SAND2012-1383C

Geological and Practical Aspects of Deep Borehole Disposal

Nuclear Waste Technical Review Board
Spring Meeting
Albuquerque, New Mexico

March 7, 2012

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Sandia National Laboratories

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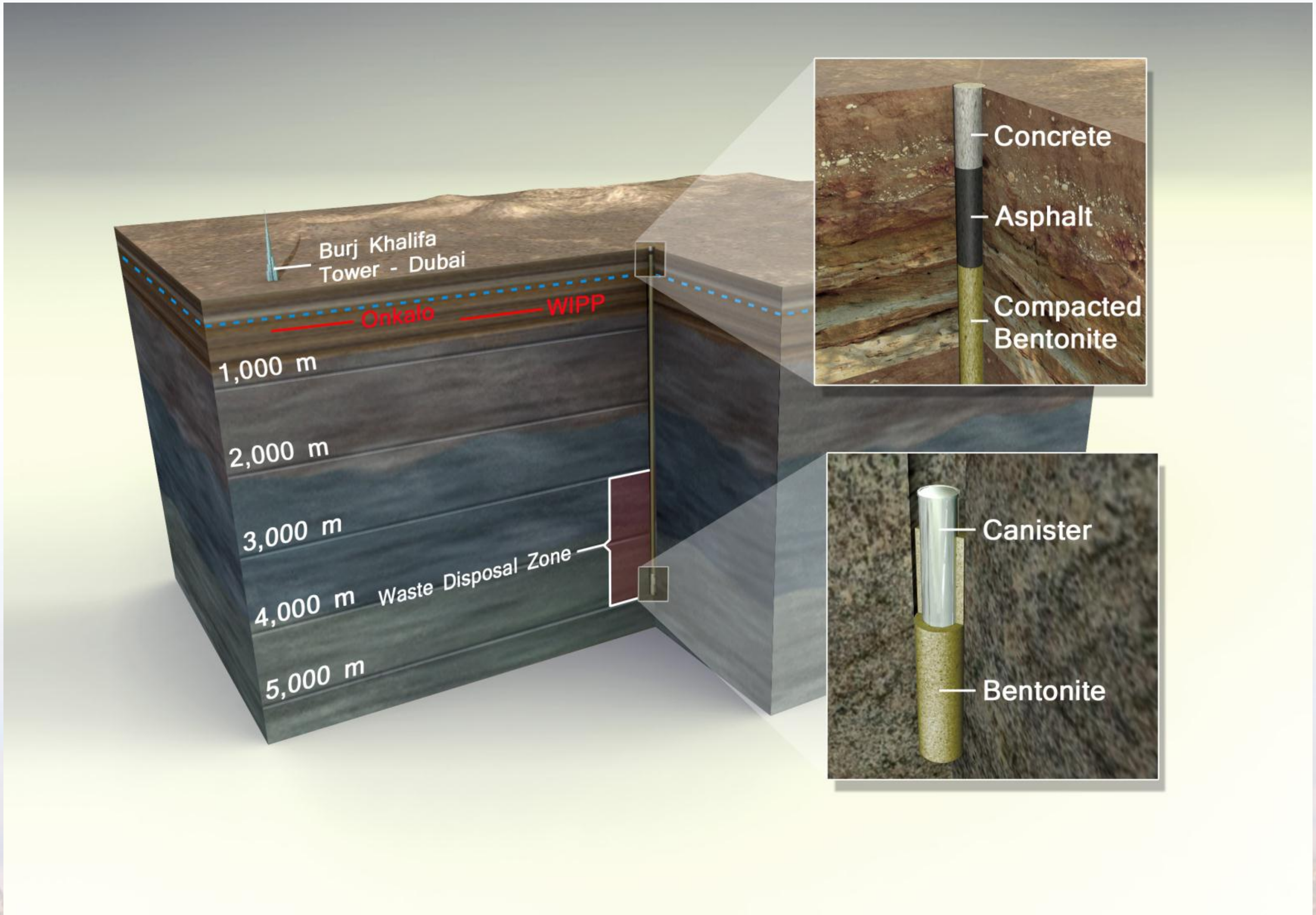
Outline

- Deep borehole disposal concept
- Geological aspects of disposal system safety and borehole siting
- Reference design and operations for a deep borehole disposal system
- Practical aspects of deep borehole disposal
- Conclusions

