# Examining Repository Loading Options to Expand Yucca Mountain Repository Capacity

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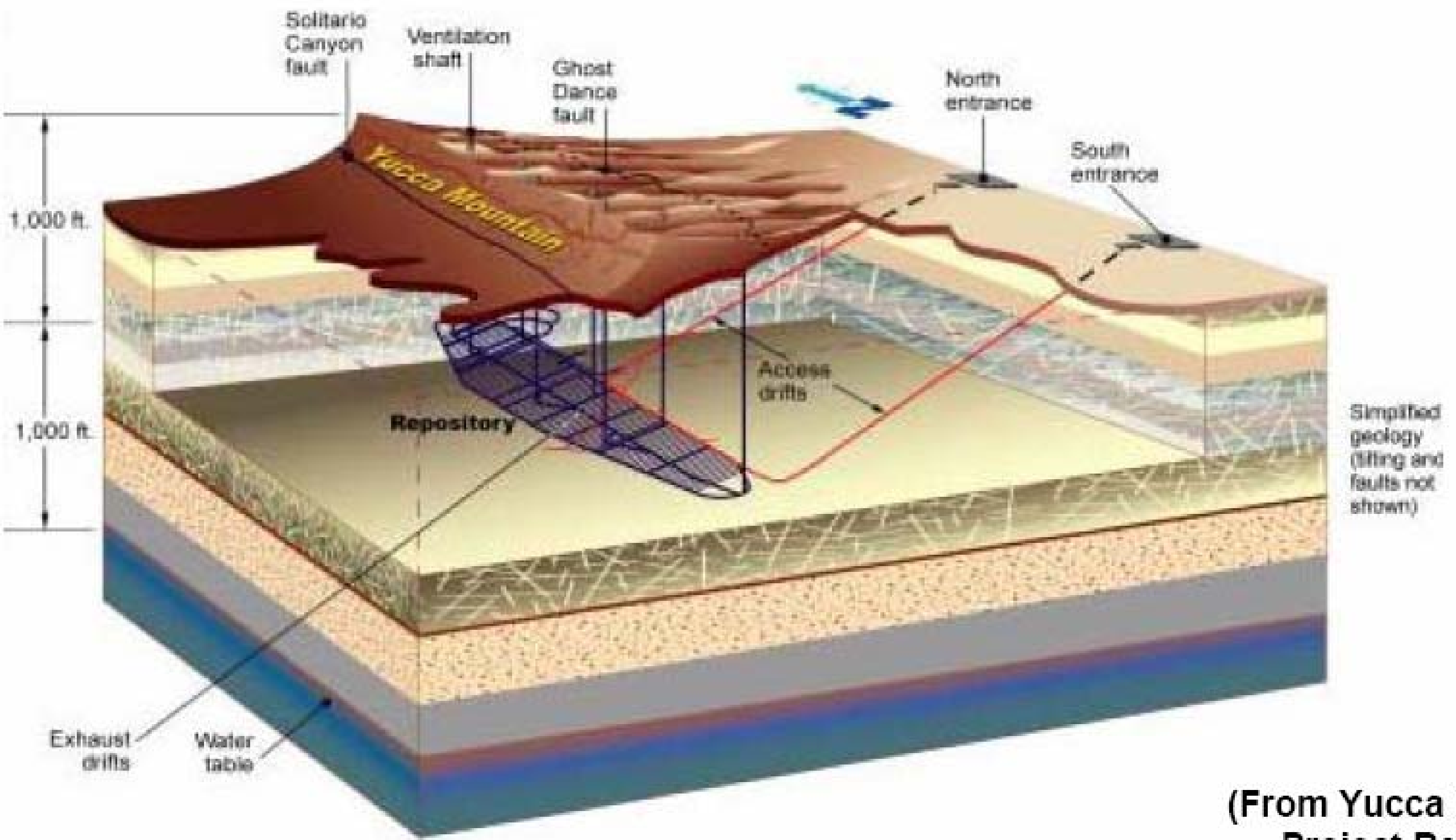
# Outline

