A Model for Estimating Heat Transfer Through Drift Degradation Based Natural Backfill Materials

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40th U.S. Rock Mechanics Symposium
Anchorage, Alaska
June 25-29, 2005

Outline

- Background
- Objective
- New Approach
- Assumptions
- Sample Results
- Conclusions

Background

- Yucca Mountain has been proposed as a potential site for the disposal of high-level radioactive waste

- High-level waste, disposed in waste packages, will generate heat by radioactive decay

- Waste emplacement drifts are expected to degrade; rubble may accumulate and affect heat loss from the waste packages

- Existing models estimate substantial decrease in heat losses, thus substantial increase in waste package temperature

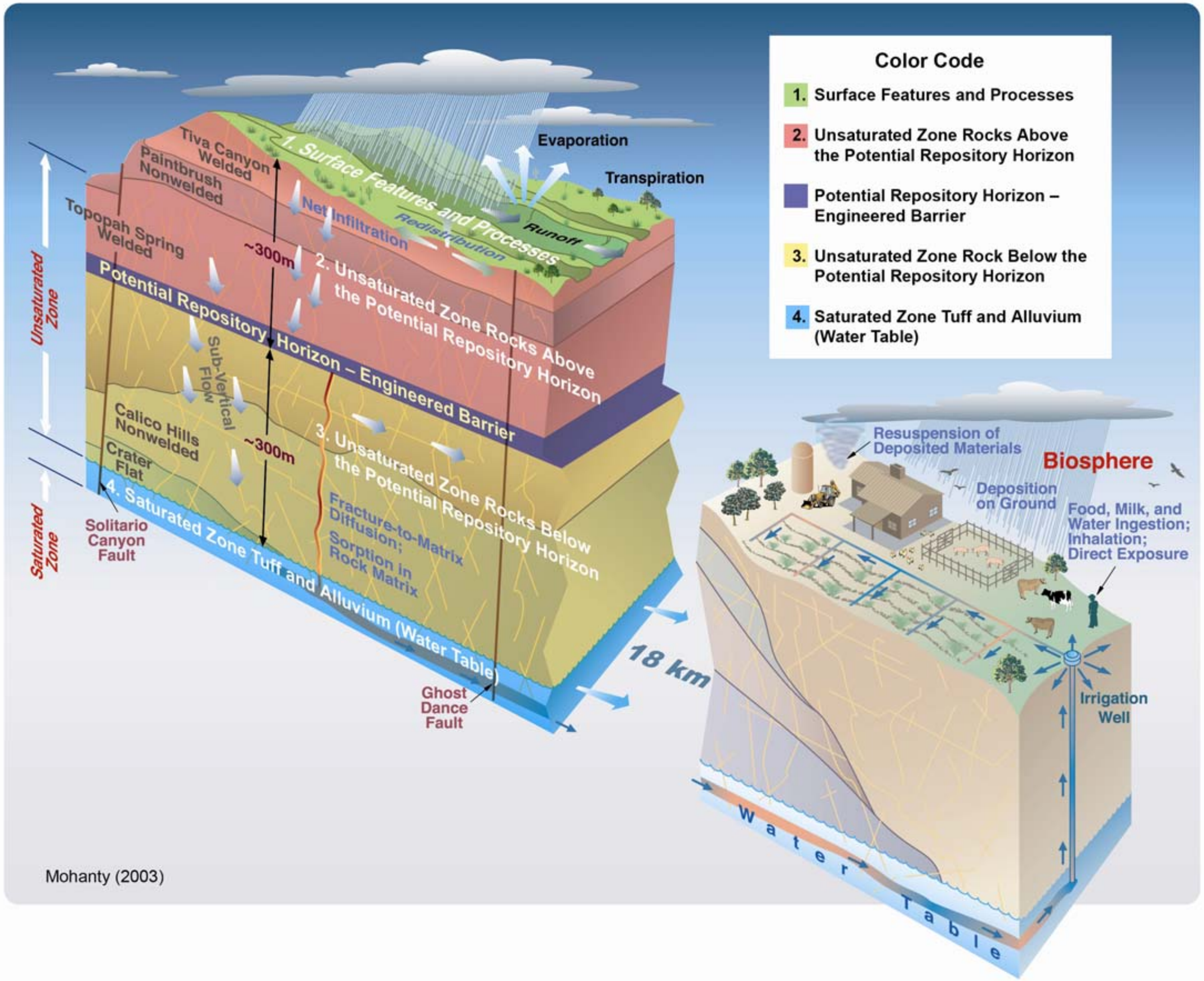
Background (cont’d)

