U.S. DEPARTMENT OF ENERGY
OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT

NUCLEAR WASTE TECHNICAL REVIEW BOARD

SUBJECT: SITE RESPONSE TO THERMAL LOADING

INFORMATION EXPECTED FROM LARGE BLOCK TEST

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PRESENTER'S TITLE: TECHNICAL AREA LEADER
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WASHINGTON, D.C.
NOVEMBER 17-18, 1994
Yucca Mountain Matrix Saturation conditions as Currently Understood

Matrix Saturation - %

% Occurrence

30% 46% 65% 84% 95%

Design Envelope

Bounding

Expected
Type of coupling

Primary coupling

Primary but judged lesser magnitude

Secondary or judged smallest magnitude

Heat from waste and Thermal conductivities
Post-emplacement Saturation Conditions around borehole of typical Spent Fuel Canister

100% | Ambient
86% | Direction of moisture movement induced by saturation gradient

Note: From Cove 3
0.1 mm/yr recharge
8.6 yr old spent fuel
25 yrs after emplacement

Distance from W.P. emplacement borehole

ES-01/02/90-DW-24
Predicted and measured radial profiles are different.

Predicted profile vs. measured values.
Some locations remained at boiling temperature

- thermocouple 86
- thermocouple 87
- thermocouple 88
- thermocouple 89
Where can water go?

- 22 m drift spacing
- 66 m drift spacing
Waste package surface temperature at repository center

- 110.5 MTU/acre; 12-yr-old SNF
- 83.4 MTU/acre; 12-yr-old SNF
- 55.3 MTU/acre; 12-yr-old SNF
- 110.5 MTU/acre; 34.5-yr-old SNF
- 83.4 MTU/acre; 34.5-yr-old SNF
- 35.9 MTU/acre; 34.5-yr-old SNF
- 55.3 MTU/acre; 34.5-yr-old SNF
- 35.9 MTU/acre; 34.5-yr-old SNF
<table>
<thead>
<tr>
<th>Spatial</th>
<th>Temporal</th>
<th>Low AML</th>
<th>High AML</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste Package/</td>
<td>Years 1-20</td>
<td>Hot (50-80°C)/ Humid (70%) with possible liquid water. MMM and biological coupling. Locally Hot (130°C)</td>
<td>Hot (approaching 100°C) both average and locally. Lowered RH. Minimal liquid water.</td>
</tr>
<tr>
<td>Drift</td>
<td>Years 20-100</td>
<td>Hot (60-90°C)/ Humid with possible liquid water. MMM and biological coupling. Locally Hot (130°C)</td>
<td>Hot (&gt;100°C) Low Relative Humidity. No liquid water. No MMM and biological coupling.</td>
</tr>
<tr>
<td></td>
<td>Years 100-2000</td>
<td>Warm (50-80°C)/Humid, possible liquid water. Locally 100-120°C. MMM and biological coupling</td>
<td>Hot (~150°C), low RH. No liquid water. No MMM and biological coupling.</td>
</tr>
<tr>
<td></td>
<td>Years 2000-10000</td>
<td>Warm (40-60°C), Humid. Liquid water. MMM &amp; biological.</td>
<td>Hot (~150°C), low RH. No liquid water. No MMM and biological coupling.</td>
</tr>
<tr>
<td></td>
<td>Years 10000</td>
<td>Cool humid</td>
<td>Warm to cool and dry</td>
</tr>
</tbody>
</table>
The moisture balance in the unsaturated zone (and above the repository) is affected by both ambient and repository-heat-driven processes.
Dry steam boiling conditions persist at waste package environment for thousands of years for high APDs; For 30-yr-old fuel, the threshold APD for significant dry-out by boiling lies between 36 and 57 kW/acre.

Temperature and liquid saturation history at drift wall at repository center for 30-yr-old fuel and a recharge flux of 0.0 mm/yr.
The dry-out front closely follows the nominal boiling point, \( T_b = 96°C \), while the re-wetting front lags considerably behind \( T_b \).

Time history of the vertical location of \( T_b \) and the dry-out/re-wetting front for 60-yr-old fuel, an APD of 114 kW/acre, and a recharge flux of 0.0 mm/yr.
Minimum relative humidity and peak temperature depend on the location in the repository and Areal Mass Loading (AML).

