Modeling Convective Heat Transfer around a Waste Cask stored in the Yucca Mountain Repository

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Overview

It's well-known that the Yucca Mountain, Nye County, Nevada, located 100 miles north of Las Vegas has been determined by the US department of energy as a suitable place for building America's first geologic repository for storing nuclear wastes from commercial power plants and defense programs.

The view of Yucca Mountain and its location with respect to Las Vegas

Advantages of Yucca Mountain over other places

Yucca Mountain has certain advantages over other places:

1. its remote location and long distance from a large population center-100 miles from Las Vegas, Nevada;

2. its very dry climate--less than 6 inches of rainfall a year;

3. its extremely deep water table--800 to 1,000 feet below the level of the potential repository.

Potential dangers of the project

- *How dangerous is the project?*
- *1. At least 100,000 shipments of high-level nuclear waste will be transported by truck and by rail through 43 states for 30 years*
- *2. This high level waste will remain hazardous for 100,000 years*
- *3. A fuel pellet of this waste (about the size of a pencil eraser) could kill an unprotected person in less than 5 minutes*

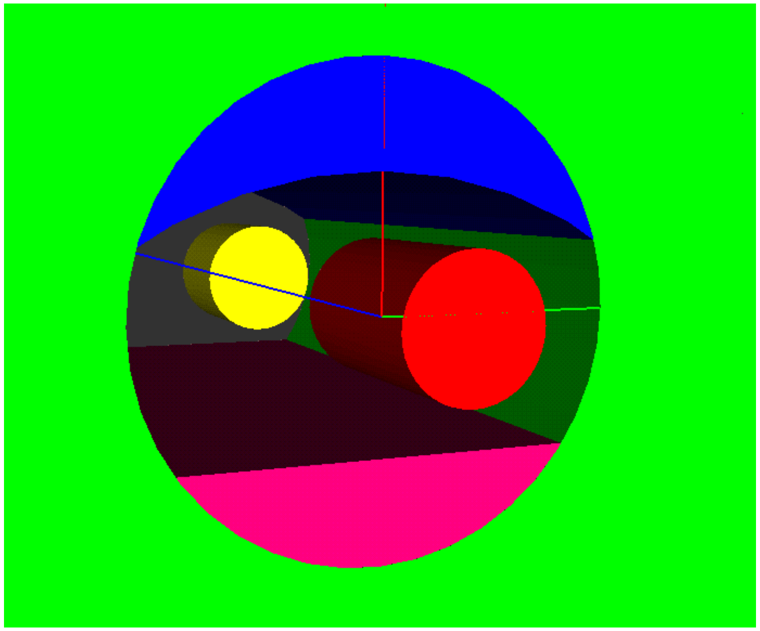
Literature review - 1

Yucca Mountain has been under intensive investigation by biologists, geologists, physicists, engineers, etc. for the last ten years. UNLV has been one of the major contributors to YMP. Among others, Dr. Moujaes and his research group has been studying this problem and they published a few papers about their efforts on YMP simulations. One of the papers is **"Moujaes, S. and Bhargava, A., "Simulation of Heat Transfer around a Canister Placed Horizontally in a Drift," Proc. Intl. Conf. High Level Radioactive Waste Management, Las Vegas, Nevada, May 22-26, 1994, pp.801-808."**. In the paper, the authors used the FIDAP software package for both the calculation of the repository drift and the calculation of the surrounding mountain rock. Ventilation inside the drift was ignored. The rock calculations were carried out for 1,000 years. The heat flux on the canister was considered decaying with time. The calculation of the rock was the first step of their coupling, using temperature values on the drift wall as boundary conditions for the drift calculations. They also found that without ventilation, radiation was a major mode of heat transfer between the canister and the drift.

