Deep Borehole Disposal – Performance Assessment and Criteria for Site Selection

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SNL-MIT Workshop on Deep Borehole Disposal

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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.

Outline

- Deep borehole disposal concept
- Potential viability and safety of the concept
- Preliminary performance assessment (PA) analyses
- Research on unresolved technical issues
- Potential criteria for site selection

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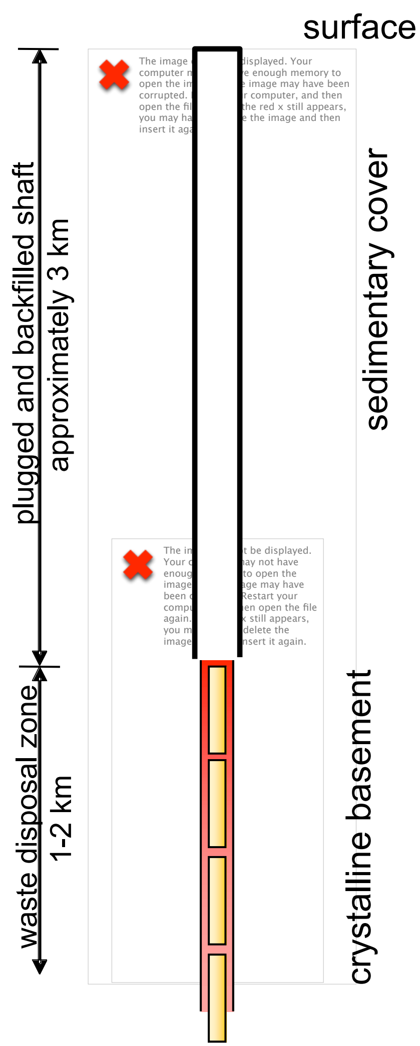
Deep Borehole Disposal Concept

- Vertical borehole drilled into crystalline basement to a depth of about 5 km
- Borehole is assessed for stress conditions, borehole stability, geochemistry, fluid pressures, permeability, etc.
- A string of waste containers with spent nuclear fuel assemblies or high-level radioactive waste glass is emplaced in the lower 2 km of borehole with approximately 45 cm diameter
- A borehole seal system consisting of compacted bentonite clay, asphalt, and concrete is used to seal the upper 3 km of the borehole



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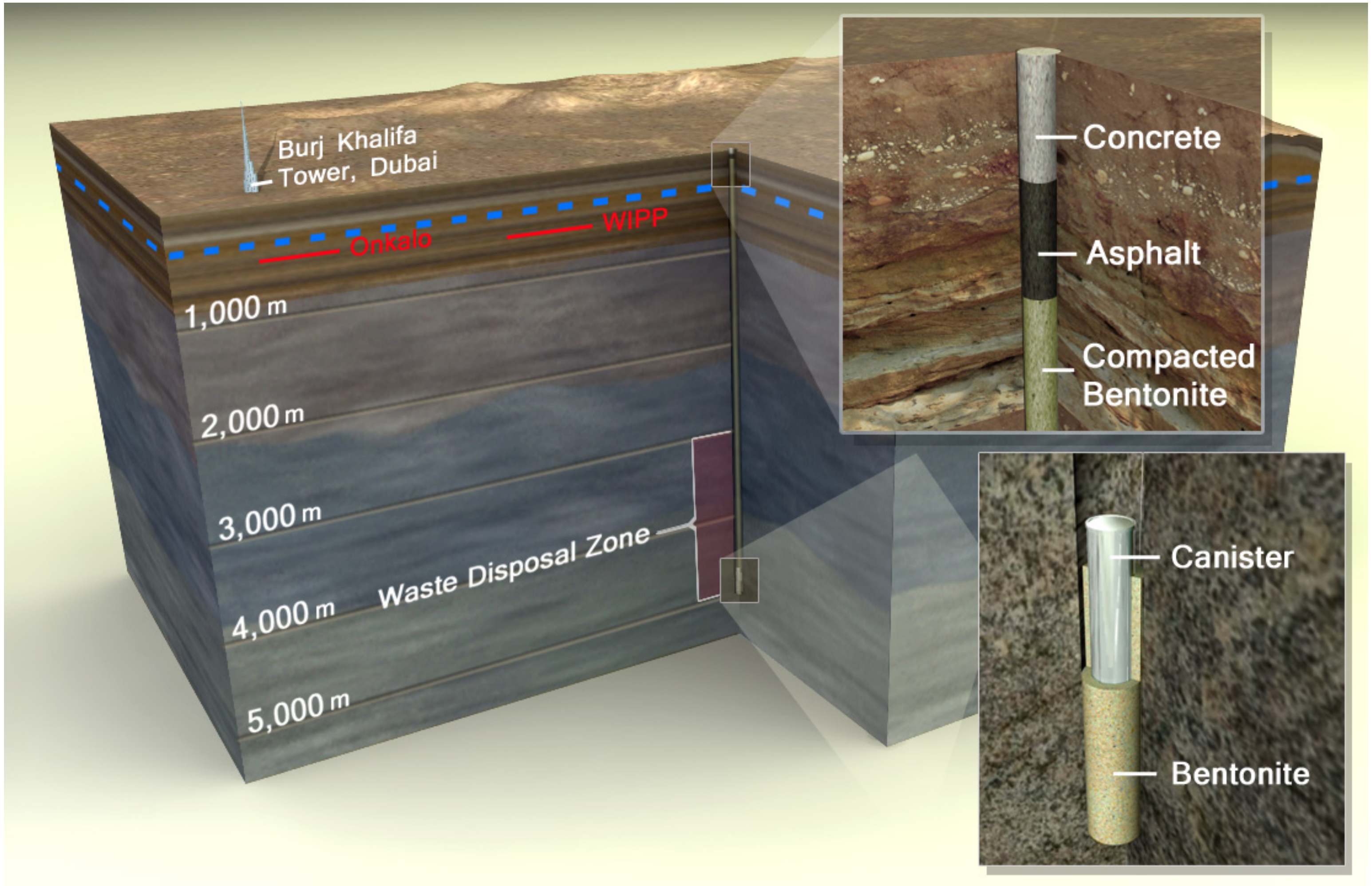
Deep Borehole Disposal Concept