- Introduction
- Objective
- Method & Tool
- Case Study & Results
- Discussions

# Introduction

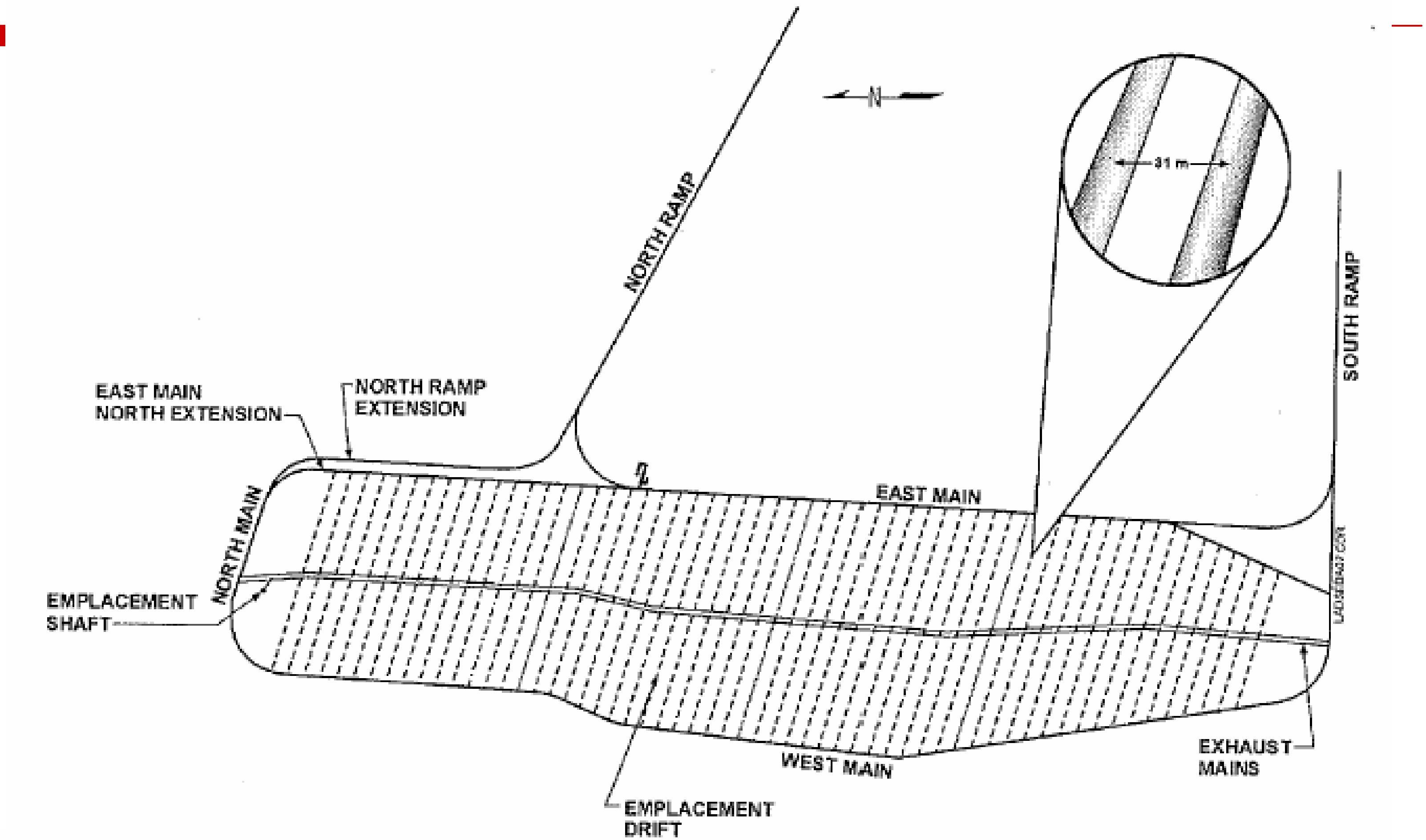
- Given the difficulty in siting the Yucca Mountain repository and the already identified need for additional capacity, the concept of expanding the capacity of the Yucca Mountain repository is of significant interest to the nuclear industry and the Department of Energy (DOE).

# Yucca Mountain




(From Yucca Mountain Project Reports)

# Waste Package Layout



# Alternative options to expand repository capacity

- Increase the footprint size
- Implement multiple-level repository design for the given footprint
- Allow the drift distance to vary within thermal limits*
- Allow non-uniform loading of wastes into the drifts within thermal limits*
- Reduce the inventory of HLW and its decay heat through advanced fuel cycle implementation

# Objectives

- To examining possible expansion of repository capacity for a given fixed footprint size (single layer repository) by implementing:
  - Variable drift spacing
  - Non-uniform loading (variable drift thermal loading) of wastes into drifts
- To examine the uncertainty in the estimation.

# Tasks

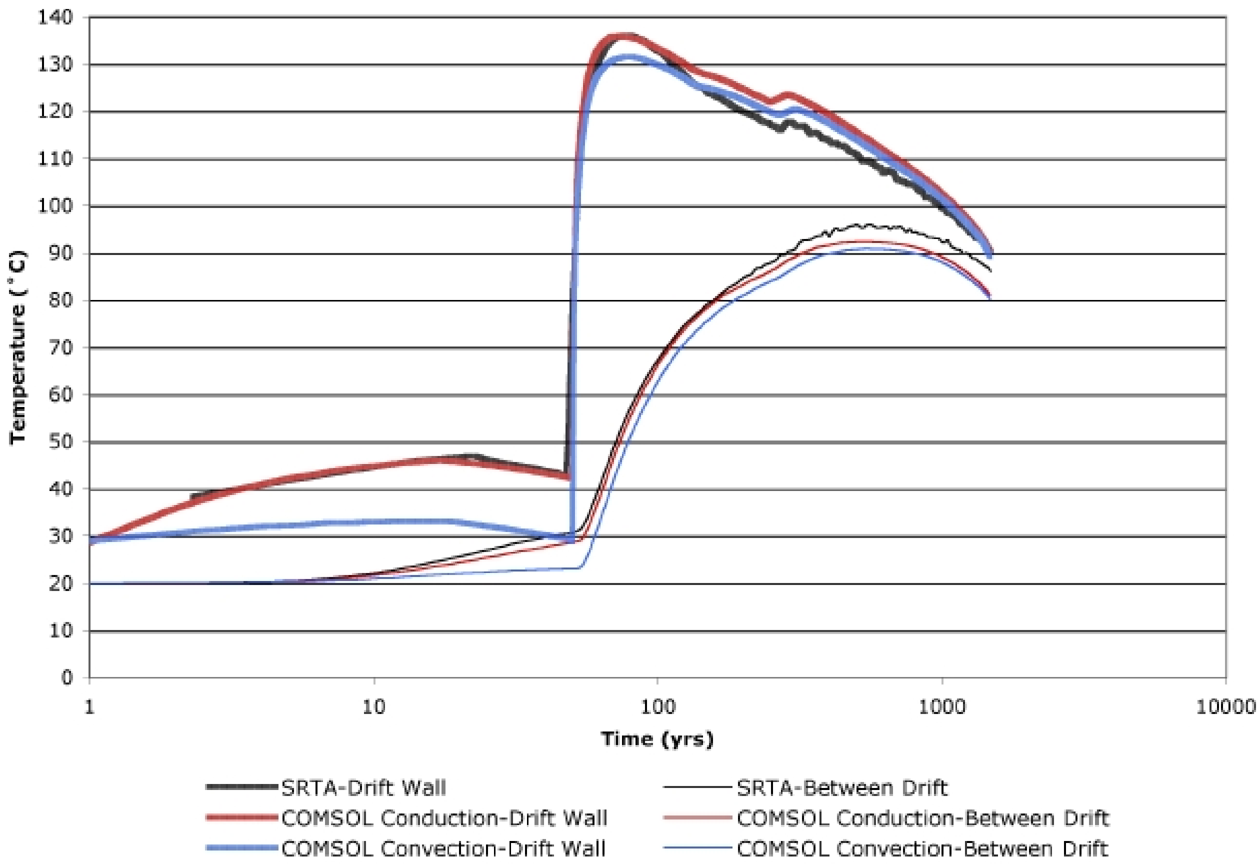
- A computer model (SRTA) was developed for efficient repository heat transfer calculations
- Effect of implementing variable drift spacing and variable drift thermal loading on the repository capacity was analyzed.
- Sensitivity and uncertainty analyses (using Crystal Ball 7.2.2) were performed to identify key parameters and to estimate the uncertainty in the results.
- The capacity increase of the repository was investigated based on the mean as well as the ninety-fifth percentile estimates.

