Geological and Practical Aspects of Deep Borehole Disposal

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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
Geological Aspects of Safety and Borehole Siting

from Perry (2011)
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:
  - 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
  - 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

- 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
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).
Geological Aspects of Safety: 2D Mechanical Numerical Modeling

- 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>thermal conductivity (W/m °K)</td>
<td>3.0</td>
</tr>
<tr>
<td>density (kg/m³)</td>
<td>2750.</td>
</tr>
<tr>
<td>porosity (-)</td>
<td>0.01</td>
</tr>
<tr>
<td>specific heat (J/kg °K)</td>
<td>790.</td>
</tr>
<tr>
<td>linear coefficient of thermal expansion (°K⁻¹)</td>
<td>8 x 10⁻⁶</td>
</tr>
<tr>
<td>Poisson ratio (-)</td>
<td>0.25</td>
</tr>
<tr>
<td>elastic modulus (MPa)</td>
<td>5 x 10⁴</td>
</tr>
</tbody>
</table>
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.
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

Arnold et al. (2011)
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.
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.
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)
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.
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.

<table>
<thead>
<tr>
<th>Cost per Borehole</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Drilling, Casing, and Borehole Completion</td>
<td>$27,296,587</td>
</tr>
<tr>
<td>Waste Canisters and Loading</td>
<td>$7,629,600</td>
</tr>
<tr>
<td>Waste Canister Emplacement</td>
<td>$2,775,000</td>
</tr>
<tr>
<td>Borehole Sealing</td>
<td>$2,450,146</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$40,151,333</td>
</tr>
</tbody>
</table>

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

from Arnold et al. (2011)
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.

<table>
<thead>
<tr>
<th>Year</th>
<th>PWR</th>
<th>BWR</th>
<th>Total</th>
<th>PWR</th>
<th>BWR</th>
<th>Total</th>
<th>PWR</th>
<th>BWR</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>97,400</td>
<td>128,600</td>
<td>226,000</td>
<td>42,300</td>
<td>23,000</td>
<td>65,200</td>
<td>3.74</td>
<td>3.12</td>
<td>39,600</td>
</tr>
<tr>
<td>2030</td>
<td>165,000</td>
<td>219,200</td>
<td>384,200</td>
<td>72,000</td>
<td>39,200</td>
<td>111,100</td>
<td>4.24</td>
<td>3.87</td>
<td>45,400</td>
</tr>
<tr>
<td>2055</td>
<td>209,000</td>
<td>273,000</td>
<td>483,000</td>
<td>91,000</td>
<td>49,000</td>
<td>140,000</td>
<td>4.40</td>
<td>4.09</td>
<td>47,300</td>
</tr>
</tbody>
</table>

### Table 3-6 Maintain current nuclear generation.

<table>
<thead>
<tr>
<th>Year</th>
<th>PWR</th>
<th>BWR</th>
<th>Total</th>
<th>PWR</th>
<th>BWR</th>
<th>Total</th>
<th>PWR</th>
<th>BWR</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>97,400</td>
<td>128,600</td>
<td>226,000</td>
<td>42,300</td>
<td>23,000</td>
<td>65,200</td>
<td>3.74</td>
<td>3.12</td>
<td>39,600</td>
</tr>
<tr>
<td>2020</td>
<td>131,000</td>
<td>173,000</td>
<td>304,200</td>
<td>57,000</td>
<td>30,900</td>
<td>88,800</td>
<td>4.04</td>
<td>3.57</td>
<td>43,100</td>
</tr>
<tr>
<td>2040</td>
<td>198,600</td>
<td>261,600</td>
<td>460,200</td>
<td>86,600</td>
<td>46,800</td>
<td>133,400</td>
<td>4.36</td>
<td>4.05</td>
<td>46,900</td>
</tr>
<tr>
<td>2060</td>
<td>266,000</td>
<td>350,000</td>
<td>616,000</td>
<td>116,000</td>
<td>63,000</td>
<td>179,000</td>
<td>4.52</td>
<td>4.29</td>
<td>48,800</td>
</tr>
<tr>
<td>2080</td>
<td>333,000</td>
<td>439,000</td>
<td>772,000</td>
<td>146,000</td>
<td>79,000</td>
<td>224,000</td>
<td>4.62</td>
<td>4.43</td>
<td>49,900</td>
</tr>
<tr>
<td>2100</td>
<td>401,000</td>
<td>527,000</td>
<td>928,000</td>
<td>175,000</td>
<td>95,000</td>
<td>270,000</td>
<td>4.68</td>
<td>4.53</td>
<td>50,600</td>
</tr>
</tbody>
</table>

- 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
- the estimated number of assemblies has been rounded to the nearest 200 prior to 2050 and nearest 1,000 thereafter, totals may not appear to sum correctly
- 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.

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


Perry, F., 2011, GIS Map of Depth to Crystalline Basement, personal communication, Los Alamos National Laboratory.