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Disposal Concept Viability and Safety

- Crystalline basement rocks are relatively common at depths of 2 to 5 km
- Existing drilling technology permits construction of boreholes at a cost of about $20 million each
- Low permeability and high salinity in the deep continental crystalline basement suggest extremely limited interaction with shallow groundwater resources
- Geochemically reducing conditions limit the solubility and enhance the sorption of many radionuclides
- Disposal could occur at multiple locations, reducing waste transportation costs and risks
- The deep borehole disposal concept is modular, with construction and operational costs scaling approximately linearly with waste inventory
- Disposal capacity would allow disposal of projected U. S. spent nuclear fuel inventory in about 950 boreholes

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Preliminary Performance Assessment

- Define performance metric
- Identify relevant features, events, and processes (FEPs)
- Develop release scenario
- Define conceptual design and radionuclide inventory
- Develop conceptual and numerical models
- Representative parameter values used (probabilistic analyses not performed in preliminary PA)
- Compare PA analytical results to assumed performance metric

Preliminary Performance Assessment: Performance Metric

- **Performance metrics are typically defined by regulations**
- **Given the lack of governing regulations for deep borehole disposal, the performance metric was assumed to be a risk-based dose standard**
- **The preliminary PA analysis was designed to estimate dose to a reasonably maximally exposed individual, similar in concept to the Yucca Mountain standard**

Preliminary Performance Assessment: FEPs Analysis

- The list of 374 FEPs from the Yucca Mountain license application were considered for potential relevance to deep borehole disposal
- No new FEPs unique to deep borehole disposal were identified during the FEPs evaluation
- Preliminary screening of FEPs was based on several assumptions, such as the assumption that waste packages corrode quickly and are not significant barriers to flow and radionuclide transport
- Retrievability of waste assumed to be excluded as a position of policy
- Preliminary screening resulted in 110 FEPs that should be included in the PA analysis

