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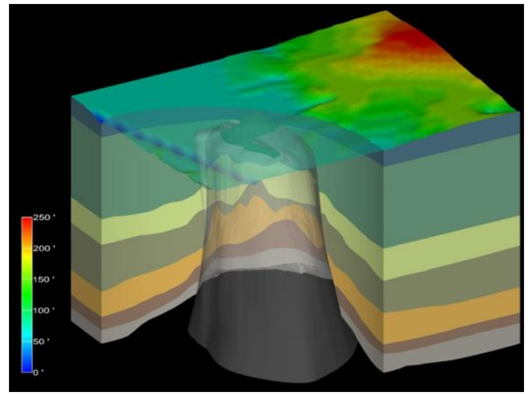

Deep Borehole Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste

Baylor University Geology Seminar

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

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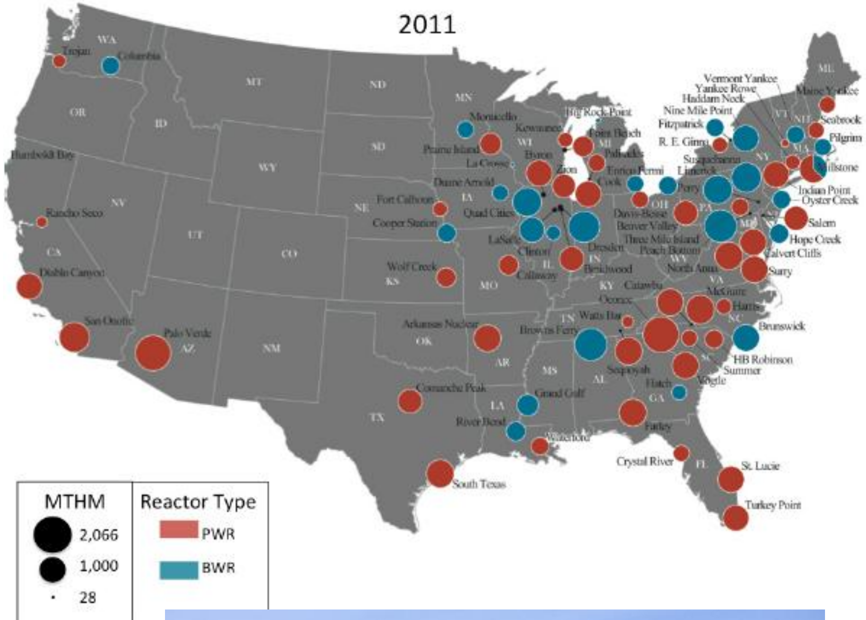
- Background on nuclear waste
- Deep borehole disposal concept
- Disposal concept viability and safety
- Deep borehole disposal reference design
- Numerical modeling of thermal-hydrology
- Borehole stability and thermal-mechanical modeling
- Summary and conclusions

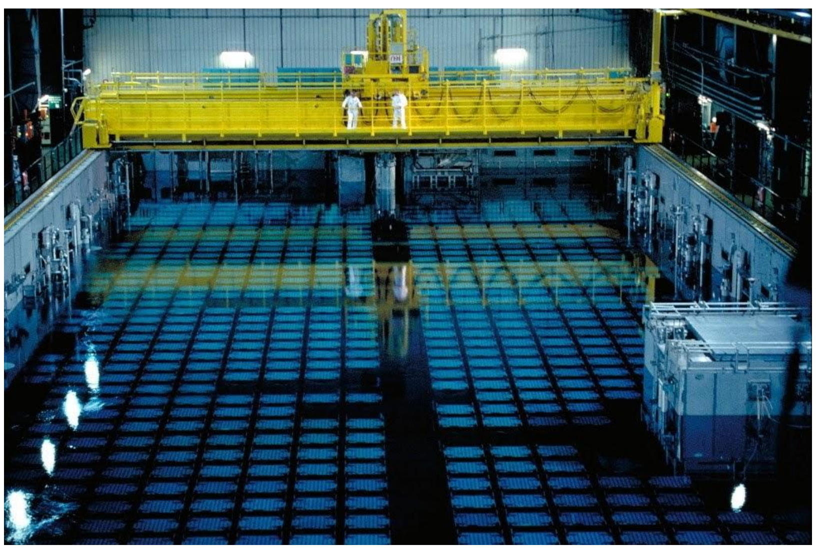
Background on Nuclear Waste

- Nuclear waste encompasses a diverse group of waste materials, including spent nuclear fuel, high-level radioactive waste, and others
- International consensus exists that geological disposal is a practical, safe, and preferred option
- Research and repository development programs have been underway around the world for more than five decades
- The only operating repository is the Waste Isolation Pilot Plant (WIPP) in New Mexico – disposal of transuranic waste in bedded salt
- Current disposal research and development efforts by the Department of Energy are focused on geological disposal in mined repositories in granite, salt, or shale; or deep borehole disposal
- Significant political and social barriers exist to disposal, including extreme risk aversion regarding radiation hazards – psychology of risk perception is very subjective

Background on Nuclear Waste

- **Majority of nuclear waste is spent fuel assemblies from commercial power plants**
- **About 75% is in pool storage and about 25% is in dry cask storage at reactor sites**





Background on Nuclear Waste

- **Radioisotopes in spent nuclear fuel consist of a mixture of fission products, activation products, and decay products**
- **These radioisotopes vary widely in half-life, solubility, mobility, and radiotoxicity**
- **Disposal system risks must be evaluated out to very long time scales (1 million years, based on Yucca Mountain regulations)**