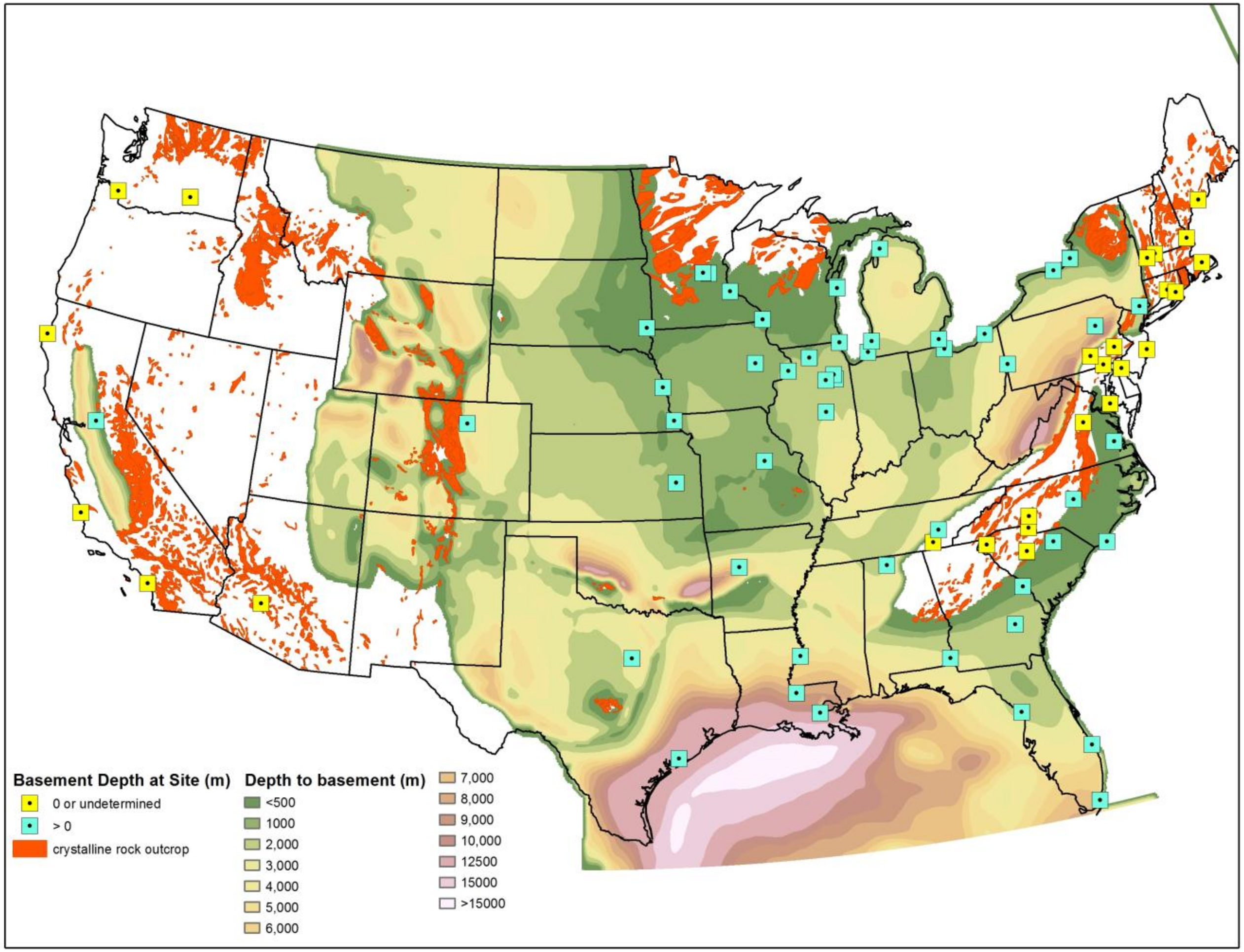
Deep Borehole Disposal Concept

- Disposal concept consists of drilling a borehole or array of boreholes into crystalline basement rock to about 5,000 m depth
- 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 and cement plugs
- Several factors suggest the disposal concept is viable and safe:
  - Crystalline basement rocks are common in many stable continental regions
  - Existing drilling technology permits dependable 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

Deep Borehole Disposal Concept



Geological Aspects of Safety and Borehole Siting



from Perry (2011)

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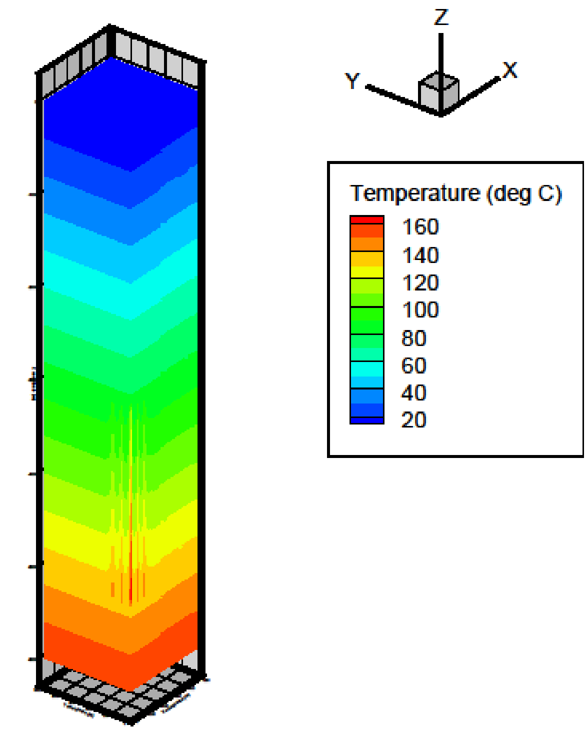
Geological Aspects of Safety and Borehole Siting

- **Geological characterization should focus on conditions that are undesirable for the deep borehole disposal concept and waste isolation:**
- **<u>Young meteoric groundwater at depths of greater than 3 km</u>**
- **<u>Low-salinity, oxidizing groundwater at depths of greater than 3 km</u>**
- **<u>Economically exploitable natural resources at depths of greater than 3 km</u>**
- **<u>Significant upward gradient in fluid potential (overpressured conditions) from below 3 km depth</u>**
- **<u>Natural interconnected zone of high permeability from the waste disposal zone to the surface or shallow subsurface environment (e.g., fault zone)</u>**
- **<u>High geothermal heat flow</u>**
- **In the absence of these unfavorable features, the most likely scenario for release of radionuclides to the biosphere is thermally driven groundwater flow (from waste heat) through the borehole or surrounding disturbed rock zone**

