U.S. Department of Energy
Office of Civilian Radioactive Waste Management

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Thermal Strategy Analysis

Presented to:
Nuclear Waste Technical Review Board

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January 16, 2008
Las Vegas, NV

Repository Thermal Management Outline

- Objectives for thermal management
- Waste form characteristics
- Postclosure reference case for total system performance assessment (TSPA)
- Estimated limiting waste stream
- Preclosure/Postclosure thermal constraints
- Mid-Pillar temperature control
- Simulated emplacement sequences
- Allowance for uncertainty and variability
- Hydrogeologic, geomechanical, and geochemical responses
- Implementation in repository operation

Repository Thermal Management Objectives

- Maximize operational flexibility for emplacement
- Document an approach for the license application (LA)
  - Limit impact to existing repository design
  - Determine applicability of current TSPA models
- Ensure consistency between the LA and waste acceptance provisions of the Standard Contract
- Establish transportation thermal limits among the criteria for transportation, aging and disposal (TAD) canister loading

Repository Thermal Management Waste Form Characteristics

- **Waste types to be received at repository**
  - TADs; ~6,600 canisters)
  - Dual-purpose canisters (DPCs; ~280 casks)
  - Bare commercial spent nuclear fuel (CSNF) in transport-only canisters (~14,000 assemblies; loaded into TADS at the repository)
  - Canisterized non-CSNF waste forms (HLW, DSNF, and naval SNF)
- **Waste package (WP) types to be emplaced**
  - CSNF (~7,400 TAD waste packages)
    - Thermal output variability controlled by: initial enrichment, fission burnup, and age out-of-reactor
  - Co-disposal and naval (~3,700 waste packages)

Source for all data: ANL-WIS-MD-000020 Rev. 01 AD 01.

(Counts are estimates, rounded to 2 significant figures.)

Repository Thermal Management Thermal Reference Case for TSPA

- 1999 DOE study *
  - CSNF available for receipt from 2010 to 2033; average age 26 yr; average burnup 38 GWd/MTU
- Adjusted waste package thermal output *
  - 12.6 kW Max. WP output at emplacement
  - 1.45 kW/m Max. lineal power at emplacement
- Emplaced in 2067 (Model Simplification); forced ventilation for 50 yr; closure in 2117
- 2-D and 3-D coupled-process simulations
  - Multiscale model uses a “Unit Cell” representing 8 WPs (6 CSNF-TAD and 2 co-disposal)

*** Sources: CAL-MGR-MD-000001 Rev. 00 and ANL-WIS-MD-000020 Rev. 01 AD 01.**

Repository Thermal Management Estimated Limiting Waste Stream

- **Updated waste stream**
  - **Addressed range of uncertainty on age, (higher) burnup, and initial enrichment ***
- **TAD canister operating concept**
  - **Schedule: 2017 start of receipt; closure at/before 2117**
  - **Limited bare CSNF waste handling capability at the repository (e.g., no pool for thermal blending)**
- **Estimated limiting waste stream (ELWS)**
  - **Use operational simulation (Total System Model or TSM) to represent CSNF selection, transport, and receipt**
  - **Resulting CSNF + non-commercial waste forms (in TAD and Co-disposal WPs) = ELWS**

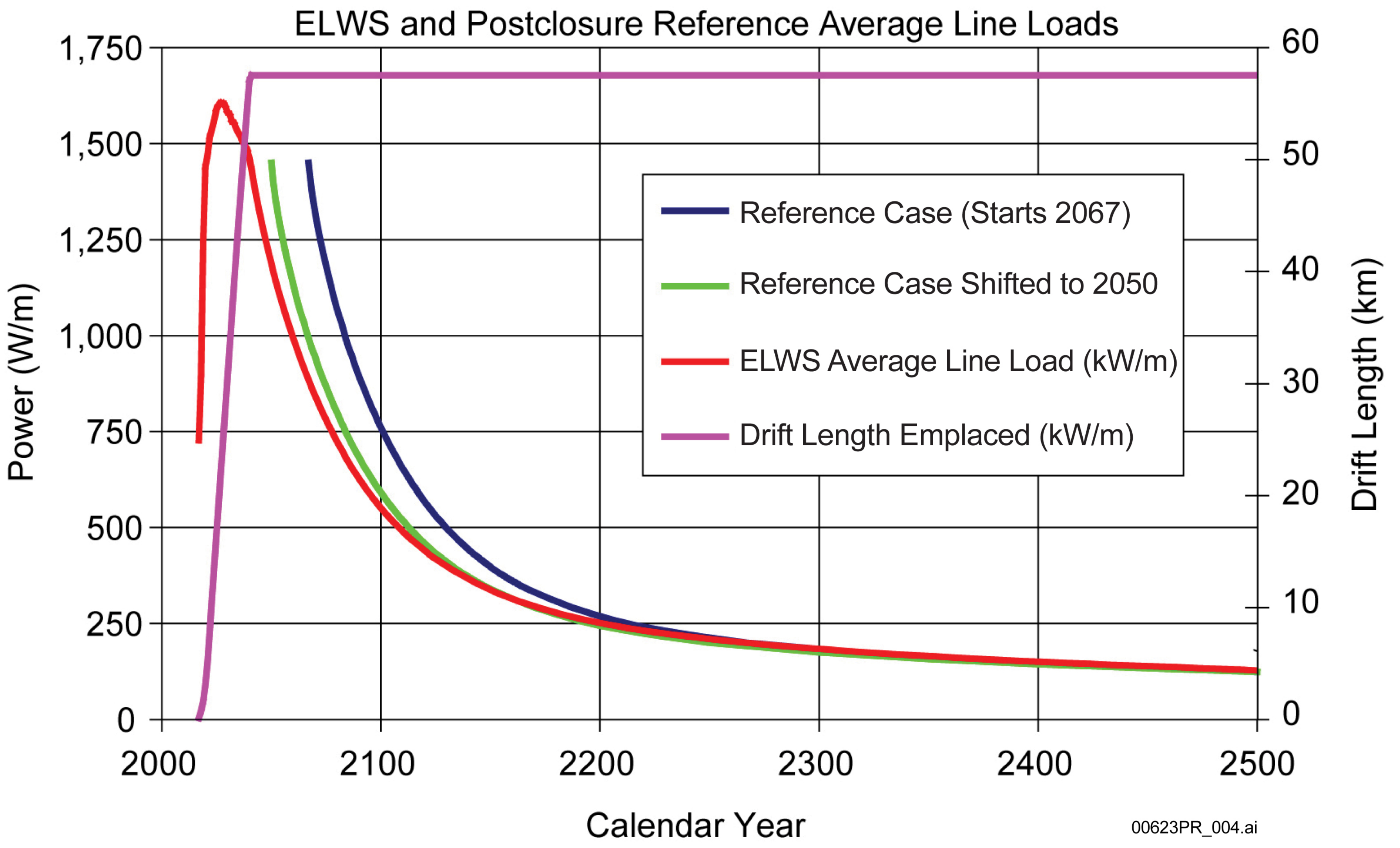
*** Sources: TDR-CRW-SE-000022 Rev. 01 and ANL-WIS-MD-000020 Rev. 01 AD01.**

