Heat Transfer by Natural Convection Through Rubble Generated by Drift Degradation

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Outline

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- Conceptualization and Approach
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Background

- Waste emplacement drifts in a potential repository may degrade and lead to rubble accumulation around engineered components such as the drip shield

- Under such conditions, existing models estimate substantial decrease in heat losses, causing substantial increase in temperatures of engineered components

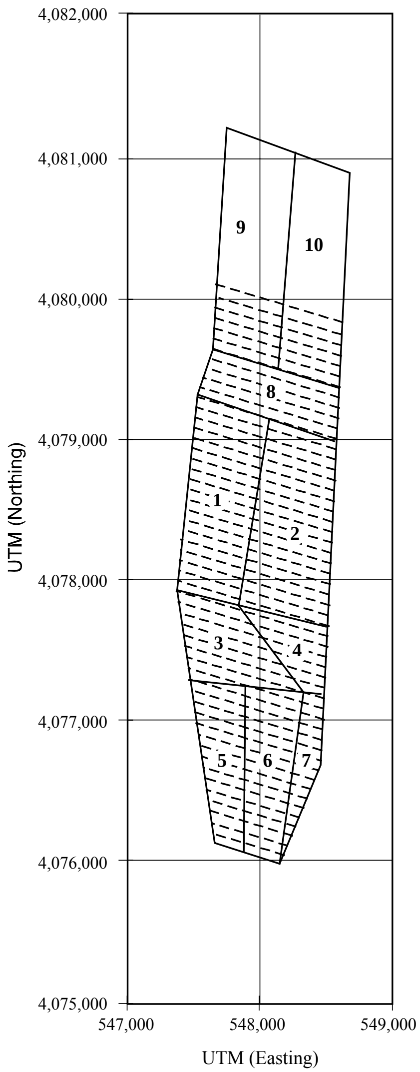
- Increased temperatures could potentially affect: waste package corrosion, water chemistry, water flow distribution, spent nuclear fuel dissolution

- Existing models simplify calculations by assuming that rubble will form an impermeable and insulating thermal blanket around the waste package