Geological Aspects of Safety: 3D Thermal-Hydrologic Modeling

- **3D coupled thermal – hydrologic model simulates waste heat in the disposal zones of multiple boreholes**
- **The model uses a variable resolution mesh and quarter symmetry boundaries**
- **Simulations are run using the FEHM software code**
- **Objectives are: (1) evaluate sensitivity to borehole spacing, (2) evaluate sensitivity to number of boreholes, and (3) provide simulated groundwater flow rates as functions of time and depth for use in the performance assessment model**

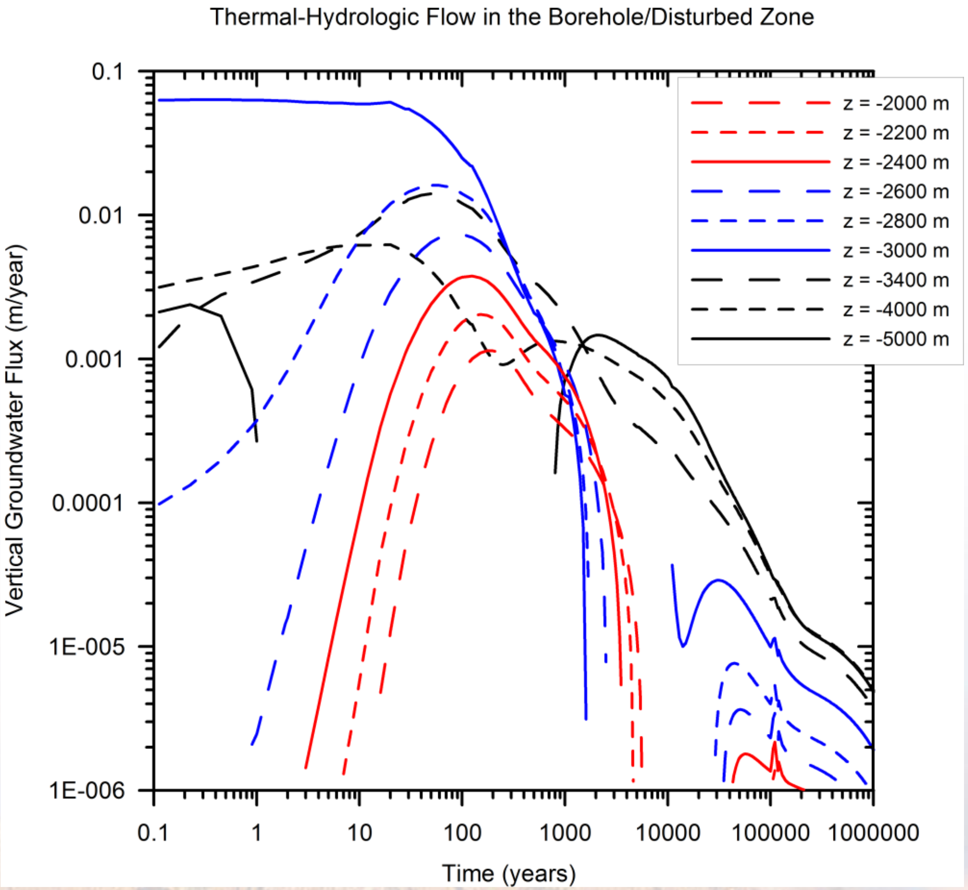


25 boreholes, 100 m well spacing, Time = 10 years

Geological Aspects of Safety: 3D Thermal-Hydrologic Modeling

- Simulated specific discharge in the borehole/disturbed zone for 9 boreholes with 200 m spacing shown
- Groundwater flow induced by waste heat occurs by thermal expansion at earlier times and buoyant free convection at later times
- Upward flow rates are overestimated because salinity stratification is not included in this model
- These results and results from a high-permeability case are used as input to the PA model (Swift et al., 2011)

