Convective Effects in a Regulatory and Proposed Fire Model*

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INTRODUCTION

Radiation is the dominant mode of heat transfer in large fires. However, convection can be as much as 10 to 20 percent of the total heat transfer to an object in a large fire. The current radioactive material transportation packaging regulations include convection as a mode of heat transfer in the accident condition scenario. The current International Atomic Energy Agency (IAEA) Safety Series 6 packaging regulation states, "the convection coefficient shall be that value which the designer can justify if the package were exposed to the specified fire." The current Title 10, Code of Federal Regulations, Part 71 (10 CFR 71) packaging regulation states "when significant, convection heat input must be included on the basis of still, ambient air at 800°C (1475°F)." Two questions that can arise in an analyst's mind from an examination of the packaging regulations are whether convection is significant and whether convection should be included in the design analysis of a radioactive materials transportation container. The objective of this study is to examine the convective effects on an actual radioactive materials transportation package using a regulatory and a proposed thermal boundary condition.

A single thermal model with six thermal boundary conditions was used in this analysis. The thermal boundary conditions were the regulatory thermal environment with and without convective effects, and a proposed thermal environment with and without convection. The proposed thermal environment is from a paper presented at PATRAM'92 by Chris Fry (1992).

The proposed thermal environment was designed for modeling two types of transportation casks. The first type contains low activity material which generates negligible heat and thermal protection provided by an insulating layer on the container exterior. The second type contains highly active materials and thermal protection is based on high thermal capacitance of the transportation cask.

The thermal model developed for this study is based on the Beneficial Uses Shipping System (BUSS) cask. The BUSS cask is a Type B shipping container used for non fissile

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radioactive materials shipment. The dimensions of the BUSS cask body are 1.24 m long by an outer diameter of 1.38 m. The BUSS cask body weight is 9,300 kg.

THERMAL MODEL DESCRIPTION

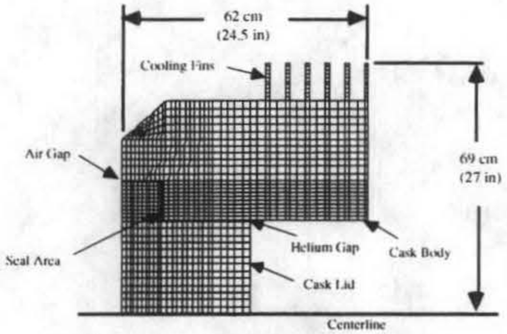

Figure 1. Thermal Model

The thermal model is a two-dimensional axisymetric representation of the cask. Another simplifying assumption is that half the length of the cask was modeled. The model consists of 1,457 nodes and 1,319 elements. PATRAN was used for pre- and postprocessing of the analysis, while P/THERMAL was used as the thermal solver. Temperature-dependent material properties were used in the analysis. Figure 1 presents the thermal model.

The materials in the cask, and simulated in the thermal model, were stainless steel, air, helium, and silicone rubber. The cask lid and body material were stainless steel. The gap between the cask lid and body was filled with air on the outside of the seal and helium on the inside of the seal. The seal material was silicone. Temperature-dependent thermal conductivity was used for the stainless steel, air, and helium, while the silicone thermal conductivity was constant. Table 1 presents the material thermal transport properties used in the model. All material properties presented in Table 1 are at 25°C.

Material	Thermal Conductivity (W/m-K)	Density (kg/m^3)	Specific Heat (J/kg-K)
Stainless Steel	13.4	7920	502
Air	0.0242	0.177	5191
Helium	0.141	1.29	992
Silicone	0.138	1300	1256

Table 1. Material Properties used in the Thermal Model

THERMAL BOUNDARY CONDITIONS

Six different thermal boundary conditions were applied to the cask thermal model. The first set of three thermal boundary conditions was based on the IAEA Safety Series No. 6 regulations. The second set of three thermal boundary conditions was based on the proposed thermal environment.