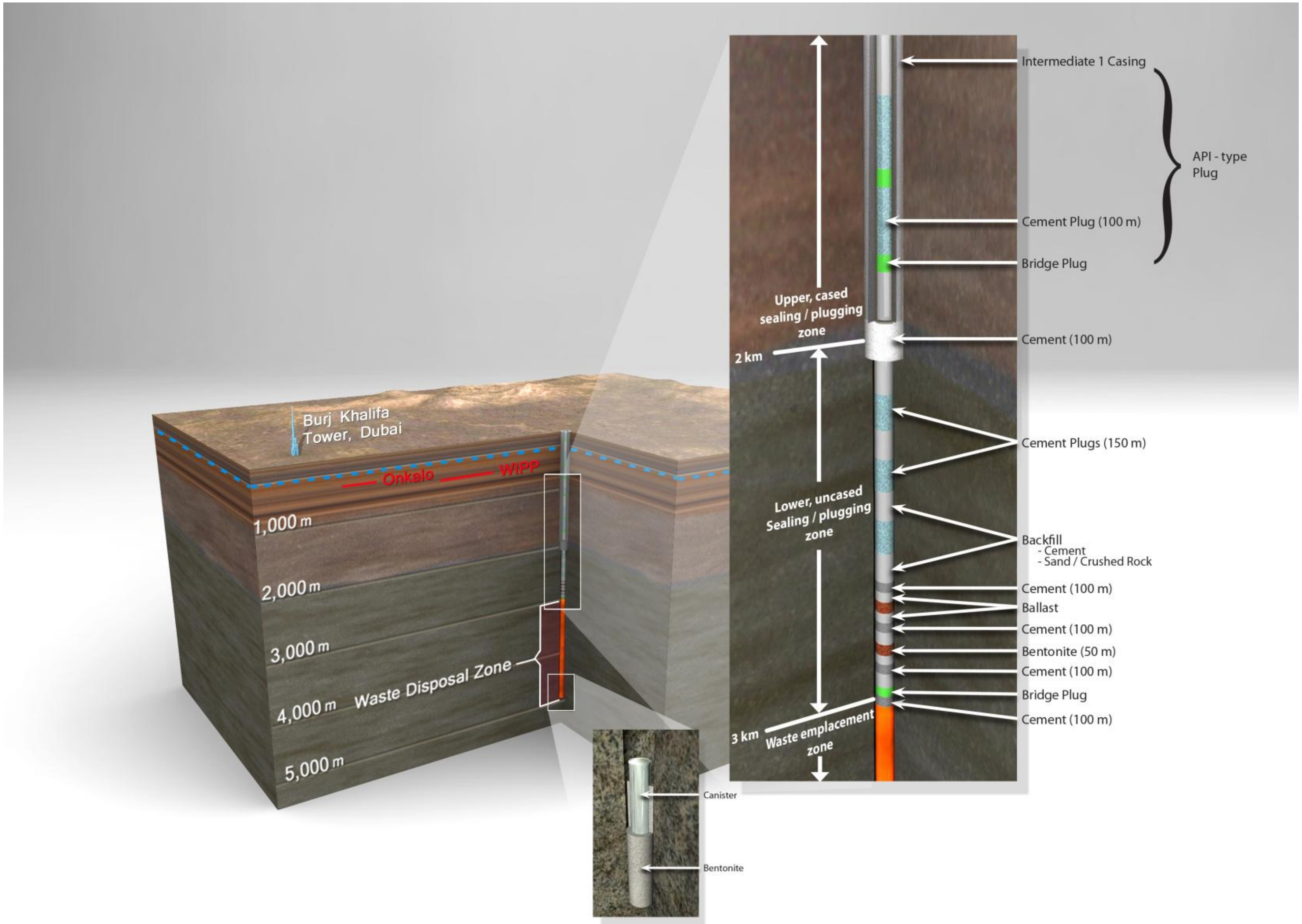
Isotope	Average Mass (g)*		Standard Deviation (g)*		Maximum Mass (g)*		Minimum Mass (g)*	
^{238}U	2.46E+05	(2.46E+05)	1.15E+05	(1.15E+05)	4.51E+05	(4.51E+05)	5.57E+04	(5.57E+04)
^{235}U	2.65E+03	(2.65E+03)	1.48E+03	(1.48E+03)	1.50E+04	(1.50E+04)	4.91E+02	(4.89E+02)
^{239}Pu	1.64E+03	(1.64E+03)	8.96E+02	(8.97E+02)	3.69E+03	(3.69E+03)	5.91E+01	(5.92E+01)
^{236}U	1.00E+03	(1.00E+03)	6.92E+02	(6.90E+02)	3.03E+03	(3.02E+03)	3.07E+01	(3.07E+01)
^{240}Pu	4.41E+02	(4.29E+02)	3.43E+02	(3.37E+02)	1.37E+03	(1.25E+03)	3.98E-01	(4.01E-01)
^{241}Am	4.08E+02	(1.23E+02)	2.46E+02	(7.15E+01)	1.08E+03	(3.32E+02)	1.13E-02	(3.97E-03)
^{99}Tc	2.00E+02	(2.00E+02)	1.32E+02	(1.32E+02)	5.74E+02	(5.74E+02)	1.51E+00	(1.51E+00)
^{242}Pu	1.63E+02	(1.63E+02)	1.00E+02	(1.00E+02)	6.22E+02	(6.22E+02)	4.38E-05	(4.38E-05)
^{237}Np	1.62E+02	(1.36E+02)	1.06E+02	(9.30E+01)	5.05E+02	(4.41E+02)	4.23E-01	(4.22E-01)
^{135}Cs	1.38E+02	(1.38E+02)	8.97E+01	(8.97E+01)	4.90E+02	(4.90E+02)	5.47E-01	(5.47E-01)
^{137}Cs	9.08E+01	(2.76E+02)	6.72E+01	(1.86E+02)	3.21E+02	(8.51E+02)	3.53E-01	(1.76E+00)
^{107}Pd	6.46E+01	(6.46E+01)	4.17E+01	(4.17E+01)	2.44E+02	(2.44E+02)	8.70E-02	(8.70E-02)
^{234}U	6.32E+01	(4.42E+01)	3.80E+01	(2.59E+01)	1.72E+02	(1.48E+02)	1.01E+01	(9.68E+00)
^{243}Am	4.64E+01	(4.66E+01)	3.27E+01	(3.28E+01)	2.60E+02	(2.61E+02)	1.31E-07	(1.32E-07)
^{129}I	4.24E+01	(4.24E+01)	2.79E+01	(2.79E+01)	1.36E+02	(1.36E+02)	2.15E-01	(2.15E-01)
^{238}Pu	4.22E+01	(6.15E+01)	3.39E+01	(4.79E+01)	2.02E+02	(2.81E+02)	3.13E-04	(5.43E-04)
^{90}Sr	3.55E+01	(1.13E+02)	2.69E+01	(7.81E+01)	1.22E+02	(3.31E+02)	1.89E-01	(1.02E+00)
^{241}Pu	3.34E+01	(3.44E+02)	2.59E+01	(2.13E+02)	1.25E+02	(9.39E+02)	2.96E-04	(8.74E-03)
^{126}Sn	5.65E+00	(5.65E+00)	3.73E+00	(3.73E+00)	1.91E+01	(1.91E+01)	2.27E-02	(2.27E-02)
^{245}Cm	1.46E+00	(1.47E+00)	1.37E+00	(1.38E+00)	1.77E+01	(1.78E+01)	4.37E-13	(4.39E-13)
^{79}Se	1.19E+00	(1.19E+00)	7.95E-01	(7.95E-01)	3.48E+00	(3.48E+00)	8.88E-03	(8.88E-03)
^{14}C	2.46E-02	(2.47E-02)	1.42E-02	(1.43E-02)	7.91E-02	(7.97E-02)	2.19E-04	(2.21E-04)
^{230}Th	8.55E-03	(1.11E-03)	4.84E-03	(6.42E-04)	2.33E-02	(3.62E-03)	1.64E-03	(1.99E-04)
^{233}U	3.36E-03	(1.09E-03)	2.16E-03	(7.50E-04)	1.06E-02	(3.50E-03)	2.29E-05	(1.35E-05)
^{93}Nb	3.32E-03	(1.32E-04)	2.03E-03	(8.59E-05)	1.09E-02	(6.81E-04)	4.29E-05	(1.03E-06)
^{232}Th	2.71E-03	(1.28E-03)	1.75E-03	(8.35E-04)	7.46E-03	(3.70E-03)	8.26E-05	(2.02E-05)
^{232}U	4.27E-04	(5.46E-04)	3.81E-04	(4.63E-04)	2.22E-03	(2.62E-03)	5.07E-09	(9.20E-09)
^{231}Pa	2.85E-04	(1.57E-04)	1.67E-04	(1.15E-04)	9.93E-04	(7.08E-04)	4.31E-05	(8.40E-06)
^{226}Ra	2.13E-06	(4.97E-08)	1.21E-06	(3.12E-08)	7.37E-06	(2.46E-07)	4.26E-07	(6.48E-09)
^{229}Th	9.11E-07	(4.54E-07)	7.04E-07	(4.72E-07)	5.22E-06	(4.19E-06)	5.85E-09	(4.33E-10)
^{227}Ac	1.26E-07	(1.81E-08)	7.55E-08	(1.33E-08)	4.54E-07	(9.14E-08)	1.82E-08	(6.94E-10)
^{126}Sb	1.16E-07	(1.16E-07)	7.67E-08	(7.67E-08)	3.94E-07	(3.94E-07)	4.67E-10	(4.67E-10)
^{210}Pb	1.11E-08	(2.64E-10)	6.59E-09	(2.43E-10)	4.51E-08	(1.66E-09)	2.23E-09	(6.75E-12)
^{228}Ra	9.90E-13	(3.16E-13)	6.37E-13	(2.07E-13)	2.72E-12	(9.66E-13)	3.02E-14	(4.21E-15)

* The number in the parentheses is the average mass at the time of discharge.

