SAND2011-2398C

Thermal-Hydrologic-Chemical-Mechanical Modeling of Deep Borehole Disposal

International High-Level Radioactive Waste Management Conference

April 10-14, 2011

Bill W. Arnold, Teklu Hadgu, Daniel Clayton, Courtney Herrick

Sandia National Laboratories

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

LOCKHEED MARTIN

Sandia National Laboratories

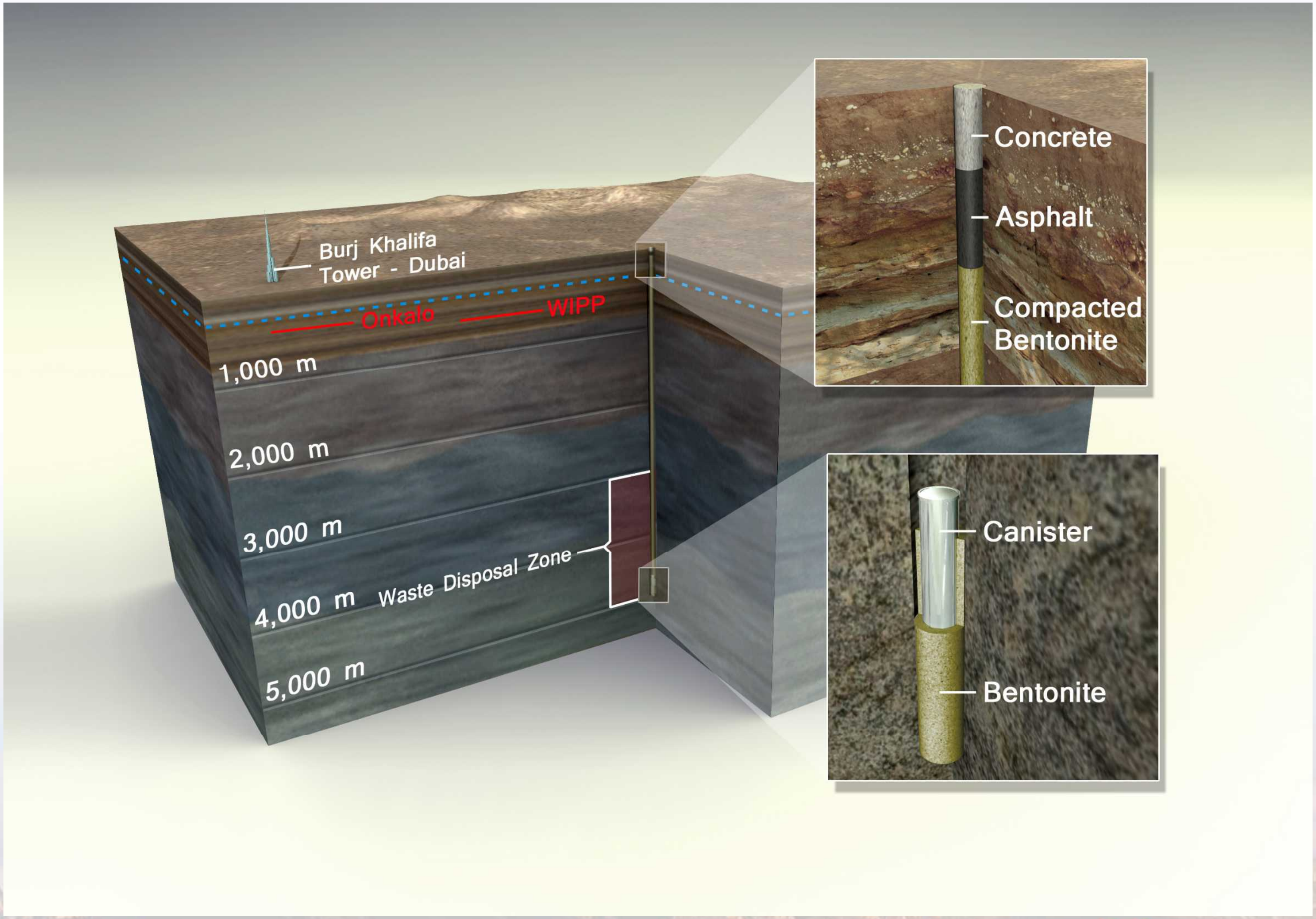
Outline

- Deep borehole disposal concept
- Thermal-mechanical-hydrological modeling near the borehole
- Thermal-hydrological modeling in the far field
- 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
- Several factors suggest the disposal concept is viable and safe:
  - Crystalline basement rocks are common in many stable continental regions
  - Existing drilling technology permits construction at a cost of about $US 20 million per borehole
  - Low permeability and high salinity 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