Repository Thermal Management
ELWS Simulation

- **Fuel selection ***
  - Based on commercial plant CSNF projected inventories and Current cask-handling capabilities
  - Youngest fuel first; min. age 5 yr out-of-reactor (YFF5)
- **Transportation system ***
  - Mostly rail (CSNF: ~90% in TADs, ~10% uncanistered in truck casks and DPCs)
  - 22 kW max. TAD canister output (reasonably high and consistent with current transportation cask designs)
- **ELWS characteristics**
  - Waste received at repository from 2017 to 2040 *
  - Overall average lineal thermal output similar to TSPA reference case **

Sources: * 000-00R-G000-00600-000-001 and ** ANL-NBS-HS-000057 Rev. 00.

Comparison of Average Lineal Thermal Loads



Source: ANL-NBS-HS-000057 Rev. 00, Fig. 6.1-1.

Repository Thermal Management Postclosure Thermal Limits

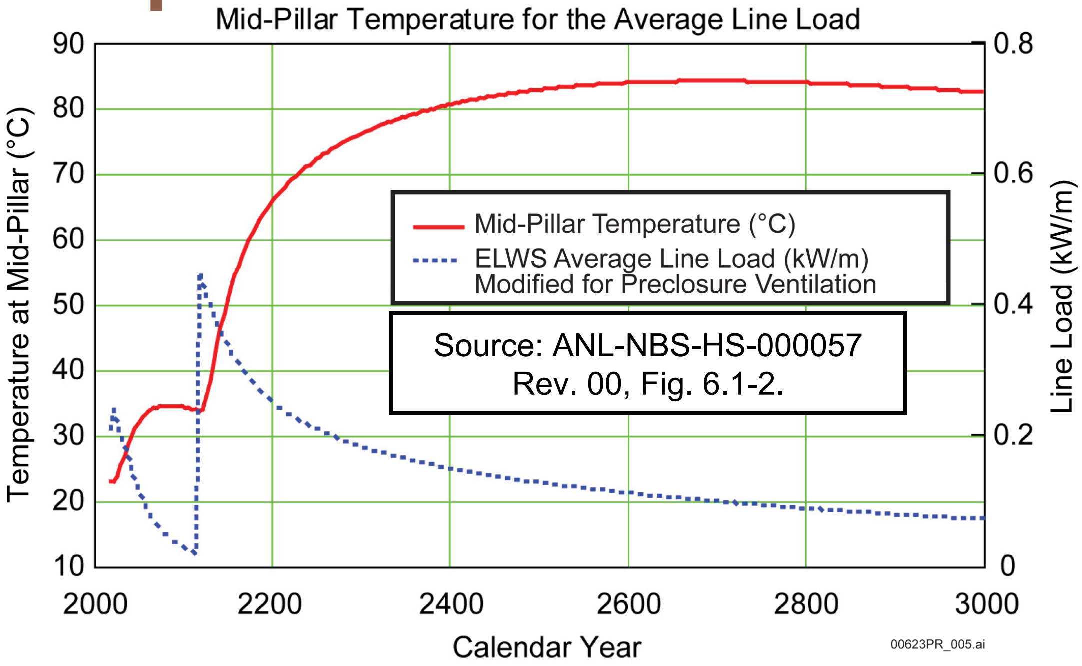
- **Mid-pillar temperature limit (96ºC) promotes drainage between drifts ***
- **Drift-wall temperature limit (200ºC) controls rock strength changes**
- **Waste package outer barrier limit (300ºC, 500 yr) precludes phase separation in Alloy-22**
- **CSNF cladding limit (350ºC) limits degradation to cladding barrier capability**

(Mid-pillar is the controlling limit)

Source for Limits Discussion: ANL-NBS-HS-000057 Rev. 00, Section 6.1.

Repository Thermal Management Mid-Pillar Temperature Control

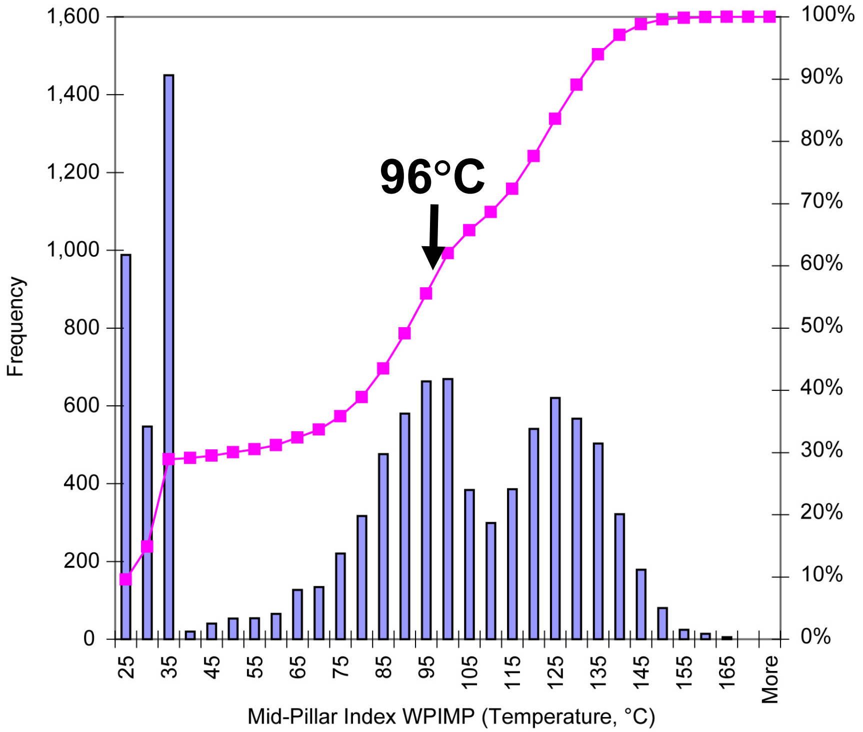
- **Thermal energy density (mid-pillar) index for each waste package**
  - **Conduction-only superposition solution; use <u>calendar year</u>**



Source: ANL-NBS-HS-000057 Rev. 00, Fig. 6.1-2.