- Existing models assume that drift degradation aggregate forms an impermeable thermal blanket around the waste package.
- Increased temperatures will potentially affect: waste package corrosion, water chemistry, water flow distribution, spent nuclear fuel dissolution.
- In reality, the drift degradation aggregate is likely permeable and natural convection could be a major source of heat transfer, thus decreasing waste package temperature

Objective

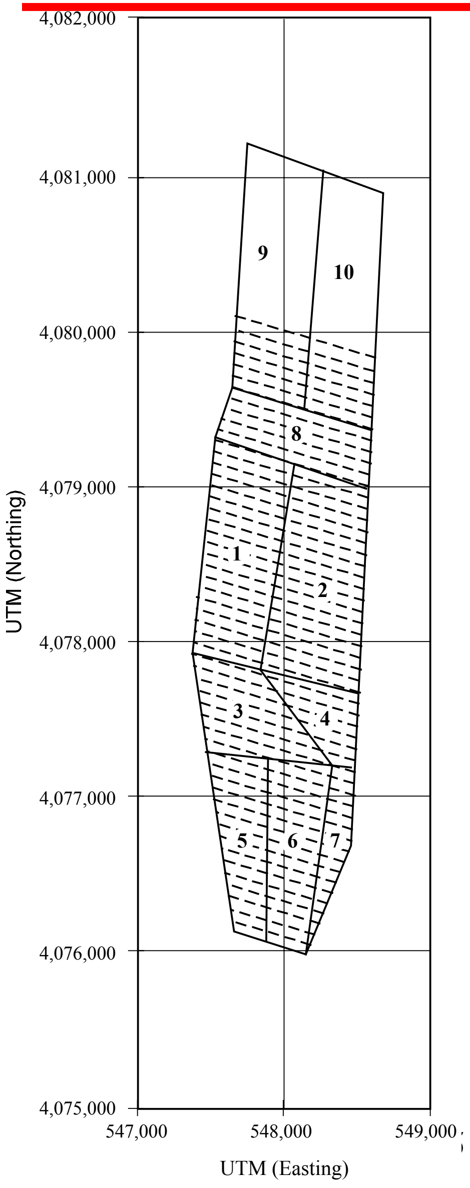
- Develop an abstracted model for estimating heat transfer through the drift degradation aggregate (i.e., natural backfill) surrounding the engineered barriers (waste package and drip shield)