Note that these curves are representative of average conditions at the respective repository locations.
Peak temperature and corresponding relative humidity on the waste package depend on AML and the age of spent nuclear fuel (SNF). Note that the time to reach peak temperature varies significantly.
Above a threshold bulk permeability, the cooling effect of mountain-scale, buoyant, gas-phase convection begins to substantially reduce the duration of boiling conditions in the repository area-weighted duration of the boiling period as a function of bulk permeability for AMLs of 49.2 and 154.7 MTU/acre. Note the time scales differ by a factor of 10.
Table 3. Time to rewet to indicated relative humidity RH on WP, and WP temperature when that RH is attained for different AMLs and a binary gas-phase diffusion tortuosity factor $t_{\text{eff}} = 2.0$, based on the drift-scale model. The heat generation is for a composite of 21-PWR WPs and 40-BWR WPs with 12-m WP spacing. Also, applicable to 12-PWR and 21-BWR WPs with 6.86-m WP spacing.

Table 3a AML = 24.2 MTU/acre; 99.0-m drift spacing.

<table>
<thead>
<tr>
<th>SNF age (yr)</th>
<th>Time to rewet to indicated relative humidity (yr)</th>
<th>Temperature when indicated relative humidity is attained (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60% 70% 80% 90%</td>
<td>60% 70% 80% 90%</td>
</tr>
<tr>
<td>41</td>
<td>210 440 760 2250</td>
<td>77.6 71.7 65.4 52.3</td>
</tr>
<tr>
<td>12</td>
<td>580 970 1710 3290</td>
<td>86.8 78.4 68.0 53.3</td>
</tr>
</tbody>
</table>

Table 3b AML = 35.9 MTU/acre; 66.8-m drift spacing.

<table>
<thead>
<tr>
<th>SNF age (yr)</th>
<th>Time to rewet to indicated relative humidity (yr)</th>
<th>Temperature when indicated relative humidity is attained (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60% 70% 80% 90%</td>
<td>60% 70% 80% 90%</td>
</tr>
<tr>
<td>41</td>
<td>230 490 990 1890</td>
<td>87.8 83.1 76.7 65.2</td>
</tr>
<tr>
<td>12</td>
<td>710 1160 2280 6720</td>
<td>105.0 94.5 75.7 48.4</td>
</tr>
</tbody>
</table>

Table 3c AML = 55.3 MTU/acre; 43.4-m drift spacing.

<table>
<thead>
<tr>
<th>SNF age (yr)</th>
<th>Time to rewet to indicated relative humidity (yr)</th>
<th>Temperature when indicated relative humidity is attained (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60% 70% 80% 90%</td>
<td>60% 70% 80% 90%</td>
</tr>
<tr>
<td>41</td>
<td>300 800 1550 5920</td>
<td>106.5 102.9 90.5 54.2</td>
</tr>
<tr>
<td>12</td>
<td>1900 6560 17,260 38,600</td>
<td>103.0 57.2 39.8 28.5</td>
</tr>
</tbody>
</table>

Table 3d AML = 110.5 MTU/acre; 21.7-m drift spacing.

<table>
<thead>
<tr>
<th>SNF age (yr)</th>
<th>Time to rewet to indicated relative humidity (yr)</th>
<th>Temperature when indicated relative humidity is attained (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60% 70% 80% 90%</td>
<td>60% 70% 80% 90%</td>
</tr>
<tr>
<td>41</td>
<td>7360 14,250 24,860 42,120</td>
<td>69.8 56.2 45.1 35.8</td>
</tr>
<tr>
<td>12</td>
<td>15,120 21,570 29,500 38,420</td>
<td>62.0 52.5 44.9 36.9</td>
</tr>
</tbody>
</table>

Table 3_se_10/94
Table 2. Time to rewet to indicated relative humidity RH on WP, and WP temperature when that RH is attained for different AMLs and a binary gas-phase diffusion tortuosity factor $\tau_{eff} = 0.2$, based on the drift-scale model. The heat generation is for a composite of 21-PWR WPs with 12-m WP spacing. Also, applicable to 12-PWR and 21-BWR WPs with 6.86-m WP spacing.