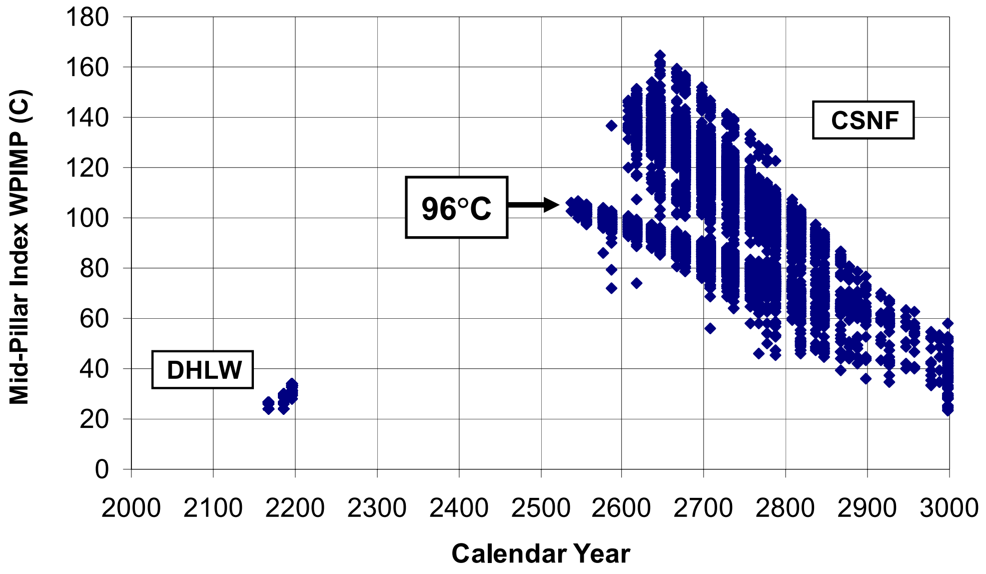
  - **Definition: Peak mid-pillar temperature if the entire repository is loaded with identical packages**
    - **Typical far-field thermal conductivity (1.81 W/m-K)**
    - **Neglect aging duration and timing of postclosure peak**
  - **Use a running average of indices for every 7 adjacent WPs, to generate emplacement sequences**

Repository Thermal Management Mid-Pillar Temperature (Continued)



◀ **ELWS grouping of CSNF and cooler HLW waste packages (average < 96°C, with ambient temperature 23.8°C)**

ELWS range of time to peak mid-pillar temperature ▶



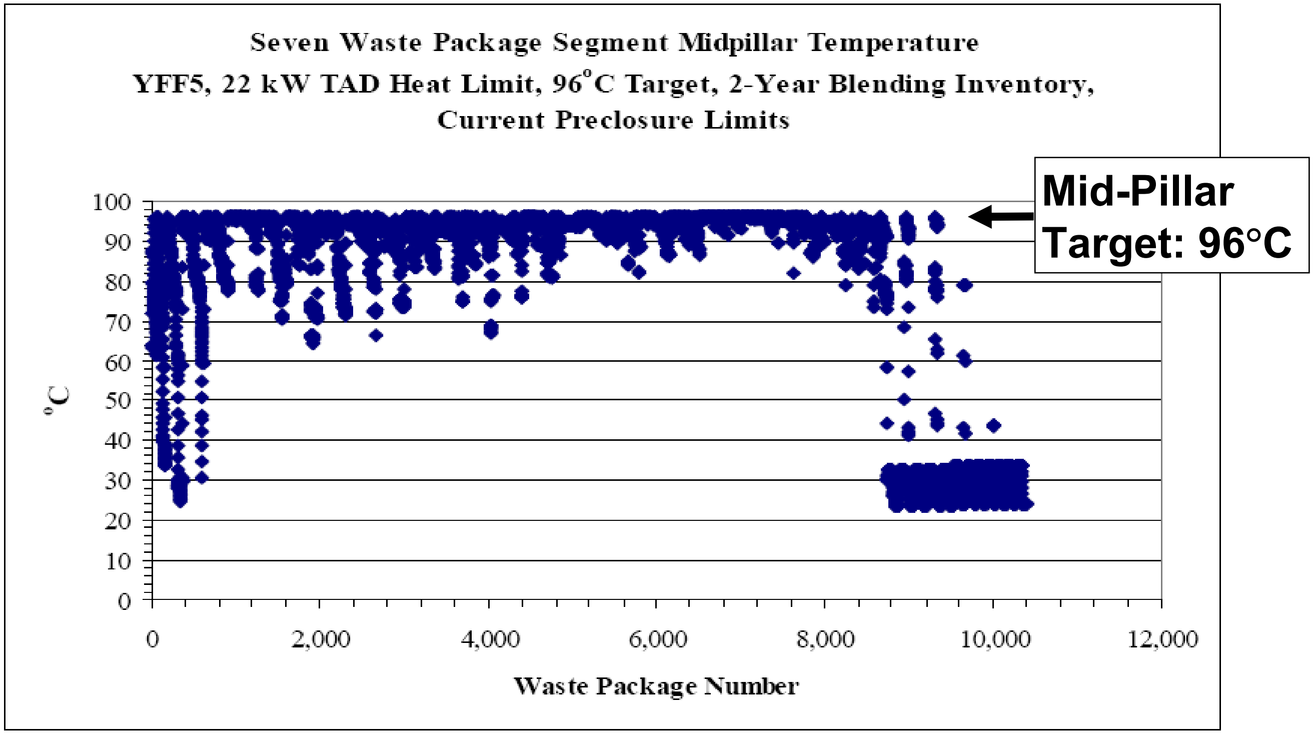
Sources: ANL-NBS-HS-000057 Rev. 00, Figs. 6.1-3 and 6.1-4, and DTN: MO0705SUPPCALC.000 Rev. 1.