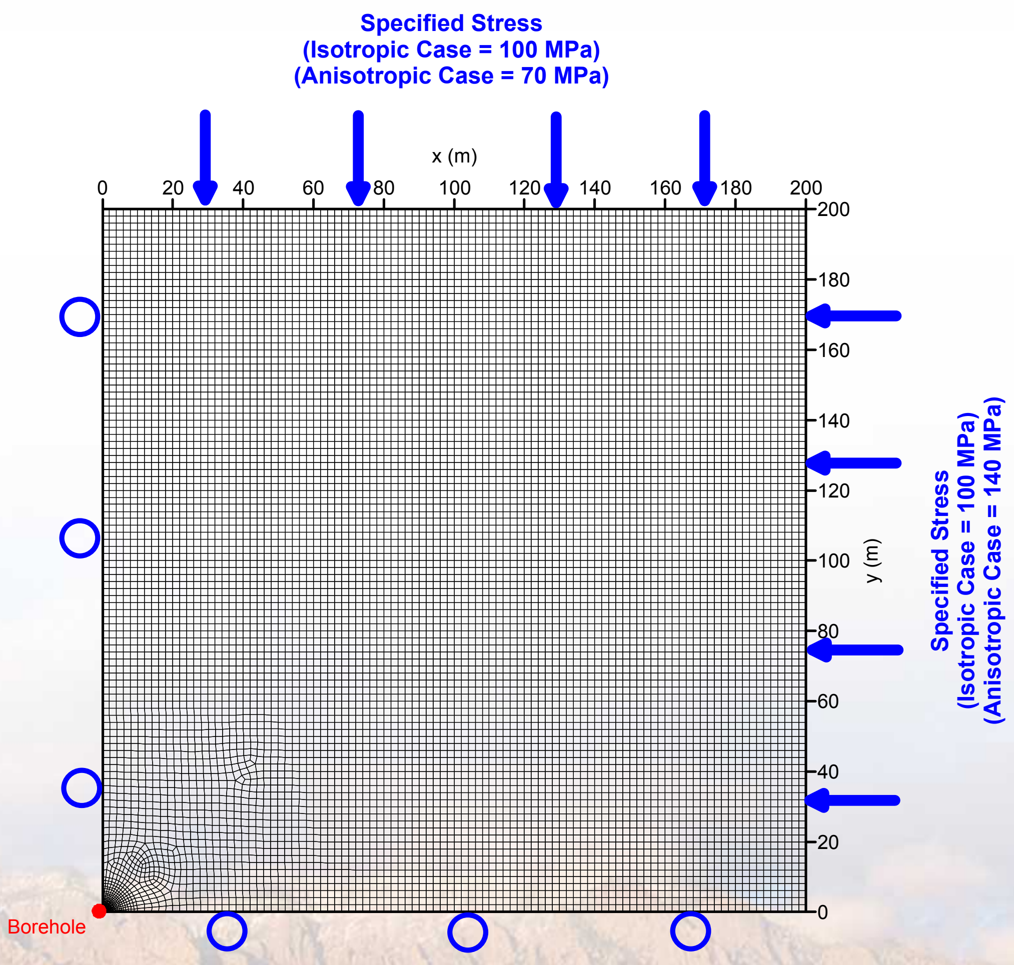


Coupled Process Modeling

- Coupled thermal-hydrologic-chemical-mechanical processes induced by decay heat may impact fluid flow, properties of the host rock near the borehole, and borehole wall stability
- Coupled process models:
  - Near-borehole thermal-mechanical model
  - Far-field thermal-hydrologic model for multiple boreholes
- Objectives of the near-borehole model included evaluation of temperature history, mechanical stress and strain, and software code comparisons (FEHM, Calorie-JAS3D, and Aria-Adagio)
- Objectives of the far-field model included evaluation of groundwater flow rates and sensitivity to number of boreholes, spacing of boreholes, and permeability