Disposal of Used Fuel Assemblies



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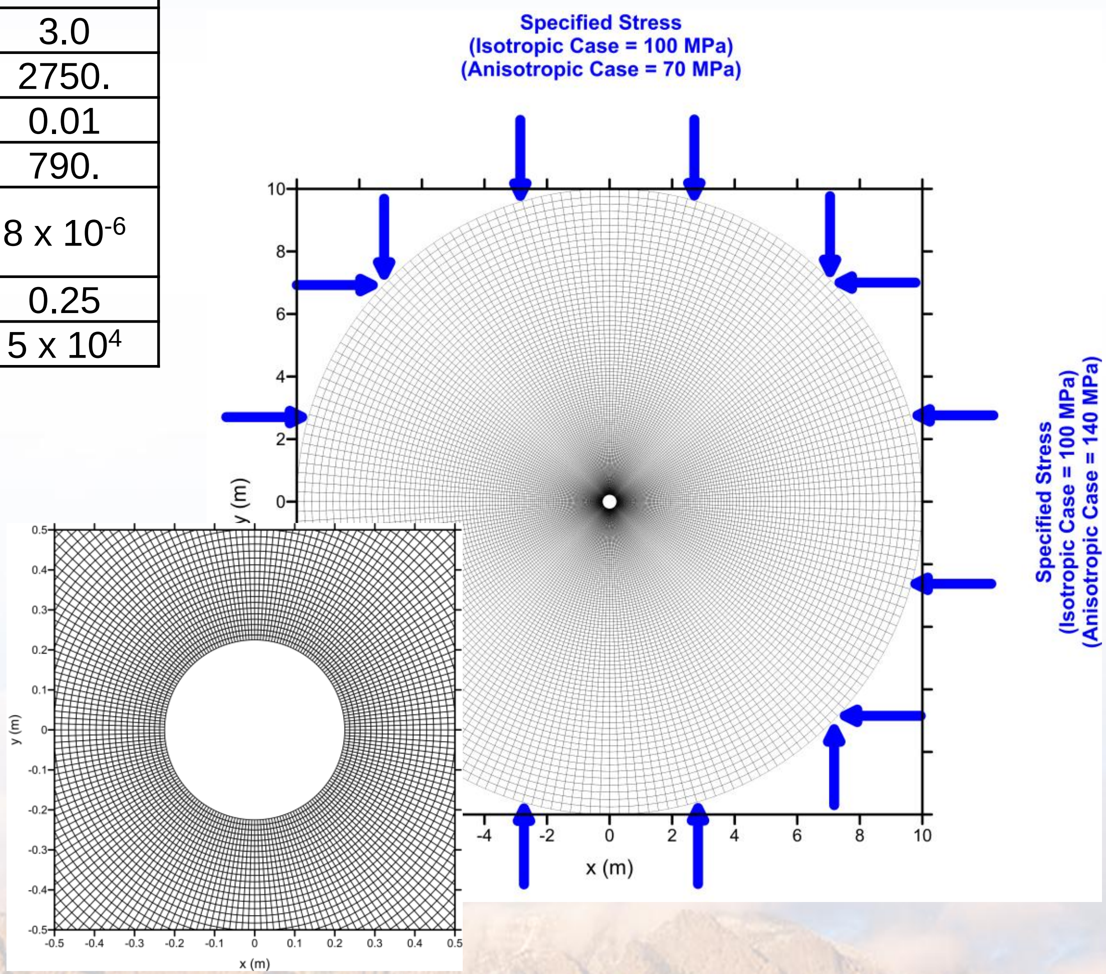
Geological Aspects of Safety: 2D Mechanical Numerical Modeling

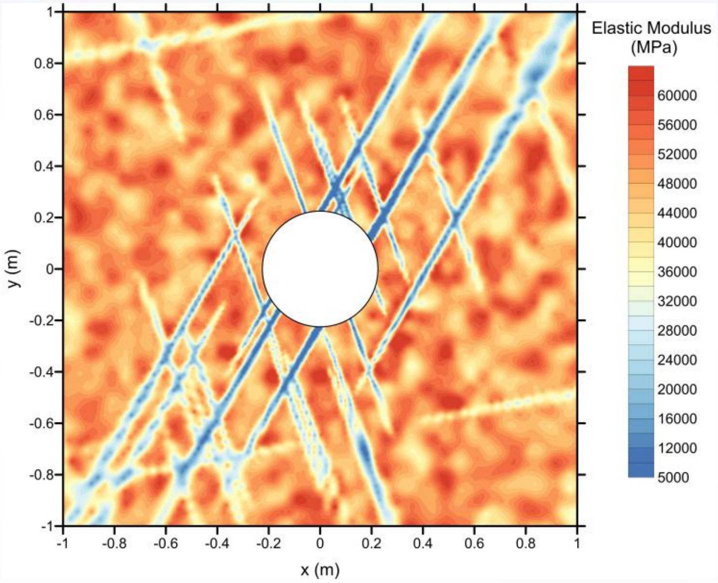
Parameter	Value
thermal conductivity (W/m ^oK)	3.0
density (kg/m^3)	2750.
porosity (-)	0.01
specific heat (J/kg ^oK)	790.
linear coefficient of thermal expansion ($^oK^{-1}$)	8×10^{-6}
Poisson ratio (-)	0.25
elastic modulus (MPa)	5×10^4

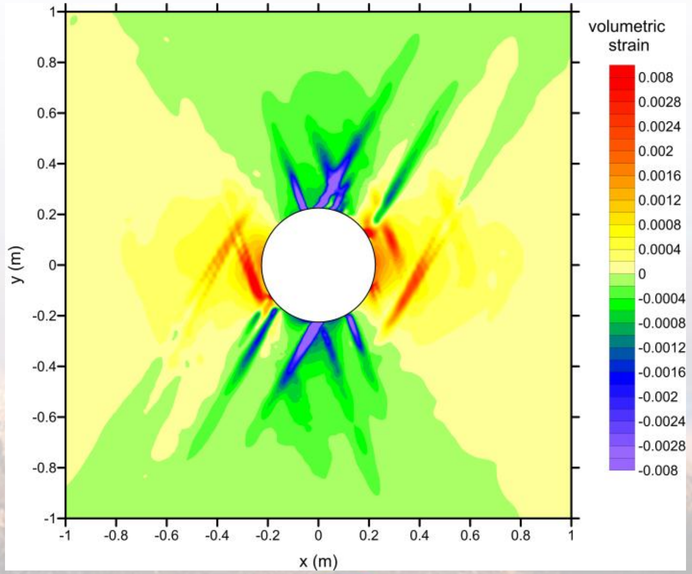
- **2D model of linear elastic and thermo-elastic processes implemented with the FEHM code (Zyvoloski et al., 1997)**
- **Boundary and initial conditions consistent with a nominal depth of 4000 m**
- **Parameter values representative of granite**



