Generic Disposal Concepts and Thermal Load Management for Larger Waste Packages

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Disposal concepts ("enclosed"): crystalline, clay/shale, salt, deep borehole (Re: January, 2012 briefing)

Thermal analysis for mined, "enclosed" concepts

Finite element analysis for generic salt repository (waste package size up to 32-PWR)

“Open” disposal concept development: shale unbackfilled, sedimentary backfilled, and hard-rock unsaturated (waste package sizes up to 32-PWR)

Thermal analysis for mined, “open” concepts

Summary and conclusions
Disposal Concept Definition, and Settings Evaluated

1. Waste inventory
   – Commercial SNF, 40 and 60 GW-d/MT burnup (existing inventory and bounding SNF case; Carter et al. 2012a)
   – Representative MOX and HLW types (summary: Hardin et al. 2012)

2. Geologic settings
   – Crystalline, clay/shale, bedded salt, crystalline basement, massive shale, sedimentary (e.g., alluvium), “hard rock”

3. Engineering concepts of operation
   – Crystalline (enclosed)*
   – Clay/shale (enclosed)*
   – Generic salt repository (enclosed)*
   – Deep borehole*
   – Hard-rock unsaturated (open)
   – Shale unbackfilled (open)
   – Sedimentary backfilled (open)

* January, 2012 briefing
Transient Superposition Solution for Multiple Packages & Drifts

- A central waste package is modeled as a finite line source.
- Adjacent waste packages are point sources.
- Adjacent drifts (or emplacement boreholes) are infinite line sources.
- Homogeneous host medium.

*Back-calculate approximate temperatures for radial layers representing the engineered barrier system.*
Relative Contributions to Transient Temperature Histories

Example: Relative contributions to calculated host rock temperature (at EBS boundary)

- LWR UOX spent fuel (60 GW-d/tHM; bounding)
- 10-yr age out-of-reactor
- 4-PWR package
- Clay/shale reference (enclosed) concept, similar to Andra (2005) concept for SNF

Thermal Analysis Results
Effect of Varying 100°C or 200°C Limits

Decay Storage Needed to Meet WP Surface Temperature Limits vs. WP Size or Capacity (PWR Assemblies; 60 GW-d/MT Burnup)

Temperature limits based on current international and previous U.S. concepts:
- 100°C for clay buffers and clay/shale media (e.g., SKB 2006)
- 200°C for salt (e.g., Salt Repository Project, Fluor 1986)

Final temperature constraints will be site- and design-specific

*Thermal conductivity for all media selected at 100°C.*

Disposal of Large Waste Packages in Salt Generic Salt Repository

- Generic salt repository layout (Carter et al. 2011)

- Abstracted to right-angle geometry (Hardin et al. 2012)
Generic Salt Repository
T-M and T-only Simulation Approach

- Coupled thermal-mechanical model (Clayton et al. 2012)
- Sierra codes (Sandia)
- Salt properties and constitutive models
  - Multi-mechanism creep model (Munson et al. 1989)
  - Crushed salt creep (Callahan 1999)
  - Thermal conductivity (Bechthold et al. 2004)

- Approach:
  - Test T-M dependence for initial problem
  - Use T-only model for sensitivity analyses

<table>
<thead>
<tr>
<th>Waste Package Size</th>
<th>Diameter (m)</th>
<th>Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 PWR assemblies</td>
<td>0.82</td>
<td>5.00</td>
</tr>
<tr>
<td>12 PWR assemblies</td>
<td>1.29</td>
<td>5.13</td>
</tr>
<tr>
<td>21 PWR assemblies</td>
<td>1.60</td>
<td>5.13</td>
</tr>
<tr>
<td>32 PWR assemblies</td>
<td>2.0</td>
<td>5.13</td>
</tr>
</tbody>
</table>
Intact salt thermal conductivity (WIPP values)