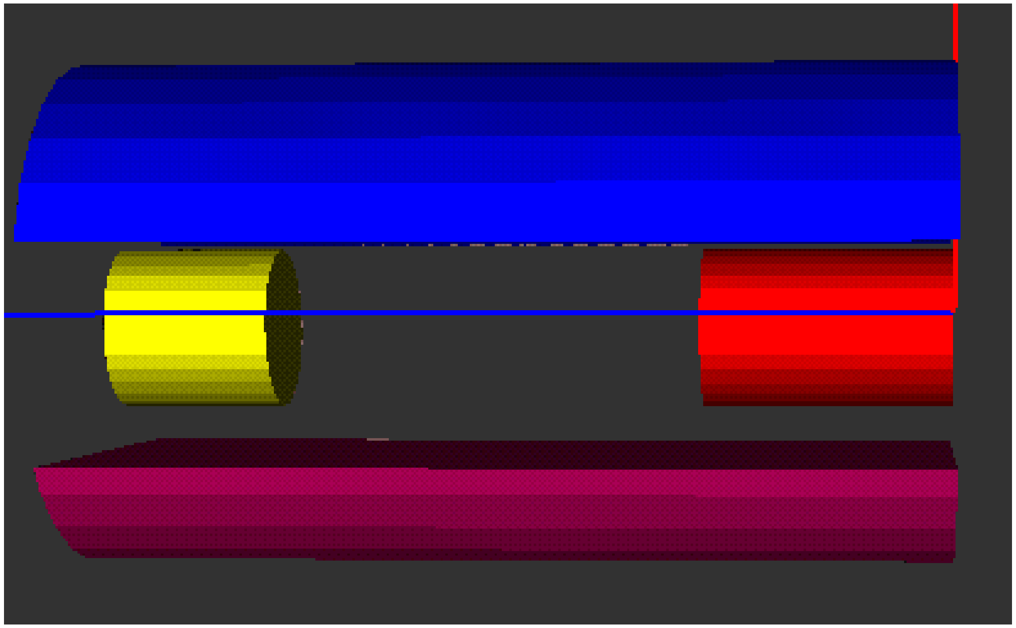
Literature review - 2

Danko et al, in the paper **"Danko, G., Buscheck, T.A., Nitao, J.J. and Saterlie, S., "Analysis of Near-Field and Psychometric Waste Package Environment Using Ventilation," Proc. Intl. Conf. High Level Radioactive Waste Management, Las Vegas, Nevada, April 30–May 5, 1995, pp.323-330."** coupled the temperature and humidity calculations in the rock using the VTOUGH (Vectorized Transport Of Unsaturated Groundwater and Heat) software package along with their own boundary element code. The drift temperature was calculated first with the temperature values on the drift wall serving as boundary conditions for the rock calculations in VTOUGH. Eight different cases with differing numbers of canisters and spacing between them, as well as different numbers of the emplacement drifts, were studied. The authors assumed that radiation was a major component of heat transfer between the canister and the drift, neglecting natural and forced convection (taking the air flow equal to zero). The authors found a case whereby 1,000 years after emplacement, the drift wall temperature would not exceed 100^{o}C - and therefore ventilation was not required. For all other seven cases considered ventilation was required to decrease the drift wall temperature.

Views of the repository



General View



Side View

Modes of Heat Transfer in the drift

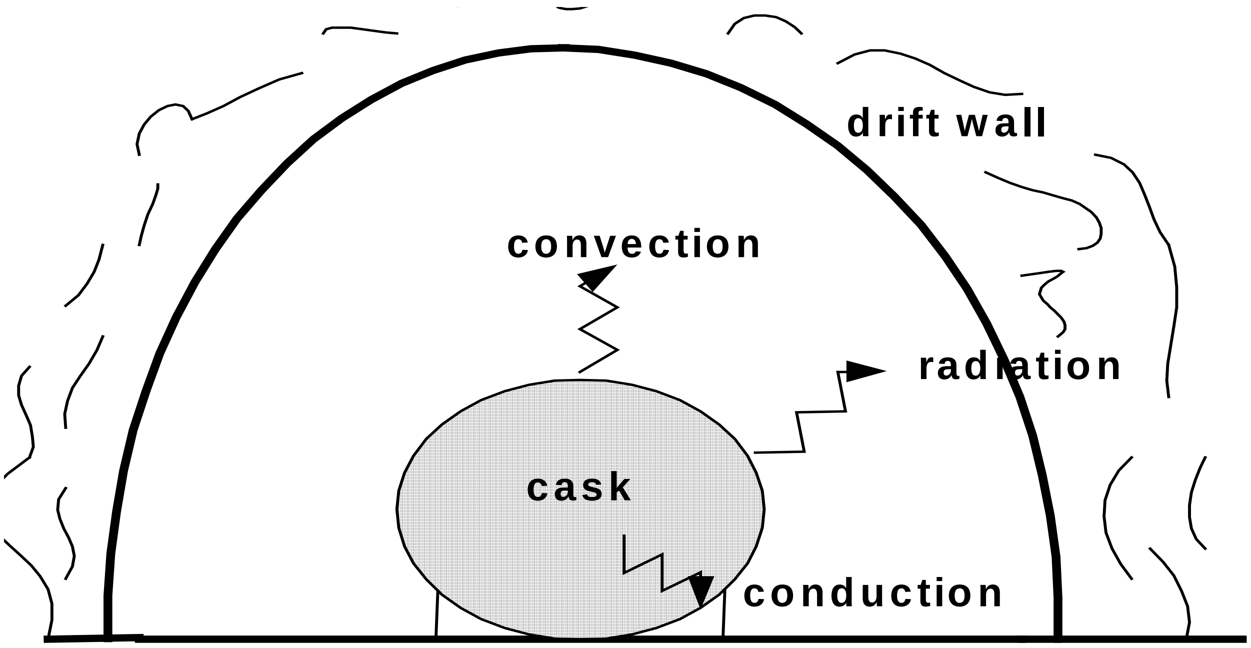


Figure 1. Modes of heat transfer associated with the cask and drift interior.