| Table 2a | AML = 24.2 MTU/acre; 99.0-m drift spacing. |
|-----------------|-----------------|-----------------|
| SNF age (yr)    | Time to rewet to indicated relative humidity (yr) | Temperature when indicated relative humidity is attained (°C) |
| 60% 70% 80% 90% | 60% 70% 80% 90% |
| 41   | 90 220 640 2110 | 87.5 77.0 70.0 54.1 |
| 12   | 220 300 600 2320 | 116.8 108.7 101.7 94.8 |

| Table 2b | AML = 35.9 MTU/acre; 66.8-m drift spacing. |
|-----------------|-----------------|-----------------|
| SNF age (yr)    | Time to rewet to indicated relative humidity (yr) | Temperature when indicated relative humidity is attained (°C) |
| 60% 70% 80% 90% | 60% 70% 80% 90% |
| 41   | 70 150 420 1440 | 98.6 91.2 85.8 72.7 |
| 12   | 590 880 1180 1740 | 110.5 103.7 95.4 84.7 |

| Table 2c | AML = 55.3 MTU/acre; 43.4-m drift spacing. |
|-----------------|-----------------|-----------------|
| SNF age (yr)    | Time to rewet to indicated relative humidity (yr) | Temperature when indicated relative humidity is attained (°C) |
| 60% 70% 80% 90% | 60% 70% 80% 90% |
| 41   | 90 580 1010 1550 | 110.6 106.5 101.1 92.3 |
| 12   | 1710 880 16,770 27,640 | 112.3 62.5 45.9 36.3 |

| Table 2d | AML = 110.5 MTU/acre; 21.7-m drift spacing. |
|-----------------|-----------------|-----------------|
| SNF age (yr)    | Time to rewet to indicated relative humidity (yr) | Temperature when indicated relative humidity is attained (°C) |
| 60% 70% 80% 90% | 60% 70% 80% 90% |
| 41   | 17,180 23,190 28,720 34,260 | 52.3 46.2 42.2 38.2 |
| 12   | 20,120 23,110 26,100 29,100 | 53.4 50.5 47.6 44.7 |
Table 1. Peak temperature and corresponding relative humidity on the WP during the indicated time period for different AMLs and a binary gas-phase diffusion tortuosity factor \( \tau_{eff} = 0.2 \), based on the drift-scale model. The heat generation is for a composite of 21-PWR WPs and 40-BWR WPs with 12-m WP spacing. Also, applicable to 12-PWR and 21-BWR WPs with 6.86-m WP spacing.

<table>
<thead>
<tr>
<th>Table 1a. AML = 24.2 MTU/acre; 99.0-m drift spacing.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SNF age (yr)</strong></td>
</tr>
<tr>
<td>------------------</td>
</tr>
<tr>
<td>41</td>
</tr>
<tr>
<td>12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 1b. AML = 35.9 MTU/acre; 66.8-m drift spacing.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SNF age (yr)</strong></td>
</tr>
<tr>
<td>------------------</td>
</tr>
<tr>
<td>41</td>
</tr>
<tr>
<td>12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 1c. AML = 55.3 MTU/acre; 43.4-m drift spacing.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SNF age (yr)</strong></td>
</tr>
<tr>
<td>------------------</td>
</tr>
<tr>
<td>41</td>
</tr>
<tr>
<td>12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 1d. AML = 110.5 MTU/acre; 21.7-m drift spacing.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SNF age (yr)</strong></td>
</tr>
<tr>
<td>------------------</td>
</tr>
<tr>
<td>41</td>
</tr>
<tr>
<td>12</td>
</tr>
</tbody>
</table>
Table 1. Time required to rewet to indicated relative humidity at various repository locations, and temperature when that value of relative humidity is attained for 22.5-yr-old SNF. Locations are identified as the percentage of the repository area enclosed, with 0% corresponding to the repository center, and 100% corresponding to the edge.

Table 1a. AML = 55.3 MTU/acre.

<table>
<thead>
<tr>
<th>Repository area enclosed (%)</th>
<th>Time to rewet to indicated relative humidity (yr)</th>
<th>Temperature when indicated relative humidity is attained (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>70%</td>
<td>80%</td>
</tr>
<tr>
<td>50</td>
<td>670</td>
<td>1660</td>
</tr>
<tr>
<td>75</td>
<td>410</td>
<td>940</td>
</tr>
<tr>
<td>90</td>
<td>NAa</td>
<td>200</td>
</tr>
<tr>
<td>97</td>
<td>NAa</td>
<td>NAa</td>
</tr>
</tbody>
</table>

Table 1b. AML = 110.5 MTU/acre.

<table>
<thead>
<tr>
<th>Repository area enclosed (%)</th>
<th>Time to rewet to indicated relative humidity (yr)</th>
<th>Temperature when indicated relative humidity is attained (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>70%</td>
<td>80%</td>
</tr>
<tr>
<td>50</td>
<td>15,960</td>
<td>27,910</td>
</tr>
<tr>
<td>75</td>
<td>9540</td>
<td>15,520</td>
</tr>
<tr>
<td>90</td>
<td>3190</td>
<td>4890</td>
</tr>
<tr>
<td>97</td>
<td>1410</td>
<td>1810</td>
</tr>
</tbody>
</table>

Table 1c. AML = 150.0 MTU/acre.