Thermal-Mechanical Modeling: Near Field

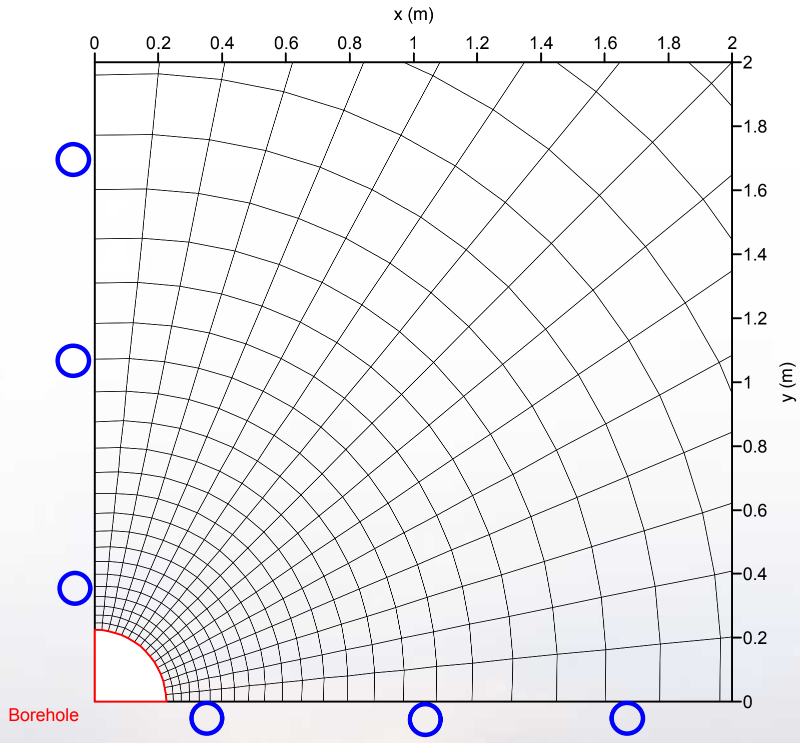
- Model domain set up for quarter symmetry in 2-D stress and thermal transport in a horizontal plane
- Specified stress applied to the outer boundaries (for both isotropic and anisotropic ambient horizontal stress)
- Zero normal-displacement boundary conditions applied to symmetry boundaries
- Specified ambient temperature at the outer boundaries
- Linear models of elastic stress, thermal conductivity, and thermal expansion used



Thermal-Mechanical Modeling: Near Field

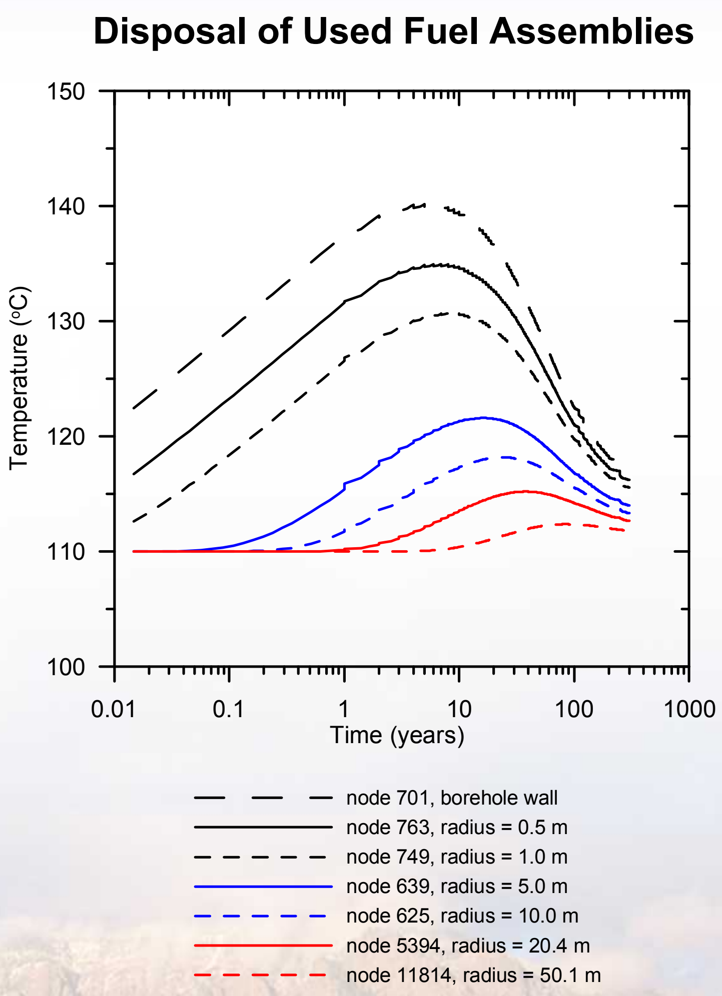
- **An unstructured, hexahedral grid was developed to conform to the borehole wall**
- **Parameter values representative of granite were used**

Parameter	Value
thermal conductivity (W/m °K)	3.0
density (kg/m^3)	2750.
porosity (-)	0.01
specific heat (J/kg °K)	790.
linear coefficient of thermal expansion ($°K^{-1}$)	8×10^{-6}
Poison ratio (-)	0.25
elastic modulus (MPa)	5×10^{4}
permeability of host rock (m^2)	1×10^{-19}
permeability of borehole disturbed zone (m^2)	1×10^{-16}