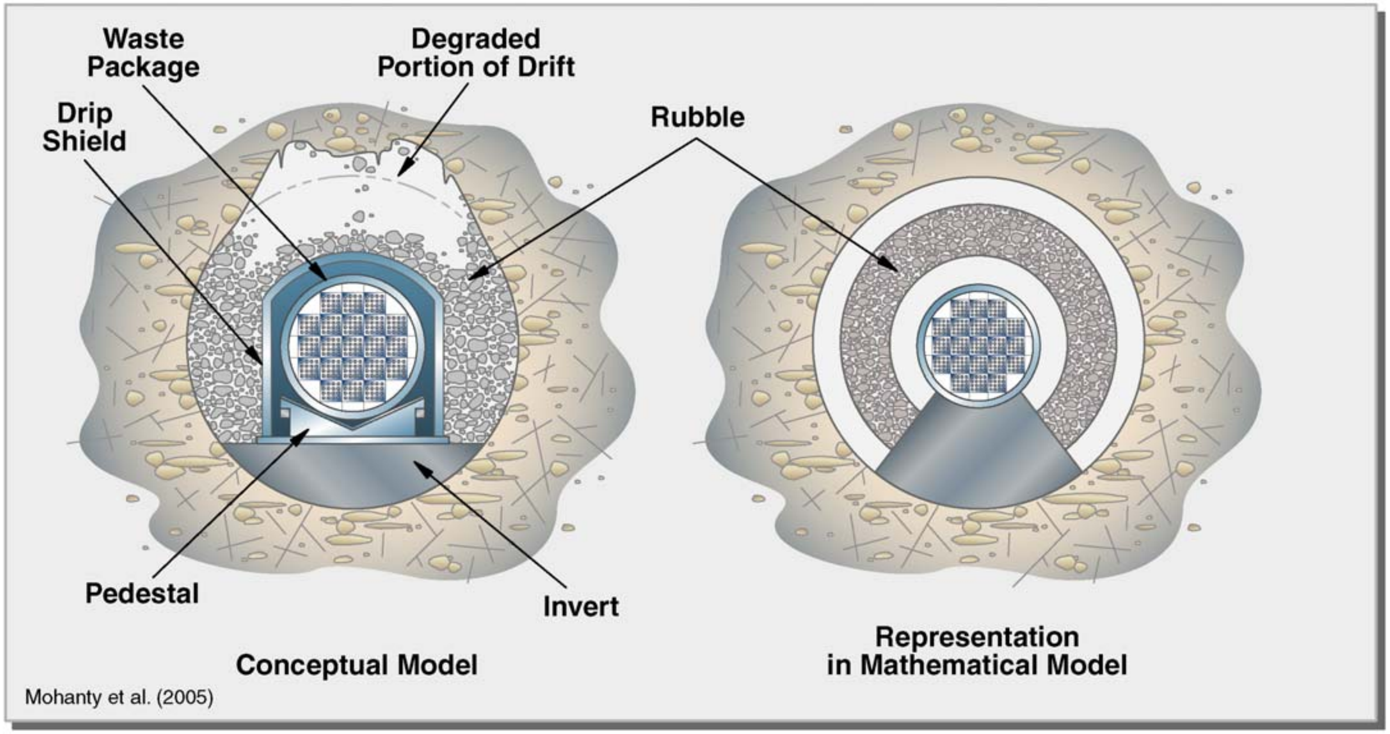
Objective

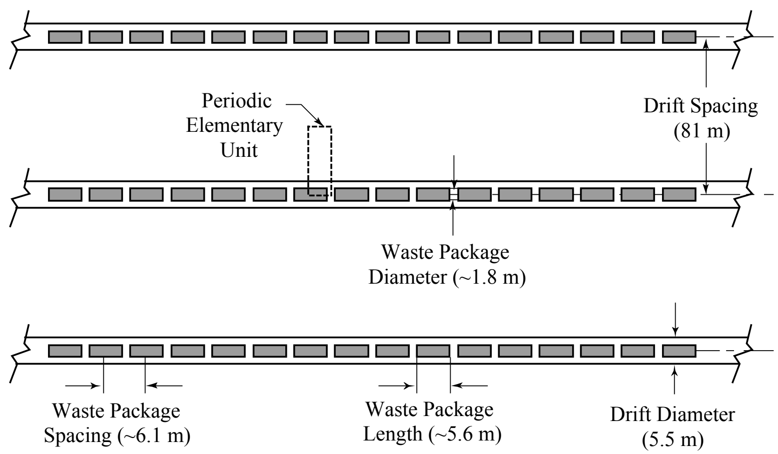
- Develop a more realistic abstracted model for estimating heat transfer through accumulated rubble (i.e., natural backfill) surrounding engineered components
- Provide rationale for the choice of values for key parameters
- Identify the convective heat transfer regime

Conceptualization



Schematic of the Potential Repository Layout





Mohanty et al. (2002)

Approach

- Consider rubble aggregate with a distribution of rubble sizes
- Estimate the rate of natural convection through the aggregate
- Estimate the rate of heat transfer resulting from natural convection
- Estimate an equivalent thermal conductivity considering natural convection
- Compute the overall heat transfer rate from the waste package to the surrounding region

Natural Convection: Rayleigh Number

- Determine the flow regime: convection radially outward in the annular permeable region between two horizontal concentric cylinders

$$Ra_{r_i} = g \beta K r_i \frac{T_{do} - T_{bfo}}{\nu \alpha_m}$$

Ra_{r_i}	Rayleigh number [unitless]	ν	Air kinematic viscosity [m²/s]
g	Gravitational Acceleration [m/s²]	α_m	Air thermal diffusivity [m²/s]
β	Coefficient of thermal expansion [1/K]	T_{bfo}	Lower temperature at the backfill outer surface [K]
r_i	Backfill inner radius [m]	T_{do}	Higher temperature at the backfill inner surface [K]
K	Permeability [m²]		