<table>
<thead>
<tr>
<th>$K_{th}$</th>
<th>5.4 W/m-K</th>
<th>25°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2</td>
<td>100 °C</td>
<td></td>
</tr>
<tr>
<td>3.2</td>
<td>200 °C</td>
<td></td>
</tr>
</tbody>
</table>

Crushed salt backfill (BAMBUS II) values scaled to intact WIPP salt

$K_{th}$ 0.6 W/m-K 40%

porosity (100°C)

| 2.0 | 20% |
| 4.2 | 0%  |

Recess for better heat transfer
- **Peak salt temperature** vs. initial package thermal power correlation (>200°C limit shown shaded)
- Burnup, age, and package dimensions are 2nd order
- Also true for other geologic media and disposal concepts
- Use waste package surface temperature to control interface with in-package analyses

\[ y = 19.194x + 25 \]
\[ R^2 = 0.9882 \]
Reference Mined Disposal Concepts: Open vs. Enclosed Emplacement Modes

- **Open**: excavated emplacement openings persist
  - Heat spread by thermal radiation $\rightarrow$ lower temperature at the waste package
  - Pre-closure ventilation possible while drifts remain open for decades

- **Enclosed**: emplacement openings close (salt, clay/shale) and/or clay buffer surrounds the waste package (crystalline rock)
  - More thermal resistance than radiation across a gap $\rightarrow$ higher peak temperature in the EBS (e.g., KBS-3, Andra 2005, others)
Problem Statement (discussed in January, 2012 briefing):

For reference portfolio: Develop (open mode) disposal concepts that allow: 1) earlier emplacement, and 2) larger waste packages. Focus on commercial SNF, using a range of geologic settings and concepts of operation.

Potential benefits:

- Improved cost/schedule efficiency
- Flexibility not to transport SNF with age > 50 yr
- Limit packaging and re-packaging (especially if existing storage canisters can be disposed directly)
- Fewer package-specific operations of all types
Open Emplacement Modes (mined disposal; ventilated in-drift emplacement)

- Plastic Host Media (low perm.; nominally saturated or unsaturated)
  - Host Medium
    - Eventually Consolidates Around Packages
  - Open modes in low-permeability host media require low-permeability backfill prior to repository closure, if the host medium will not collapse to seal openings. This prevents preferential water flow in the repository (even for unsaturated conditions).

- Competent Host Media
  - High Perm. (e.g., fractured)
  - Low Perm. (sat. or unsat.)
  - Unsaturated
  - Saturated
  - Includes waste packages designed for containment longevity.

5. Sedimentary Backfilled (open) Concept

4. Unbackfilled Shale (open) Concept

6. Hard-Rock Unsaturated (open) Concept C

Install these measures at or before repository closure, as thermal and operational conditions permit.

Notes:
A. Open modes in low-permeability host media require low-permeability backfill prior to repository closure, if the host medium will not collapse to seal openings. This prevents preferential water flow in the repository (even for unsaturated conditions).
B. For higher permeability media use low-permeability buffer and/or backfill, for water diversion and transport attenuation.
C. Includes waste packages designed for containment longevity.
1. KBS-3 (vertical) disposal (enclosed)
2. Generic salt repository (enclosed)
3. Clay/shale repository (enclosed)
4. Shale unbackfilled open mode
5. Sedimentary backfilled open mode
6. Hard-rock unsaturated open mode
7. Deep borehole concept
4. Shale Unbackfilled Open Mode Concept (low-permeability, nominally sat. or unsat.)

Drift segments containing small numbers of waste packages are isolated by plugging/sealing (backfill is retained as an option at repository closure).

Source: Hardin et al. (2012).
Drift segments containing small numbers of waste packages are backfilled with low permeability (e.g., clay-rich) material at closure.