Thermal-Mechanical Modeling: Near Field

- Thermal simulations performed for disposal of (1) used PWR fuel assemblies and (2) vitrified HLW from reprocessing of commercial used fuel
- Calculations performed for a nominal depth of 4,000 m
- Peak temperature increase of about 30 °C at the borehole wall calculated for disposal of used PWR fuel assemblies
- Much higher peak temperature increase of about 180 °C was calculated for disposal of vitrified waste from reprocessing

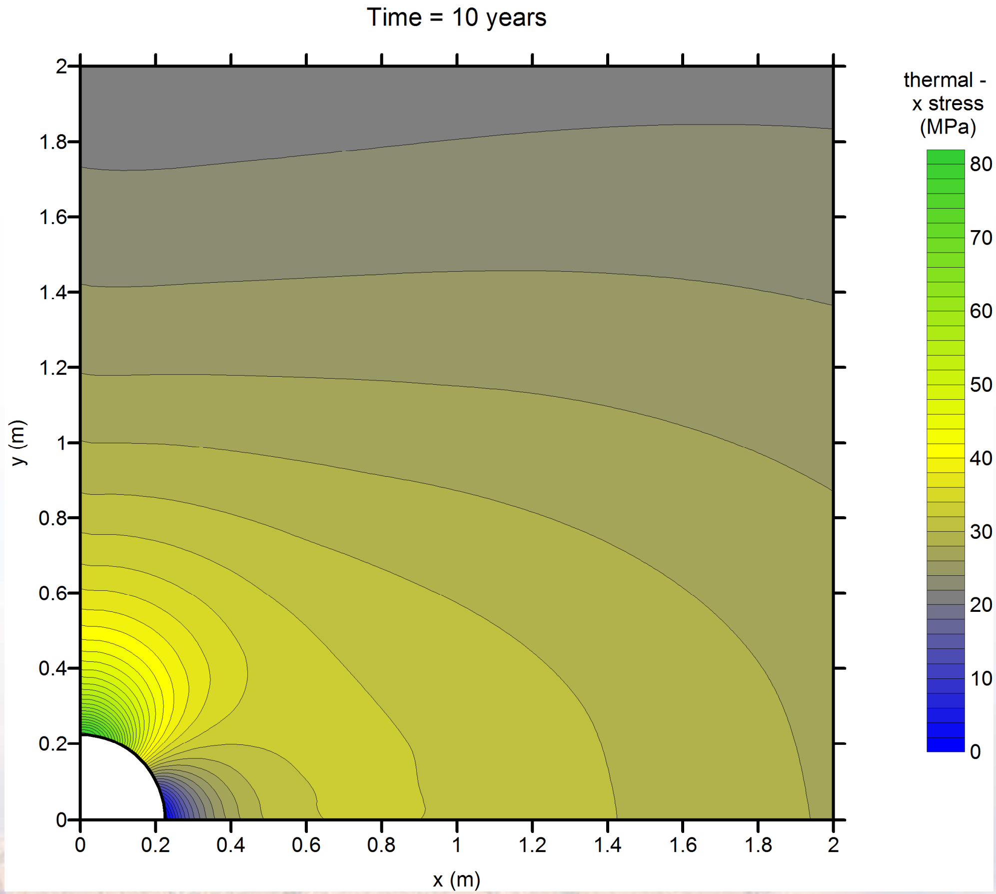


Sandia National Laboratories

Thermal-Mechanical Modeling: Near Field

- Initial conditions for thermal-mechanical simulations were calculated for distribution of equilibrium horizontal stress around the borehole
- Simulated change in the stress in the *x*-direction due to thermal expansion is shown in the figure
- Note that positive value of stress indicates compression
- The maximum increase in stress of about 90 MPa occurs at the borehole wall
- For anisotropic stress conditions, the maximum total stress is about 420 MPa, which greatly exceeds the average horizontal stress of 100 MPa