# Repository Thermal Analysis

- Due to the large number of calculations needed, an efficient computational model was needed.
- The SRTA (Simplified Repository Thermal Analysis) code was selected for this work.
- SRTA is based on an analytical solution of the heat conduction equation.
- COMSOL 3.3a was chosen for the verification of the SRTA code.
  - COMSOL is a 3-D FEM model used industry wide for research, engineering, and design applications.

# COMSOL vs. SRTA

50 Years Preclosure Period
88% Heat Loss Factor



# Sensitivity Analysis

5% Increase in Mean Values

| Parameters | Drift Wall (˚C) | Between Drift (˚C) | Parameters | Drift Wall (˚C) | Between Drift (˚C) |
|---|---|---|---|---|---|
| **Density of Tuff Rock** | **-1.00%** | **-1.46%** | **Emplacement Drift Diameter** | **-0.33%** | **0.03%** |
| **Specific Heat of Tuff Rock** | **-1.00%** | **-1.46%** | Circumferential Fraction Not Covered By Floor | 0.00% | 0.00% |
| **Thermal Conductivity of Tuff Rock** | **-2.90%** | **-1.65%** | **Ambient Repository Temperature** | **0.96%** | **1.27%** |
| Conductivity of Natural Convection | 0.00% | 0.00% | **Elevation of Repository Horizon** | **0.00%** | **-0.51%** |
| **Factor for ventilation heat losses** | **-1.80%** | **-0.66%** | **Elevation of Ground Surface** | **0.00%** | **0.13%** |
| Thermal Conductivity Of Drip Shield | 0.00% | 0.00% | Inner Waste Package Thickness | 0.00% | 0.00% |
| Thermal Conductivity Of Backfill | 0.00% | 0.00% | Outer Waste Package Thickness | 0.00% | 0.00% |
| Emissivity of Drip Shield | 0.00% | 0.00% | Thermal Conductivity of Inner Overpack | 0.00% | 0.00% |
| Emissivity of Waste Package | 0.00% | 0.00% | Thermal Conductivity of Outer Overpack | 0.00% | 0.00% |
| Waste Package Diameter | 0.00% | 0.00% | Effective Thermal Conductivity Of Basket Spent Fuel in Waste Package | 0.00% | 0.00% |
| Waste Package Length | 0.00% | 0.00% | **WPSpacing Along Emplacement Drift** | **-3.86%** | **-3.56%** |
| Drip Shield Thickness | 0.00% | 0.00% | Thermal Conductivity Of Floor | 0.00% | 0.00% |
| Drip Shield Eqv Int Dia | 0.00% | 0.00% | Emissivity Of Drift Wall | 0.00% | 0.00% |

# Input Parameter Uncertainties

| Parameter Description: | Code Parameters | Units | Initial Value | Standard Deviations | Distribution | Source |
|---|---|---|---|---|---|---|
| Thermal Conductivity of Outer Overpack | akcs | W/(m-˚C) | 15.49 | 4.21 | Normal | DOE 2001 |
| Thermal Conductivity of Inner Overpack | akss | W/(m-˚C) | 16.62 | 2.10 | Normal | DOE 2001 |
| Thermal Conductivity of Tuff Rock | cond | W/(m-K) | 2.603 | 0.341 | Normal | DOE 2004 |
| Thermal Conductivity Of Drip Shield | condds | W/(m-˚C) | 20 | 0.77 | Normal | DOE 2001 |
| Specific Heat of Tuff Rock | Cp | J/(kg-K) | 930 | 170 | Normal | DOE 2004 |
| Emplacement Drift Diameter | driftdia | m | 5 | 0.089 | Normal | Bechtel 2004 |
| Emissivity of Drip Shield | emissds | - | 0.64 | 0.05 | Normal | Michels 1949 |
| Emissivity of Waste Package | emisswp | - | 0.87 | 0.02 | Normal | Bechtel 2004 |
| Factor for ventilation heat | hloss_fact | - | 0.88 | 0.01 | Normal | Bechtel 2004 |
| Density of Tuff Rock | rho | $Kg/m^3$ | 2593 | 138 | Normal | DOE 2004 |
| Waste Package Diameter | wpdia | m | 1.644 | 0.089 | Normal | Bechtel 2004 |