The IAEA Safety Series No. 6 boundary conditions consist of an 800°C environment temperature with an emissivity of 0.9, and a package surface emissivity of 0.8 for 30 minutes. After 30 minutes, the ambient temperature drops to 38° C for the subsequent cool down period. Convection was included in two of the thermal boundary conditions, and the convection coefficients used were 5 and 10 W/m^2. These convective coefficient values are typical for natural convection.

The proposed thermal environment is a modification of the IAEA Safety Series 6 regulatory thermal environment. The modifications are raising the environmental temperature to 1100°C and including a reduction factor of 0.3. The reduction factor is equivalent to a flame emissivity but physically represents a reduced effective flame temperature adjacent to the container surface and ensures the heat flux specified in the IAEA regulations is met. The thermal environment is modeled with the following equation.

$$Q = 0.3\varepsilon\sigma\left[(1100+273)^4 - (T_s+273)^4\right] + h(1100 - T_s)$$

where,

ε is the emissivity of the container surface,
σ is the Stefan-Bolzman constant,
T_S is container surface temperature (°C), and,
h is the convection coefficient.

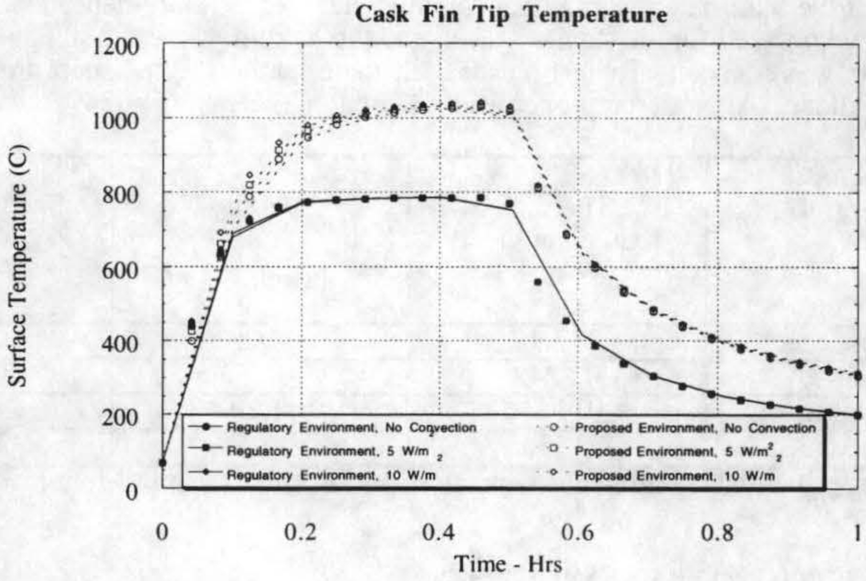

Figure 2. Cask Fin Temperature

The package surface emissivity was not specified in the proposed thermal boundary conditions, so the IAEA regulation package surface emissivity of 0.8 was used. The duration of the proposed thermal environment is 30 minutes, after which the environmental temperature drops to 38°C for the subsequent cool down period. Convection was included in two of the thermal boundary conditions and the convection coefficents used were 5 and 10 W/m^2.

RESULTS

Figures 2 and 3 present time-temperature plots of the cask fin tip temperature and the cask seal area temperature, respectively. The cask fin tip is where the highest temperature on the cask occurred. The cask fin tip temperature difference due to convection for the regulatory environment is small when compared to the proposed environment. The larger cask fin tip temperature difference in the proposed environment is due to the greater sensitivity to convection.