Preliminary Performance Assessment: Release Scenario Selection

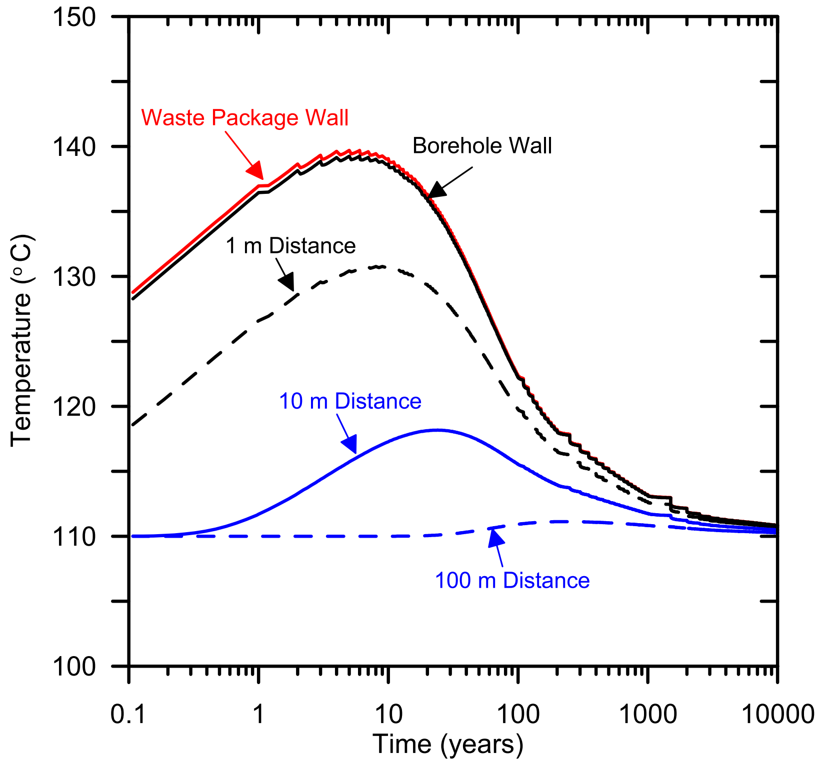
- **A single release scenario that incorporates many of the most likely included FEPs was constructed for use in the PA**
- **This scenario includes the following:**
  - **Enhanced permeability in the disturbed zone and/or borehole**
  - **Thermally driven upward groundwater flow**
  - **Dissolution of radionuclides from the waste form and transport in the groundwater**
  - **Release of radionuclides into the shallower fresh groundwater system**
  - **Pumping of the contaminated groundwater and release to a receptor population**

Preliminary Performance Assessment: Conceptual Design and Inventory

- Assume 400 used pressurized water reactor (PWR) fuel assemblies are stacked in a single borehole
- Radionuclide inventory and thermal output is based on average used PWR fuel that has been aged for 25 years
- Although fuel assemblies are sealed in waste canisters, assume rapid corrosion and degradation of canisters

Preliminary Performance Assessment: Conceptual and Numerical Models

- **Thermal conduction model used to simulate temperatures**
- **Results indicate a maximum temperature increase of about 30°C at the borehole wall**
- **Significant temperature increases do not persist beyond 100 to 200 years**
- **Results show a temperature increase of about 125 °C for disposal of vitrified waste from reprocessing**



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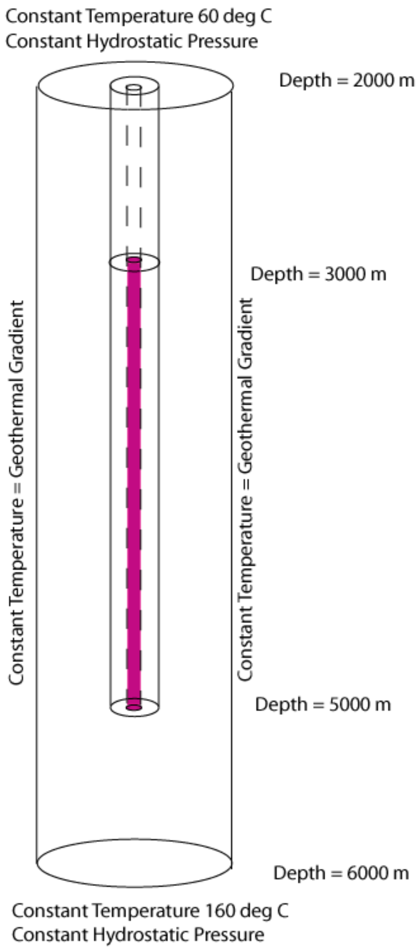
Coupled Thermal-Hydrologic Model



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

- **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**
- **Results indicate upward vertical flow near the borehole driven primarily by thermal expansion, and not by free convection**
- **Upward flow (about 1.5 cm/year) persists for about 200 years at the top of the waste disposal zone**
- **Lesser upward flow (flux of up to 3.5 mm/year) occurs for about 600 years in the borehole at a location 1000 m above the waste**