Geological Aspects of Safety: 2D Mechanical Modeling

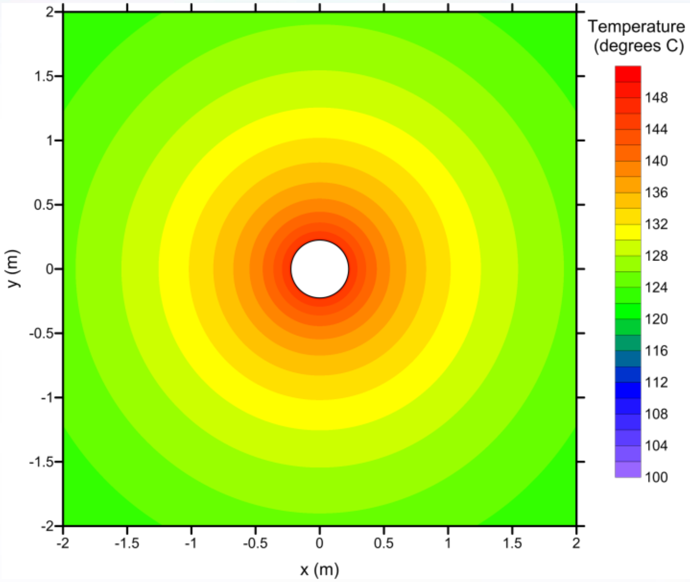
- **For differential horizontal stress (anisotropic case), the host rock is placed in compression in the direction of maximum horizontal stress and in extension in the direction of minimum horizontal stress**
- **Concentration of stress at the borehole walls in the direction of minimum horizontal stress can result in borehole breakouts (not explicitly analyzed here)**
- **Permeability will be increased by extensional strain and decreased by compression**
- **Permeability changes are a function of strain, fracture porosity, and fracture orientation – sensitivity is amplified by the cubic relationship between permeability and fracture aperture**

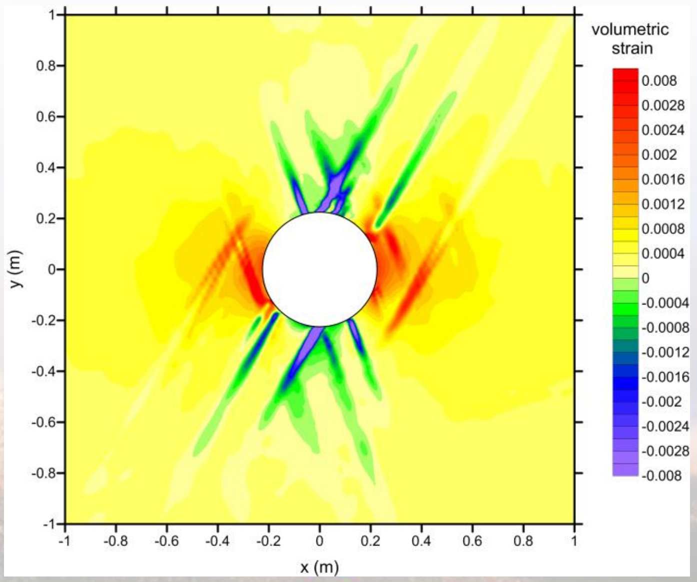




Geological Aspects of Safety: 2D Thermal-Mechanical Modeling

- **Coupled thermal-mechanical modeling results for heterogeneous fractured granite and anisotropic horizontal stress shown for disposal of average used PWR fuel assembly – 5 years after disposal**
- **Higher temperatures near the borehole and related thermal expansion of the granite places much of the host rock in compression and decreases the permeability**
- **However, 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: Objectives and Requirements

- Overarching objective: A simple and achievable, internally consistent system for waste disposal that meets regulatory requirements for operational and public safety
- Update and refine the conceptual design presented in Brady et al. (2009)
- Consider preliminary design alternatives
- Provide a reference design for performance assessment and risk analysis
- Provide a reference design for more accurate cost estimates
- Numerous viable design alternatives exist – this reference design is one choice that provides a basis for the objectives stated above

SANDIA REPORT
SAND2011-6749
Unlimited Release
Printed October 2011

Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste

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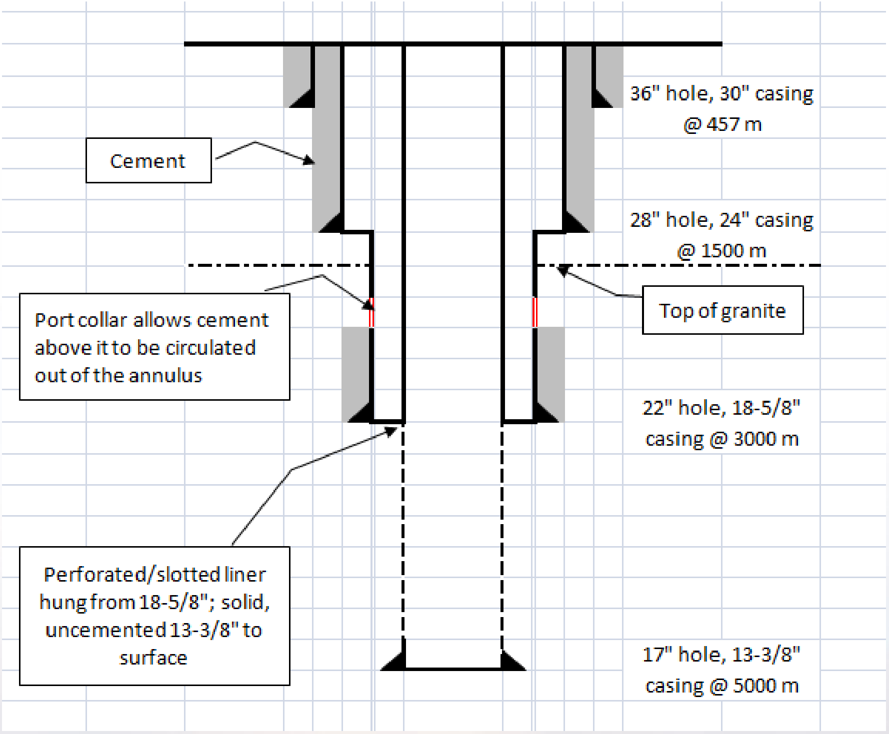
Arnold et al. (2011)