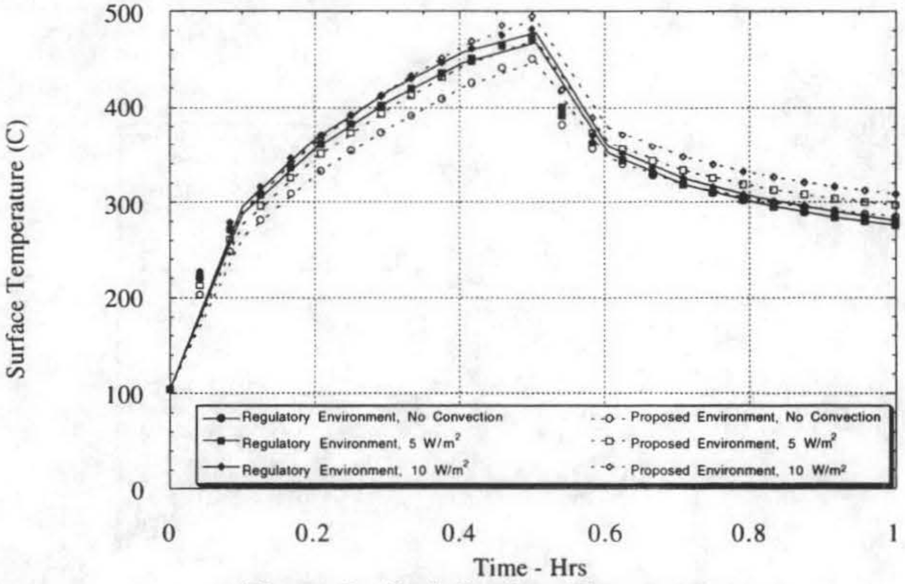

Figure 3 . Cask Surface Temperature

Figure 3 shows that adding convection does not dramatically increase the seal temperature for this model. For the regulatory environment, the increase in seal area temperature due to convection is between 5 and 10 °C. For the proposed environment, the increase in seal area temperature is between 10 and 20° C. Again these results point to the greater sensitivity to convection for the proposed environment.

Figure 4 presents the total calculated surface heat flux for all thermal boundary conditions. The total surface heat flux was calculated using two methods. The first method was for the regulatory environment and used the following equation.

$$Q = \varepsilon_s \sigma \left[\varepsilon_f (800 + 273)^4 - (T_s + 273)^4 \right] + h(800 - T_s)$$

where,

ε_s is the emissivity of the container surface, and,

ε_f is the emissivity of the flame.

The second method was for the proposed environment and used the equation that defined the proposed environment. Since the cask surface temperature was known from the calculations, the total heat surface heat flux for both environments was calculated.

The maximum surface heat fluxes for the regulatory environment were 51.3 W/m^2, 53.9 W/m^2, and 56.4 W/m^2 for no convection and convection coefficients of 5 W/m^2 and 10 W/m^2, respectively.

The maximum surface heat fluxes for the proposed environment were 47.6 W/m^2, 51.8 W/m^2, and 56.0 W/m^2 for no convection and convection coefficients of 5 W/m^2 and 10 W/m^2, respectively.