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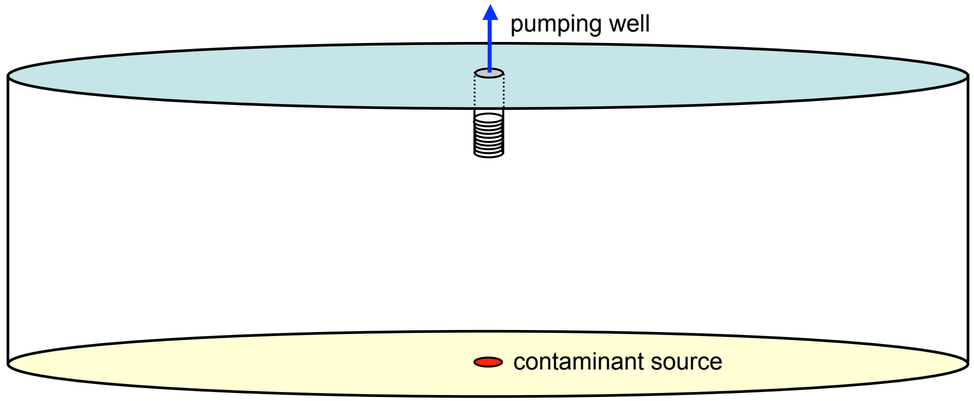
Groundwater Pumping and Dilution

- 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
- 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 PA calculations



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.

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Preliminary Performance Assessment: Conceptual and Numerical Models

- Dissolved solubility limits of radionuclides estimated for thermal – chemical conditions in the borehole and assuming solid oxide phases of radionuclides
- Representative values of sorption coefficients under reducing conditions were based on literature
- Decay and ingrowth of 31 radionuclides included
- One-dimensional analytical solution for the advection – dispersion equation with sorption used for the analysis
- Delay and dilution from pumping included in the analysis to calculate radionuclide concentrations released from the well
- Biosphere dose conversion factors from the Yucca Mountain project used to calculate radiological dose

Performance Assessment Results

- **Peak radiological dose to an individual using contaminated groundwater from the hypothetical pumping well was calculated as 1.4 x 10^{-10} mrem/year (1.4 x 10^{-12} mSv/year)**
- **The only radionuclide contributing to the calculated dose is ^{129}I, which has high solubility and is nonsorbing**
- **Peak dose was calculated to occur about 8,200 years following waste emplacement**
- **For comparison, the regulatory limit for dose from the Yucca Mountain repository is 15 mrem/year (for the first 10,000 years) and 100 mrem/year (for up to 1,000,000 years)**
- **Preliminary analyses also indicate that nuclear criticality, molecular diffusion, and thermally induced hydrofracturing would not impact the safety of the disposal system**

Publication of Preliminary Results

SANDIA REPORT
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Deep Borehole Disposal of High-Level Radioactive Waste

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Key Technical Issues

- Long-term behavior of borehole seals
- Modeling of coupled thermal-hydrologic-mechanical-chemical behavior near the borehole
- Compounds that sorb/sequester radionuclides (in particular, radioactive iodine) in the borehole or seals
- More detailed performance assessment analyses:
  - Full consideration of features, events, and processes relevant to potential release pathways and scenarios
  - Incorporation of more detailed modeling, including coupled processes, in particular
  - Scaling up from single to multiple boreholes
- Criteria for site selection and borehole characterization
- Operational and engineering analysis of waste emplacement process
- More detailed cost analyses

Potential Criteria for Site Selection

- Siting criteria should be based on potential impact to disposal performance
- Discussion outlined here is limited to technical criteria for site selection – political/legal/economic considerations are clearly important, but outside the scope of this presentation
- Criteria for site selection can be developed and applied at the scale of regional screening or at the scale of an individual borehole
- For the screening level, criteria should be directed at improving the probability of success at any given location
- Specific criteria for site suitability need to be defined at the level of an individual borehole