Permeability of Natural Backfill

- Permeability of the rubble aggregate with a distribution of rubble sizes:

$$K = \frac{\overline{D}_p^2 \phi^3}{72\tau(1-\phi)^2}\left[\frac{\left(\gamma C_{D_p}^3 + 3C_{D_p}^2 + 1\right)^2}{\left(1 + C_{D_p}^2\right)^2}\right]$$

(based on Panda and Lake, 1994)

C_{D_p} = Coefficient of variation of the rubble size distribution [unitless]

ϕ = Void porosity [unitless]

$\overline{D}_p$ = Mean rubble diameter [m]

τ = Tortuosity of the medium (bulk property) [unitless]

γ = Skewness [unitless]

Equivalent Thermal Conductivity

$$\mathrm{Nu} \cong 0.44\,\mathrm{Ra}_{r_i}^{1/2} \frac{ln(r_o/r_i)}{\mathbf{1} + \mathbf{0.916}(r_i/r_o)^{1/2}}$$

$$q' = \mathrm{Nu} \cdot q_c$$

$$k_{\mathrm{bf}} = \frac{q'}{2\pi} \frac{ln\left(\frac{r_o}{r_i}\right)}{T_{do} - T_{\mathrm{bfo}}}$$

$$q_c = 2\pi k_m \frac{T_{\mathrm{do}} - T_{\mathrm{bfo}}}{ln\left(\frac{r_o}{r_i}\right)}$$

Nu = Nusselt Number [unitless]

k_{bf} = Equivalent thermal conductivity of the rubble aggregate [W/(m-K)]

k_m = Stagnant thermal conductivity of the rubble aggregate [W/(m-K)]

T_{do} = Drip shield outer temperature [K]

T_{bfo} = Backfill outer temperature [K]

r_i, r_o = Inner and outer radii of the rubble aggregate [m]

q', q_c = Heat flux with and without convection [W]

Estimation of Rubble Size Distribution

- Gaudin–Schuhmann distribution to characterize rubble distribution

$$\frac{dy}{dx} = \frac{100\alpha}{F^{\alpha}} x^{\alpha-1}$$

y = percentage fine than x
x = fragment size
F = maximum fragment size
α = uniformity parameter

- A two-parameter model
  - $\alpha = 1$: uniform distribution
  - $\alpha < 1$: fine fragment fraction increases with the associated decrease in large fragments
  - $\alpha > 1$: large fragment fraction increases with the associated decrease in small fragments

Estimation of Rubble Size Distribution (continued)

- Experiments and natural analog evidences are rare - high uncertainty

- Proposed approach derives rubble size distribution from the fracture size distributions at Yucca Mountain