<table>
<thead>
<tr>
<th>Repository area enclosed (%)</th>
<th>Time to rewet to indicated relative humidity (yr)</th>
<th>Temperature when indicated relative humidity is attained (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>70%</td>
<td>80%</td>
</tr>
<tr>
<td>50</td>
<td>20,630</td>
<td>34,850</td>
</tr>
<tr>
<td>75</td>
<td>16,400</td>
<td>24,520</td>
</tr>
<tr>
<td>90</td>
<td>8660</td>
<td>12,090</td>
</tr>
<tr>
<td>97</td>
<td>4330</td>
<td>6020</td>
</tr>
</tbody>
</table>

Table 1d. nonuniform, optimized AML = 128.4 MTU/acre.

<table>
<thead>
<tr>
<th>Repository area enclosed (%)</th>
<th>Time to rewet to indicated relative humidity (yr)</th>
<th>Temperature when indicated relative humidity is attained (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>70%</td>
<td>80%</td>
</tr>
<tr>
<td>50</td>
<td>17,860</td>
<td>32,330</td>
</tr>
<tr>
<td>75</td>
<td>14,820</td>
<td>25,470</td>
</tr>
<tr>
<td>90</td>
<td>10,470</td>
<td>15,280</td>
</tr>
<tr>
<td>97</td>
<td>6330</td>
<td>8830</td>
</tr>
</tbody>
</table>

*Not Applicable; relative humidity always greater than indicated value.*
Ambient conditions dominate:

Typical of early (1-2 yrs) for high AML's or both early and longer term for low AML's

Ambient conditions

- Hot/humid
- T - H - C - M (including MMM)
- Increased saturation and temperature THC - M
- Saturation lowered TMC H

Bouyant convection increases saturation
Intermediate conditions (20-100 yrs high AMLs)

Hot/ambient saturations THC – M

Hot/dry
(no coupling w/MMM and biological except for decomposition)

Bouyant convection
Long term – higher AMLs (100's to 1000's years)
Very long term (1000's to 100,000's years)
higher AMLs
WP corrosion depends strongly on $T$ and $RH$

Time required to penetrate 1 cm of the WP, based on corrosion model of Stahl et al. (1994)
At the repository edge, WP corrosion rate decreases with increasing AML
(with an optimized-high-AML distribution yielding the greatest reduction)

$T$ and $RH$ near the repository edge (97% location) for various AML distributions

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**Diagram Description**

- The graph shows the relationship between temperature ($^\circ$C) and relative humidity (%) over time (years) for various AML concentrations.
- The y-axis represents temperature, ranging from 20 to 100 $^\circ$C.
- The x-axis represents relative humidity, ranging from 60 to 100%.
- Different lines indicate various AML concentrations:
  - 24.2 MTU/acre
  - 35.9 MTU/acre
  - 55.3 MTU/acre
  - 110.5 MTU/acre
  - Optimized 128.4 MTU/acre

- The shaded region indicates the optimal conditions for reduced WP corrosion.

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**Legend**

- **24.2 MTU/acre**
- **35.9 MTU/acre**
- **55.3 MTU/acre**
- **110.5 MTU/acre**
- **Optimized 128.4 MTU/acre**

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**Note:**

- The graph is sourced from ES-TB-7 (10-13-94).
WP corrosion rate decreases with increasing AML; this trend levels off at 110 MTU/acre for the interior of the repository. Temperature ($T$) and relative humidity ($RH$) in the inner half of the repository (50% location) for various AML distributions.
Repository heating can result in a single-phase above-boiling zone, a two-phase boiling zone, and a condensate zone.

Dimensionless liquid saturation contours for 30-yr-old SNF, an APD of 114 kW/acre, and an AML of 154.7 MTU/acre.

Diagram showing radial distance from repository centerline (m) and depth below ground surface (m) for different time periods (t = 100 yr and t = 1000 yr).
Comparison of measured rates of dissolution and precipitation

![Graph showing comparison of dissolution and precipitation rates.](image-url)
IMPACT ON HYDROLOGY OF EQUILIBRIUM

- Model porosity change through changes in mineral volumes.
- J-13 water, Tpt mineralogy (using approach of Delany, 1985)
EQUILIBRIUM AND KINETICS IN THE ALTERED ZONE

- Evolution is slower than in near-field.