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
- Borehole casing or liner assures unrestricted emplacement of waste canisters
- Waste would consist of spent nuclear fuel and/or high-level radioactive waste
- 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

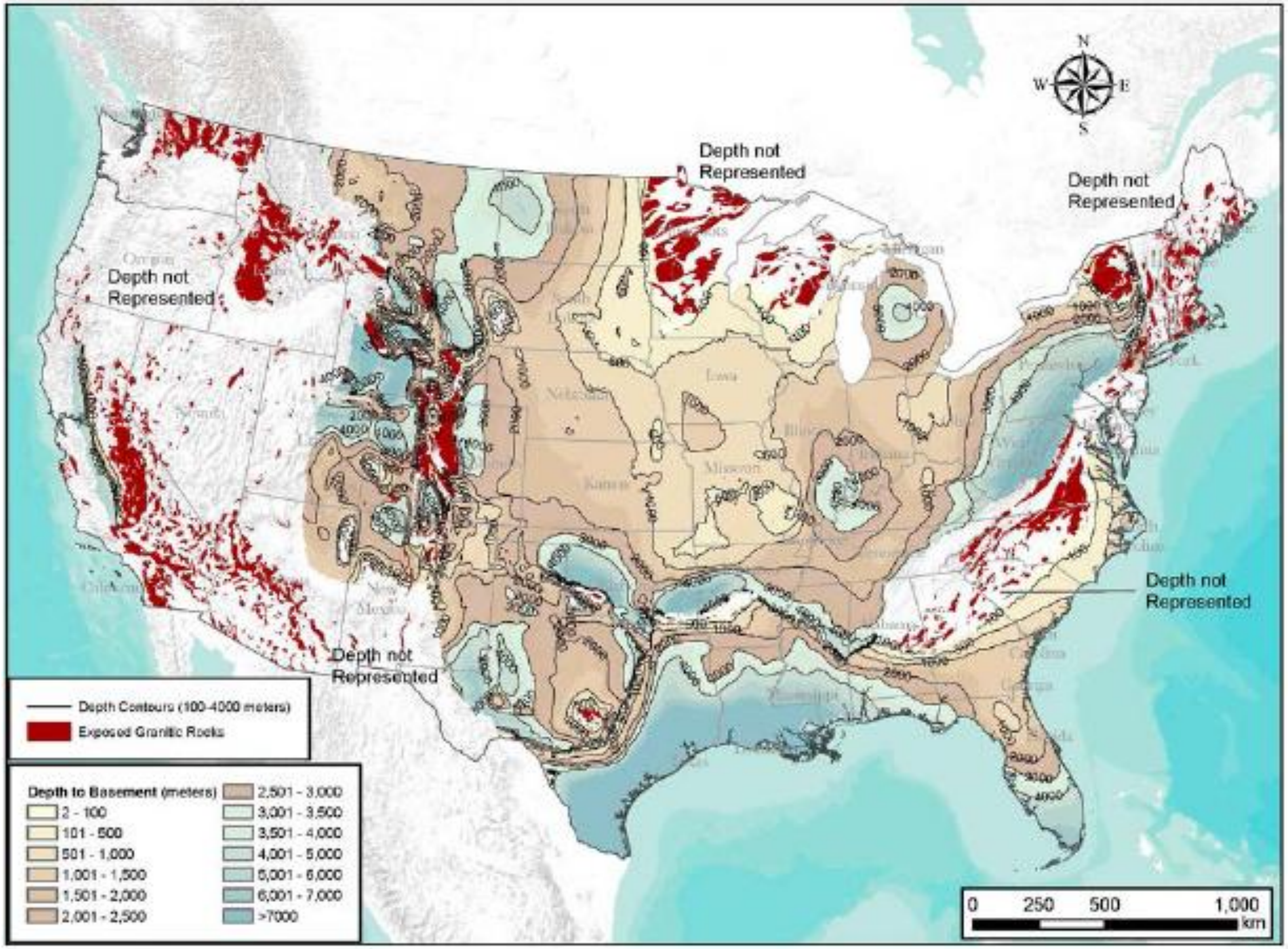
Deep Borehole Disposal Concept



Deep Borehole Disposal Concept: Viability and Safety

- Crystalline basement rocks within 2,000 m of the surface 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

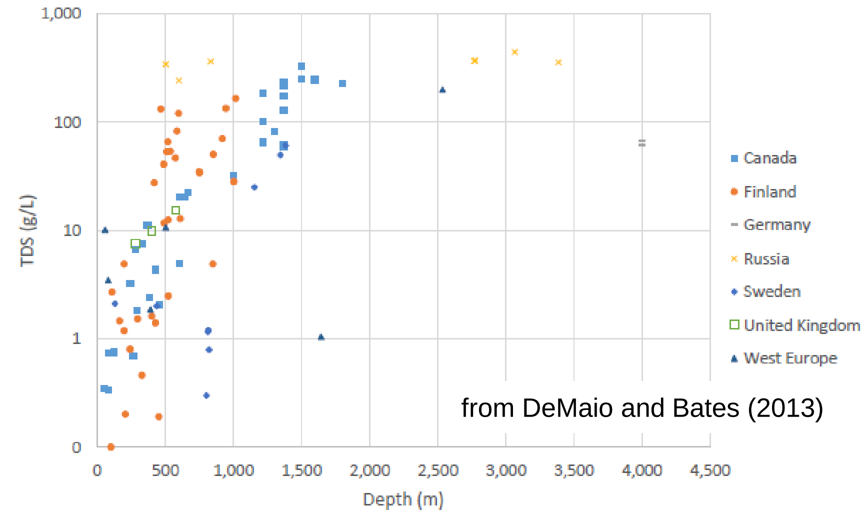
Disposal Concept Viability: Depth to Crystalline Basement



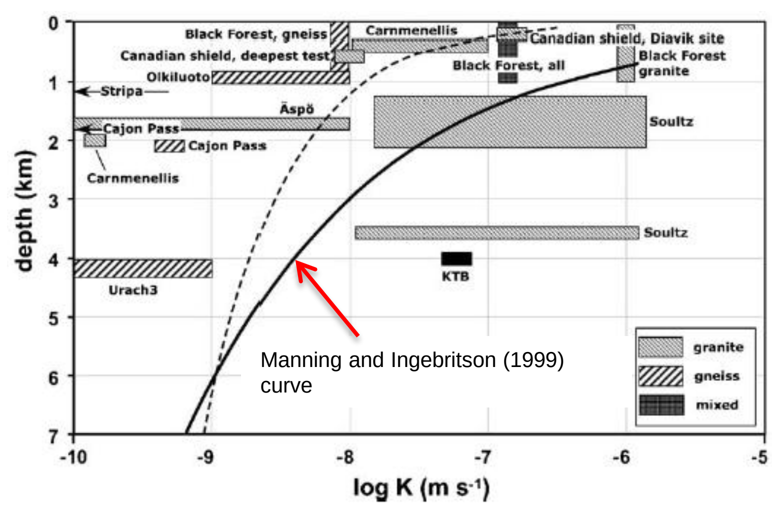
from Perry (2014)