  – Rubble is likely to form when rock fails along fractures

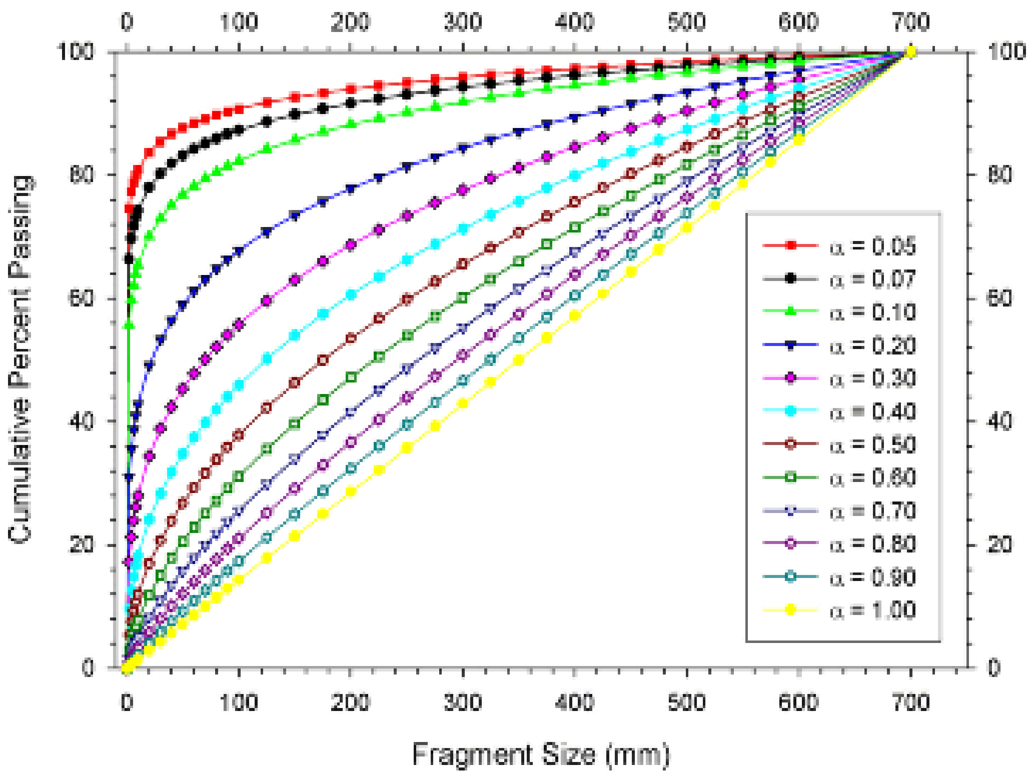
  – Significant portion of the repository in the lower lithophysal unit of Topopah Springs

Estimation of Rubble Size Distribution (continued)

- Two types of fractures measured
  - Long fractures (trace length > 1m; 5 per 10 m with mean spacing 4.6 to 9 m, median 1.4 to 6.2 m)
  - Abundance of short fractures with much shorter trace lengths: Distribution highly skewed toward large spacing (mean 0.10 to 1.08 m; median 0.03 to 0.12 m)
- Small fractures controlling block formation
- Potential mode of failure under seismicity: raveling mode creating many small blocks

Rock Block Size Distribution

- Size of block assumed to be smallest dimension of the block
- 0.7 m, the likely maximum block size, assumed to have significant uncertainty
  - alpha parameter varied to capture the uncertainty
  - assumed the median value of the true spacing of the fracture sets are appropriate (skewed distribution)
  - Investigation underway to study the effect of uncertainty in the maximum block size
- Statistics: mean: 0.13 m; std. dev.: 0.18 m; skewness: 1.5 m



Void Porosity

- Collapsed rock mass adjacent to the drifts results in bulking of the rock mass and creates void porosity
- Bulking factor defined as percentage increase in volume of rock in going from an intact rock mass to rubble
- Void porosity can be determined from bulking factor
- Significant uncertainty in the packing of rubble material. Selected range: 0.1-0.6