Source: Hardin et al. (2012).
Comprehensive design selection study (CRWMS M&O 1999)

Pre-closure ventilation for at least 50 years (all design alternatives considered in the study included this feature)

Long-term surface decay storage is not needed

Ventilation >> 50 years provides an option for a cooler repository

Free drainage → No need for complete backfilling at closure

Unsaturated → Shallow depth, facilitating ramp access

Key point: A similar open concept for saturated fractured rock would require complete backfilling at closure (remote operation) to limit groundwater movement through the repository.
Open Mode Thermal Analysis Results for Shale Unbackfilled Open Concept: Host Rock Thermal Conductivity

- Repository closure at 300 yr SNF age; surface storage 50 yr
- Burnup 40 GW-d/MT; $V_{\text{eff}} = 75\%$; Package size 21-PWR
- “High” host rock $K_{\text{th}}$ for thermal analyses is $\sim 3 \, \text{W/m-K}$
Open Mode Thermal Analysis Results for Shale Unbackfilled Open Concept: Ventilation Duration and Drift Spacing

- Surface storage 50 yr (vary SNF age at closure from 100 to 300 yr)
- Burnup 40 GW-d/MT; $V_{\text{eff}} = 90\%$; Package size 21-PWR
- Diminishing effect from ventilation duration $> 200$ yr
- Effect from $\sim 2X$ drift spacing is greater than $\sim 3X$ SNF age at closure

<table>
<thead>
<tr>
<th>Ventilation Period (yr)</th>
<th>Drift Spacing (m)</th>
<th>Peak Rock Temp. ($^\circ$C)</th>
<th>Peak Time (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>30</td>
<td>127.6</td>
<td>659</td>
</tr>
<tr>
<td>200</td>
<td>30</td>
<td>134.3</td>
<td>602</td>
</tr>
<tr>
<td>150</td>
<td>30</td>
<td>142.0</td>
<td>518</td>
</tr>
<tr>
<td>100</td>
<td>30</td>
<td>152.0</td>
<td>424</td>
</tr>
<tr>
<td>50</td>
<td>30</td>
<td>167.4</td>
<td>322</td>
</tr>
<tr>
<td>50</td>
<td>40</td>
<td>141.3</td>
<td>349</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td>124.2</td>
<td>322</td>
</tr>
</tbody>
</table>
Open Mode Thermal Analysis Results for Shale Unbackfilled Open Concept: “Design Test Case”

- Surface decay storage 50 yr; repository closure at 100 to 150 yr SNF age
- Burnup 40 GW-d/MT; $V_{\text{eff}} = 75\%$; 21-PWR; 4.5 m drift diameter
- Strategy: Heat a zone of host shale to $>100^\circ\text{C}$ (3 meters into the drift wall)
- Compare no-backfill with backfill options (varying backfill $K_{\text{th}}$)

<table>
<thead>
<tr>
<th>Host Medium</th>
<th>Description</th>
<th>SNF Age at Closure (yr)</th>
<th>Peak Rock Temp. ($^\circ\text{C}$)</th>
<th>Peak Time (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shale</td>
<td>Drift wall</td>
<td>100</td>
<td>121.3</td>
<td>129</td>
</tr>
<tr>
<td></td>
<td>$r_{\text{DW}} = 5.25$ m $^A$</td>
<td>100</td>
<td>100.9</td>
<td>470</td>
</tr>
<tr>
<td></td>
<td>Drift wall</td>
<td>150</td>
<td>107.3</td>
<td>384</td>
</tr>
<tr>
<td></td>
<td>$r_{\text{DW}} = 5.25$ m $^A$</td>
<td>150</td>
<td>95.1</td>
<td>562</td>
</tr>
</tbody>
</table>

$^A$ Location 3 m into the drift wall

Sources: Greenberg et al. (2012b); Hardin et al. (2012).
Summary and Conclusions (1/4)
Disposal Concepts

Identified 3 Generalized “Open” Disposal Concepts:

- **Shale Unbackfilled Open Concept**
  - Low permeability, massive shale, limited water inflow
  - Compartmentalize emplacement areas at closure (e.g., seal crossing drifts)