Potential Repository Conceptualization

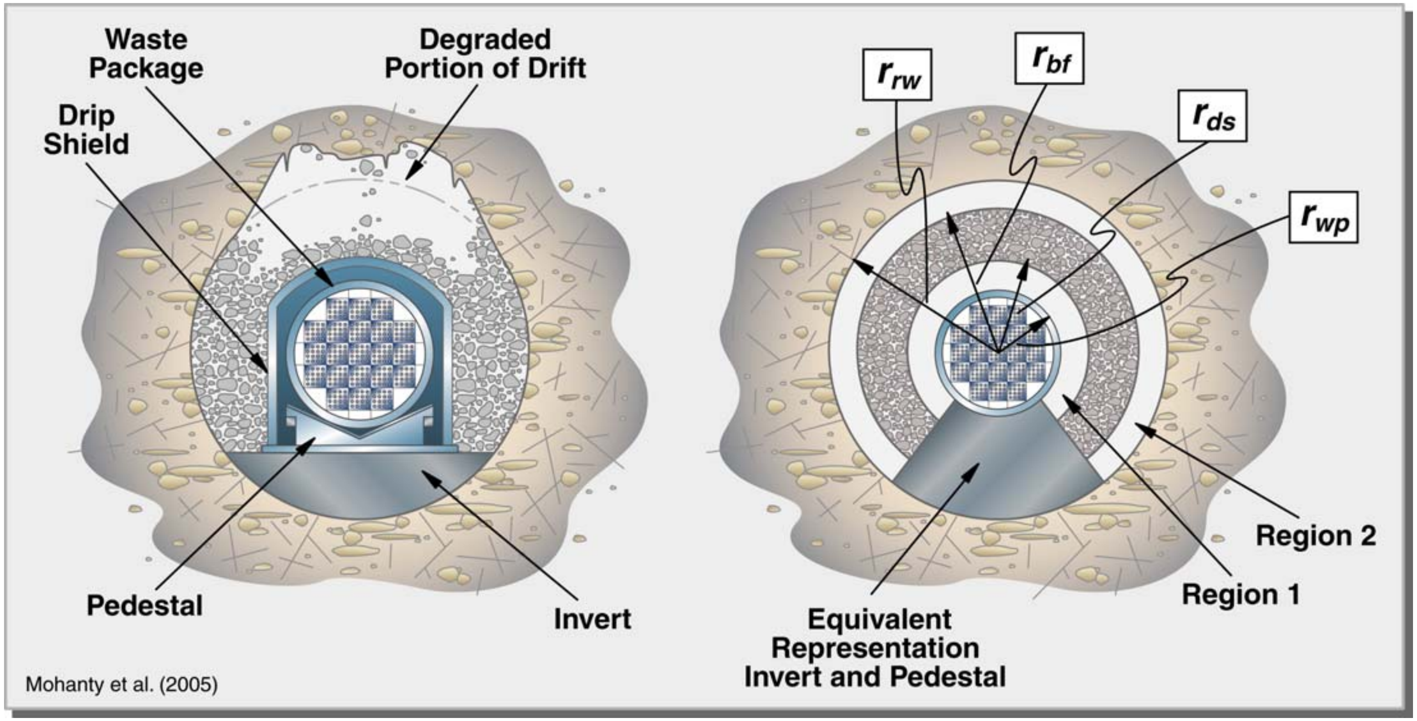


Mohanty (2003)

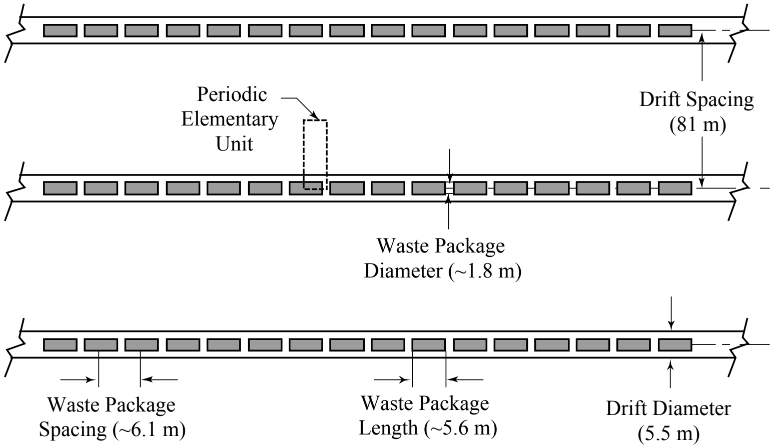
Model Conceptualization



Potential Repository Layout



Mohanty et al. (2005)



Mohanty et al. (2002)

Approach

- Consider an aggregate of the rubble material (i.e., natural backfill) 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 in excess of the no-convection case