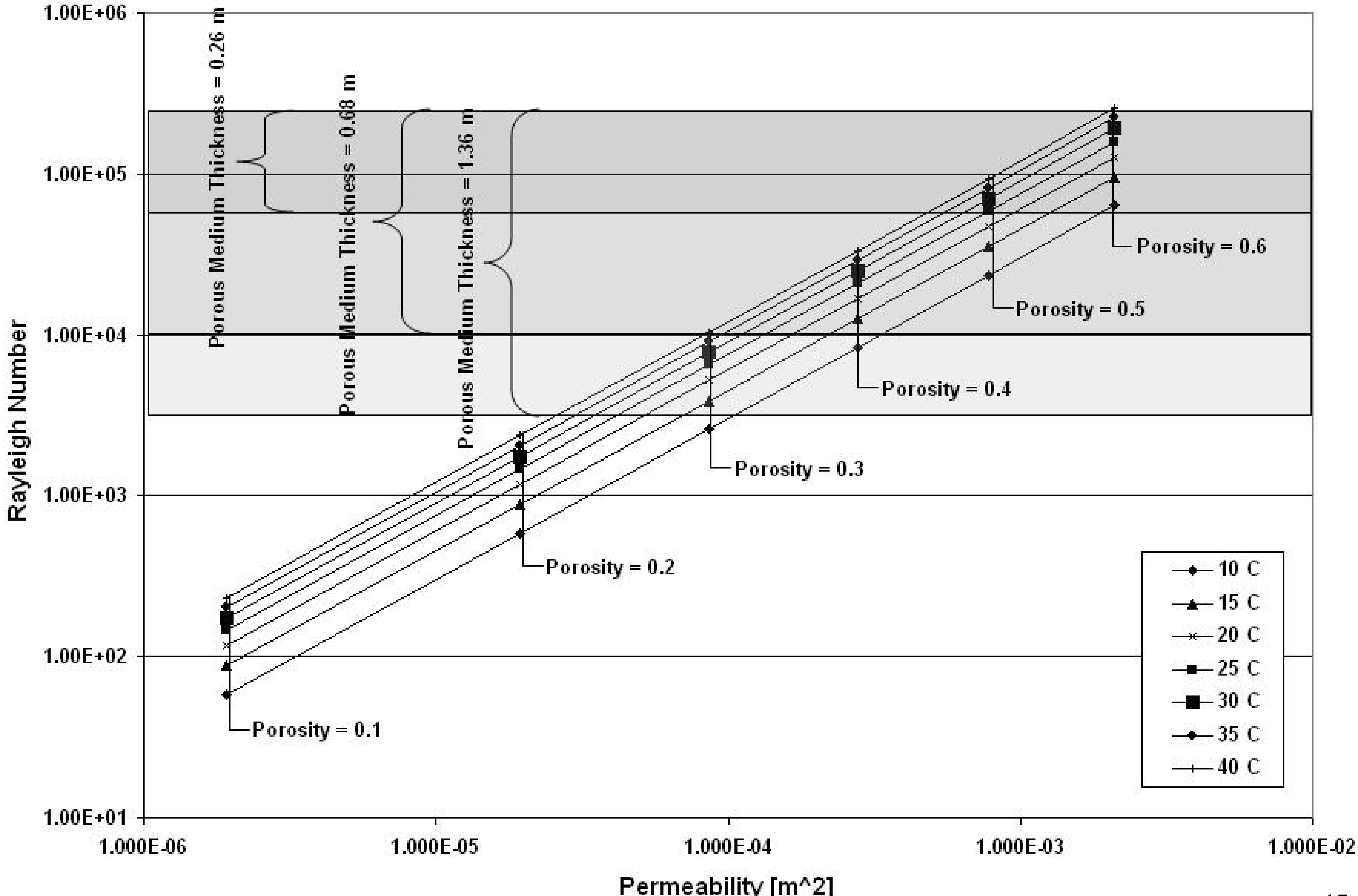
Assumptions

- Rubble consists of spherical particles with a range of diameters
- Schuhmann distribution assumes a continuous rubble size distribution; site-specific characterization should be carried out to determine if a truncated distribution is more appropriate
- Dry air inside the porous medium; no consideration of the effect of seepage on backfill material thermal conductivity