# Case Study

- Two scenarios:
  - Uniform Loading with variable drift spacing
  - Non-uniform loading with fixed drift spacing
- Two steps:
  - Peak temperature uncertainty
  - Repository capacity change due to the temperature uncertainty

# Assumptions of the variable drift spacing analysis

- Available repository footprint is 4.9km2 (1,165 acres)
- Ventilation system on for 50 yrs or 75 yrs
- Uniform loading of spent nuclear fuel

| | PWR | BWR |
|---|---|---|
| Years Cooled: | 25 | 25 |
| Blend: | 0.645 | 0.355 |
| Burnup (MWd/MTU: | 39136 | 31949.5 |
| Days Irradiated: | 366 | 571 |
| Enrichment: | 3.094 | 3.004 |

# Uniform Loading

**Uncertainty Analysis Results, 50 Years (81m Spacing)**

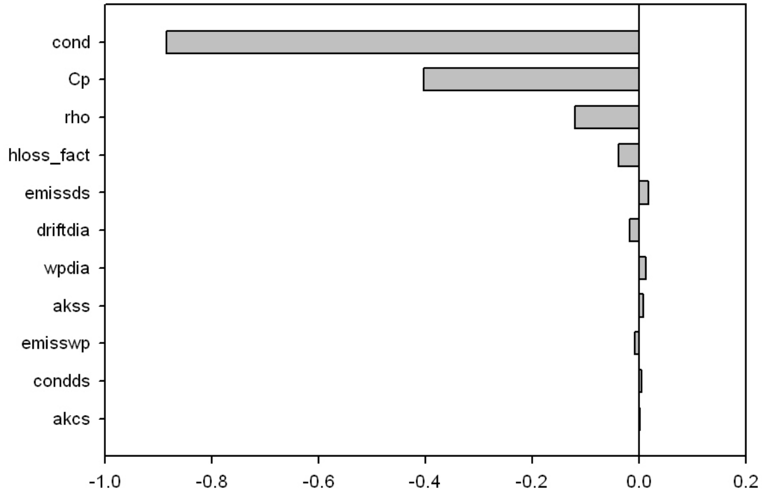
| | Temperature (˚C) | | | | |
|---|---|---|---|---|---|
| **Location:** | **Mean** | **Standard Deviation** | **Min/Max** | **90th %ile** | **95th %ile** |
| Drift Wall | 106 | 10 | 78/164 | 119 | 124 |
| Between Drift | 80 | 7 | 60/129 | 90 | 93 |

**Uncertainty Analysis Results, 75 Years (81m Spacing)**

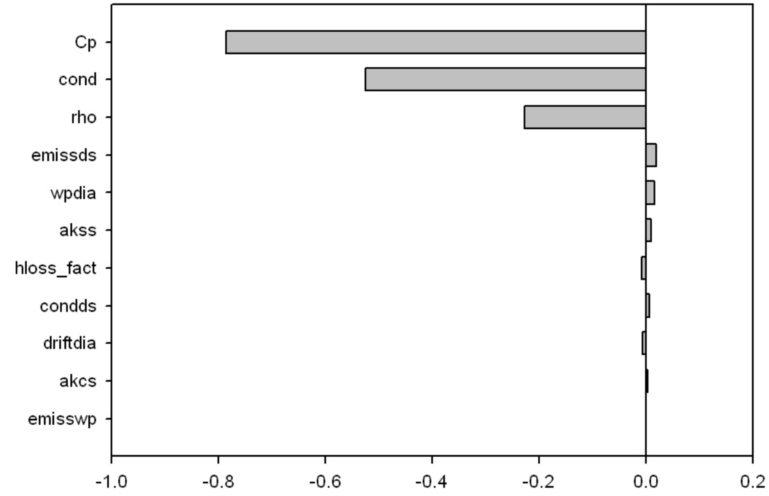
| | Temperature (˚C) | | | | |
|---|---|---|---|---|---|
| **Location:** | **Mean** | **Standard Deviation** | **Min/Max** | **90th %ile** | **95th %ile** |
| Drift Wall | 92 | 8 | 71/146 | 103 | 107 |
| Between Drift | 77 | 7 | 58/130 | 86 | 89 |

# Uniform Loading
## Key Contributors

Drift Wall




Between Drift



# Uniform Loading

Increase in Capacity-Based on the Mean Value of the calculated temperature (By changing Drift Distance)

**50 Years**

| Drift Spacing [m] | Drift Wall [˚C] | Between Drift [˚C] | Total MTU | Increase in MTU |
|---|---|---|---|---|
| 81 | 104.36 | 78.86 | 70000 | - |
| 63 | 110 | 96 | 95942 | 37.1% |