- Estimate the equivalent thermal conductivity of the natural backfill

- 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

$$\mathrm{Ra}_{\mathrm{r_i}} = g\,\beta\,K\,r_i\,\frac{\mathrm{T_{do}} - \mathrm{T_{bfo}}}{\nu\alpha_m}$$

Where, *K* is the permeability

$\mathrm{Ra}_{\mathrm{r_i}}$	Rayleigh number [unitless]	ν	Air kinematic viscosity [m^2/s]
g	Acceleration caused by gravity [m/s^2]	α_m	Air thermal diffusivity [m^2/s]
β	Volume of thermal expansion [1/K]	$\mathrm{T_{bfo}}$	Lower temperature at the backfill outer surface [K]
r_i	Backfill inner radius [m]	$\mathrm{T_{do}}$	Higher temperature at the backfill inner surface [K]

Permeability of Natural Backfill

- Permeability of a permeable medium consisting of an assembly of spheres with a distribution of sizes:

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

(Panda and Lake, 1994)

C_{D_p}	Coefficient of variation of the particle size distribution [unitless]
ϕ	Porosity (bulk property) [unitless]
$\overline{D}_p$	Mean particle diameter [m]
τ	Tortuosity of the medium (bulk property) [unitless]

Equivalent Thermal Conductivity

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

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

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

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

Nu	Nusselt Number [unitless]
k_{bf}	Equivalent thermal conductivity of the backfill [W/(m-K)]
k_m	Stagnant thermal conductivity of the backfill [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 backfill [m]
q', q_c	Heat flux with and without convection [W]

Drift Scale Model

- Estimate drift wall temperature using the mountain-scale model
- Compute waste package temperature from the drift wall temperature (quasi-steady state assumption)
- Represent in-drift heat transfer using a thermal network model that incorporates the details of the drift (drip shield, invert, air gaps, and potential backfill)
- Include heat transfer modes of conduction, convection, and radiation

$$T_{\mathrm{wp}} - T_{\mathrm{rw}} = \frac{q(t)}{2\pi L_{\mathrm{wp}}} \left[\frac{ln\left(\frac{r_{\mathrm{rw}}}{r_{\mathrm{bfo}}}\right)}{k_{cv2}+k_{\mathrm{r}2}} + \frac{ln\left(\frac{r_{\mathrm{bfo}}}{r_{\mathrm{dso}}}\right)}{k_{\mathrm{bf}}} + \frac{ln\left(\frac{r_{\mathrm{dso}}}{r_{\mathrm{dsi}}}\right)}{k_{\mathrm{ds}}} + \frac{Inn\left(\frac{r_{\mathrm{dsi}}}{r_{\mathrm{wp}}}\right)}{k_{cv1}+k_{\mathrm{r}1}} \right]$$

Assumptions

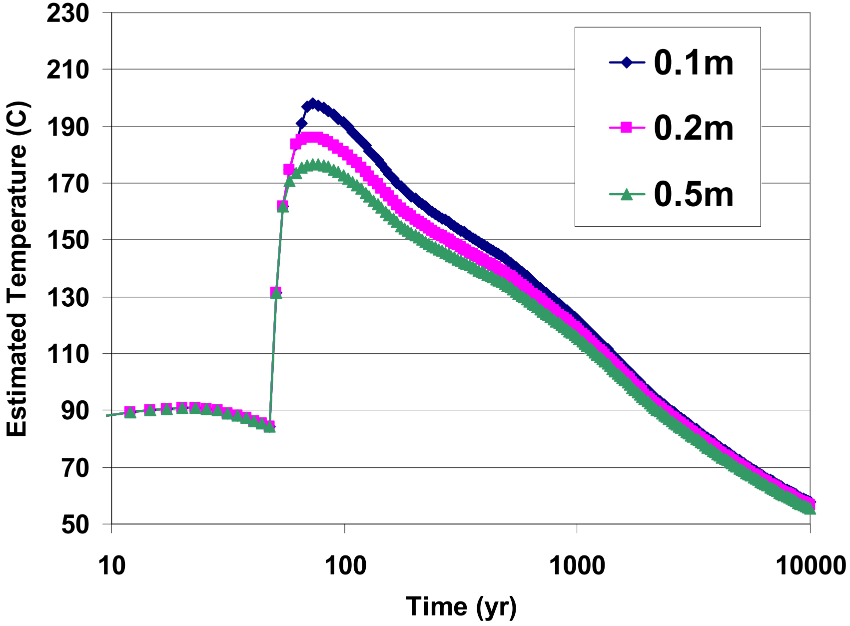
- The waste package is coaxial with the drift, the invert is a wedge occupying 25 percent of the drift volume, and the drip shield is circular and coaxial with the drift
- The natural backfill material is a concentric annular region coaxial with the waste package and drip shield
- The natural backfill material remains unconsolidated during the entire simulation period
- Particles are spherical, and particles with a range of diameters are present in the system