Results

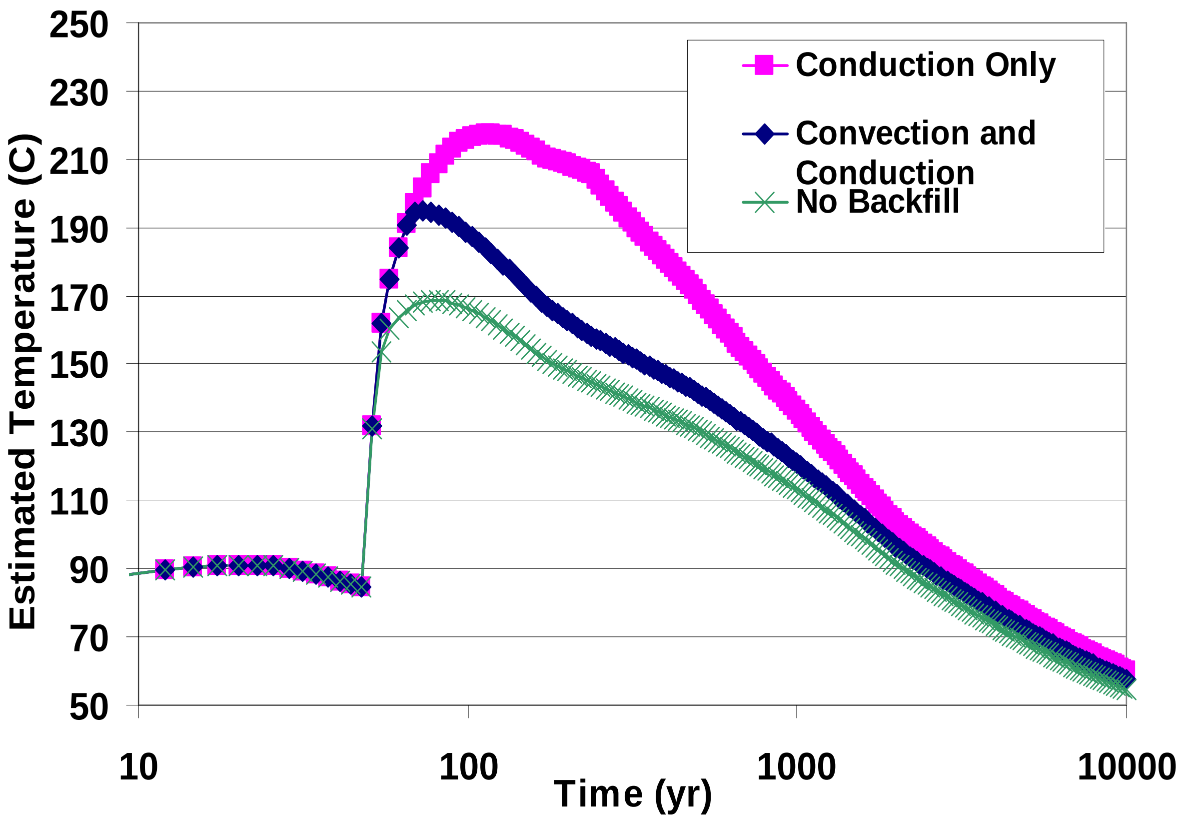
- A high permeability leads to high Rayleigh number
- Permeability is strongly sensitive to
  - mean rubble diameter
  - void porosity
- Tortuosity has only a moderate influence on permeability
- Coefficient of variation, skewness also show sensitivity
- Convection dominates at higher porosities and at higher temperature gradients in regions where the porous medium is thickest

Results (continued)



Results (continued)

An example of waste package average surface temperature with and without convection in natural backfill (Mohanty and Adams, 2005)



Summary and Conclusions

- Natural backfill material is likely to have a large variation in rock/rubble sizes, potentially ranging from a very small diameter to as large as 1 m (although highly unlikely)
- Provided rationale for the choice of rubble size and void porosity
- Uncertainties in the rubble size distribution may result in heat transfer ranging from pure conduction to convection-dominated heat transfer
- Convection will lower waste package temperatures from what they would be if conduction alone were considered
- Convection will dominate when the porosities are high and the temperature gradient is large
- A spatial distribution of conduction-dominated and convection-dominated heat transfer is anticipated