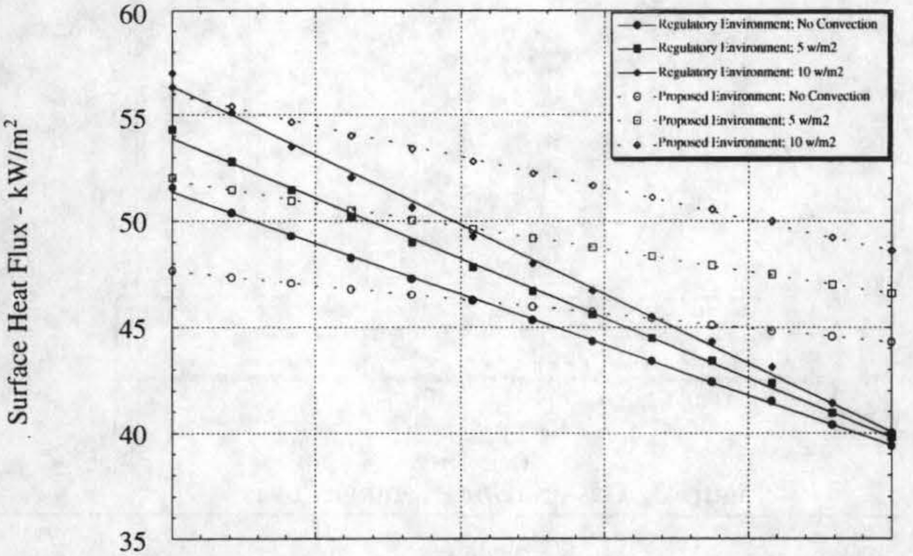

Figure 4 . Total Surface Heat Flux

Figure 5 presents the percentage amount of convective heat transfer for both thermal environments. The percentage of convective heat transfer, when compared to the total heat transfer, for the regulatory environment was 5.1 for 5 W/m^2 and 9.6 for 10 W/m^2 .

For the proposed environment, the percentage of convective heat transfer was 9.3 for 5 W/m^2 and 15.2 for 10 W/m^2. Again Figure 5 shows the increased sensitivity to convective heat transfer for the proposed environment.

CONCLUSIONS

Convection contributes between 5 and 9 percent of the total heat flux for the regulatory fire, assuming a range of between 5 and 10 W/m^2 for the convective heat transfer coefficient. Again assuming a range of 5 to 10 W/m^2 for a convective heat transfer coefficient, the convective heat transfer loading is between 9 and 15 percent for the proposed thermal environment.

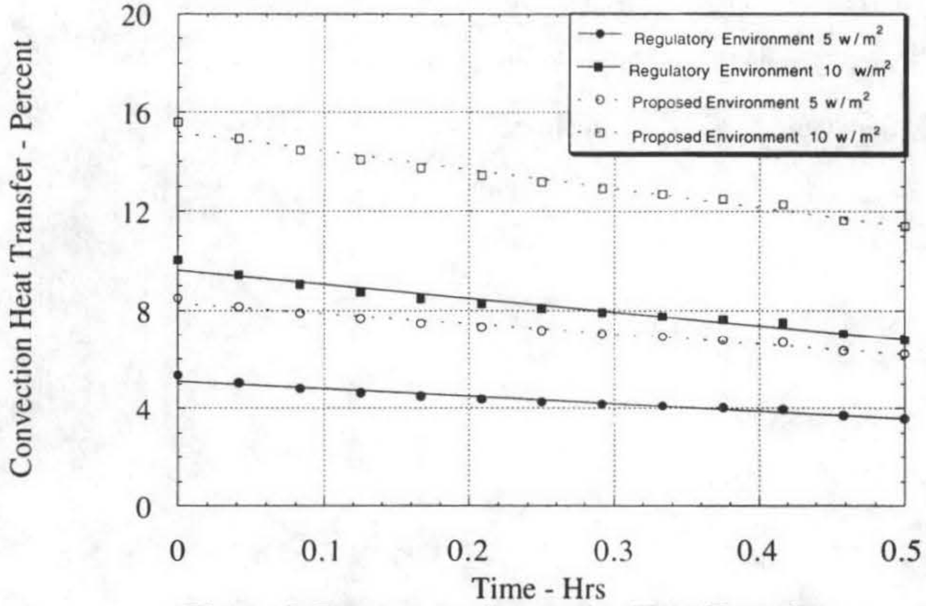

Figure 5. Percentage Convective Heat Transfer

An equivalent maximum heat flux between the regulatory and proposed thermal environment can occur by including convection as a heat transfer mechanism. To make the environments approximately equivalent for the maximum surface heat flux, a convection coefficient of 5 W/m^2 for the proposed environment and no convection for the regulatory environment can be used. Of course there exist an infinite number of combinations between the regulatory and proposed environments to make the maximum surface heat flux equivalent.

Experimental data indicate that convection contributes between 10 and 20 percent toward the total surface heat flux. Therefore, a minimum heat transfer coefficient of 10 W/m^2 is recommended.

Including convection doesn't greatly affect seal temperature in this case due to the massive size and amount of thermal capacitance. However, the convection component will affect thin, low-capacitance components, such as fins.

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