Waste Packages in the Drift

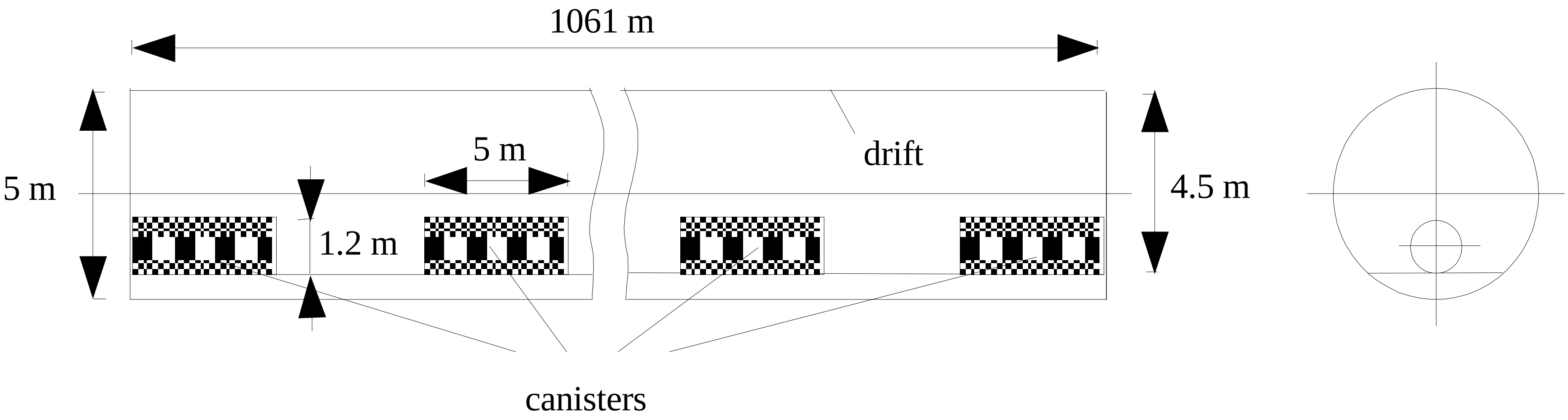


Figure 2. Waste packages in the drift.

Research Project Objectives

- *Research Project Objectives*
  - Develop a thermal model for heat transfer in the potential repository at Yucca Mountain, Nevada, USA,
  - Analyze influence of various parameters such as the number of canisters in the repository, thermal loading of each canister, velocity of the ventilating air and radiation on the temperature on the upper wall of the repository,
  - On the base of the calculations, determine the importance of the drift ventilation and radiation for the drift wall temperature

Assumptions and approximations - 1

- The 3-d problem was reduced to a 2-d problem and heat transfer from canisters to the drift walls was studied in a longitudinal section of the drift;
- The speed of the ventilating air was considered big enough to carry away the heat from the canisters’ surfaces, so that the upper wall and a part of the lower wall, located in between canisters, was considered adiabatic, which allowed to separate the drift from the surrounding rock;
- The media in the drift was considered optically thick enough, so that the Rosseland radiation model was valid;

Assumptions and approximations - 2

- The heat flux on the canister was set to a constant, corresponding to the worst scenario where the heat, generated by the canisters, would remain constant throughout the life of the waste storage;
- Since the walls are considered adiabatic and the heat, generated by the canisters, does not decay with time, the process of fluid flow and heat transfer is considered steady;
- A uniform velocity profile is assumed taking place at the inlet;

Mathematical Model – Continuity and Momentum

Continuity equation

$$\frac{\partial}{\partial x_i}\left(\rho u_i\right)=0$$

Momentum equation

$$\frac{\partial}{\partial t}\left(\rho u_i\right)+\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right)=$$

$$\frac{\partial}{\partial x_j}\left(\mu\left[\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right]-\frac{2}{3}\left(\mu\frac{\partial u_l}{\partial x_l}\right)\right)$$

$$-\frac{\partial p}{\partial x_i}+\rho g_i+F_i+\frac{\partial}{\partial x_j}\left(\rho\overline{u'_i u'_j}\right)$$

Mathematical Model - Energy

Energy equation

$$\frac{\partial}{\partial t}(\rho h)+\frac{\partial}{\partial x_i}(\rho u_i h)=\frac{\partial}{\partial x_i}(\kappa+\kappa_T)\frac{\partial T}{\partial x_i}$$

$$-\frac{\partial}{\partial x_i}\sum_{j'} h_{j'} J_{j'}+\frac{Dp}{Dt}\tau_{ik}\frac{\partial u_i}{\partial x_k}+S_h$$

Mathematical Model – Terms in the above equations

where F*i* represents body forces;

g – gravitational forces;

kT – the turbulent conductivity due to turbulent transport;

J *j* – the diffusion flux of species *j*;

S*h* - source term that includes chemical reaction, any interphase exchange of heat, or any other volumetric heat sources;

D/Dt is a substantial derivative;

h – is enthalpy defined as h=C*p**T;

C*p* – specific heat at constant pressure.

Mathematical Model – Reynolds Stresses

Reynolds stresses

$$\frac{\partial}{\partial x_j}\left(\rho\overline{u'_i\, u'_j}\right)=\rho\frac{2}{3}k\delta_{ij}-\mu_T\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)$$

$$+\frac{2}{3}\mu_T\,\frac{\partial u_i}{\partial x_i}\delta_{ij}$$

Mathematical Model – k and epsilon

k and epsilon equations

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho u_i k)=\frac{\partial}{\partial x_i}\frac{\mu_T}{\sigma_\varepsilon}\frac{\partial k}{\partial x_i}+G_k-\rho\varepsilon$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho u_i\varepsilon)=\frac{\partial}{\partial x_i}\frac{\mu_T}{\sigma_\varepsilon}\frac{\partial\varepsilon}{\partial x_i}+C_{1\varepsilon}\frac{\varepsilon}{k}G_k$$

$$-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}$$

Mathematical Model – G*k* and turbulent viscosity

Production of turbulence

$$G_k = \mu_T \left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) \frac{\partial u_j}{\partial x_i}$$