- Consider cumulative time at temperature, vs. time required to achieve equilibrium (example using Rimstidt and Barnes, 1980 rate):

\[ R_I = \frac{t}{\left[ \frac{5}{\left( 10^{-0.707 \cdot 2598.0 / T} \right)} \right] / (SA / M)} \]

- Values of \( R_I \) greater than 1.0 indicate where available time exceeds by the computed factor the amount of time necessary to achieve equilibrium.
Is time sufficient to achieve equilibrium for SiO₂ precipitation?

Duration of 60°–100°C period, compared to time required to achieve equilibrium for SiO₂ precipitation (114 Kw/acre APD).
CONCLUSIONS REGARDING COUPLED PROCESSES IN THE ALTERED ZONE

• With the exception of regions near waste packages where fluid velocities are high, preliminary results suggest chemical and mineralogical equilibrium will probably be achieved in most areas.

• In regions where equilibrium may be achieved, changes in porosity may be on the order of several tens of percent, but are sensitive to temperature, initial mineralogy, and water chemistry.
The dry-out front closely corresponds to the nominal boiling point; the condensate zone results in re-fluxing above the dry-out zone.

Vertical liquid saturation and temperature profiles at the repository center for 30-yr-old fuel, an APD of 114 kW/acre, and a recharge flux of 0.0 mm/yr.
The re-wetting front lags considerably behind the nominal boiling point; the dry-out zone persists long after boiling ceases.

Vertical liquid saturation and temperature profiles at the repository center for 30-yr-old fuel, an APD of 114 kW/acre, and a recharge flux of 0.0 mm/yr.
There are two fundamental (temporal and spatial) regimes for repository-heat-altered flow and transport processes

Heat-driven flow regime: the regime for which repository heat significantly drives gas- and liquid-phase flow

Heat-altered property regime: the regime for which the intrinsic flow and transport properties have been significantly altered by repository heat

The heat-altered property regime continues after the heat-driven flow regime ceases
The temporal and spatial extent of the *heat-altered property regime* in the SZ depend on site properties and thermal design.

For both the MD and ED repository concepts, the primary factors include:

- the spatial extent of the heat-driven flow regime
- the repository depth below ground surface
- the standoff between the repository and the water table
- the total emplaced inventory of SNF

The temporal and spatial extent of this regime is less sensitive to the Areal Mass Loading (AML), SNF aging, and drift ventilation.
The temporal and spatial extent of the heat-driven flow regime in the SZ depend on site properties and thermal design.

For both the MD and ED repository concepts, the primary factors include:

- the repository depth below ground surface
- the standoff between the repository and the water table
- the total emplaced inventory of SNF

The temporal and spatial extent of this regime is less sensitive to the Areal Mass Loading (AML), SNF aging, and drift ventilation.
The duration of time between 95.9°C and 100.4°C along the repository centerline for AMLs of 49.2, 77.4, and 154.7 MTU/acre, a $k_b$ of 280 millidarcy, a net recharge flux of 0 mm/yr, RIB Version 4 $K_{th}$ data, including hydrothermal flow in the saturated zone.
The depth intervals where geochemical alteration due to refluxing may occur depend strongly on AML, the duration of time between 96 and 100°C along the repository centerline for 22.5-yr-old SNF.
Repository heat drives liquid-phase buoyant convection in the saturated zone (SZ) that will dominate SZ transport for tens of thousands of years.

Temperature buildup contours and liquid-phase velocity vectors at 5000 yr.
Coupling investigations Sequence

Through testing identify which linkages are important. Work towards adequate coupling (full coupling may be unrealistic and unnecessary)

- Thermal-mechanical
- Thermal-hydrological
- Thermal-geochemical
- Mechanical-hydrological
- Hydrologic-geochemical
- Add second level of coupling
  - Thermal-hydrological-mechanical
  - Thermal-hydrological-geochemical
  - Thermal-mechanical-geochemical
Objectives of Thermal Tests

• Identify processes (physics) to be included in mechanistic models (early tests)
• To develop necessary empirical model(s) if mechanistic models are unavailable
• To build confidence in modelling ability
  - Representativeness of model abstractions
  - Appropriateness of assumptions and boundary conditions
• To gather rock mass property data or characterization where can’t gather from other sources
• To characterize heterogeneity of system or assist in model building
## Test Strategy