Disposal Concept Viability: Characterization Priorities

- Groundwater age and history (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
- Thermally driven flow



from DeMaio and Bates (2013)



from Stober and Bucher (2007)

Reference Design and Operations: Borehole Design

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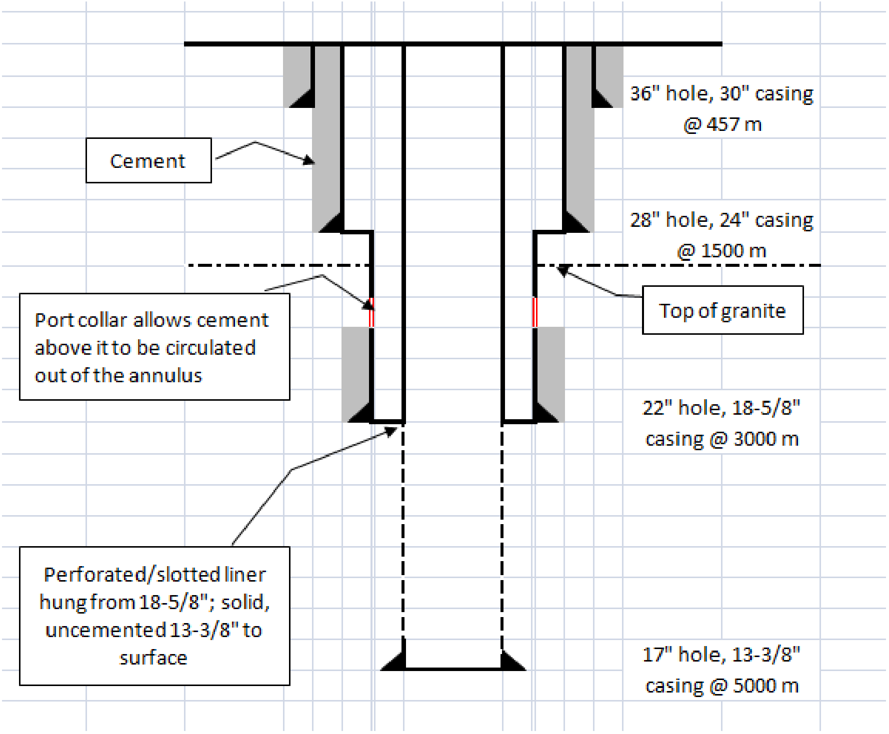
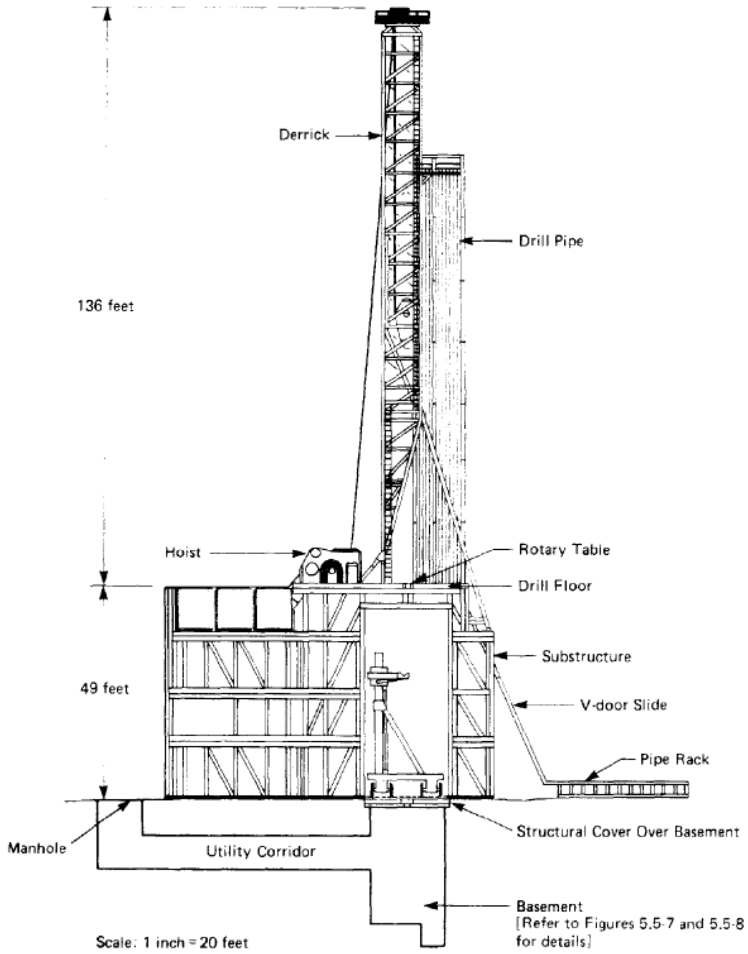
- Drilling to 5 km depth is not exceptional for geothermal development and 17 inches diameter should be feasible with current technology
- Testing and logging for the large diameters specified in the nested borehole design may be difficult to achieve, leading to consideration of a pilot hole
- A liner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

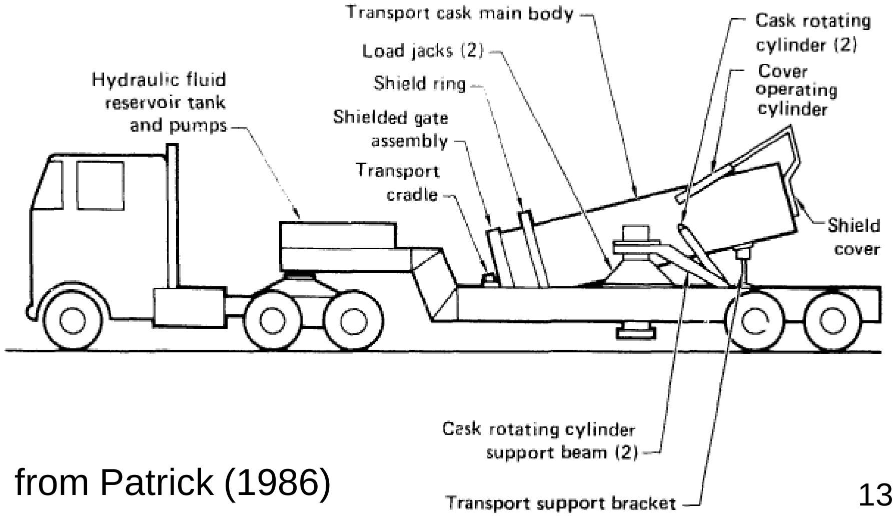
- Loaded waste canisters would be transported to the site by tractor trailer using shipping casks
- Surface handling would rotate the shipping cask to a vertical position, move the cask by a short rail system over the borehole, attach the canister to the canister string and lower it into the borehole 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)