**75 Years**

| Drift Spacing [m] | Drift Wall [˚C] | Between Drift [˚C] | Total MTU | Increase in MTU |
|---|---|---|---|---|
| 81 | 89.03 | 74.69 | 70000 | - |
| 60.5 | 106 | 96 | 99809 | 42.6% |

# Uniform Loading

Increase in Capacity-Based on the 95th %ile of the calculated temperature (By changing Drift Distance)

**50 Years**

| Drift Spacing [m] | Drift Wall [˚C] | Between Drift [˚C] | Total MTU | Increase in MTU |
|---|---|---|---|---|
| 81 | 104.36 | 78.86 | 70000 | - |
| 78.5 | 124 | 96 | 76833 | 9.8% |

**75 Years**

| Drift Spacing [m] | Drift Wall [˚C] | Between Drift [˚C] | Total MTU | Increase in MTU |
|---|---|---|---|---|
| 81 | 89.03 | 74.69 | 70000 | - |
| 75 | 111 | 96 | 80565 | 15% |

# Assumptions for the non-uniform loading analysis

- The existing inventory of SNF generated until 2002 based on the DOE/RW-859 database was used.
- Used repository footprint is 3.07 (759.60 acres).
- Ventilation system on for 50 yrs or 75 yrs
- Five different schemes were assumed.

# The Nuclear Fuel Data Survey

- DOE/RW-859
- All fuel assemblies irradiated in commercial nuclear reactors in the U.S. (through 2002)
- ~160,000 Assemblies
- Detailed information for each assembly: maximum burnup, enrichment, charge/discharge time, fuel type (PWR/BWR), etc.

# Decay Profile Calculation

$$Q(t) = D_1 * t^{-\beta} * (burnup/33{,}000)$$

$$D_1 = \alpha_1 + \alpha_2 \cdot \ln(burnup) + \alpha_3 \cdot IrradiationDays + \alpha_4 \cdot enrichment + \alpha_5 \cdot \ln(burnup) \cdot IrradiationDays + \alpha_6 \cdot \ln(burnup) \cdot enrichment + \alpha_7 \cdot IrradiationDays \cdot Enrichment + \alpha_8 \cdot \ln(burnup)^2 + \alpha_9 \cdot IrradiationDays^2 + \alpha_{10} \cdot enrichment^2$$

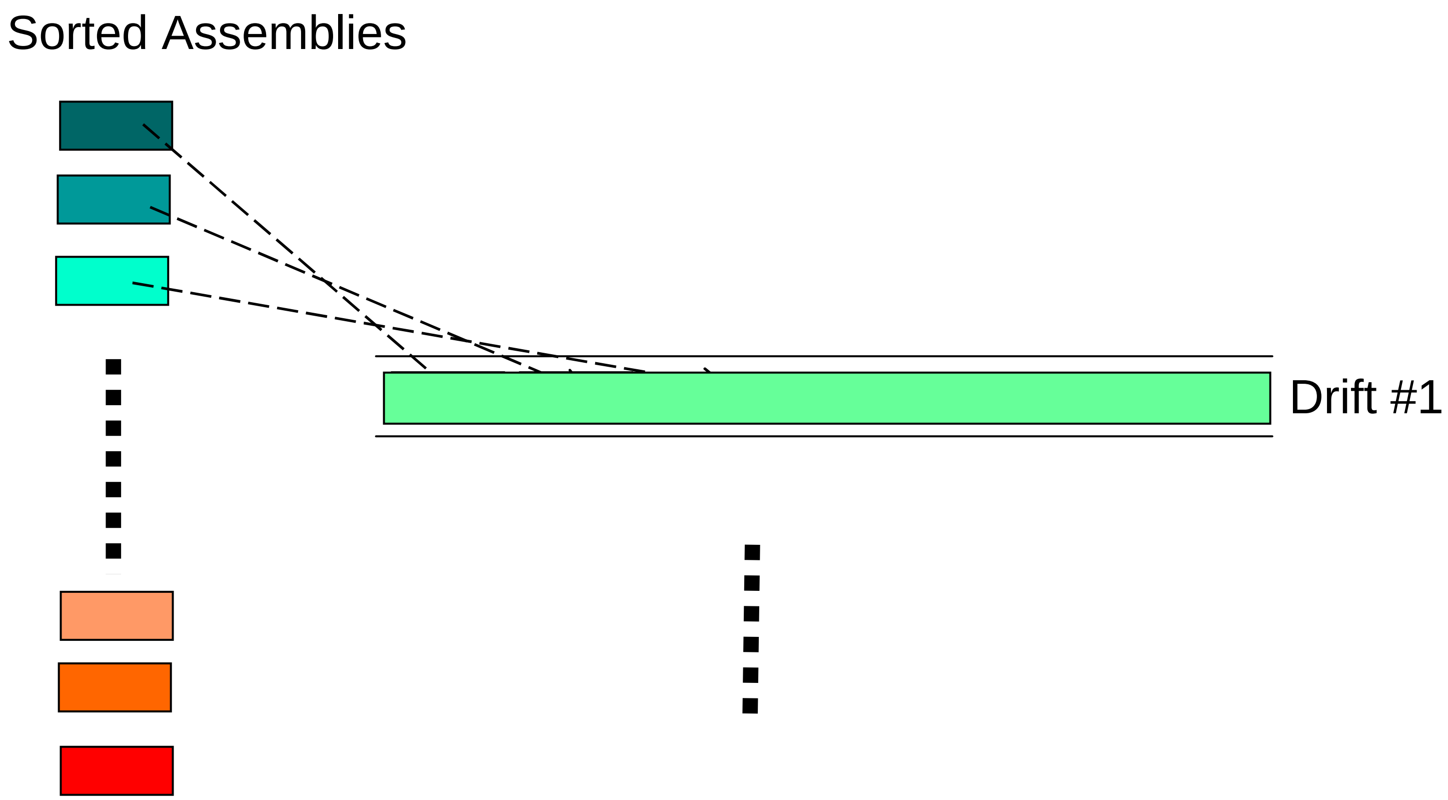
$$\beta_1 = \gamma_1 + \gamma_2 \cdot \ln(burnup) + \gamma_3 \cdot IrradiationDays + \gamma_4 \cdot enrichment + \gamma_5 \cdot \ln(burnup) \cdot IrradiationDays + \gamma_6 \cdot \ln(burnup) \cdot enrichment + \gamma_7 \cdot IrradiationDays \cdot Enrichment + \gamma_8 \cdot \ln(burnup)^2 + \gamma_9 \cdot IrradiationDays^2 + \gamma_{10} \cdot enrichment^2$$