<table>
<thead>
<tr>
<th>Scale</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lab Scale</strong></td>
<td></td>
</tr>
<tr>
<td>Core - 1/2 m</td>
<td>Property Measurements</td>
</tr>
<tr>
<td>hours to days</td>
<td>Matrix Processes</td>
</tr>
<tr>
<td>(some long-term)</td>
<td>Single-Fracture Processes</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Block Scale</strong></td>
<td></td>
</tr>
<tr>
<td>1/2 m to 3-5 m</td>
<td>Multiple-Fracture Processes</td>
</tr>
<tr>
<td></td>
<td>Fracture Interconnectivity Phenomena</td>
</tr>
<tr>
<td></td>
<td>Coupled Processes</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>In Situ Scale</strong></td>
<td></td>
</tr>
<tr>
<td>ESF tests (30M - 100M)</td>
<td>Site characterization</td>
</tr>
<tr>
<td>1 - 3 yrs</td>
<td><em>In Situ</em> but overdriven Coupling–THMC Model Testing</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Large Scale (&gt;100 m, 7-10 yrs)</td>
<td>Scaling Effects, Natural Heterogeneity Impacts</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Repository Scale</strong></td>
<td>Performance Confirmation, Representative scale Coupling, Mountain scale Heterogeneity</td>
</tr>
<tr>
<td>(50 - 100 yrs)</td>
<td></td>
</tr>
</tbody>
</table>
Intended Use of Testing Results

• Depends on which test and its schedule
  – Prototype or early testing to identify overall processes (e.g., dryout, condensate shedding, etc.)
  – ESF tests to consider impact of fracture networks, potential for condensate shedding under reasonable design options, test of modeling ability, bulk properties for use in LA, etc.

• Determine thermal transfer mechanisms

• Investigate relationships such as temperature and dryout, condensate development and drainage, geochemical and geomechanical process impact on hydrologic properties, etc.

• Investigate material performance in representative conditions
Field testing role

Field test

Phenomena identified

Mechanistic model conceptualizations (abstractions)

Mechanistic model applications results

Expected bounds, functional relationships, sensitivity analyses

NFER & AZR

Parameter values

Abstractions

Subsystems requirement performance assessments

Systems

Total system P.A. model applications

Design experiments to test or distinguish between conceptualizations, eg. condensate shedding vs. buildup

Conceptualization of real world (hypothesis)

Interpretation or analysis
The temporal and spatial extent of the *heat-driven flow regime* in the UZ depend on site properties and thermal design.

For both the minimally-disturbed (MD) and extended-dry (ED) repository concepts, the primary factors include:

- the importance of buoyant gas-phase convection
- the importance of binary gas-phase diffusion
- heterogeneity in the network of gas- and liquid-phase pathways
- heterogeneity in the heat load distribution (particularly for an MD repository)
- the repository depth below ground surface
- drift ventilation
- SNF aging
The Use of Hypothesis Testing in Model Validation

• Our models have utilized idealizations of:
  • the repository thermal load
  • the distribution of thermo-hydrological properties
  • boundary and initial conditions
• No individual model of the repository-UZ-SZ system is itself a "valid" representation
• However, the combined use of complementary models and analyses provides a means to
  • evaluate the impact of our assumptions,
  • identify critical dependencies,
  • evaluate worst-case scenarios,
  • and develop fundamental hypotheses, which can be addressed by subsequent analysis and testing
Hypothesis testing can help determine whether a low-AML repository is capable of avoiding significant heat-mobilized fluid flow in the UZ.

The primary hypotheses concern:

- **L-1** whether mountain-scale, buoyant, gas-phase convection significantly affects UZ moisture movement.
- **L-2** whether sub-repository-scale, buoyant, gas-phase convection significantly affects UZ moisture movement.
- **L-3** whether binary gas-phase diffusion significantly affects UZ moisture movement.
- **L-4** whether heterogeneity in the heat load distribution and/or gas- and liquid-phase pathways focus enough condensate drainage to cause water to drip onto WPs.

For AMLs that significantly mobilize fluid, these hypotheses address how that mobilization occurs.

Resolution of these hypotheses will require both above- and below-boiling heater tests.
Hypothesis testing can help determine the extent to which a high-AML repository is capable of generating conditions that benefit WP integrity and reduce the potential for radionuclide dissolution and transport.