Parameters for Determining Drift-Scale Heat Transfer

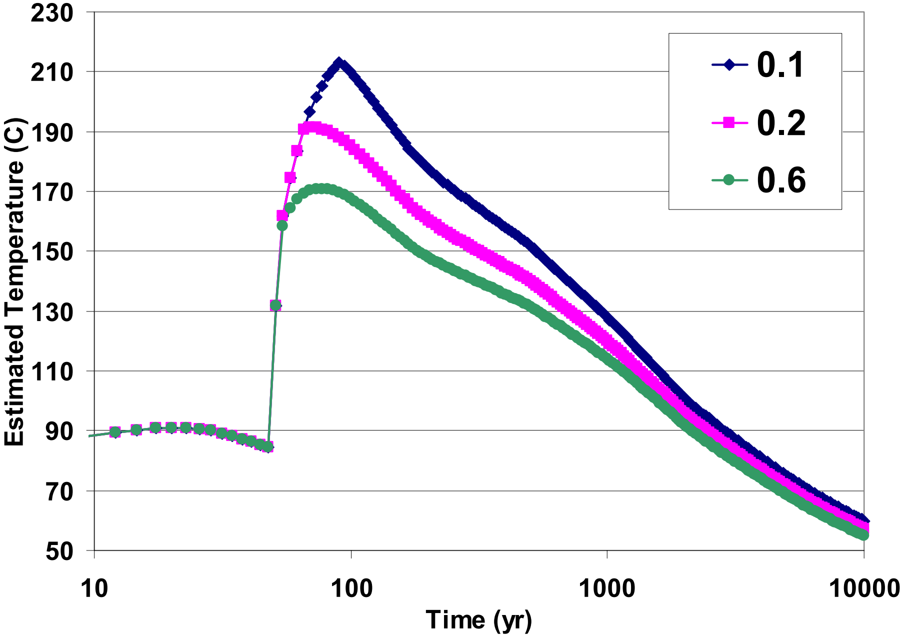
Parameter	Value
Emissivity of backfill, drift wall, drip shield, and WP	0.8, 0.8, 0.63, 0.87
Kinematic viscosity [m^2/s]	32.39×10^{-6}
Mean diameter of backfill particle [m]	0.1 – 0.5
Porosity	0.1 – 0.6
Skewness of particle size distribution	0 – 1.5
Thermal conductivity of air, backfill [W/(m-K)]	0.0373, 0.27
Thermal diffusivity [m^2/s]	3.417×10^{-4}
Time of repository closure	50 yr
Tortuosity of the medium	1.25 – 3.0
Volume of thermal expansion[1/K]	0.00285

Example Results

Effect of mean particle diameter and porosity on waste package temperature (deterministic cases)