Decay Profile for Reference Cases by OrigenArp → SAS Regression Tool for coefficients → Matlab Code Validation

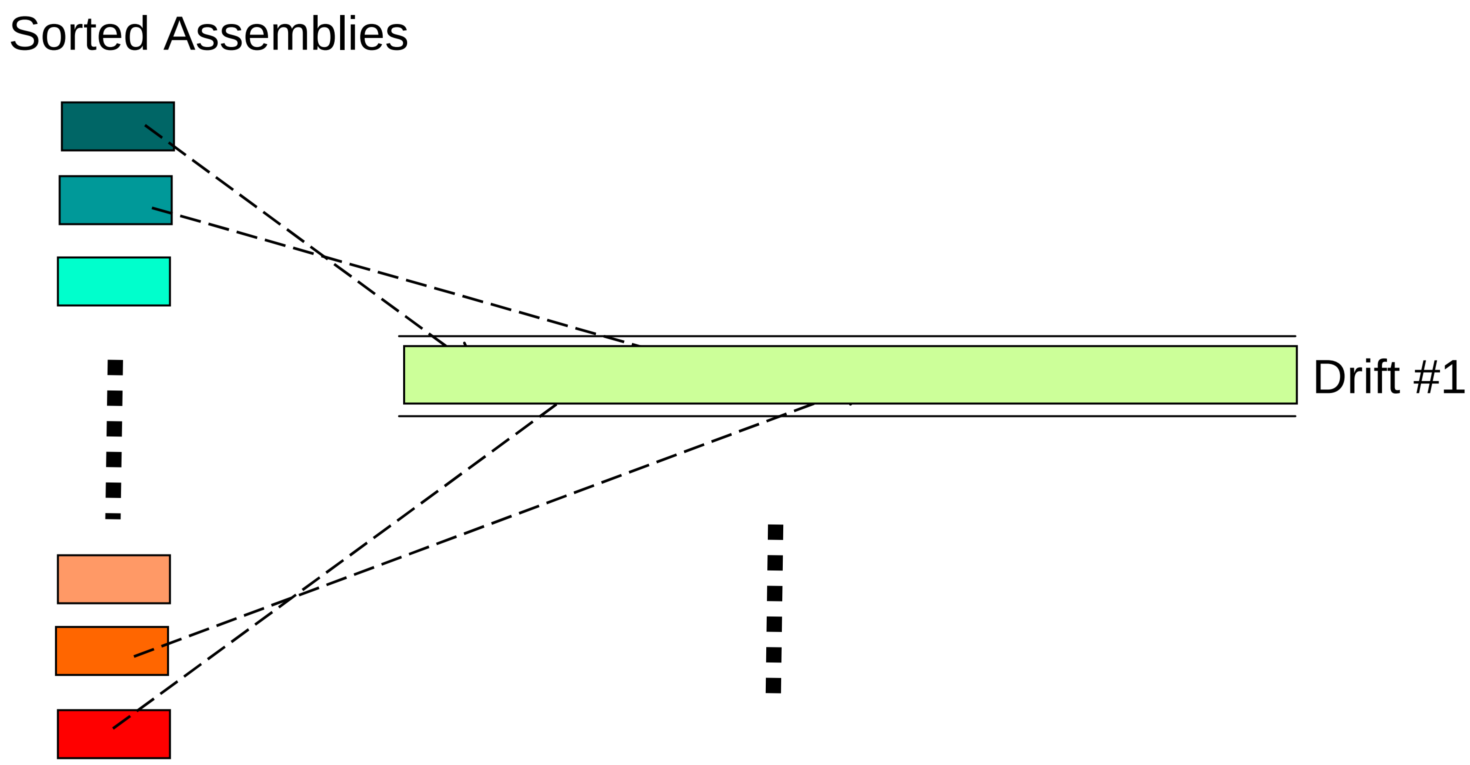
# Loading Patterns

- Age-based sequential loading (Scheme #1)
- Age-based mixed loading (Scheme #2)
- Decay heat load-based mixed loading (Scheme #3)
- Age-based bi-sequential loading (Scheme #4)
- Decay heat load-based bi-sequential loading (Scheme #5)