Reference Design and Operations: Waste Canister Emplacement

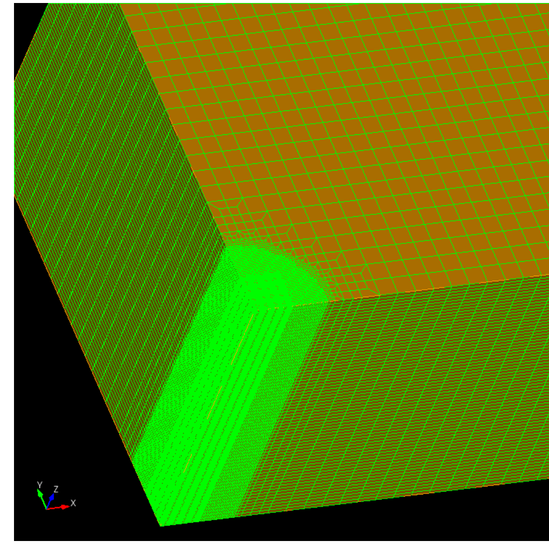
- **Engineering feasibility has been demonstrated for surface handling and borehole emplacement of waste canisters with the Spent Fuel Test – Climax (SFT-C) at the Nevada Test Site (NTS) (Patrick, 1986)**
- **Spent fuel assemblies from Turkey Point reactor were transported to NTS, packaged in canisters, 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**

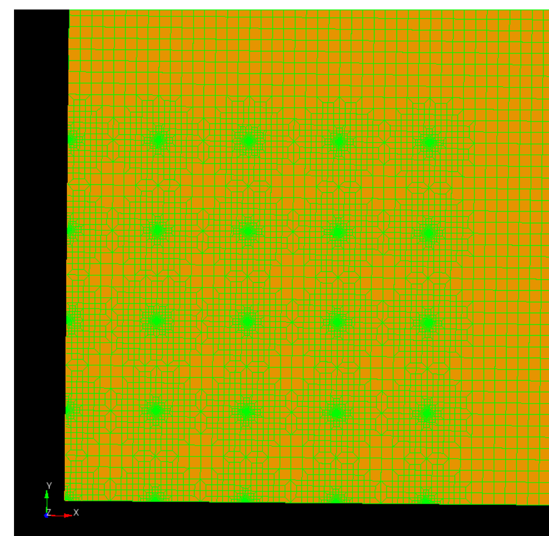


from Patrick (1986)

Thermal-Hydrologic Modeling

- The thermal-hydrologic model of the deep borehole system was constructed to simulate transient temperature and fluid flow rates for an array of multiple boreholes
- The unstructured grid was generated with the CUBIT software code (SNL, 2012) and has a horizontal grid resolution of less than 1 meter near the boreholes
- Quarter symmetry boundary conditions are used for a total simulation domain of 20 km by 20 km by 7 km depth
- Fluid boundary conditions consist of specified hydrostatic pressure on the top and sides, with no-flow on the bottom boundary
- Thermal boundary conditions are specified temperature on sides, top, and bottom

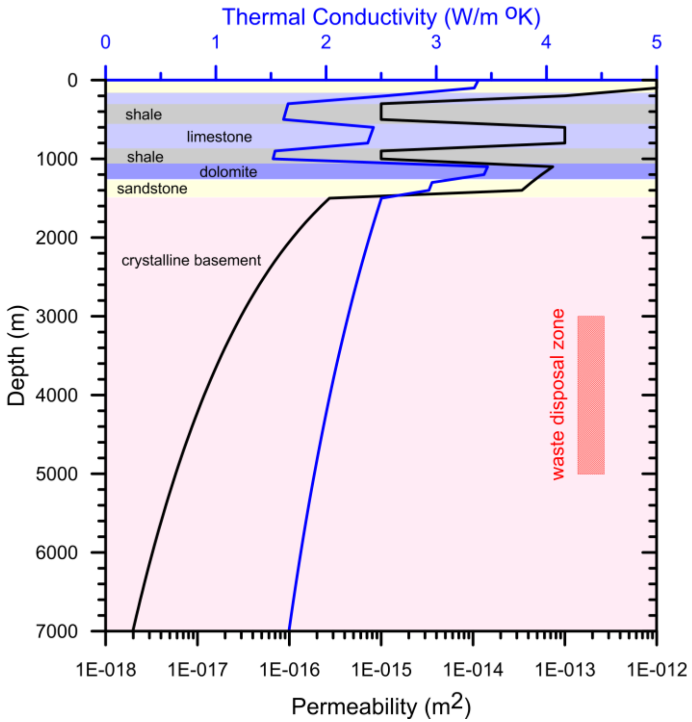




Thermal-Hydrologic Modeling

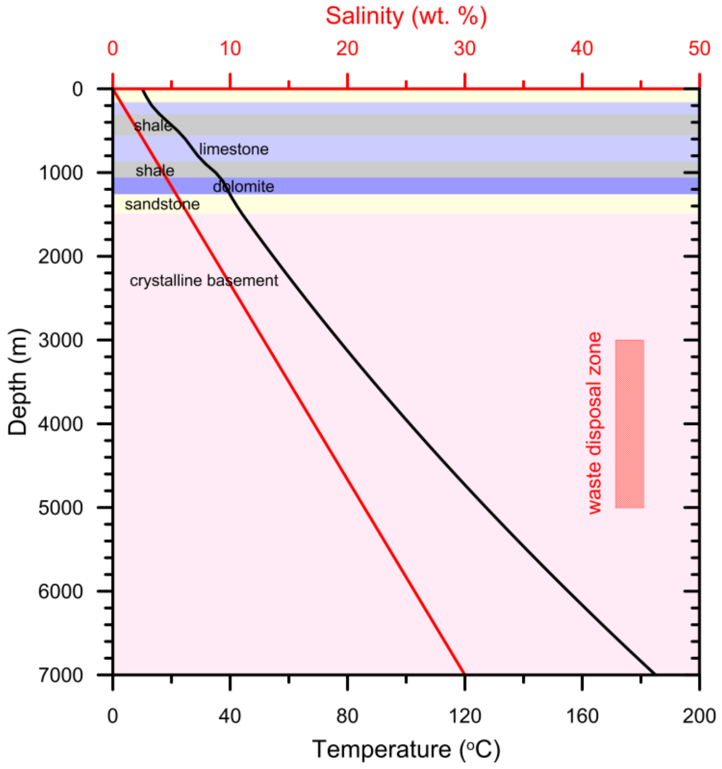
- The assumed hydrogeological domain for the model consists of granite, capped by 1,500 m of horizontal, layered sedimentary rocks representative of stable continental interior regions of North America
- Average reference values of permeability are assigned using the functional relationship with depth for average crustal conditions from Manning and Ingebritsen (1999)
- Thermal conductivity is assigned based on rock type and ambient temperature with depth, using the relationship from Vosteen and Schellschmidt (2003)
- Representative values of porosity and heat capacity are assigned to each rock type

Lithology	Permeability (m^2)	Porosity (-)	Thermal K (W/mK)	Heat Capacity (J/kg °K)
granite	1×10^{-14}	0.01	3.0	880.
sandstone	1×10^{-12}	0.30	3.5	840.
shale	1×10^{-15}	0.02	1.8	840.
limestone	1×10^{-13}	0.05	2.7	840.
dolomite	1×10^{-13}	0.05	4.0	840.