Repository Thermal Management Simulated Emplacement Sequences

- ELWS: 22 kW/TAD thermal limit for transportation
  + YFF5 acceptance criterion for CSNF
- Preclosure emplacement limits (“loading rules”)
  - 18 kW/package (CSNF cladding < 350°C)
  - 2.0 kW/m 7-Package running average (drift wall < 200°C)
- ELWS Emplacement Scenarios
  - Consider 2-yr and 4-yr inventories of CSNF receipts initially available on aging pad; co-disposal packages available on demand
  - Choose package from receipt and/or aging pad to optimize seven-waste package average mid-pillar index at 85°C or 96°C target
- Used a post-processing tool developed for the TSM
- Mid-pillar limit ensures other postclosure limits are met

Repository Thermal Management Simulated Emplacement Sequence (Continued)

- **ELWS emplacement for YFF5, 96/2 case**
  - Optimize average mid-pillar index at 96°C
  - 2-yr initial inventory of CSNF receipts available in surface aging; co-disposal packages available on demand



Mid-Pillar Target: 96°C

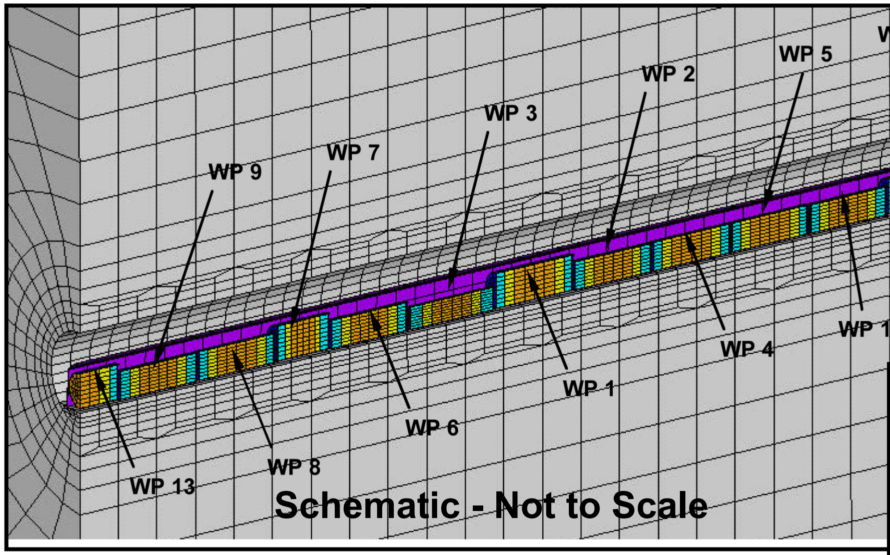
Source: 000-00R-G000-01000-000-000, Fig. 1.

Repository Thermal Management Simulated Emplacement Sequence (Continued)

- **ELWS emplacement sequences reanalyzed using recently developed WPLOAD tool ***
  - Layered-stratigraphy, conduction-only simulation
  - Apply margin analysis from thermal-hydrologic analyses
- **Obtained results comparable to TSM-based scoping analysis**

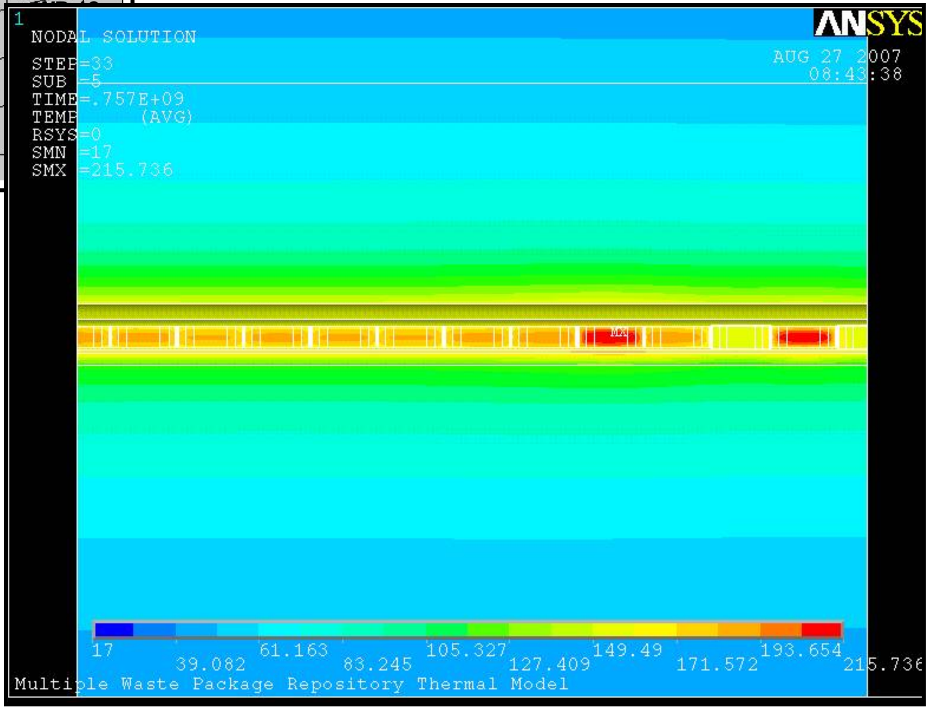
* Source: 800-00C-WIS0-00500-000-00A

Repository Thermal Management Simulated Emplacement Sequence (Continued)



Schematic - Not to Scale

- Find hottest segment of 96/2 case, for analysis of near-field effects
  - Use drift-wall thermal energy density



```
1                                                        ANSYS
 NODAL SOLUTION
                                                     AUG 27 2007
 STEP=33                                                08:43:38
 SUB =5
 TIME=.757E+09
 TEMP     (AVG)
 RSYS=0
 SMN =17
 SMX =215.736

  17         61.163       105.327       149.49       193.654
       39.082       83.245       127.409       171.572       215.736
Multiple Waste Package Repository Thermal Model
```