Turbulent viscosity

$$\mu_T = \rho C_\mu \frac{k^2}{\varepsilon}$$

Boundary conditions

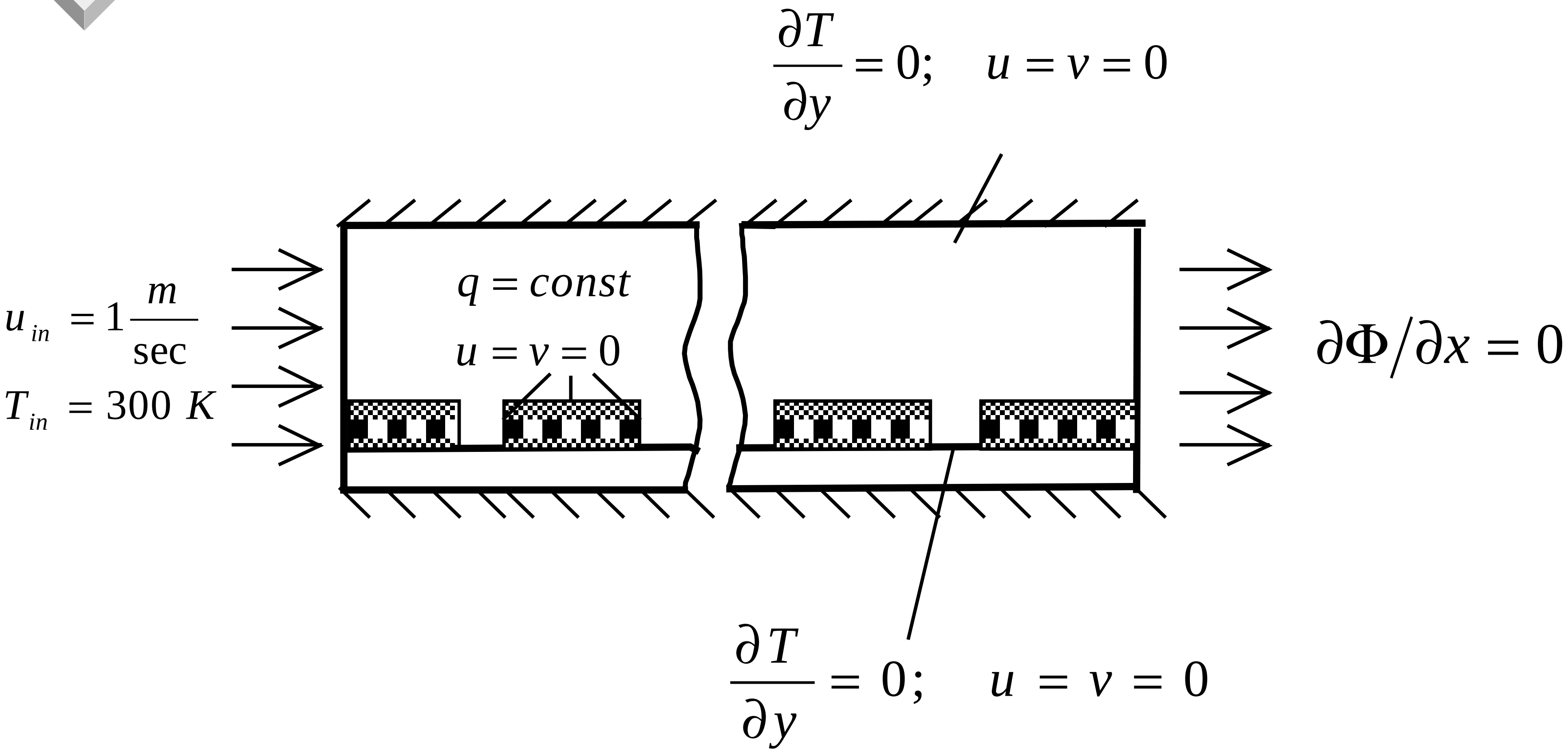


Figure 3. Computational domain with boundary conditions.