Thermal-Hydrologic Modeling

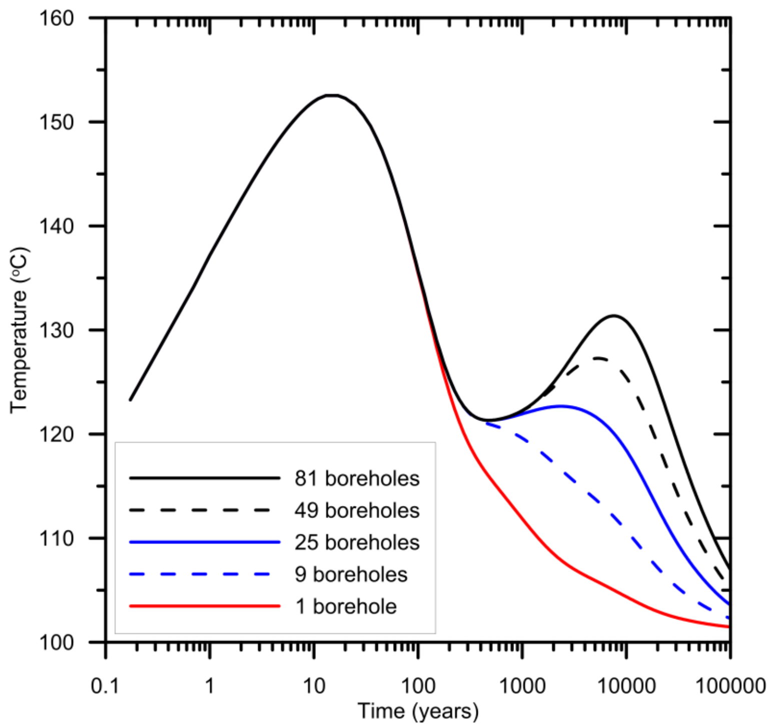
- **Fluid density is also a function of salinity in the model and a linear salinity gradient with depth is specified, with salinity increasing from 0 to about 20 weight % at the bottom of the borehole**
- **Simulations were conducted using the FEHM software code (Zyvoloski et al., 1997), which is capable of multi-phase modeling of fluid flow, heat transport, and solute transport**
- **The simulated ambient temperature gradient corresponds to an average geothermal gradient of 25 °C/km**



Thermal-Hydrologic Modeling

- The thermal output from the waste canisters is based on the disposal of used pressurized water reactor (PWR) fuel with average characteristics given for waste in Carter et al. (2011), and on the reference deep borehole disposal design system from Arnold et al. (2011)
- Simulated temperature history near the central borehole of the array at 4 km depth indicates a maximum temperature rise of greater than 50 °C, which occurs within 20 years of waste emplacement
- Results for multiple boreholes placed in a regular array with 200-m spacing show a smaller secondary peak temperature at up to 10k years caused by interaction among the boreholes

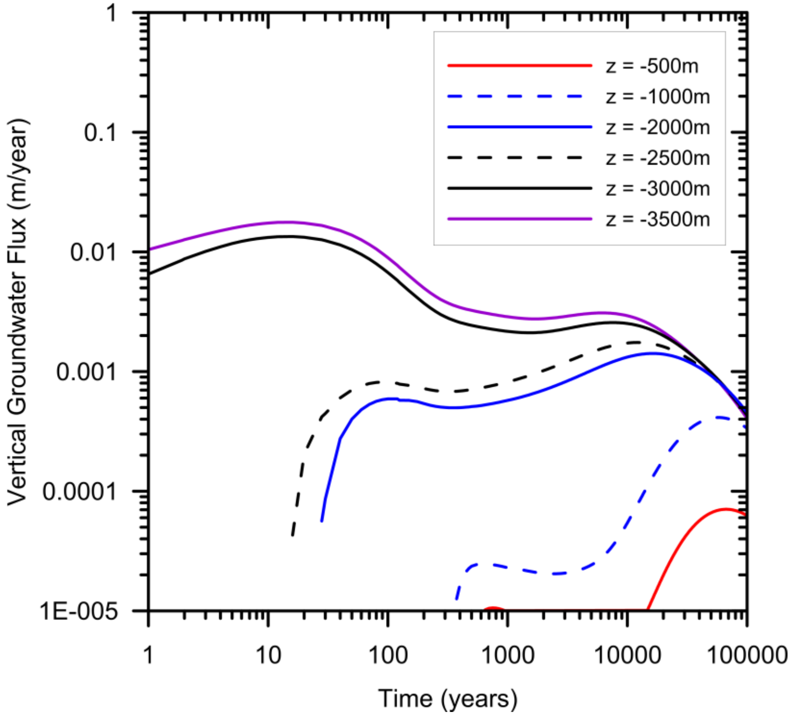
Simulated Temperature at 4 km Depth Near the Central Borehole



Thermal-Hydrologic Modeling

- The permeability of the borehole and surrounding rock (1 m^2) is assumed to be greater than the host rock by a factor of 10 to account for the disturbed rock zone and potentially degraded borehole seals
- Simulated groundwater flow from an 81 borehole array shows upward flow within and above the waste disposal zone for the first 100 years resulting directly from thermal expansion of fluid in the borehole and adjacent host rock
- Results indicate upward flow for much longer periods of time from larger-scale buoyant thermal convection
- The magnitude of upward flow decreases with distance above the waste disposal zone

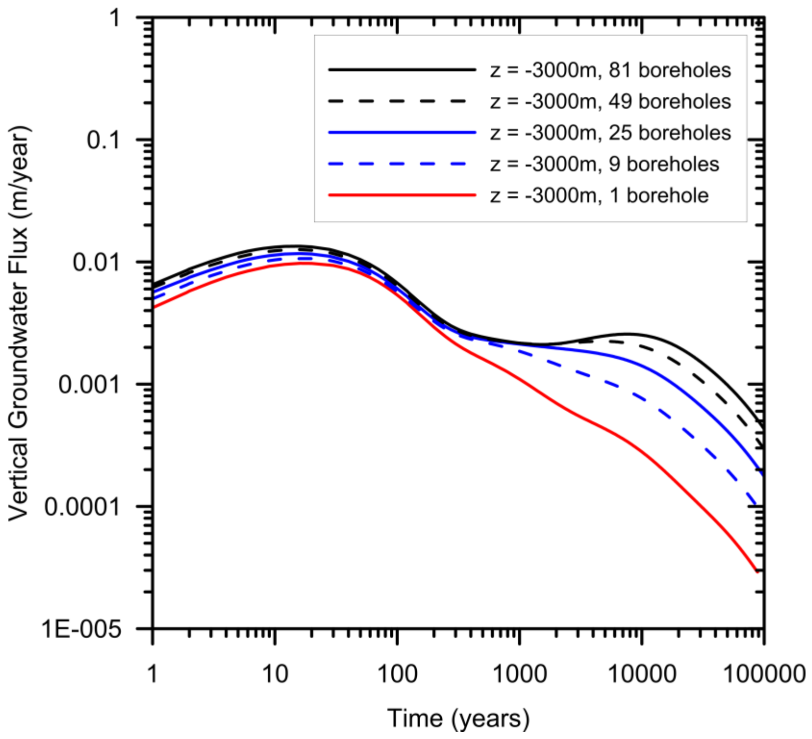
Simulated Vertical Flux in the Central Borehole of an 81 Borehole Array



Thermal-Hydrologic Modeling

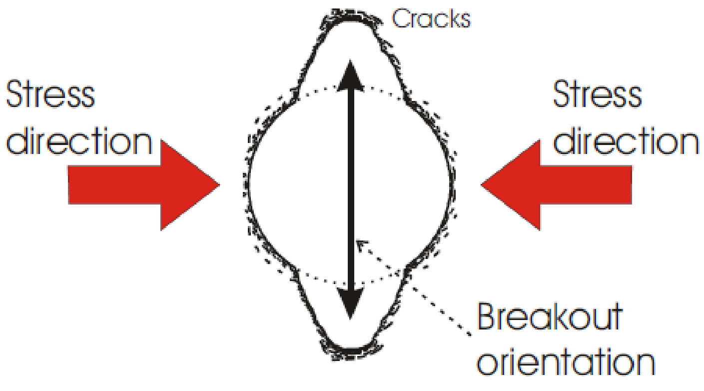
- **Simulated upward groundwater flow in the central borehole of larger borehole arrays is higher at times beyond a few hundred years, indicating more vigorous buoyant convection**
- **Slightly higher flow rates occur with larger arrays for earlier times, caused by overlapping effects of fluid thermal expansion**
- **The differences of cumulative volumetric throughflow over long time periods for varying borehole array size are quite significant, and could have important impacts on performance of the disposal system and associated risk**