The primary hypotheses concern:

- **H-1** whether heat conduction dominates heat flow
- **H-2** whether above-boiling temperatures correspond to a significant reduction in $RH$ and the absence of mobile liquid water near WPs
- **H-3** how long re-wetting the WP environment to humid conditions lags behind the end of the boiling period
- **H-4** whether enough condensate buildup occurs to significantly impact drying and re-wetting

Resolution of these hypotheses will require heater tests conducted under both above- and below-boiling conditions.
## Value of Heater Test Information for Hypothesis Testing

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Lab-Scale Tests</th>
<th>Large-Block Test</th>
<th>Early <em>In Situ</em> Tests</th>
<th>Main <em>In Situ</em> Tests</th>
<th>Performance Confirmation Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-1</td>
<td>L</td>
<td>L</td>
<td>P</td>
<td>S</td>
<td>C</td>
</tr>
<tr>
<td>L-2</td>
<td>L</td>
<td>L</td>
<td>S</td>
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<td>C</td>
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<tr>
<td>L-3</td>
<td>P</td>
<td>S</td>
<td>S</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>L-4</td>
<td>L</td>
<td>P</td>
<td>S</td>
<td>S</td>
<td>C</td>
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<tr>
<td>H-4</td>
<td>L</td>
<td>P</td>
<td>S</td>
<td>S</td>
<td>C</td>
</tr>
</tbody>
</table>

L = limited information, P = preliminary indication, S = substantial understanding, C = confirmation
Chronology of Testing

- SFT-C  thermal-mechanical (some hydrology)
- Oricle test of fracture hydrology and geophysical techniques
- G-Tunnel Hydrology dye study and HFEM
- G-Tunnel horizontal heater test (mainly thermal-hydrological)
- LBT  Thermal-hydrological-geochemical-geomechanics
- EBSFT  all of above plus characterization of YM
Long range plan for field testing

Calendar Years


- TBR-RK char
- TSS Data Input
- W.P. Title 2
- L.A. data input
- License defense
- L.A.

- NFER
- AZR

- LBT lab

- ESF

- North Ramp

- Pre-test & monitoring

- Accelerated test
- Heating
- Cooling

- Core testing

- Coring

- Analysis

- Lab samples

- 7 year duration test

TBR - Technical Basis Report
NFER - Near-Field Environment Report
AZR - Altered Zone Report
Heater power cycle is highly accelerated
Conclusions of Geomechanics

During thermal phase, essentially elastic (including shear zones)

During cooling, early phase elastic; later phase inelastic

Modulus differences associated with alteration, weathering, and fracturing

Response to excavation fundamentally different from response during thermal heating and cooling
Lab Testing Role – small blocks (up to 1 m) from ridge

- Design experiments to test or distinguish between conceptualizations, e.g., condensate shedding vs. buildup
- Conceptualization of real world (hypothesis)
- Interpretation or analysis of lab test results
- Phenomena identified
- Parameter values
- Mechanistic model conceptualizations (abstractions)
- Mechanistic model applications results (expected bounds, functional relationships, sensitivity analyses)
- Abstractions
- Subsystems requirement performance assessments
- Systems
- Total system P.A. model applications
- NFER & AZR
Field testing role – Large Block Test

Field test

Phenomena identified

Mechanistic model applications results
(expected bounds, functional relationships, sensitivity analyses)

Parameter values

Mechanistic model conceptualizations (abstractions)

Interpretation or analysis

Design ESF experiments to test or distinguish between conceptualizations eg. condensate shedding vs. buildup

Conceptualization of real world (hypothesis)

Subsystems requirement performance assessments

Abstractions

Systems

NFER & AZR

Total system P.A. model applications
ESF: Engineered Barrier System

Field test

Phenomena identified

Mechanistic model conceptualizations (abstractions)

Mechanistic model applications results (expected bounds, functional relationships, sensitivity analyses)

Design experiments to test or distinguish between conceptualizations eg. condensate shedding vs. buildup

Parameter values

Abstractions

Subsystems requirement performance assessments

Conceptualization of real world (hypothesis)

Interpretation or analysis

Abstractions

Total system P.A. modal applications

Systems

NFER & AZR
The temperature distribution during the performance confirmation period is highly diagnostic of the significance of mountain-scale, buoyant gas-phase convection for high (above-boiling) Areal Mass Loadings (AMLs), while it is not for low (below boiling) AMLs; diagnosing the significance of mountain-scale, buoyant, gas-phase convection for low AMLs will require the use of above-boiling heater tests and/or emplacing some region(s) of the repository with an above-boiling AML vertical temperature profile through repository center for indicated AMLs and times.