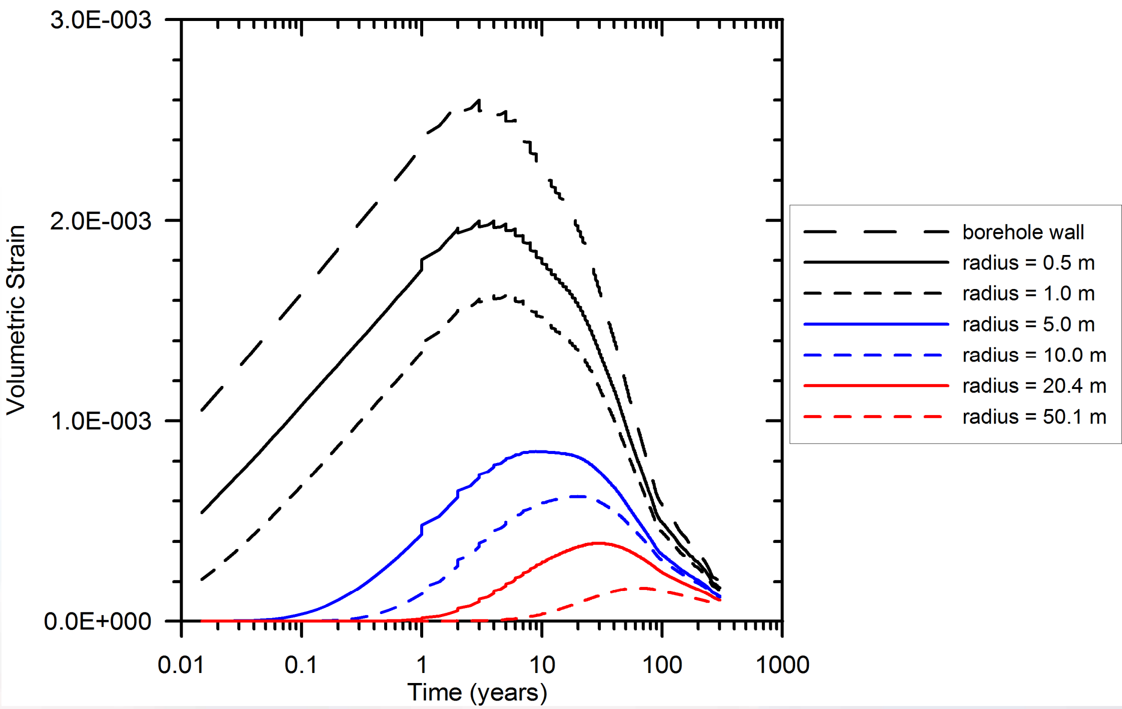
Disposal of Vitrified Waste from Reprocessing



Thermal-Mechanical Modeling: Near Field

- **Volumetric strain caused by the thermal input is compressive and concentrated concentrically around the borehole**
- **Peak volumetric strain is associated with peak temperatures and peak stress in the simulations**
- **The magnitude of peak strain near the borehole of greater than 1,000 microstrain could have a significant impact on fracture apertures and result in reduction of permeability in the borehole disturbed zone**

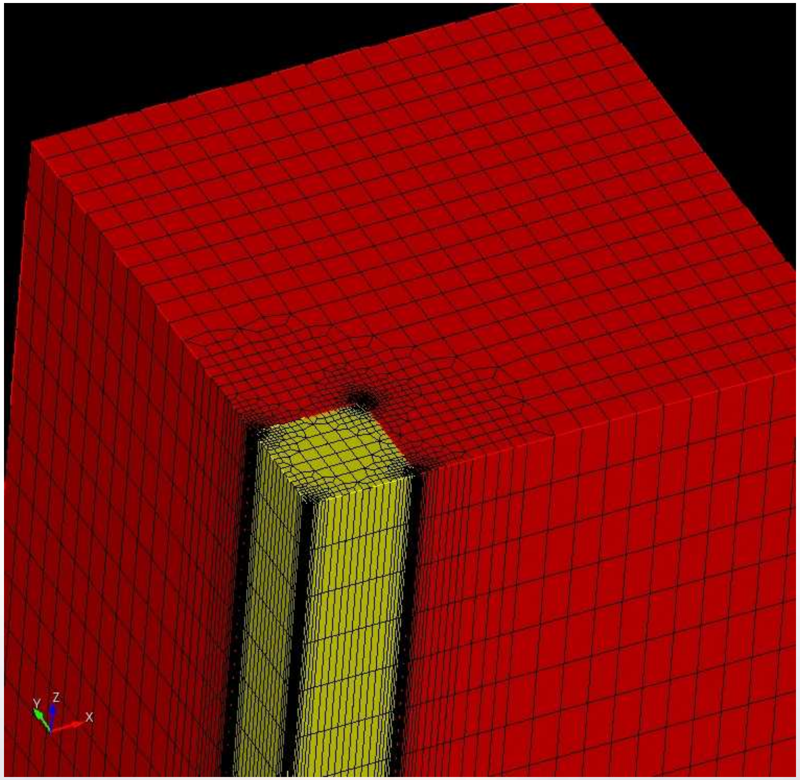
Disposal of Vitrified Waste from Reprocessing