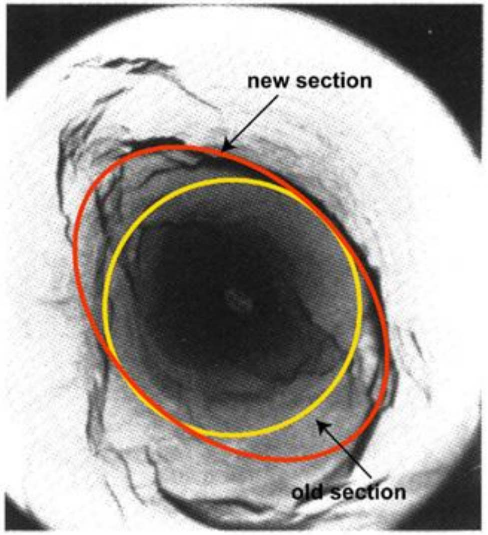
Simulated Vertical Flux at 3 km Depth in the Central Borehole



Borehole Stability and Disturbed Rock Zone

- **Mechanical stress is redistributed when a borehole is drilled into the subsurface**
- **Differential horizontal stress may impact deep, vertical borehole stability through the formation of borehole breakouts and spallation of rock fragments from the borehole wall**
- **Redistribution of stress around the borehole may also affect the distribution of permeability in the disturbed rock zone near the borehole**





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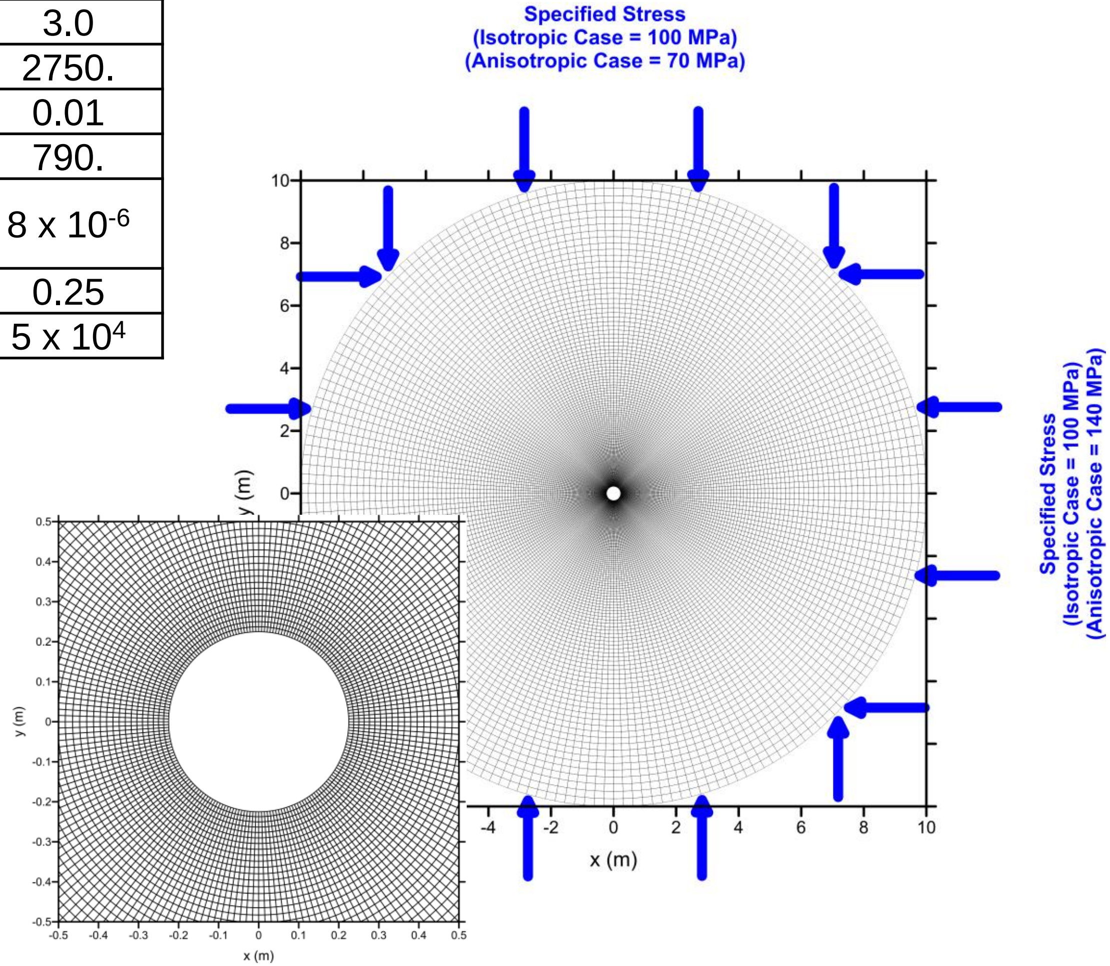
Thermal-Mechanical Modeling

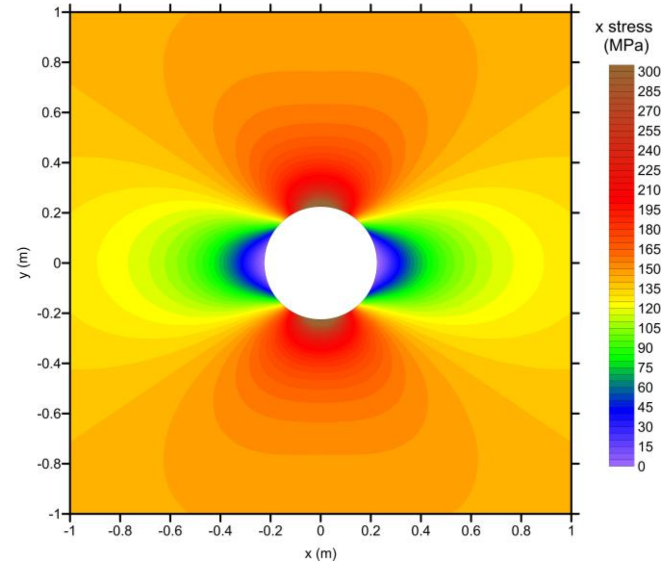
Parameter	Value
thermal conductivity (W/m ^{o}K)	3.0
density (kg/m^{3})	2750.
porosity (-)	0.01
specific heat (J/kg ^{o}K)	790.
linear coefficient of thermal expansion (^{o}K^{-1})	8 x 10^{-6}
Poisson ratio (-)	0.25
elastic modulus (MPa)	5 x 10^{4}