Parameters of the air at the inlet

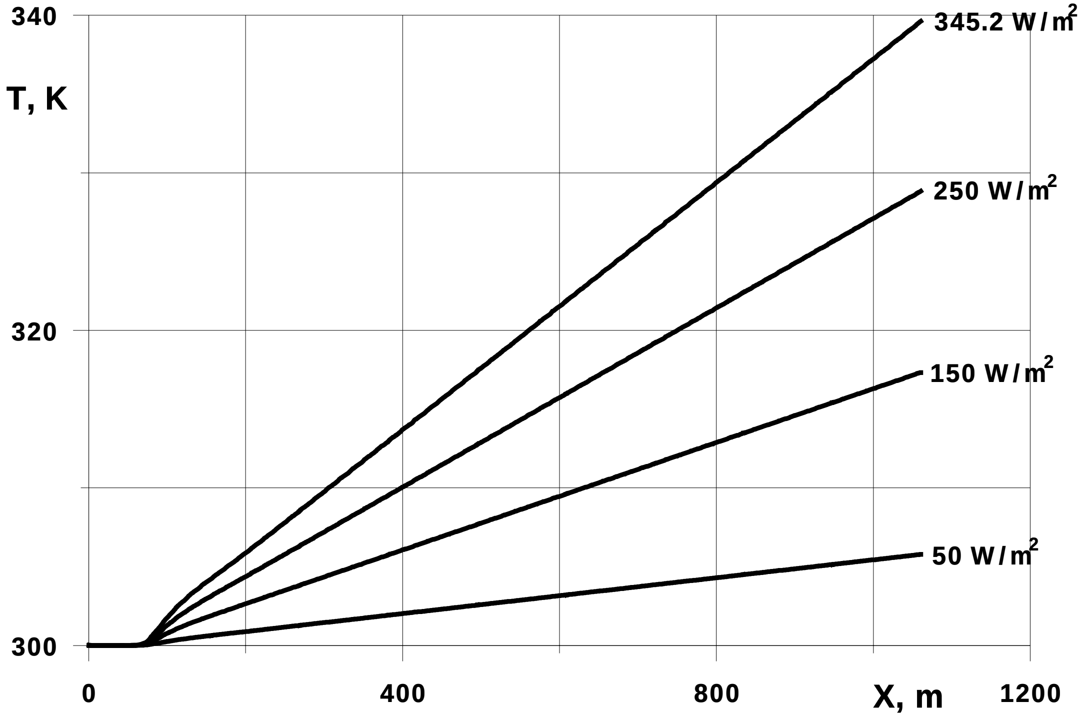
- $T = 300^{o}K$,
- $\rho = 1.225\ kg/m^3$,
- $Cp = 1006.43\ J/(kg*K)$,
- $\kappa = 0.0242\ W/(m*K)$;
- $\mu = 0.000017894\ kg/(m*s)$.
- $U = 1\ m/s$ (also $0.2\ m/s$ and $5\ m/s$)

Description of the numerical method and code (FLUENT)

FLUENT was used to calculate fluid flow and heat transfer phenomena in the Yucca Mountain repository. FLUENT is a finite volume code that solves equations in the conservative form. Computational nodes are located at the centroids of elements. The SIMPLE method by Patankar and Spalding is used for pressure-velocity coupling. The mesh generated by Gambit was uniform in both X and Y directions.

FLUENT is a well-known commercial software package which has a wide range of mathematical models for heat transfer phenomena and the ability to model complex geometries including turbulence modeling and radiation.

Results – influence of thermal loadings of canisters on the drift wall temperature distribution

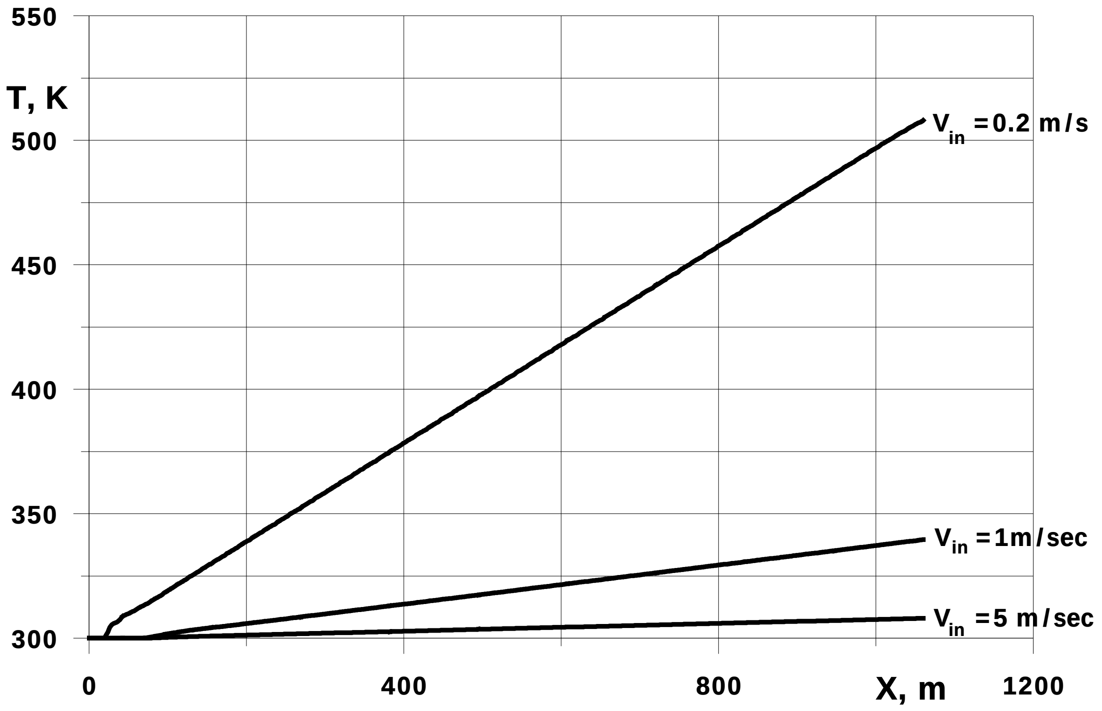


ΔT_{max}=40°K - 345 W/m^2

ΔT_{min} =6°K - 50 W/m^2

Figure 4. The drift wall temperature distribution along the drift for several thermal loadings (the number of canisters is 67, the velocity of the air at the inlet is 1 m/sec)