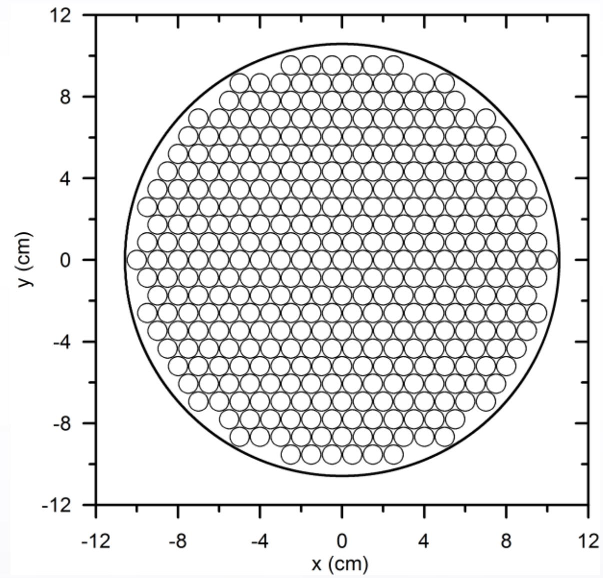
Reference Design and Operations: Borehole Design

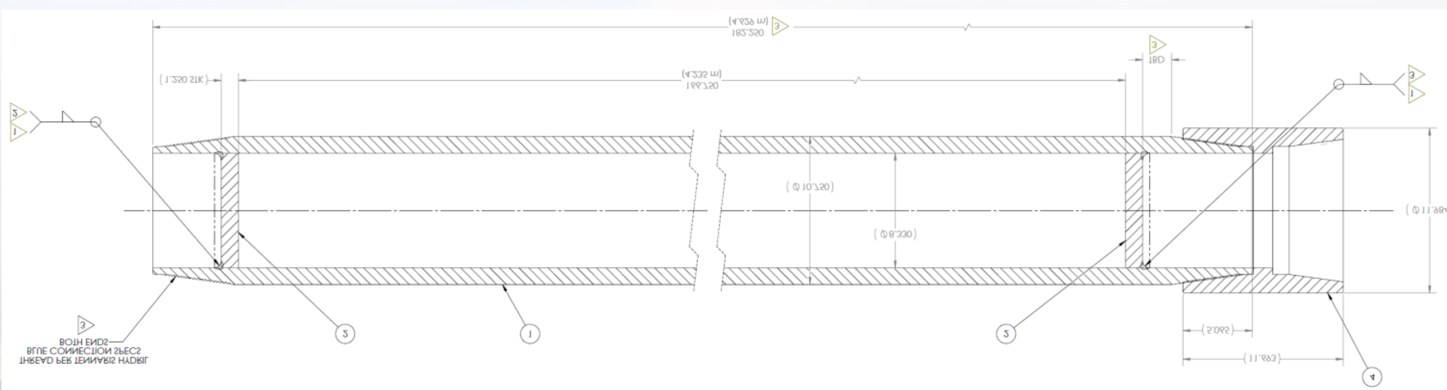
- **Drilling to 5 km depth is not exceptional for geothermal development and 17 inches diameter should be feasible with current technology**
- **Testing and logging for the large diameters specified in the nested borehole design may be difficult to achieve, leading to consideration of a pilot hole**
- **A 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**



Reference Design and Operations: Waste Canister Design

- Waste canisters consist of carbon steel tubing with welded plugs and threaded connections
- Canisters are designed to withstand projected hydrostatic pressure and mechanical load of overlying canisters
- Used PWR fuel assemblies would be dismantled and 367 fuel rods would be placed in the canister (lower-temperature design)
- Waste canisters would retain their integrity until after the borehole is loaded and sealed