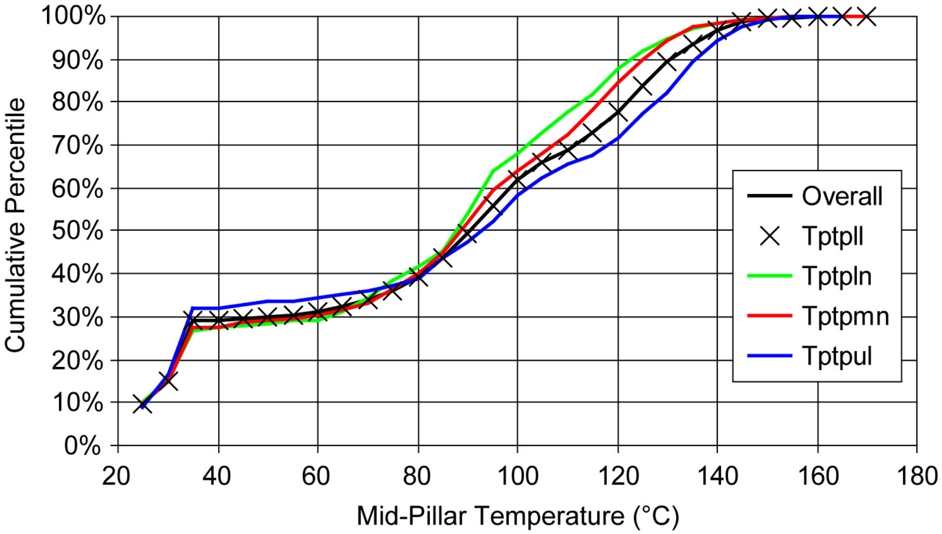
- Result: 2.0 kW/m local sequence; emplaced in 2045
- Drift wall peak temperature limit is met:
  - 3-D FEM analysis; low rock thermal conductivity
  - Peak drift wall T=160.3°C
- Other limits are met by inference

Sources: ANL-NBS-HS-000057 Rev. 00, Figs. 6.3-1 and 6.3-14.

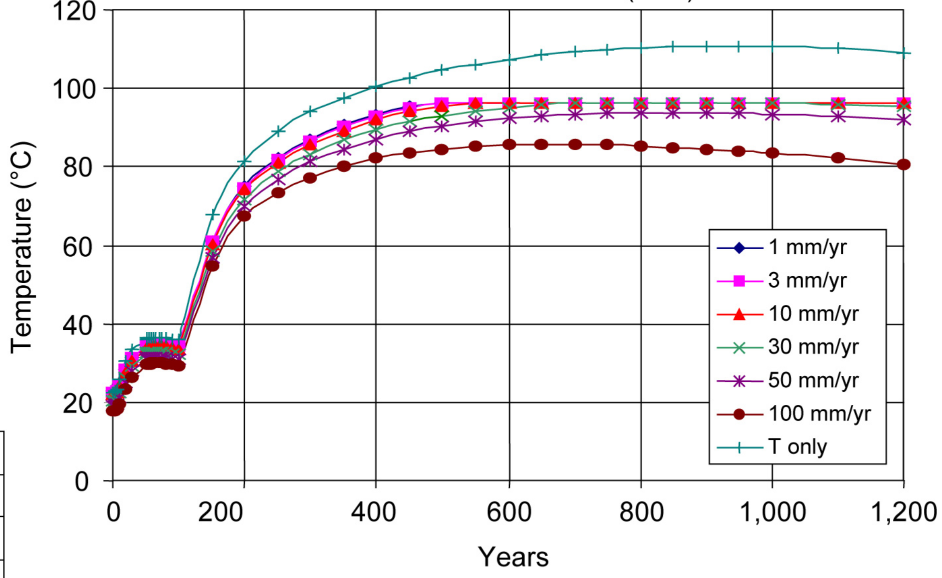
Repository Thermal Management Allowance for Uncertainty and Variability

- **Host-rock thermal properties: mid-pillar index with thermal conductivity variability and uncertainty**

CDFs for Mid-Pillar Index (WPIMP) Calculated for Each Host Rock Unit, Sampling on K_{th} Uncertainty



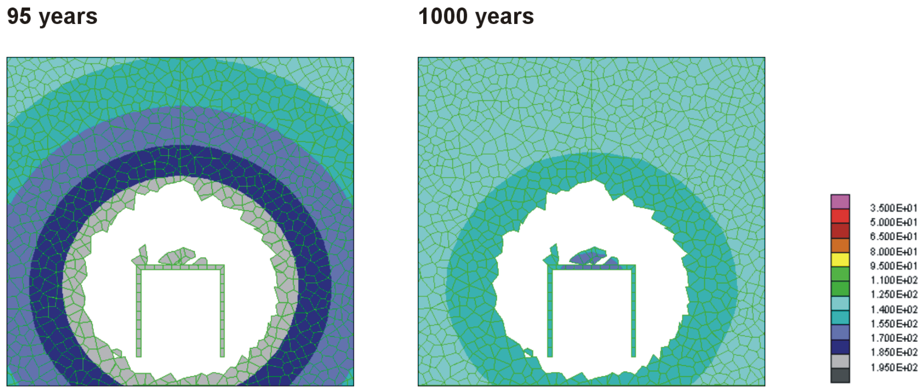
Mid-Pillar Temperature from Thermal-Hydrologic Calculation with Modified Heat Load (x1.3)



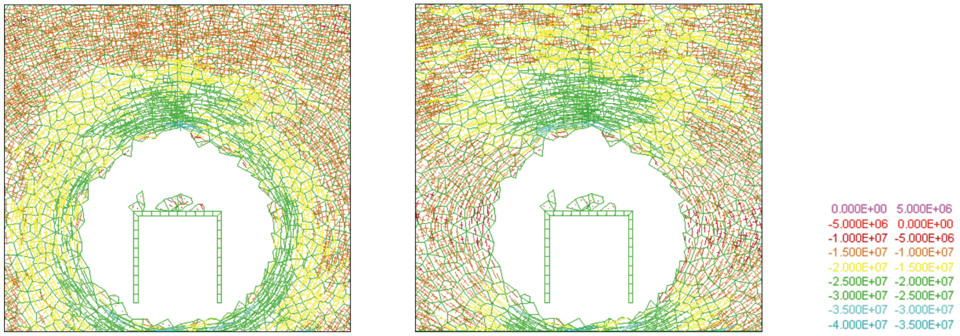
- **Model layering and hydrology: mid-pillar temperature with layered-stratigraphy, and percolation flux**

Sources: ANL-NBS-HS-000057 Rev. 00, Figs. 6.1-4 and 6.2-7.