Influence of the velocity of the ventilating air on the drift wall temperature distribution

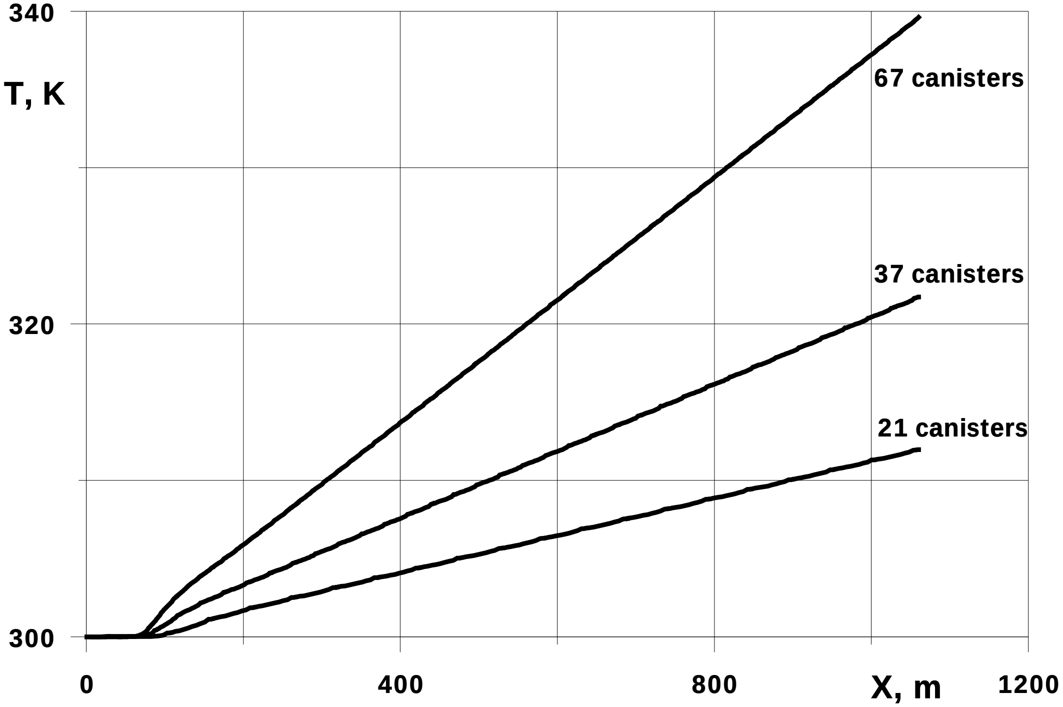


ΔT_{max}=208°K - 0.2 m/sec

ΔT_{min} = 8°K - 5 m/sec

Figure 5. The drift wall temperature distribution along the drift for several values of the velocity of the air at the inlet (the number of canisters is 67, the thermal loading is 345.2 W/m^2)

Influence of the number of canisters on the drift wall temperature distribution



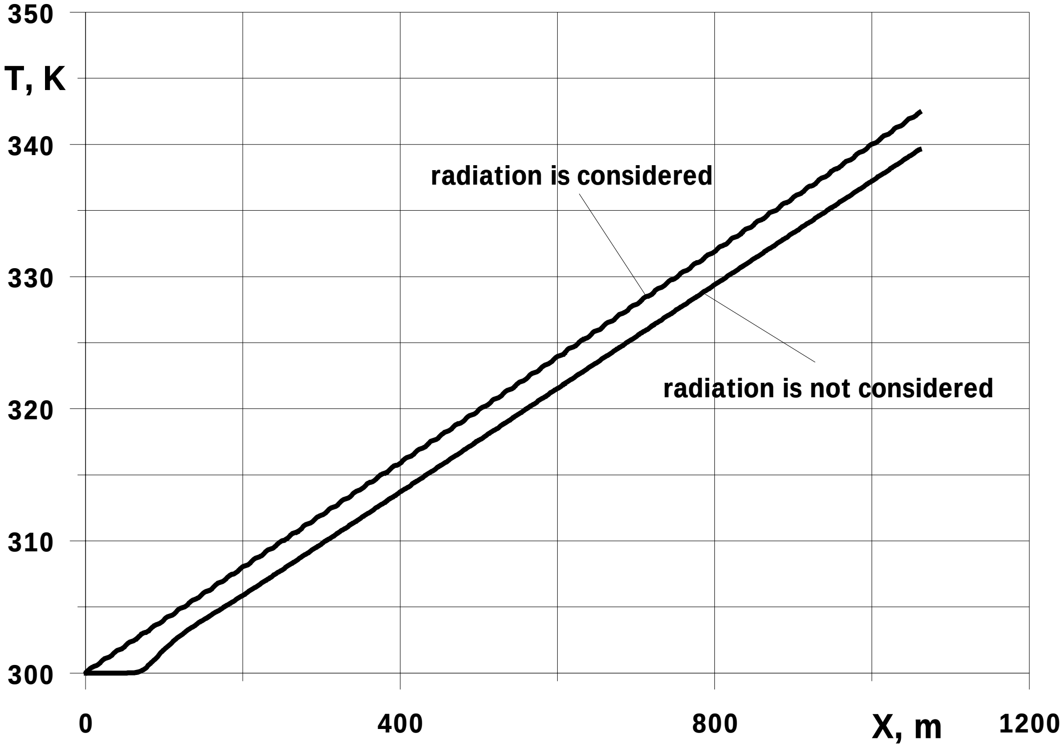
ΔT=40°K - 67 canisters

ΔT=22°K - 37 canisters

ΔT=12°K - 21 canisters

Figure 6. The drift wall temperature distribution along the drift for several numbers of canisters (the thermal loading is 345.2 W/m^2, the velocity of the air at the inlet is 1 m/sec)