Acknowledgments

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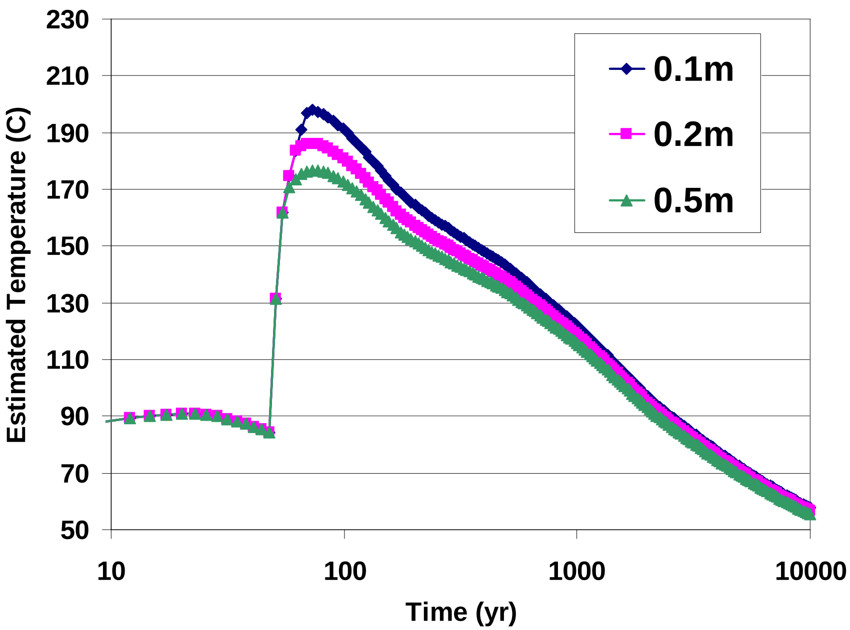
– This presentation is an independent product of CNWRA and does not necessarily reflect the views or regulatory position of NRC.

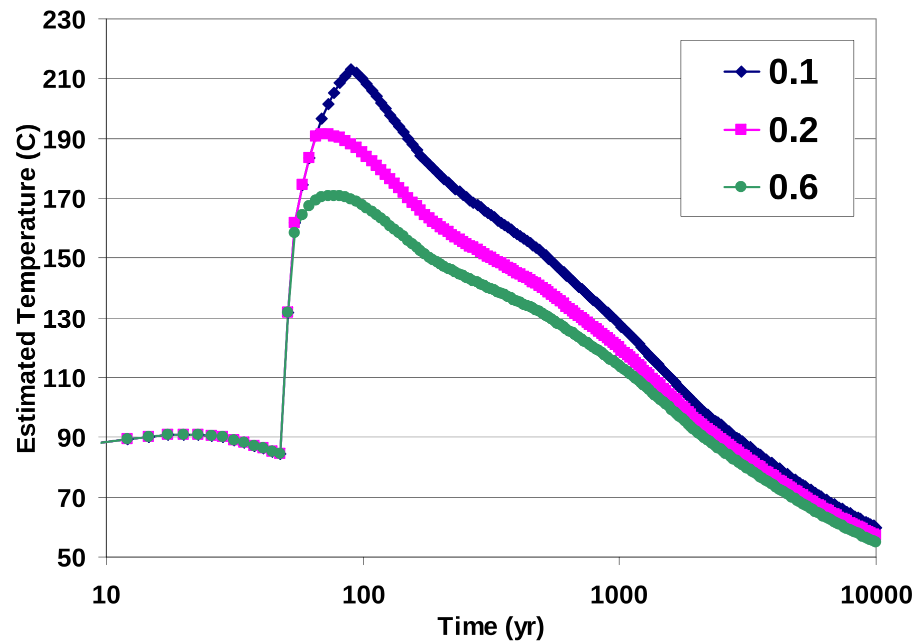
Back-up Slide

Results (continued)

Effect of mean particle diameter and porosity on waste package temperature (deterministic cases) [Mohanty and Adams (2005)]



Mean Particle Diameter



Porosity