# Age-based sequential loading (Scheme #1)

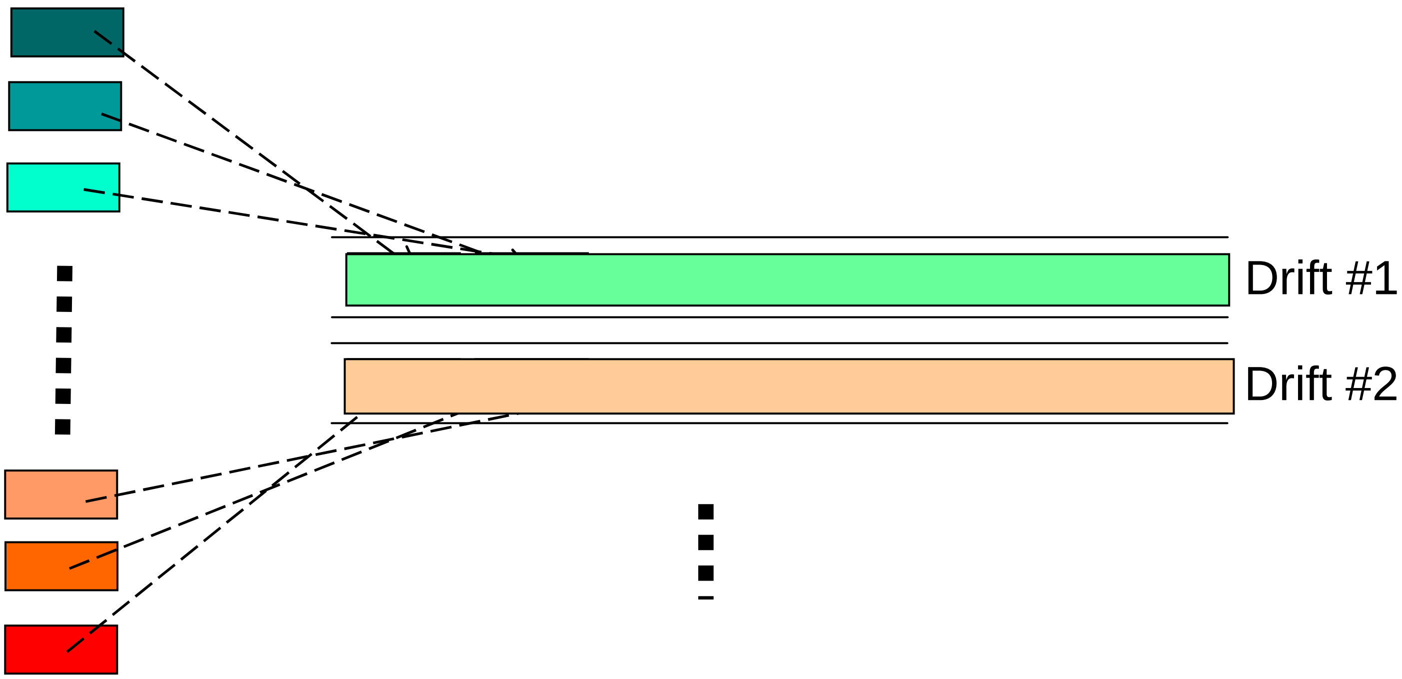


# Age-based mixed loading (Scheme #2)



# Age-based bi-sequential loading (Scheme #4)

Sorted Assemblies



# Non-Uniform Loading

50 Year Preclosure Period

**Drift Wall Uncertainty Analysis Results**

| | Temperature (˚C) | | | |
|---|---|---|---|---|
| **Loading Scheme:** | **Mean** | **Standard Deviation** | **90th %ile** | **95th %ile** |
| Scheme 1 | 129 | 13 | 146 | 152 |
| Scheme 2 | 103 | 9 | 115 | 119 |
| Scheme 3 | 102 | 9 | 114 | 118 |
| Scheme 4 | 124 | 12 | 141 | 147 |
| Scheme 5 | 137 | 14 | 156 | 164 |

**Between Drift Uncertainty Analysis Results**

| | Temperature (˚C) | | | |
|---|---|---|---|---|
| **Loading Scheme:** | **Mean** | **Standard Deviation** | **90th %ile** | **95th %ile** |
| Scheme 1 | 87 | 8 | 98 | 102 |
| Scheme 2 | 76 | 7 | 85 | 88 |
| Scheme 3 | 76 | 7 | 85 | 88 |
| Scheme 4 | 76 | 7 | 85 | 88 |
| Scheme 5 | 75 | 7 | 85 | 88 |

# Non-Uniform Loading

## 75 Year Preclosure Period

**Drift Wall Uncertainty Analysis Results**

| | Temperature (˚C) | | | |
|---|---|---|---|---|
| **Loading Scheme:** | **Mean** | **Standard Deviation** | **90th %ile** | **95th %ile** |
| Scheme 1 | 109 | 10 | 123 | 127 |
| Scheme 2 | 89 | 8 | 101 | 104 |
| Scheme 3 | 88 | 8 | 98 | 102 |
| Scheme 4 | 103 | 10 | 116 | 121 |
| Scheme 5 | 113 | 11 | 127 | 132 |