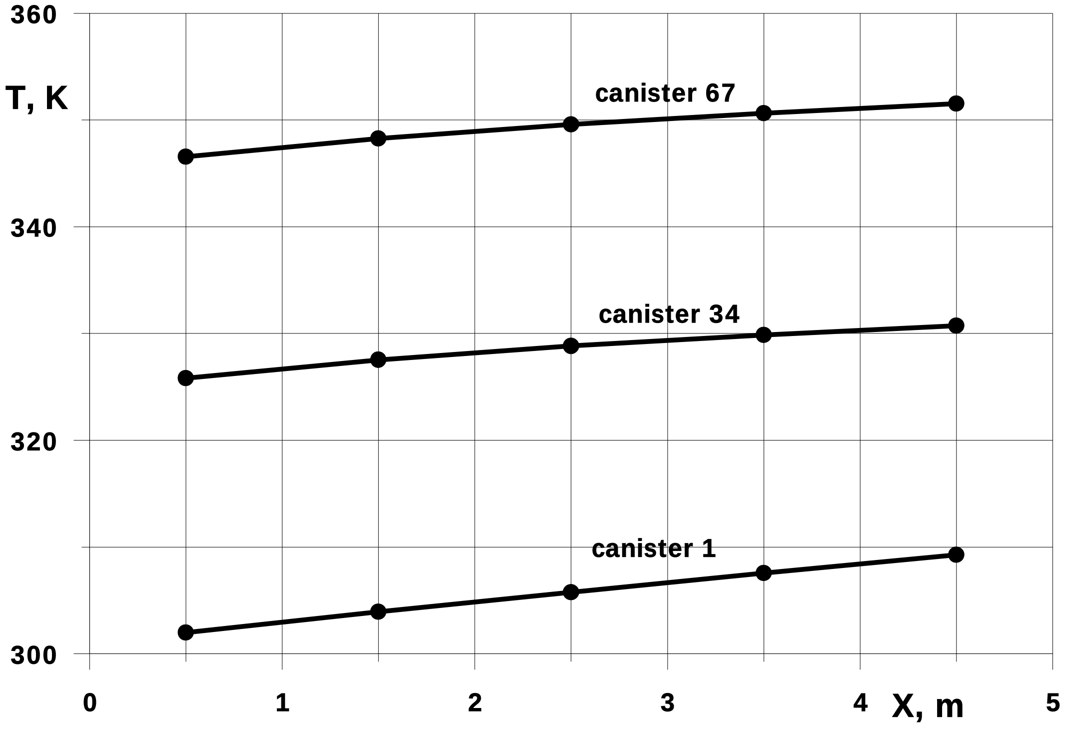
The drift wall temperature distribution with radiation and without radiation



difference is 3°K

Figure 7. The drift wall temperature distribution along the drift when the radiation heat transfer is considered and not considered (the number of canisters is 67, the thermal loading is 345.2 W/m^2, the velocity of the air at the inlet is 1 m/sec)

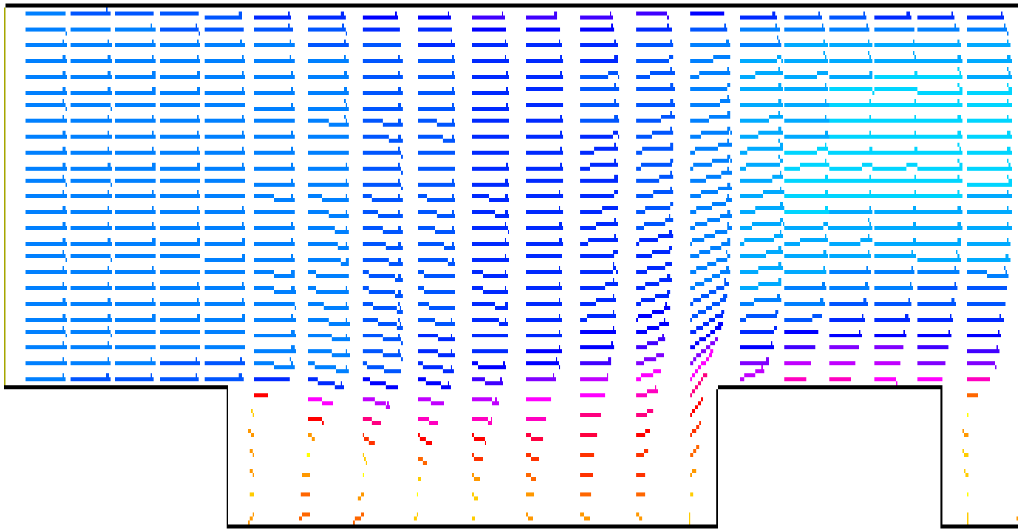
Distribution of the temperature on the surfaces of canisters 1, 34, 67