Sandia National Laboratories

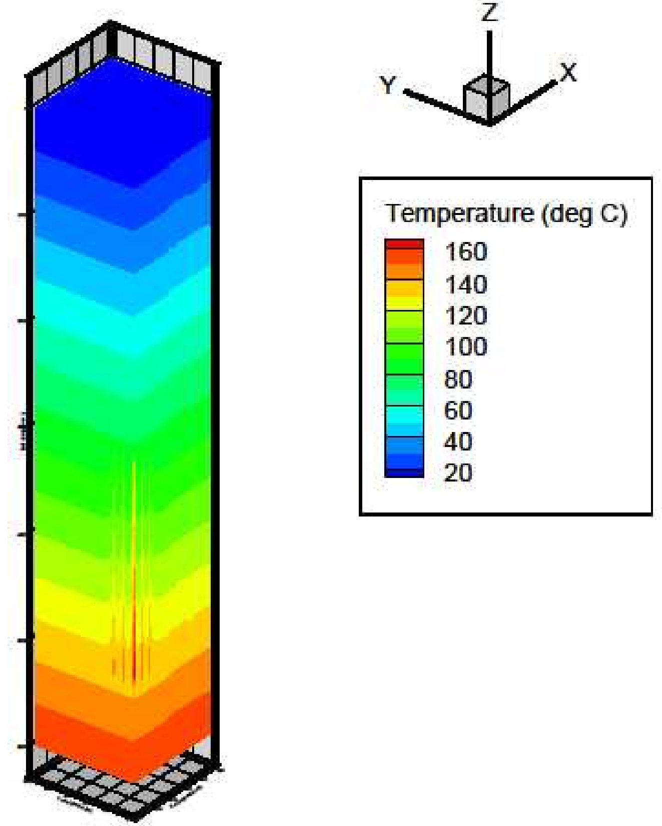
Thermal-Hydrological Modeling: Far Field

- The 3-D far-field model domain extends from the ground surface to a depth of 6,000 m
- Quarter symmetry around the central borehole is used to define the boundary conditions:
  - Specified temperature on top, bottom, and exterior sides of model
  - Specified hydrostatic pressure on the top, bottom, and exterior sides of the model
  - Specified heat flux from waste applied at depths from 3,000 to 5,000 m in boreholes
- Unstructured, hexahedral grid used with refinement near boreholes
- Thermal-hydrologic simulations performed with the FEHM software code



Thermal-Hydrological Modeling: Far Field

- Simulations were conducted for 1, 9, and 25 boreholes
- Sensitivity runs with spacing of 50, 100, and 200 m between the boreholes
- Note that groundwater near the boreholes will remain in the liquid state due to the high hydrostatic pressure at depths of the waste disposal zone