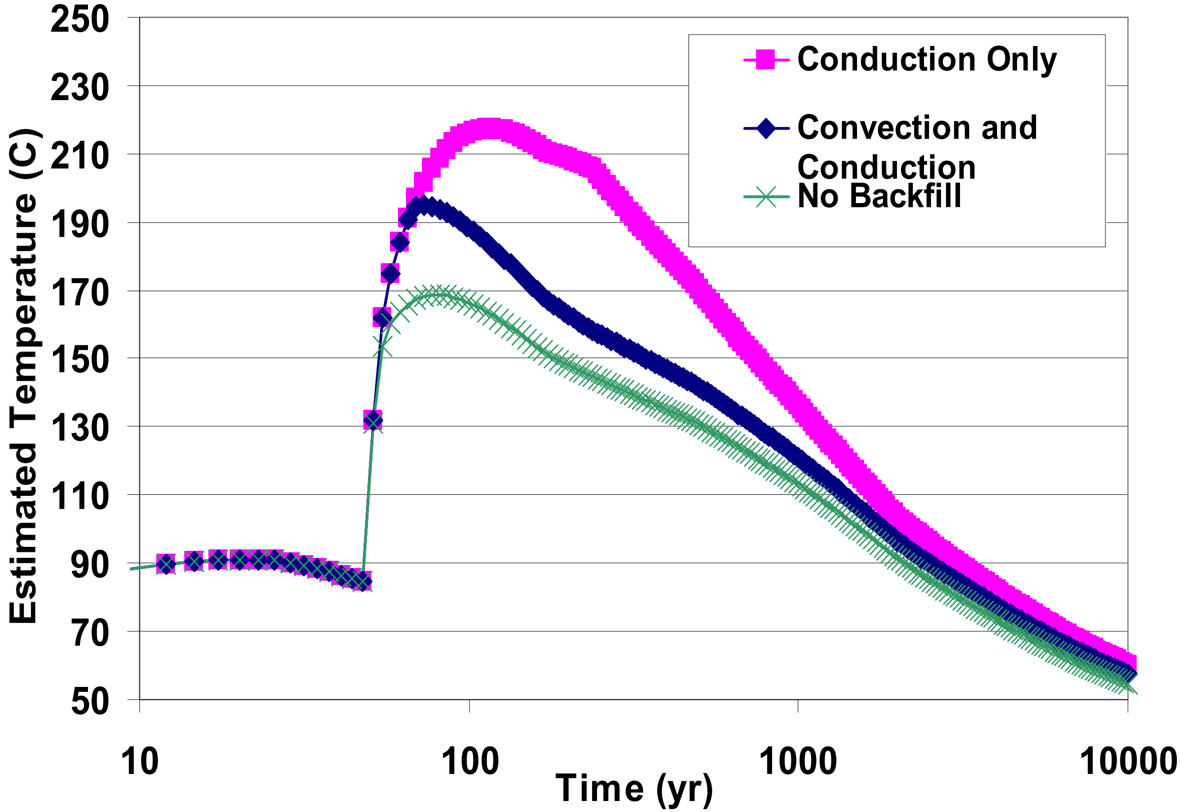
Mean Particle Diameter



Porosity

Example Results (continued)

Waste package average surface temperature with and without convection in natural backfill (stochastic cases: 450 Monte Carlo realizations)



Conclusions

- A natural convection-based model has been developed to estimate more realistic heat transfer through the drift degradation rubble material accumulated in the drift

- Estimates indicate drift degradation rubble may increase the peak waste package temperature up to 50 °C compared to the no-degradation case depending upon rubble size and the amount of convective cooling

- Uncertainties in the rubble size distribution may result in heat transfer ranging from pure conduction to convection-dominated heat transfer

- Estimates indicate convection through the natural backfill results in lower waste package temperatures than if conduction alone is considered

Acknowledgments

- This presentation was prepared based on work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the U.S. Nuclear Regulatory Commission (NRC) under Contract No. NRC-02-02-012. The activities reported here were performed on behalf of the NRC Office of Nuclear Material Safety and Safeguards, Division of Waste Management.