Potential Criteria for Site Selection

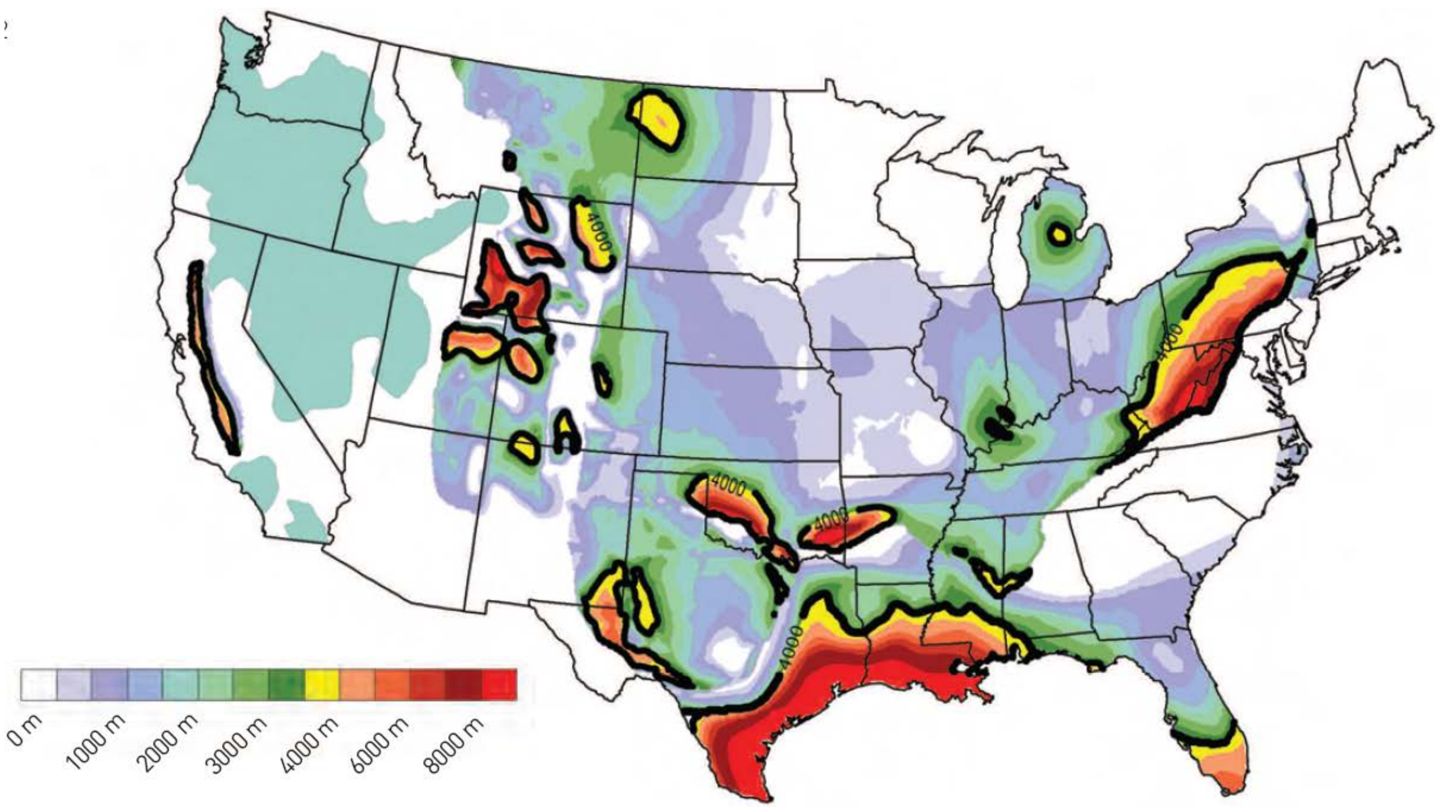
- **Preliminary list of siting criteria:**
  - **Depth to crystalline basement**
  - **Depth to saline groundwater**
  - **Anisotropy in horizontal stress**
  - **Fluid overpressure at depth**
  - **Geochemically reducing conditions at depth**
  - **Permeability of host rock**
  - **Tectonic stability**
  - **Volcanism**
  - **Geothermal gradient**
  - **Mineral resource potential**
  - **Topographic relief**

Potential Criteria for Site Selection

- **Potential Criterion: Depth to crystalline basement**
- **Issues:**
  - **Crystalline basement should be less than 2 km deep**
  - **Overlying sedimentary strata with porous media-hosted fresh groundwater flow system may be desirable for isolation of the deeper fractured crystalline basement**
  - **Granite may be desirable type of crystalline basement**
- **Can be evaluated at the screening level in many areas**