T_{max}=352°K on the surface of canister 67

Figure 8. Distribution of the temperature on the surfaces of canisters 1, 34, 67 along the canister's relative length (the number of canisters is 67, the thermal loading is 345.2 W/m^2, the velocity of the air at the inlet is 1 m/sec)

Velocity vectors at the beginning of the drift



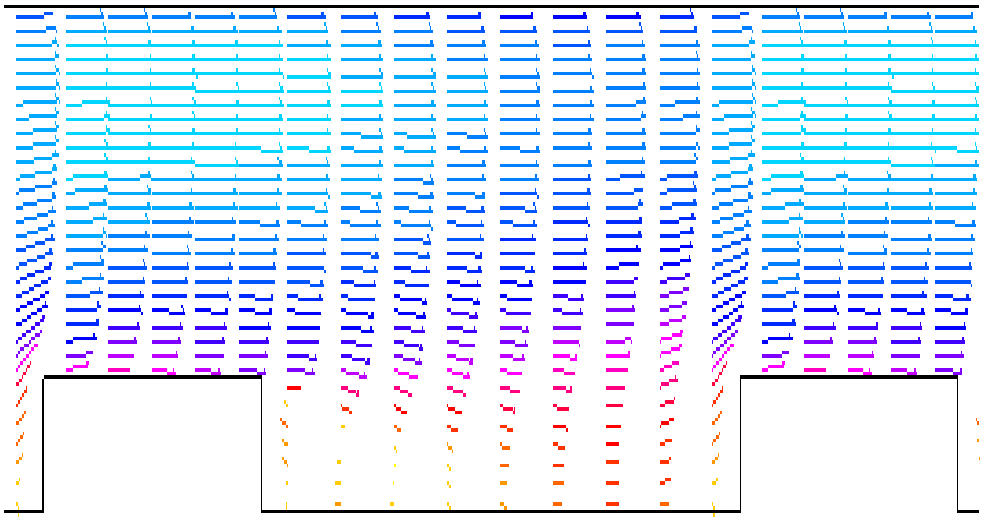
Colors were inverted:

blue - high values;

red - low values;

Figure 9. Velocity vectors at the beginning of the drift (the number of canisters is 67, the thermal loading is 345.2 W/m^2, the velocity of the air at the inlet is 1 m/sec)

Velocity vectors in the middle of the drift



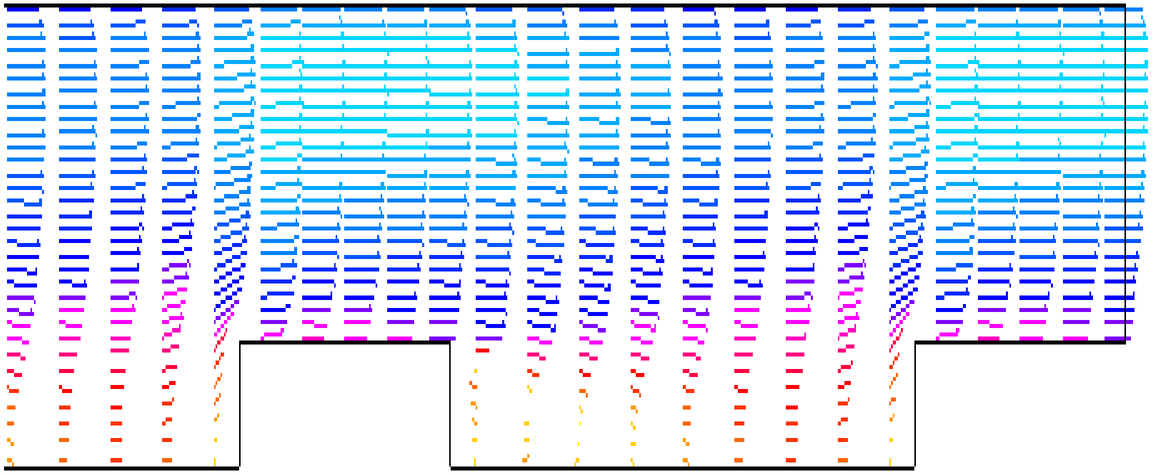
Colors were inverted:

blue - high values;

red - low values;

Figure 10. Velocity vectors in the middle of the drift (the number of canisters is 67, the thermal loading is 345.2 W/m^2, the velocity of the air at the inlet is 1 m/sec)

Velocity vectors at the end of the drift



Colors were inverted:

blue - high values;

red - low values;

Figure 11. Velocity vectors at the end of the drift (the number of canisters is 67, the thermal loading is 345.2 W/m^2, the velocity of the air at the inlet is 1 m/sec)

Conclusions

A 2-D thermal-fluid model for convective heat transfer around a nuclear waste cask located within a drift (tunnel) at Yucca Mountain has been developed. The model separates the rock surfaces of the drift wall from the air surrounding the waste cask. Ventilation in the drift is a critical component of the model. FLUENT, a well-known commercial finite-volume code, was used to solve the turbulent flow and energy equations. Several factors, that include thermal loading of canisters, the number of canisters, the speed of ventilating air and radiation, were examined that influence the temperature distribution surrounding the canister. Radiation heat transfer from the canister to the drift wall was found to be an insignificant factor in the overall simulation.

Acknowledgements

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