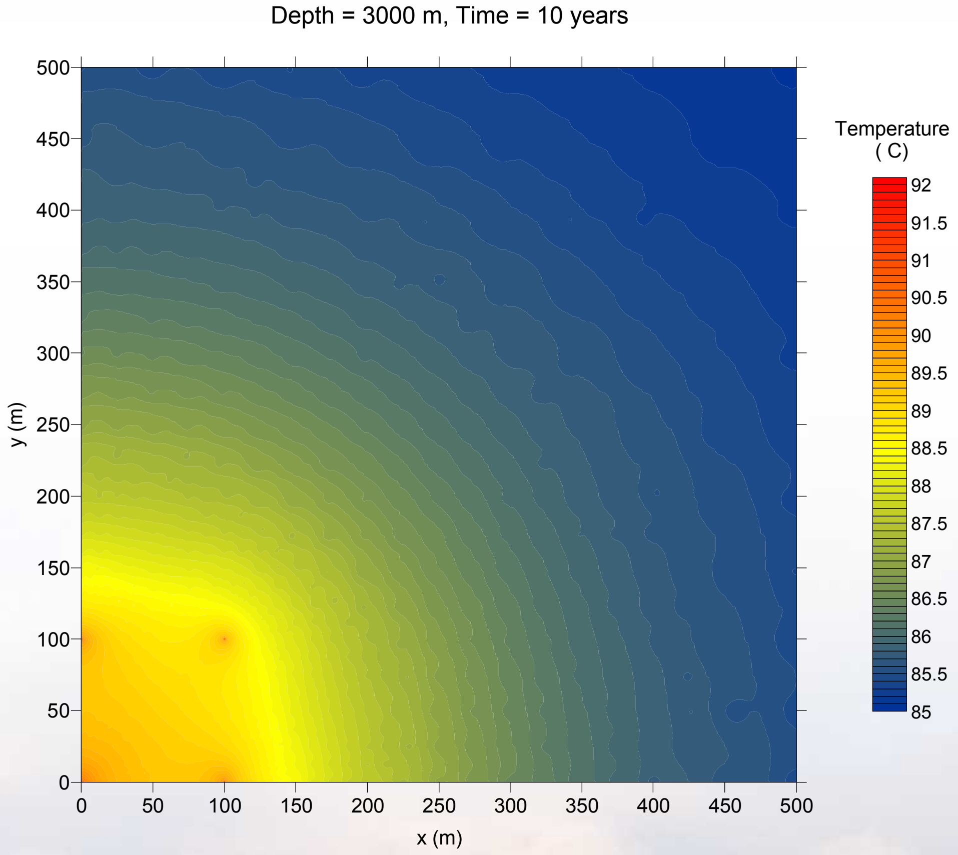


25 boreholes, 100 m well spacing, Time = 10 years

Sandia National Laboratories

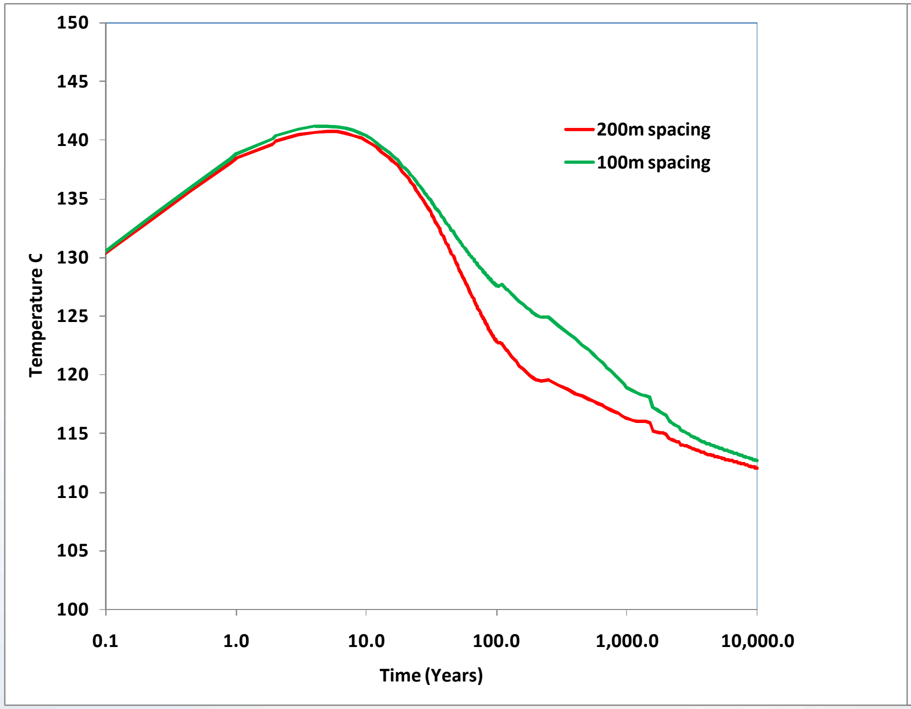
Thermal-Hydrological Modeling: Far Field

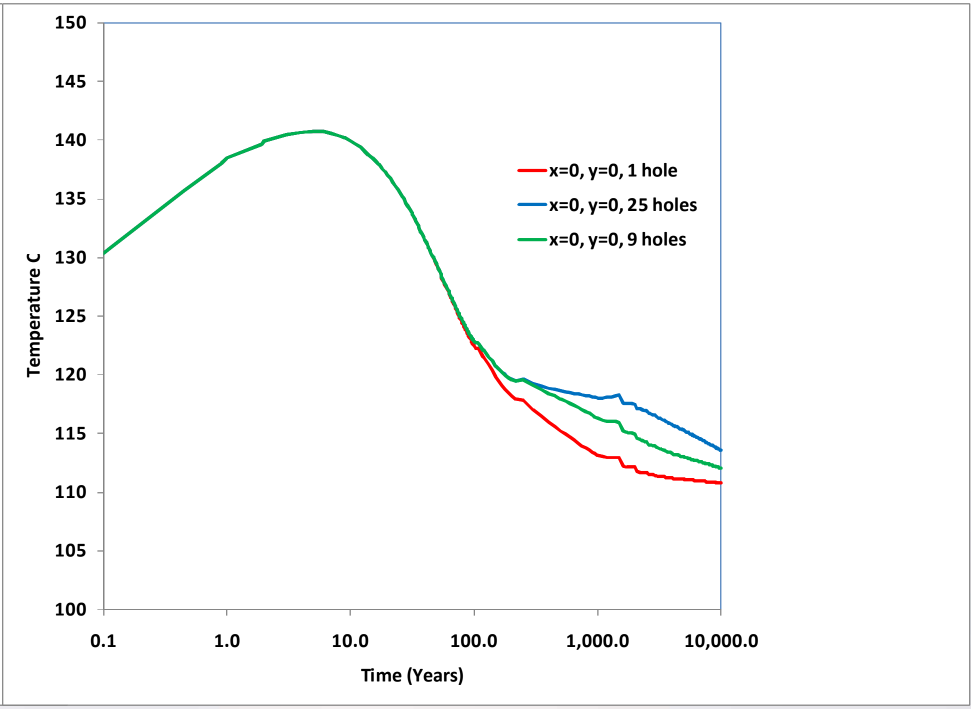
- Although some thermal interaction occurs between boreholes, simulated peak temperatures were approximately the same for 1, 9,or 25 boreholes
- Simulations indicate that groundwater near the boreholes will remain at higher temperatures for longer times for the multiple boreholes and for closer spacing
- Heat transfer is dominated by conduction due to the low fluid flow rates