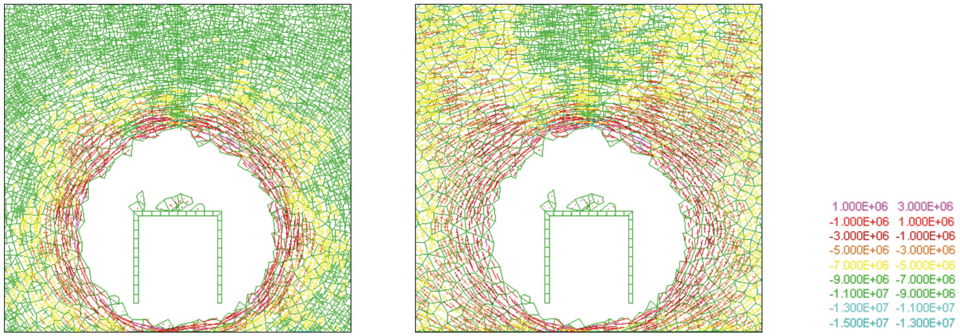
Repository Thermal Management Geomechanical Response



a) Temperature (ºC)



b) Major principal stress (Pa)

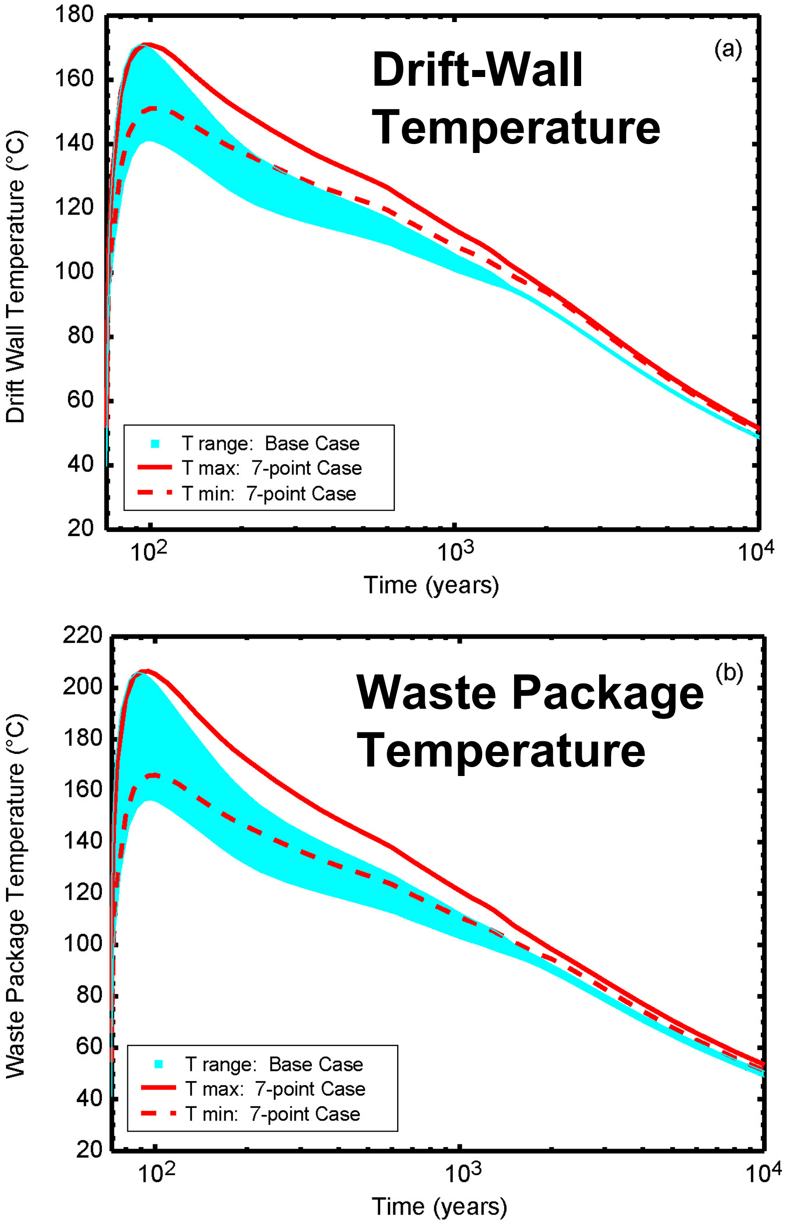


c) Minor principal stress (Pa)

- **Line load 2 kW/m at emplacement**
- **72-yr ventilation**
- **2-D UDEC analysis**
- **Category 3 lithophysal rock properties**
- **Result: stability similar to reference case**

  (Peak drift wall temp. at ~95 yr after emplacement)

Figure Source: ANL-NBS-HS-000057 Rev. 00, Fig. 6.4.1-5.
Methodology: see ANL-EBS-MD-000027 Rev. 03, Section 6.4.

