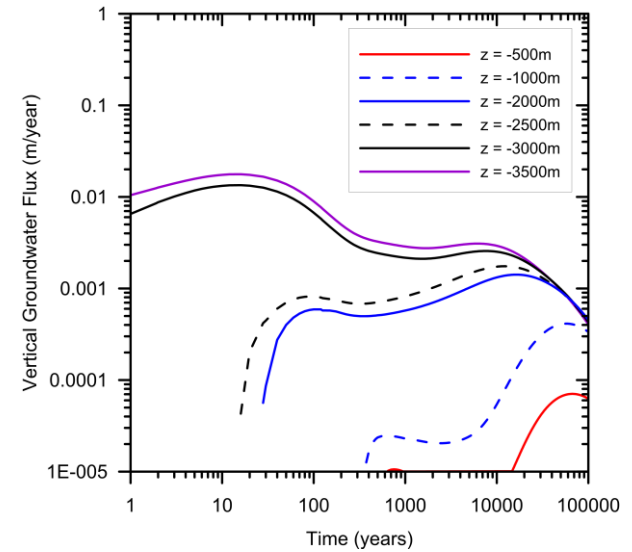
Safety Analyses: Thermal-Hydrologic Modeling

- The assumed hydrogeological domain for the model consists of granite, capped by 1,500 m of horizontal, layered sedimentary rocks, representative of stable continental interior regions of North America
- Reference values of permeability are assigned using the functional relationship with depth for average crustal conditions from Manning and Ingebritsen (1999)
- Thermal output from the waste canisters is based on the disposal of average used pressurized water reactor (PWR) fuel
- Simulated temperature history near the central borehole of the array at 4 km depth for varying borehole array sizes and spacing of 200 m



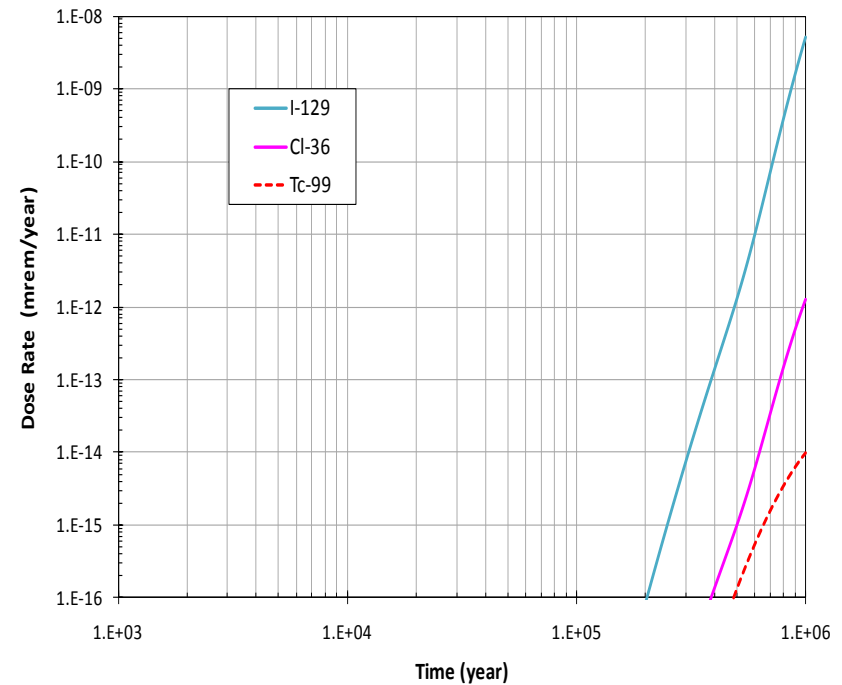
Safety Analyses: Thermal-Hydrologic Modeling

- Simulated vertical groundwater flow rates in the borehole/disturbed rock zone resulting from thermally driven convection are shown for the central borehole in an 81 borehole array in the top figure
- Near peak upward flow rates occur for a few decades within and just above the waste disposal zone
- Secondary lower peak flow rates occur within and above the waste disposal zone on the time scale of 10,000s of years
- Simulated vertical flow rates at the top of the waste disposal zone are shown for borehole arrays of varying sizes in the lower figure



Safety Analyses

- Preliminary probabilistic performance assessment modeling is used to evaluate the radiological dose from a single borehole containing about 291 metric tons of heavy metal PWR used fuel
- Fluid flow is simulated using a thermal-hydrologic model of thermal convection in the disturbed rock zone around the borehole seals
- Radiological dose is calculated for drinking water exposure from groundwater in a shallow water supply aquifer
- Model results indicate average projected radiological dose, primarily from ^{129}I , that is many orders of magnitude below regulatory limits at 1 million years



Deep Borehole Disposal: Research, Development, and Demonstration

- **Additional research, development, and demonstration (RD&D) is required in several important areas before implementation of deep borehole disposal of radioactive waste, including:**
 - **Demonstration of drilling technology and borehole construction to 5 km depth with sufficient diameter for cost effective waste disposal**
 - **Verification of deep geological, geochemical, and hydrological conditions at a representative location**
 - **Evaluation of canister, waste, and seals materials at representative temperature, pressure, salinity, and geochemical conditions**
 - **Development and testing of engineering methods for waste canister loading, shielded surface operations, waste canister emplacement, and borehole seals deployment**
- **The RD&D objectives for deep borehole disposal would be best met with a borehole demonstration project that is conducted to a depth of 5 km in a representative location (without actual waste disposal)**

Concluding Remarks

- **Multiple factors indicate that deep borehole disposal of radioactive waste is safe for widely available locations with favorable geological and hydrological characteristics**
- **Implementation of deep borehole disposal with a simple reference design and operations would be feasible, cost effective, and have sufficient capacity**
- **A deep borehole RD&D demonstration project (without emplacement of radioactive materials) is the next logical step in evaluating this waste disposal option**
- **Economic and scientific benefits of a deep borehole demonstration project for local, state, and regional stakeholders could be valuable**

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