Potential Criteria for Site Selection

• **Potential Criterion: <u>Depth to crystalline basement</u>**

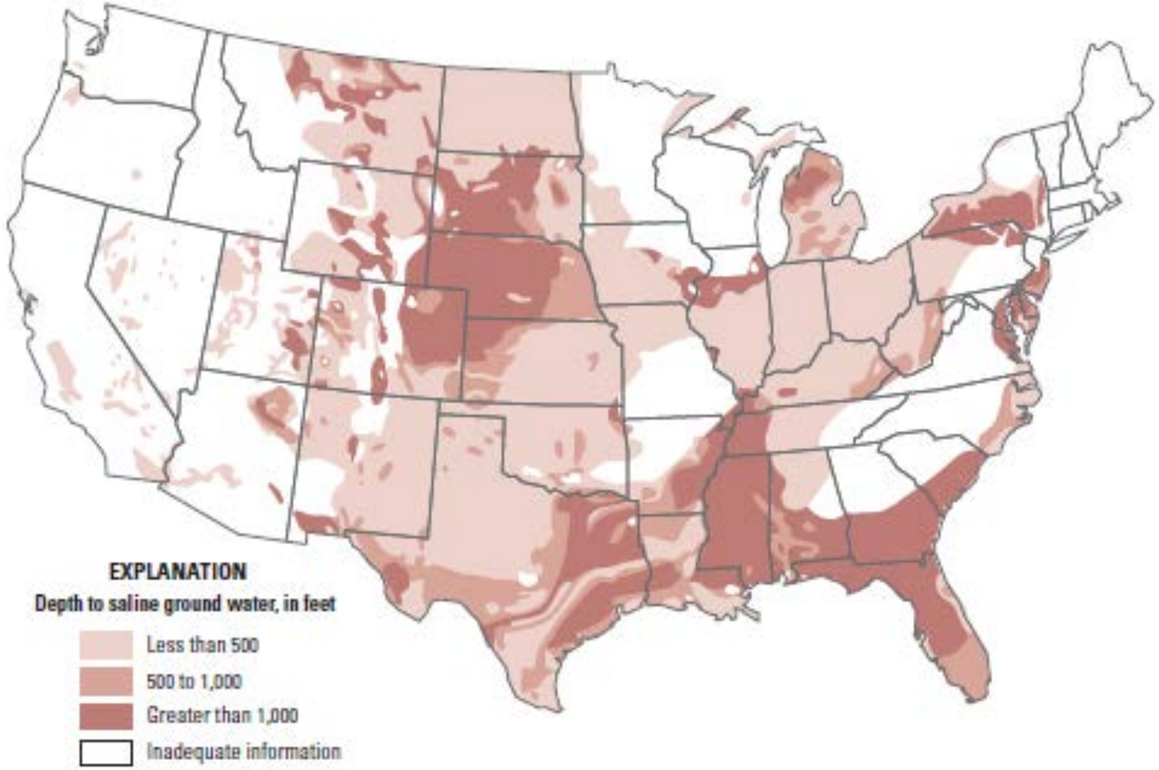


Potential Criteria for Site Selection

- **Potential Criterion: Depth to saline groundwater**
- **Issues:**
  - **Saline groundwater indicates limited natural interaction with shallow fresh groundwater resources**
  - **Higher density of saline groundwater opposes upward groundwater movement via thermal convection**
  - **Saline groundwater in crystalline rock is not a target for pumping under most circumstances**
  - **Favorable geochemical conditions are generally associated with saline groundwater (e.g., reducing conditions)**
- **Can be evaluated at the screening level in many areas, but requires confirmation by drilling**