- **Sedimentary Backfilled Open Concept**
  - Wide variety of potentially suitable host media (e.g., alluvium, tuff)
  - Backfill at closure (low permeability, e.g., crushed rock, swelling clay)

- **Hard Rock Unsaturated Concept**
  - Long-term opening stability; temperature resistant host rock
  - No backfilling, plugging, or sealing required in emplacement areas

**Thermal Analysis**

- Larger Packages Meet Temperature Limits (200°C) in **Salt** and **Hard Rock Unsaturated** concepts (<100 yr aging, ≥ 21-PWR size packages)
## Reference Enclosed Emplacement Modes (SNF)

<table>
<thead>
<tr>
<th></th>
<th>High $K_{th}$</th>
<th>Tolerance (EBS up to 200°C?)</th>
<th>WP (PWR assy.’s)</th>
<th>Min. UOX Fuel Age at Emplacement (yr)</th>
<th>Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Crystalline</td>
<td>Note A</td>
<td></td>
<td>4</td>
<td>100</td>
<td>Clay-based buffer (100°C)</td>
</tr>
<tr>
<td>2. Generic Salt</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference</td>
<td></td>
<td></td>
<td>12</td>
<td>&lt;50</td>
<td></td>
</tr>
<tr>
<td>21-PWR, 40 GWd/MT</td>
<td>√</td>
<td>√</td>
<td>21</td>
<td>50</td>
<td>Peak salt temp. (200°C)</td>
</tr>
<tr>
<td>32-PWR, 40 GWd/MT or 21-PWR, 60 GWd/MT</td>
<td></td>
<td></td>
<td>21 or 32</td>
<td>&lt;100</td>
<td></td>
</tr>
<tr>
<td>3. Clay/Shale (enclosed)</td>
<td></td>
<td></td>
<td>4</td>
<td>100</td>
<td>Clay-based buffer (100°C)</td>
</tr>
<tr>
<td>7. Deep Borehole</td>
<td></td>
<td></td>
<td>1</td>
<td>10</td>
<td>None</td>
</tr>
</tbody>
</table>

A Host rock thermal conductivity >3 W/m-K; possible for some rock types.

B All age values are approximate to ±20%.
## Reference Open Emplacement Modes (SNF)

<table>
<thead>
<tr>
<th></th>
<th>High $K_{th}$</th>
<th>Tolerance (EBS up to 200°C?)</th>
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<th>Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>4. Shale Unbackfilled</td>
<td>&lt; 21</td>
<td>300 (for 12-PWR WP)</td>
<td>21</td>
<td>&lt;150</td>
<td>Host rock (100°C)</td>
</tr>
<tr>
<td>“Design Test Case”</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Host rock (100°C at 3 m into drift wall)</td>
</tr>
<tr>
<td>5. Sedimentary Backfilled</td>
<td>&lt; 21</td>
<td>300 (for 12-PWR WP)</td>
<td></td>
<td></td>
<td>Clay-based buffer (100°C)</td>
</tr>
<tr>
<td>6. Hard Rock Unsat.</td>
<td>Note A</td>
<td>$\sqrt{\text{ }}$</td>
<td>$\geq 21$</td>
<td>$&gt;50$</td>
<td>Host rock (200°C)</td>
</tr>
</tbody>
</table>

A Host rock thermal conductivity $>3$ W/m-K; possible for some rock types.

B All age values are approximate to ±20%.
Direct Disposal of Large Canisters including Dual-Purpose Canisters (DPCs)

- Regulatory framework for disposal concepts
- Key features, events and processes affected (e.g., postclosure criticality)
- Generic performance assessments
- Thermal and logistical analyses
- Cost comparison with concepts using smaller packages

Disposal R&D

- Temperature limits greater than 100°C (clay buffer) and 200°C (salt)
- Heating of host media (e.g., heating shale above 100°C in the near field)
- Engineered materials and admixtures that improve heat transfer or thermal stability
References


Nuclear Waste Technical Review Board, October 17, 2012 (SAND2012-8074C)