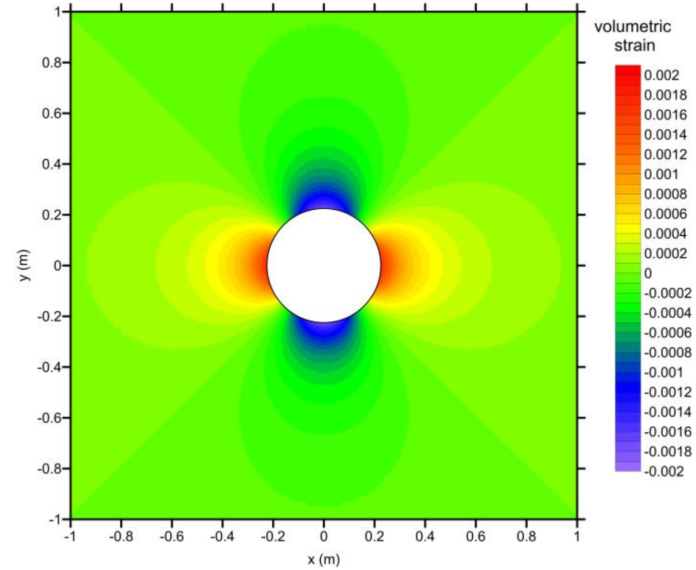
- **2D model of linear elastic and thermo-elastic processes implemented with the FEHM code (Zyvoloski et al., 1997)**
- **Boundary and initial conditions consistent with a nominal depth of 4,000 m**
- **Parameter values representative of granite**



Thermal-Mechanical Modeling

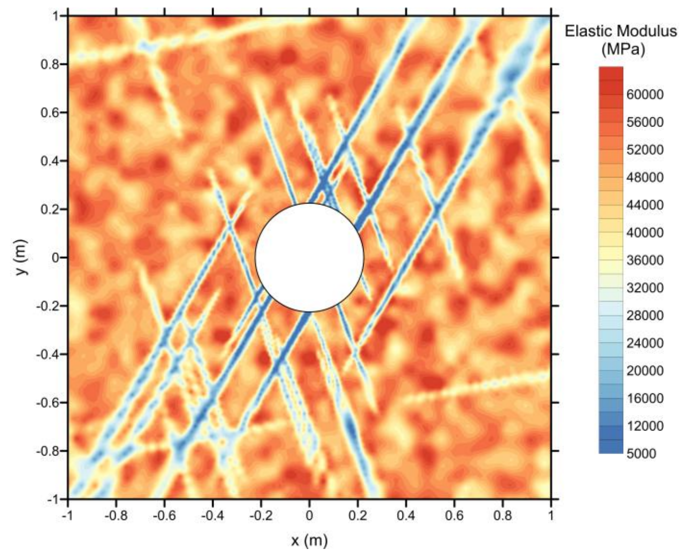
- For differential horizontal stress (anisotropic case), the host rock is placed in compression in the direction of maximum horizontal stress and in extension in the direction of minimum horizontal stress
- Concentration of stress at the borehole walls in the direction of minimum horizontal stress can result in borehole breakouts (not explicitly analyzed here)
- Numerical modeling results are shown for homogeneous rock and match the analytical solution for stress and strain distribution

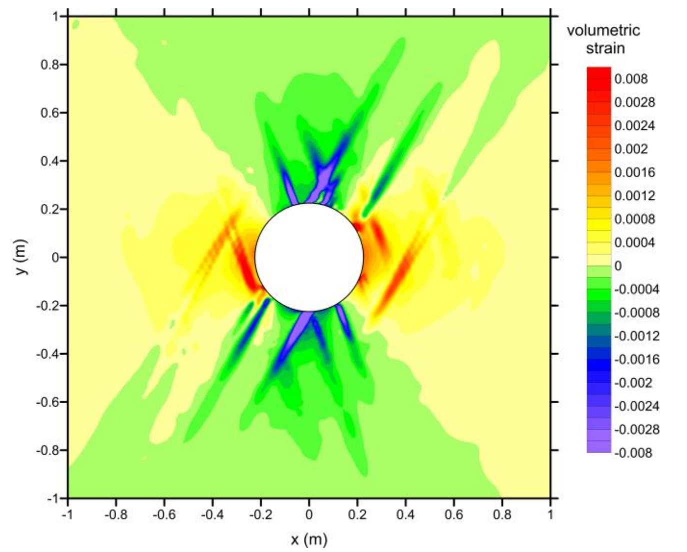




Thermal-Mechanical Modeling

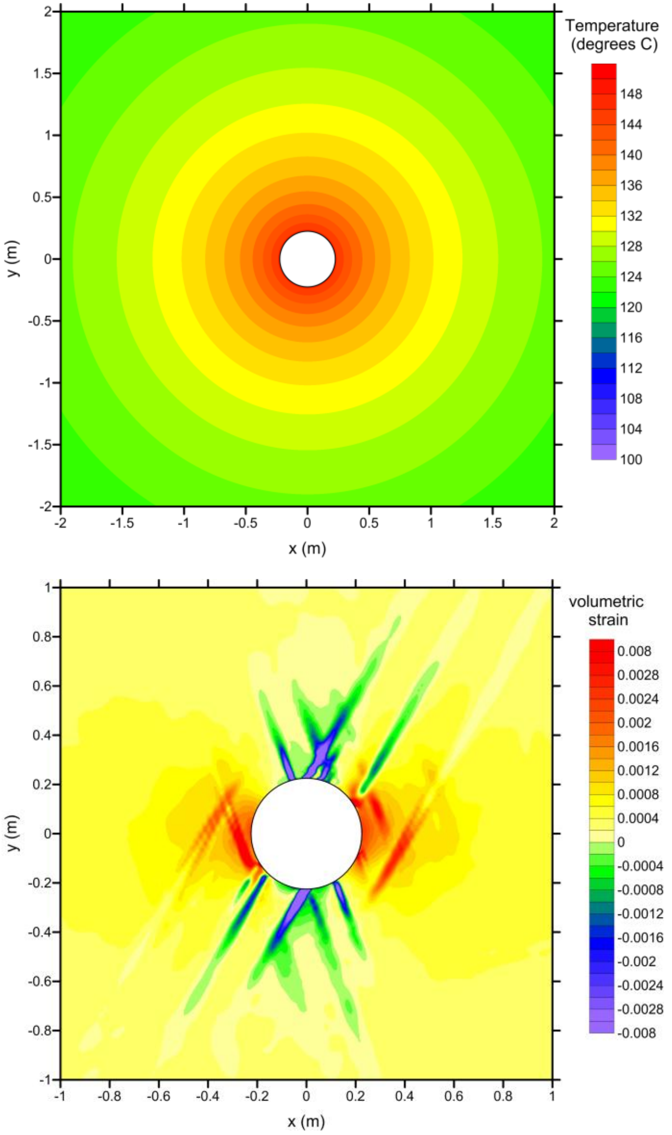
- Fractured crystalline rock realistically has heterogeneous mechanical properties, with fractures being more elastic than the rock matrix
- Geostatistical simulation methods are used to generate a spatially correlated random field of material properties, which are upscaled to the model grid
- Permeability 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





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



Summary and Conclusions

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- Permanent disposal of most nuclear waste remains an unresolved challenge in the U.S.
- Multiple factors indicate the feasibility and safety of the deep borehole disposal concept
- A reference design for deep borehole disposal and operations has been developed
- Thermal-hydrologic and thermal-mechanical modeling have been used to predict flow in a disposal system of multiple boreholes and mechanical responses near the borehole
- Flow results have been incorporated into radionuclide transport and risk assessment calculations that indicate no significant releases to the biosphere
- A five-year deep borehole disposal field test program was initiated in late 2014 and is planned to include drilling two boreholes to depths of 5,000 m in the crystalline basement

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