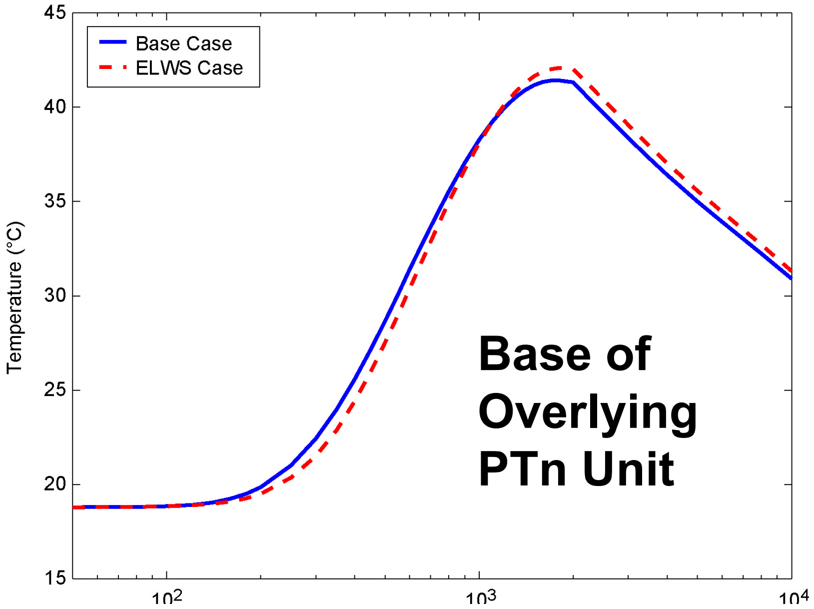


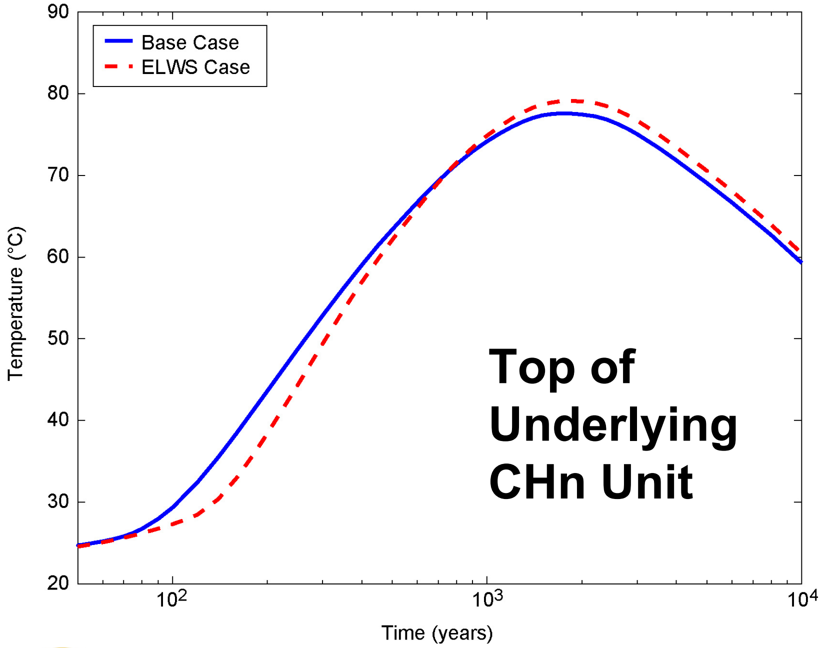
Repository Thermal Management Hydrogeologic Response

- Hottest (7-package) segment for 96/2 case; 72-yr ventilation
- 3-D NUFT analysis; discrete packages; and calibrated hydrologic properties
- Low (10th percentile) rock thermal conductivity and percolation flux
- Result: resaturation behavior is temperature controlled

Figure Source: ANL-NBS-HS-000057 Rev. 00, Fig. 6.4.2-6.
Methodology: ANL-EBS-MD-000049 Rev. 03 AD01, Section 7.

Repository Thermal Management Hydrogeologic Response (Continued)

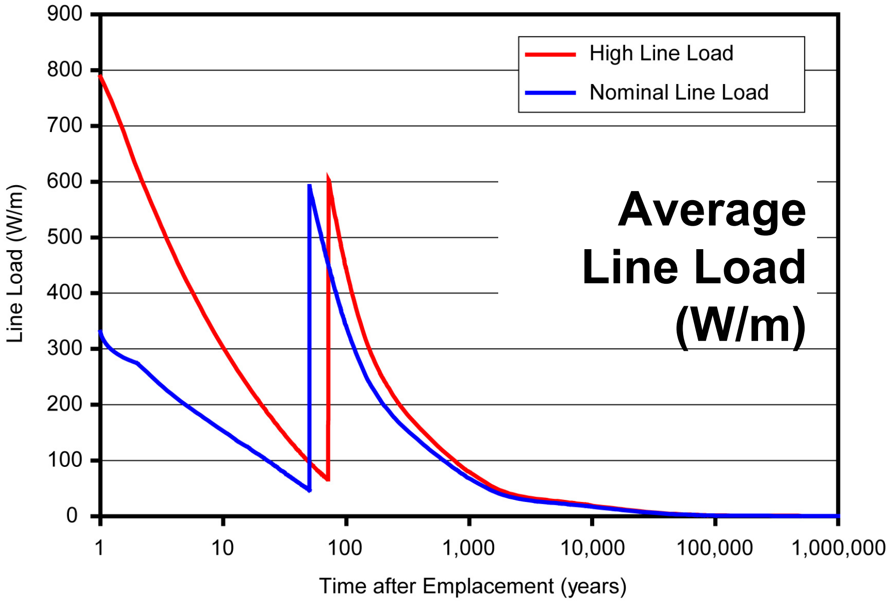


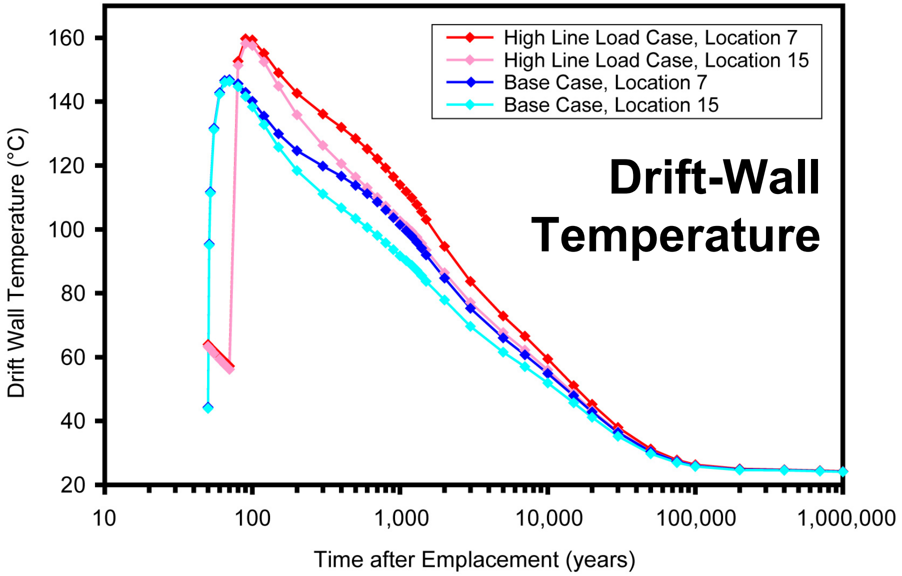


- **Hottest (7-package) segment for 96/2 case**
  - **2.0 kW/m line load; 72-yr ventilation**
  - **10th percentile flux; mean thermal conductivity**
- **Result: far-field peak temp. is within ~2 C° of reference case, at adjacent units**

Source: ANL-NBS-HS-000057 Rev. 00, Figs. 6.4.2-30 and 6.4.2-31.