Potential Criteria for Site Selection

• **Potential Criterion: <u>Depth to saline groundwater</u>**



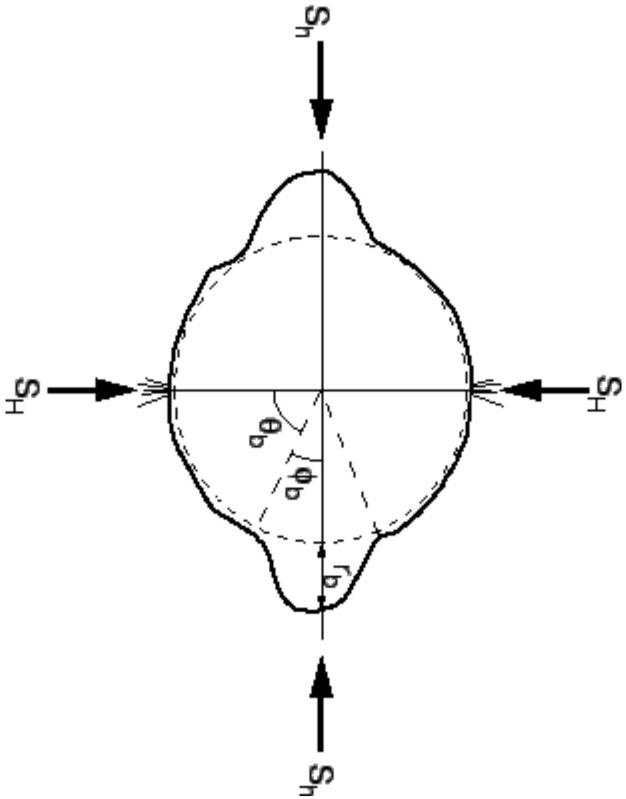
Source: USGS Circular 1323

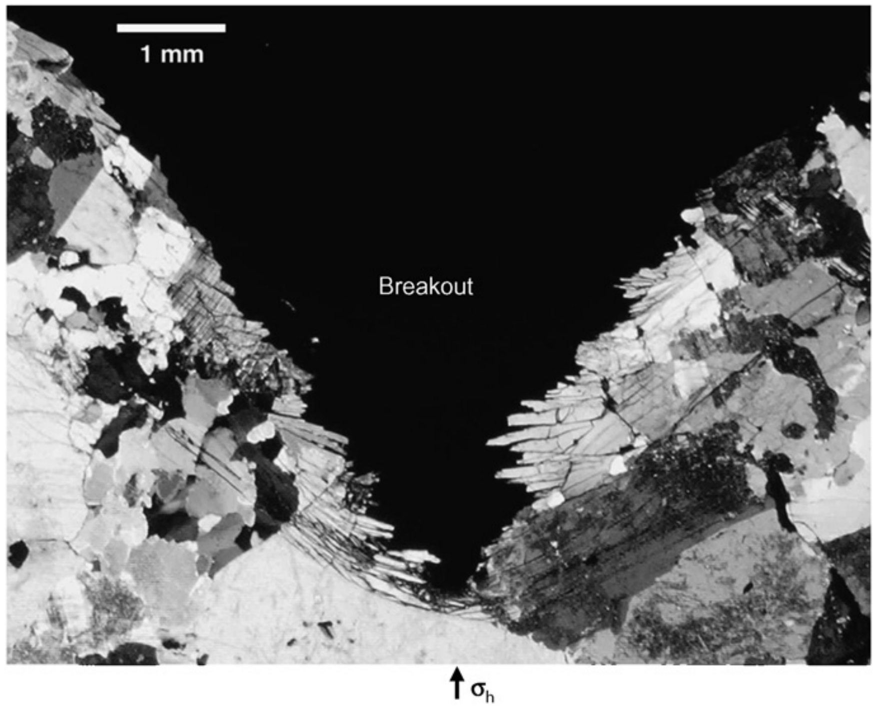
Potential Criteria for Site Selection

- Potential Criterion: <u>Anisotropy in horizontal stress</u>
- Issues:
  - Borehole stability during drilling, emplacement operations, and post-closure (development of borehole breakout)
  - Interaction with thermal stresses
  - May impact the effectiveness of borehole seals
  - Can be assessed using borehole geophysical methods
- Can be evaluated at the screening level in some areas, but requires confirmation by drilling

Potential Criteria for Site Selection

- **Potential Criterion: <u>Anisotropy in horizontal stress</u>**





Potential Criteria for Site Selection

- **Potential Criterion: <u>Fluid overpressure at depth</u>**
- **Issues:**
  - **Provides fluid potential for upward advection of groundwater in borehole or disturbed zone around borehole**
  - **Can result from a number of hydrogeological conditions, including topographically driven flow, sediment compaction in active basins, tectonic loading (e.g., faults), high thermal output in crystalline rocks (creating convective flow), generation of gas, continental glaciation, and volcanism**
  - **May be difficult to assess within a borehole**
- **Can be evaluated at the screening level in some areas, but requires confirmation by drilling**

Potential Criteria for Site Selection

- **Potential Criterion: <u>Geochemically reducing conditions</u>**
- **Issues:**
  - **Highly important to solubility and mobility of many radionuclides**
  - **In situ redox state can be determined from hydrochemistry and mineralogy of host rock**
  - **May be relevant to the stability and durability of seals, grouts, and any radionuclide “getters” added to them**
- **Expect geochemically reducing conditions at depth at all locations, but requires confirmation by drilling**

