Preliminary Performance Assessment of Deep Borehole Disposal of Radioactive Waste

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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.
• Deep borehole disposal concept
• Potential viability and safety of the concept
• Thermal, hydrologic, and geochemical modeling
• Preliminary safety assessment analyses
• Research on unresolved technical issues
Deep Borehole Disposal Concept
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
Thermal Conduction

- Assumed disposal of a single PWR fuel assembly per waste package
- Thermal output for an average fuel assembly that has been aged for 25 years
- 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
Coupled Thermal-Hydrologic Model

- Granite was assigned a permeability of $1 \times 10^{-19} \text{ m}^2$
- Sealed borehole and disturbed bedrock surrounding the borehole were assigned a value of $1 \times 10^{-16} \text{ m}^2$
- Results indicate upward vertical flow in 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 0.35 cm/year) occurs for about 600 years in the borehole at a location 1000 m above the waste
Geochemical Behavior

- Typical geochemical conditions at depths of greater than 3 km are Na-Ca-Cl brine of 2-3 M/L, pH of 8-9, and Eh of ~ -300 mV
- Solubility limits for many radionuclides are very low because of reducing conditions
- Most radionuclides are also subject to significant sorption onto host rocks and retardation during aqueous transport, with the notable exceptions of $^{129}$I and $^{14}$C

<table>
<thead>
<tr>
<th>Radioelement</th>
<th>Solubility-limiting phase</th>
<th>Dissolved concentration (M/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Am</td>
<td>Am$_2$O$_3$</td>
<td>$1 \times 10^{-9}$</td>
</tr>
<tr>
<td>Ac</td>
<td>Ac$_2$O$_3$</td>
<td>$1 \times 10^{-9}$</td>
</tr>
<tr>
<td>C</td>
<td>None</td>
<td>Not limited</td>
</tr>
<tr>
<td>Cm</td>
<td>Cm$_2$O$_3$</td>
<td>$1 \times 10^{-9}$</td>
</tr>
<tr>
<td>Cs</td>
<td>None</td>
<td>Not limited</td>
</tr>
<tr>
<td>I</td>
<td>Metal iodides</td>
<td>Not limited</td>
</tr>
<tr>
<td>Np</td>
<td>NpO$_2$</td>
<td>$1.1 \times 10^{-18}$</td>
</tr>
<tr>
<td>Pa</td>
<td>PaO$_2$</td>
<td>$1.1 \times 10^{-18}$</td>
</tr>
<tr>
<td>Pu</td>
<td>PuO$_2$</td>
<td>$9.1 \times 10^{-12}$</td>
</tr>
<tr>
<td>Ra</td>
<td>RaSO$_4$</td>
<td>Not limited</td>
</tr>
<tr>
<td>Sr</td>
<td>SrCO$_3$, SrSO$_4$</td>
<td>Not limited</td>
</tr>
<tr>
<td>Tc</td>
<td>TcO$_2$</td>
<td>$4.3 \times 10^{-38}$</td>
</tr>
<tr>
<td>Th</td>
<td>ThO$_2$</td>
<td>$6.0 \times 10^{-15}$</td>
</tr>
<tr>
<td>U</td>
<td>UO$_2$</td>
<td>$1.0 \times 10^{-8}$</td>
</tr>
</tbody>
</table>
• Radial 2-D model of groundwater pumping and contaminant transport was constructed for the freshwater 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 performance assessment calculations.
Preliminary Performance Assessment

- Single release scenario analyzed: Upward flow in a single borehole and disturbed zone – release to a pumping well
- Assume 400 spent fuel assemblies from commercial pressurized water reactors (a reasonable bounding case for other high-level waste forms)
- Assume rapid corrosion and degradation of waste containers
- Dissolved solubility limits of radionuclides estimated for thermal – chemical conditions in the borehole
- 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
- 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 $1.4 \times 10^{-10}$ mrem/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 8,000 years following waste emplacement

• For comparison, the International Atomic Energy Agency recommends a postclosure dose limit of 0.3 mSv/year (30 mrem/year)

• Preliminary analyses also indicate that nuclear criticality, molecular diffusion, and thermally induced hydrofracturing would not impact the safety of the disposal system
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
Publication of Preliminary Results

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Deep Borehole Disposal of High-Level Radioactive Waste

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Summary and Conclusions

• Deep borehole disposal of spent nuclear fuel and high-level radioactive waste is a potentially viable waste disposal concept

• Modeling of thermal conduction and coupled hydrothermal processes indicate acceptable increases in temperature and minor thermally induced groundwater flow

• Preliminary performance assessment analyses indicate that dose to a hypothetical human receptor would be limited to $^{129}\text{I}$ and would be negligible

• Several key unresolved technical issues have been identified and research is being pursued on several of these issues

• We recommend that a full-scale pilot project be undertaken to fully explore the viability of this waste disposal concept