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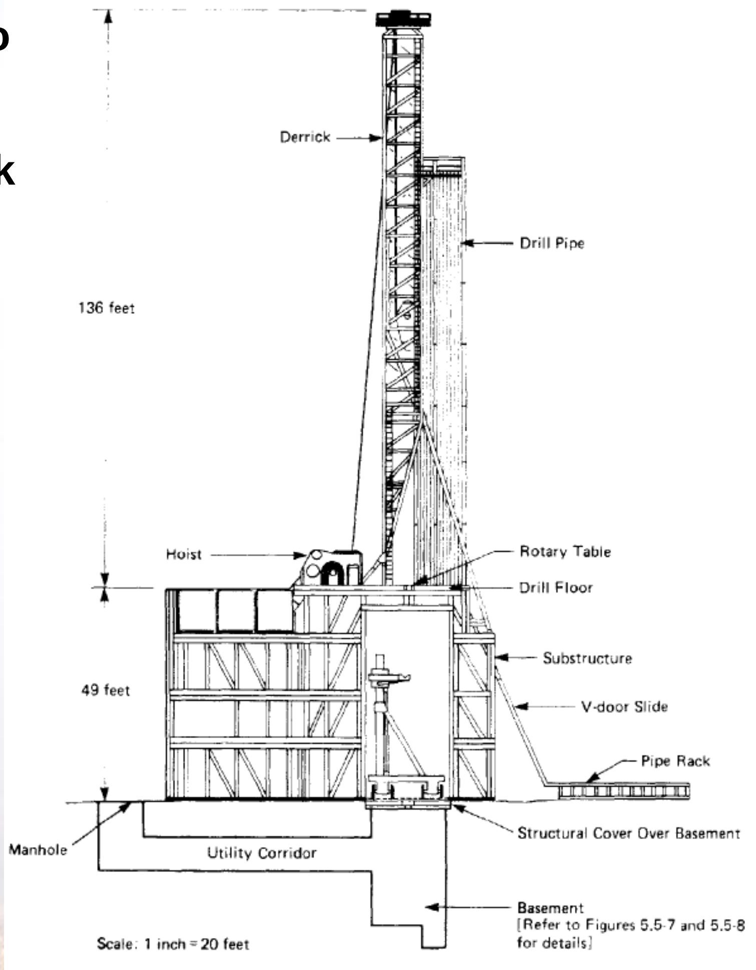
Reference Design and Operations: Waste Canister Emplacement

- Loaded waste canisters would be transported to the site by tractor trailer using shipping casks
- Surface handling would rotate the shipping cask to a vertical position, move the cask by a short rail system over the borehole, attach the canister to the canister string and lower it into the borehole by remote operation
- Strings of 40 canisters (about 200 m) would be attached to the pipe string with a J-slot assembly and lowered to the disposal zone
- A synthetic oil-base mud with a high bentonite concentration would be present in the disposal zone, forming a grout around the waste canisters
- Each canister string would be separated from overlying canister strings by a bridge plug and cement plug



from Woodward-Clyde Consultants (1983)

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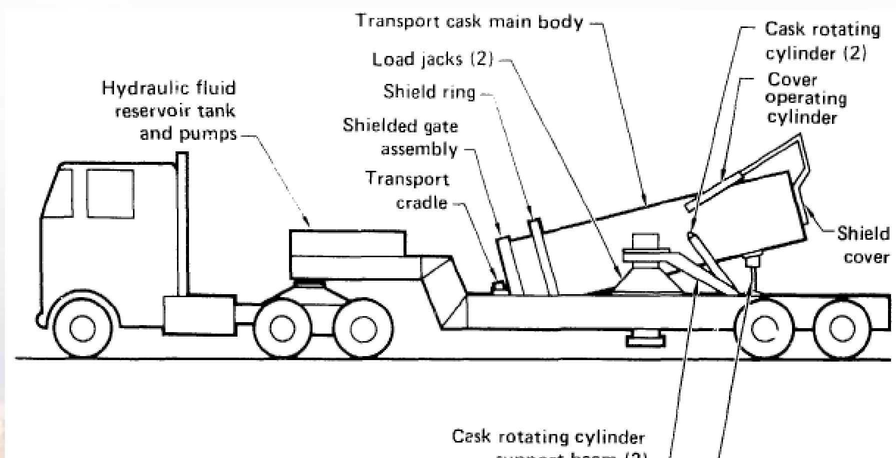
Reference Design and Operations: Waste Canister Emplacement

- **Engineering feasibility has been demonstrated for surface handling and borehole emplacement of waste canisters with the Spent Fuel Test – Climax (SFT-C) at the Nevada Test Site (NTS) (Patrick, 1986)**
- **Spent fuel assemblies from Turkey Point reactor were transported to NTS, packaged in canisters, lowered down a 420-m borehole, emplaced in the underground granite thermal test facility for 3 years, and removed to the surface via the borehole**
- **Waste handling and emplacement operations were conducted within operational safety requirements and without incident**



from Patrick (1986)