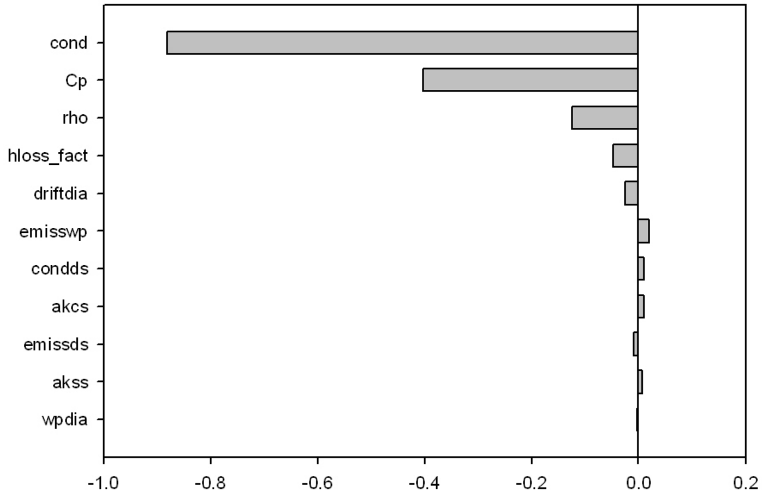
**Between Drift Uncertainty Analysis Results**

| | Temperature (˚C) | | | |
|---|---|---|---|---|
| **Loading Scheme:** | **Mean** | **Standard Deviation** | **90th %ile** | **95th %ile** |
| Scheme 1 | 82 | 8 | 92 | 96 |
| Scheme 2 | 72 | 7 | 81 | 84 |
| Scheme 3 | 72 | 6 | 81 | 84 |
| Scheme 4 | 73 | 7 | 81 | 84 |
| Scheme 5 | 72 | 6 | 80 | 84 |

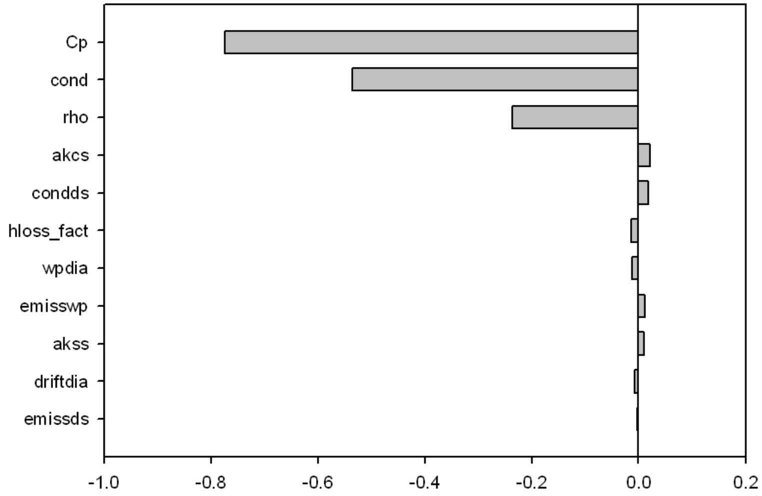
# Non-Uniform Loading

## 50 Year Preclosure Period

### Drift Wall




### Between Drift



# Non-Uniform Loading

Increase in Capacity-Based on the Mean Value of the calculated temperature (By changing MTU/Cask)

**50 Years**

| Scheme: | #1 | #2 | #3 | #4 | #5 |
|---|---|---|---|---|---|
| Maximum Capacity per 35 drifts (MTHM) | 54254 | 65424 | 65187 | 65128 | 65750 |
| Increase compared to 46757 MTU: | 16% | 39.9% | 39.4% | 39.3% | 40.6% |

**75 Years**

| Scheme # | #1 | #2 | #3 | #4 | #5 |
|---|---|---|---|---|---|
| Maximum Capacity per 35 drifts (MTHM) | 58372 | 69158 | 69069 | 69158 | 69217 |
| Increase compared to 46757 MTU: | 24.8% | 47.9% | 47.7% | 47.9% | 48% |

# Non-Uniform Loading (Scheme #2)

Increase in Capacity-Based on 95th %ile Value of the calculated temperature (By changing MTU/Cask)

| Scheme: | 50 yr preclosure period | 75 yr preclosure period |
|---|---|---|
| Maximum Capacity per 35 drifts (MTU) | 51861 | 54825 |
| Increase compared to 46757 MTU: | 10.9% | 17.3% |

# Discussions

- Sensitivity of uncertainties in the three main contributors for non uniform thermal loading showed a twenty percent reduction in uncertainty resulted an increase in capacity to 26.3% for all three contributors based on the ninety-fifth percentile.
- Analyzing the sensitivity in uncertainty for specific heat, conductivity, and density of Tuff individually resulted in an increase in capacity of 21.3%, 20.3%, and 19.2% based on the ninety-fifth percentile.

# Discussions

- For variable drift spacing under uniform loading, if the uncertainty in the three main contributors is reduced by twenty percent the capacity of the repository will increase by as much as 23.8% based on the ninety-fifth percentile.
- Analyzing the sensitivity of the specific heat of Tuff rock alone increases the capacity by 20.2% based on the ninety-fifth percentile. The sensitivity of uncertainties in the density and conductivity of Tuff rock have less impact on the increase of capacity; 15.4% and 17.5% respectively.

# Discussions

- The uncertainty study result highlights the importance of reducing the uncertainty in the key input parameters such as thermal conductivity, specific heat, and density of the tuff rocks for the Yucca Mountain repository.
- It would be economically viable to analyze the material properties of the Tuff rock in more detail.
- The analysis of the specific heat alone would be the most beneficial to increasing the capacity of the repository based on the ninety-fifth percentile.

# Questions?

Thanks.