- $k_b = 84$ darcy
- $k_b = 10$ darcy
- $k_b = 280$ millidarcy

- AML = 24.2 MTU/acre $t = 100$ yr
- AML = 110.5 MTU/acre $t = 50$ yr
- AML = 110.5 MTU/acre $t = 100$ yr
Maturation of Understanding of Environment

MONITORING OF ACTUAL COUPLED PROCESSES (PERFORMANCE CONFIRMATION MONITORING)

MONITORING OF OVERDRIVEN OR SMALL SCALE COUPLED PROCESSES FOR DEVELOPING OF PROCESS UNDERSTANDING & MODELS

LEVEL OF UNDERSTANDING

TIME (YRS)

LABORATORY STUDIES

ESF ACCELERATED TESTS

ESF LONG DURATION TESTS

ILBT

LARGE BLOCK TEST

CA-LA

LA-EMPLACE

TSS
Field testing inputs to TSS

TBR - Technical Basis Report
NFER - Near-Field Environment Report
AZR - Altered Zone Report

ES11/14/94DW#12-02
Field testing inputs to 2001 LA

Calendar Years


TBR-RK char	TSS Data Input	W.P. Title 2	L.A. data Input

NFER	AZR

LBT lab

North Ramp

Pre-test heating & monitoring

Cold test heating

Cool down

Analyses

Core testing

Submit license?

Yes

Coring

Analysis

Analyzed test samples

Lab samples

7 year duration test

Coring

Analysis report

L.A.

License defense

NFER

AZR

ESF

TBR - Technical Basis Report
NFER - Near-Field Environment Report
AZR - Altered Zone Report
Field testing inputs to 2008 LA

- TBR - Technical Basis Report
- NFER - Near-Field Environment Report
- AZR - Altered Zone Report

Calendar Years

- 95
- 96
- 97
- 98
- 99
- 2000
- 2001
- 2002
- 2003
- 2004
- 2005
- 2006
- 2007
- 2008

- TBR-RK
- TSS Data
- W.P. Title 2
- L.A. data
- License defense
- L.A. data

LBT lab

North Ramp

Pre-test & monitoring

ESF

ES11/14/94DN#12-04
Criteria for Design of Waste Package
Environment Tests

- Volume of the dry-out zone
  - G-Tunnel ~0.75 m
  - Small percentage of fractures responsible for majority of flow

- Peak rock temperatures
  - Above 200 degrees can have phase transition
  - Representative of possible repository ranges

- Velocity of dry-out front
  - Lab tests of up to one-year duration required

- Size and duration of condensate zone
PRELIMINARY LAYOUT OF ESF TESTS
A possible ESF Test Layout
A possible ESF Layout

- Heater drifts
- Geochemical, moisture sensors
- Neutron logging
- Temperature sensors
- ERT
- Geomechanical
Duration of heating for 10 m radius dryout.
(Central drift midpoint)

- 12.38 kW heaters
- 8.25 kW heaters
- 6.3 kW heaters
- 5.5 kW heaters
ESF Drift Wall Temperatures vs heater output
(Central Drift at Midpoint)

Time (yr)

Temperature (°C)

- 12.38 kW heaters
- 8.25 kW heaters
- 6.3 kW heaters
- 5.5 kW heaters

- 325°C
- 275°C
- ~250°C
ESF Heating duration that will not exceed 200°C
(6.3 kW heaters)
Rate of advance of dry-out front
Repository centerline, 30-yr-old fuel and recharge flux of 0.0 mm/yr

![Graph showing rate of advance of dry-out front over time. The x-axis represents time in years, ranging from 0 to 1000, and the y-axis represents rate in meters per year, ranging from 0 to 1.4. Two lines are shown: one for 57 kW acre and another for 114 kW acre. The graph indicates a decrease in rate as time progresses.]
Rate of Advance of dry-out front, ESF tests

---

**Rate of Advance of dry-out front, ESF tests**

![Graph showing the rate of advance of dry-out front](image)

- **8.25 kW heaters**
- **6.3 kW heaters**
- **5.5 kW heaters**

---

**Abbreviated test**

**Longer term test**

---

**200 x repository rate**

**100 x repository rate**

---

**Time (yr)**

**Rate (m/yr)**

---

**Legend:**

- Dotted line: 8.25 kW heaters
- Dashed line: 6.3 kW heaters
- Dash-dotted line: 5.5 kW heaters
Sampling regimes, ESF tests (6.3 kW heaters)

Geochemical sampling zone (both elevated temp & water contact for at least 1 year)