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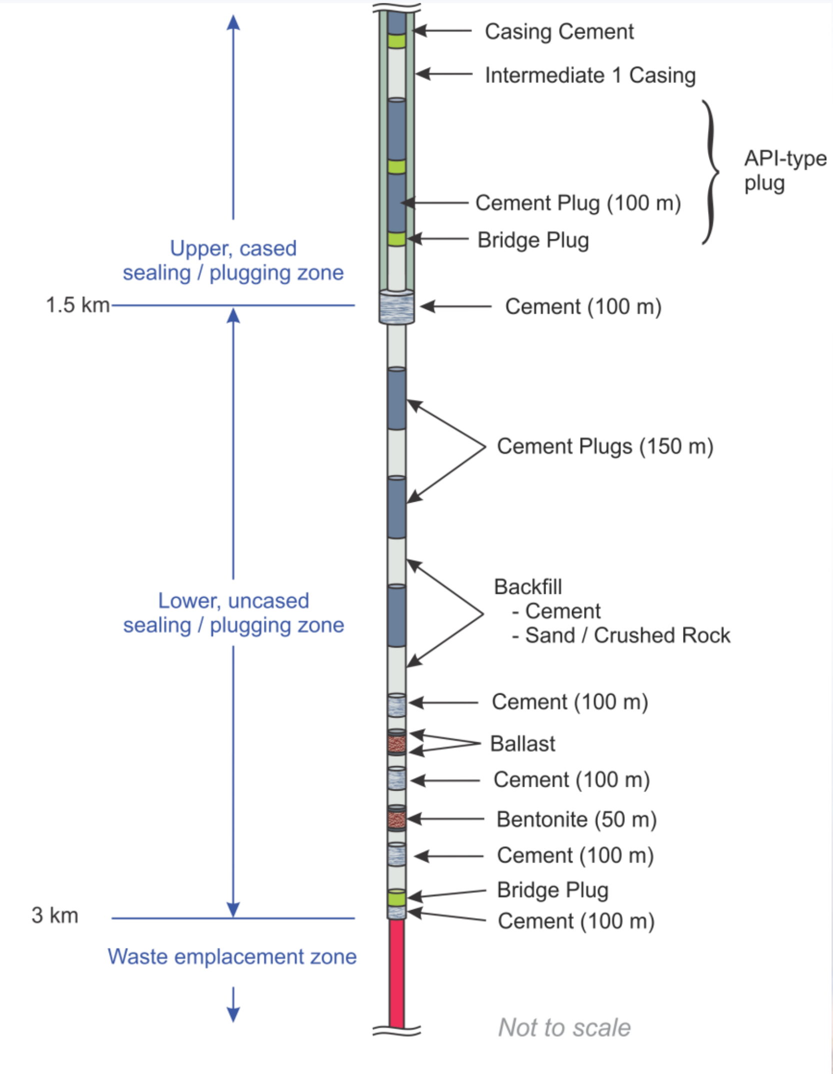
Reference Design and Operations: Seals Design

- **After the waste canisters have been emplaced and the overlying plugs have been set, the guide casing will be removed and the intermediate casing in the seal zone 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**



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Practical Aspects of Deep Borehole Disposal

- **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 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)

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Practical Aspects of Deep Borehole Disposal

- **Analysis of number of boreholes required for disposal is based on data from the Used Fuel Disposition Campaign report (Carter et al., 2011)**

Table 3-5 No replacement nuclear generation.

	Number of Assemblies[b]			Total Initial Uranium (MTU)[a]			Average Enrichment		Average Burn-up (MWd/MTU)[c]	
Year	PWR	BWR	Totals	PWR	BWR	Totals	PWR	BWR	PWR	BWR
2010	97,400	128,600	226,000	42,300	23,000	65,200	3.74	3.12	39,600	33,300
2030	165,000	219,200	384,200	72,000	39,200	111,100	4.24	3.87	45,400	42,600
2055	209,000	273,000	483,000	91,000	49,000	140,000	4.40	4.09	47,300	45,300

Table 3-6 Maintain current nuclear generation.

	Number of Assemblies[b]			Total Initial Uranium (MTU)[a]			Average Enrichment		Average Burn-up (MWd/MTU)[c]	
Year	PWR	BWR	Totals	PWR	BWR	Totals	PWR	BWR	PWR	BWR
2010	97,400	128,600	226,000	42,300	23,000	65,200	3.74	3.12	39,600	33,300
2020	131,000	173,000	304,200	57,000	30,900	88,000	4.04	3.57	43,100	39,000
2040	198,600	261,600	460,200	86,600	46,800	133,400	4.36	4.05	46,900	44,900
2060	266,000	350,000	616,000	116,000	63,000	179,000	4.52	4.29	48,800	47,800
2080	333,000	439,000	772,000	146,000	79,000	224,000	4.62	4.43	49,900	49,500
2100	401,000	527,000	928,000	175,000	95,000	270,000	4.68	4.53	50,600	50,600

a the estimated fuel discharged has been rounded to the nearest 100 MTU prior to 2050 and the nearest 1,000 thereafter, totals may not appear to sum correctly

b the estimated number of assemblies has been rounded to the nearest 200 prior to 2050 and nearest 1000 thereafter, totals may not appear to sum correctly

c the burn-up has been rounded to the next 100 MWd/MT

The complete data in Appendix B has not been rounded to allow for independent reproduction of the calculations.

Practical Aspects of Deep Borehole Disposal

- **Current commercial used fuel inventory could be disposed in 273 boreholes using the reference design and rod consolidation of all waste in canisters**
- **The slowed replacement scenario assumes half the rate of new plant construction between the no replacement and the maintain current capacity scenarios**
- **A strategic reserve of 40,000 MTU would supply a 2,000 MTU reprocessing plant with a 20 year supply of feedstock**

				Number of Boreholes Needed		
Scenario	**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

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Conclusions

- Most important undesirable or adverse geological conditions for deep borehole disposal should be the focus of site characterization
- The most likely nominal release scenario has been evaluated with thermal-hydrologic and performance assessment modeling
- Mechanical and thermal-mechanical effects on the disturbed rock zone have been modeled – volumetric strain and altered permeability are related to the differential in horizontal stress
- A feasible and simple reference design and operations have been developed for a deep borehole disposal system
- Estimated cost for deep borehole disposal using the reference design, excluding transportation costs, is about $158/kg HM, well below the roughly $400/kg waste fund fee
- The current used fuel inventory could be disposed in 273 boreholes using the reference design – the 2055 inventory in the current reactor fleet could be disposed in 585 boreholes (roughly 5 to 6 boreholes per reactor)

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