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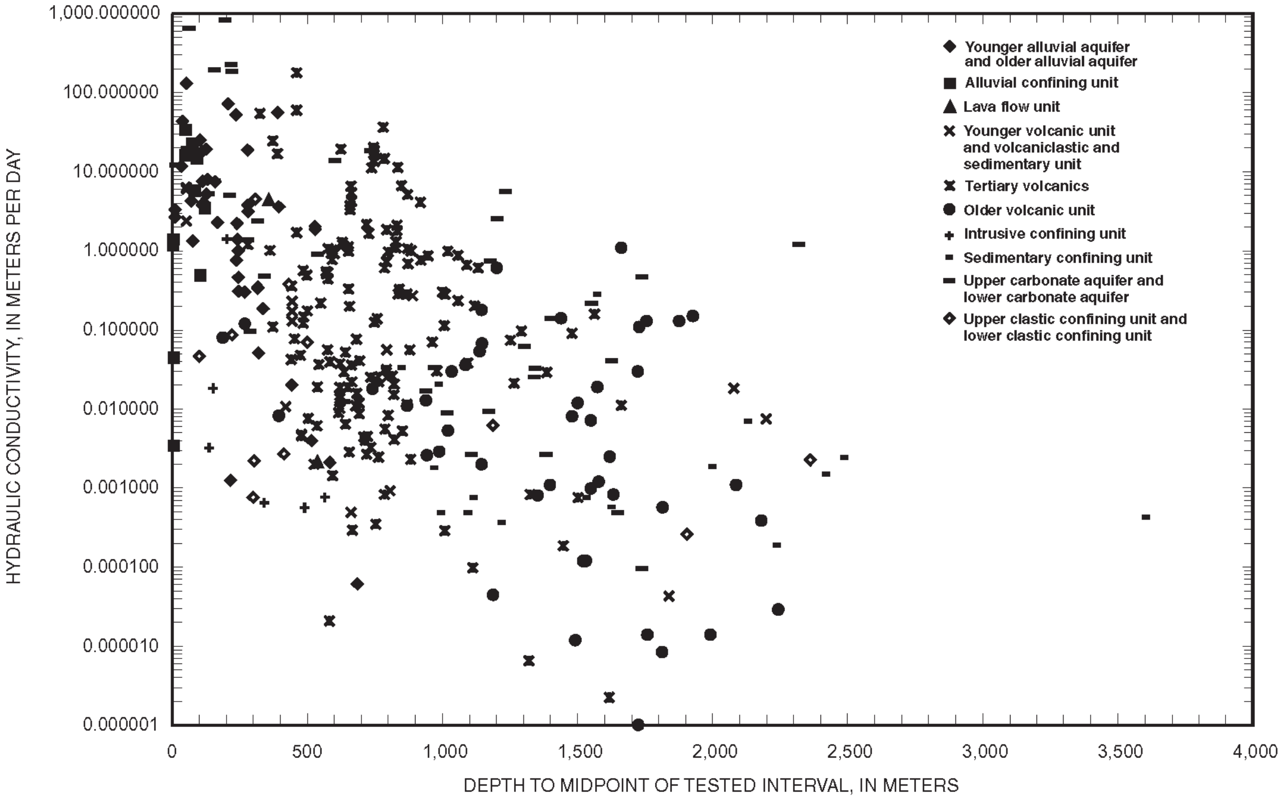
Potential Criteria for Site Selection

- **Potential Criterion: <u>Permeability of host rock</u>**
- **Issues:**
  - **Low permeability of fractured crystalline host rock is expected, but experience indicates that some fracture zones with relatively high permeability can occur at great depths**
  - **Higher-permeability fracture zones not necessarily connected to shallower groundwater flow system**
  - **Fractures can be identified with geophysical logging of borehole**
  - **Fracture apertures can be estimated with geophysical logging**
  - **Higher-permeability zones within the disposal zone can be sealed and not used for emplacement of waste**
- **Permeability generally decreases with depth, but requires confirmation by drilling**

Potential Criteria for Site Selection

- **Potential Criterion:** **<u>Permeability of host rock</u>**



Source: D'Agnese et al. (1997)

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Potential Criteria for Site Selection

- Potential Criterion: Tectonic stability
- Issues:
  - Relevant to the faulting and fault movement
  - Related to seismic hazard (probably not important to post-closure performance, but possibly important during operational phase)
  - May be relevant to overpressure (or underpressure) at depth
- Can be evaluated at the screening level in all areas

Potential Criteria for Site Selection

- Potential Criterion: Volcanism
- Issues:
  - Direct release pathway to the surface
- Can be evaluated at the screening and site-specific levels in most areas

Potential Criteria for Site Selection

- **Potential Criterion: Geothermal gradient**
- **Issues:**
  - **High geothermal gradient may be indicative of upward groundwater flow (overpressures at depth), high thermal-output crystalline basement, tectonically active regime, or volcanism**
  - **Very high geothermal gradient might be a target for geothermal resource development and lead to human intrusion**
  - **Very high geothermal gradient may lead to unacceptably high temperatures with the addition of decay heat from the waste**
- **Can be evaluated at the screening level in some areas, but requires confirmation by drilling**

Potential Criteria for Site Selection

- **Potential Criterion: <u>Mineral resource potential</u>**
- **Issues:**
  - **Presence of mineral resources in the disposal zone could lead to human intrusion**
  - **Very few mineral resources are targets for exploration or exploitation at depths of greater than 2 km in crystalline rock**
- **Can be evaluated at the screening level in many areas, but requires confirmation by drilling**

Potential Criteria for Site Selection

- Potential Criterion: **Topographic relief**
- **Issues:**
  - High topographic relief can result in regional groundwater flow that penetrates to great depths
  - Upward groundwater flow resulting from overpressure at depth occurs at some locations in deep regional groundwater flow systems
  - Topographically-driven regional groundwater flow can extend for hundreds of kilometers from some mountain fronts
- **Can be evaluated at the screening level in all areas**