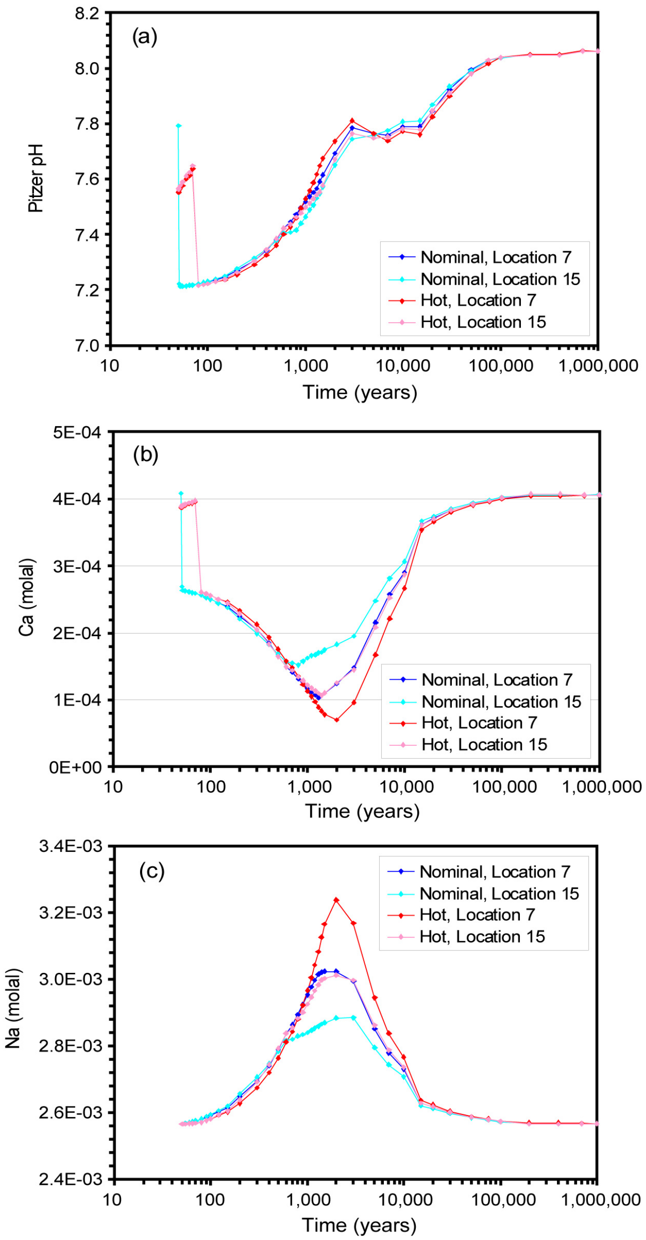
Repository Thermal Management Geochemical Response





- **Implement near-field chemistry model**
  - **2 kW/m Line Load; 72-yr ventilation**
  - **Repository-center drift; lithophysal properties**
  - **Typical percolation flux; Mean thermal conductivity**

Source: ANL-NBS-HS-000057 Rev. 00, Figs. 6.4.3-2 and 6.4.3-3.



Repository Thermal Management Geochemical Response (Continued)

- **Near-Field chemistry model results:**
  - **Increased water-rock interaction**
    - **Near-neutral pH**
    - **Decreased Ca, Mg**
    - **Increased Na, K**

Source: ANL-NBS-HS-000057 Rev. 00, Fig. 6.4.3-4.
Model Description: ANL-EBS-MD-000033 Rev. 06.

Repository Thermal Management Implementation in Repository Operation

- **Analyze thermal conditions for each drift, prior to emplacement**
  - **Determine characteristics of received waste as they are known**
  - **Verify preclosure thermal limits and “loading rules” will be met**
  - **Determine any additional conditions (e.g., package-to-package spacing) that will be imposed**
  - **Perform detailed emplacement analysis to ensure that postclosure thermal limits will be met**
    - **WPLOAD tool is prototype of future detailed methodology ***

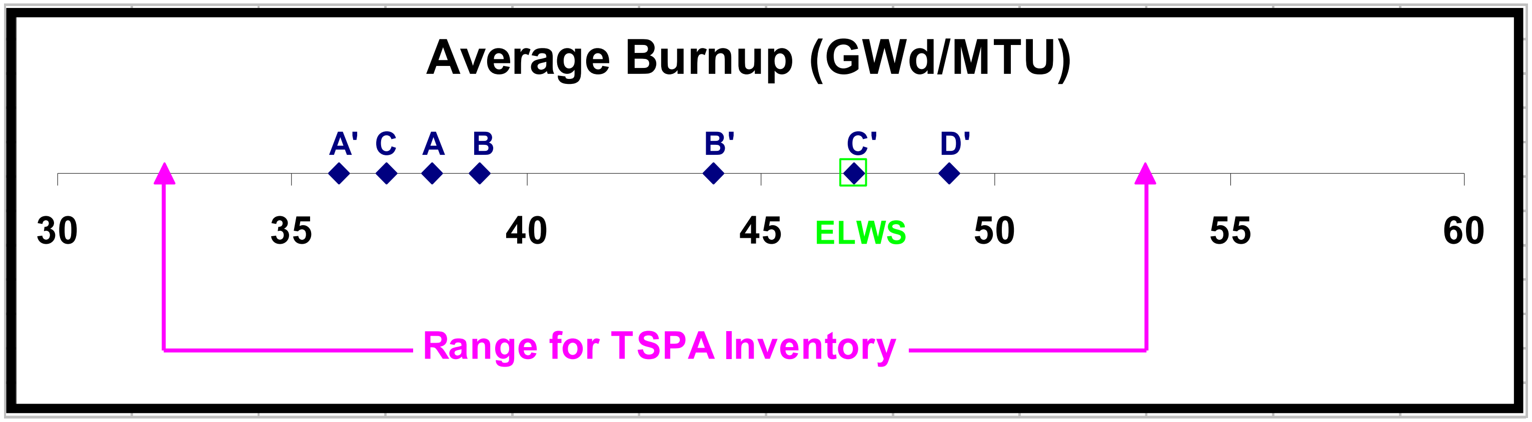
*** Source: 800-00C0WIS0-00500-000-00A**

Repository Thermal Management Summary

- **ELWS is based on reasonable and conservative projections of age and burnup**
  - **ELWS lineal average is similar to the reference case**
  - **“Loading rules” ensure that preclosure and postclosure temperature limits are met**
- **Near-field responses to ELWS emplacement are represented by the TSPA modeling basis**
  - **Similar in-drift peak temperatures; slower cooldown**
  - **Geomechanical response is similar to the TSPA base case**
  - **Small shifts in seepage chemistry**
- **Implementation strategy will evaluate each drift when waste characteristics are known**
  - **(e.g., reactor reload analyses)**

BACKUP SLIDES

Repository Thermal Management Comparison of Burnup Values



Case	Definition
A	Fuel selection begins with 10-year-old spent fuel
B	Fuel selection begins with 10-year-old spent fuel in strict order of age
C	Fuel selection begins with oldest fuel first.
A'	Oldest fuel first with no dry storage.(OFF)
B'	Youngest fuel first greater than 10 years (YFF10)
C'	Youngest Fuel first greater that 5 years old in strict age order (YFF5)
D'	Limiting YFF5: All youngest (5-year old) fuel is selected first followed by older fuel in increasing age order.

Sources: ANL-WIS-MD-000020 Rev. 01 AD01, Section 6.6.1, and ANL-NBS-HS-000057 Rev. 00, Section 6.1.