Thermal-Hydrological Modeling: Far Field

Disposal of Used Fuel Assemblies

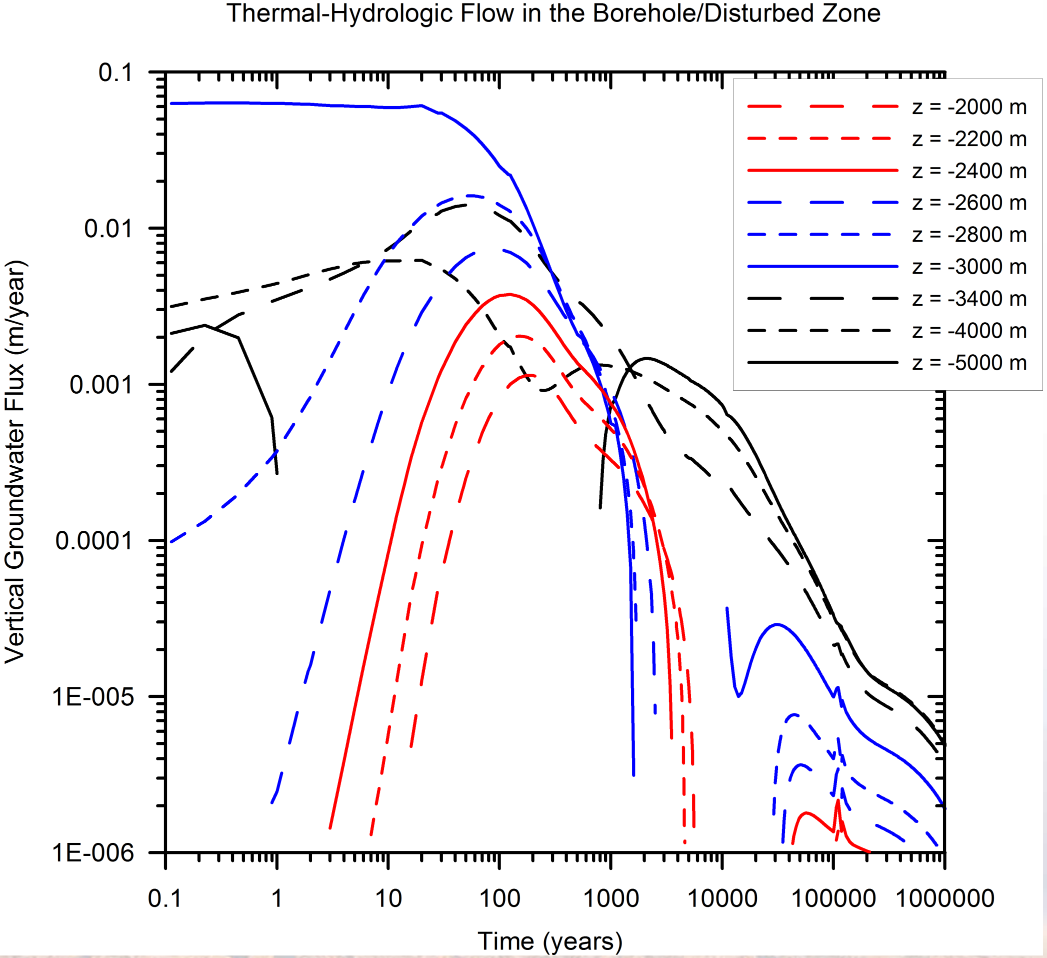




Thermal-Hydrological Modeling: Far Field

- **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 is dominated by 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, this conference)**

Disposal of Used Fuel Assemblies



Sandia National Laboratories

Conclusions

- Thermal-mechanical simulations indicate significant increases in stress and compressive strain near the borehole for limited time after disposal
- Increases in temperature, stress, and strain are much higher for disposal of vitrified waste from reprocessing than used fuel assemblies
- Under anisotropic ambient horizontal stress, simulated maximum compressive stress at the borehole wall likely exceeds the compressive strength of granite
- Compressive volumetric strain near the borehole would lead to transient decreases in fracture permeability in the host rock
- Thermal-hydrologic simulations indicate little sensitivity to the number or spacing of boreholes with regard to temperature history or induced groundwater flow rates in the borehole/disturbed zone
- Overall, these results support the conclusion that deep borehole disposal is a viable potential option for the disposition of used nuclear fuel or vitrified high-level waste