Modeling Analysis for Nuclear Material Transport Package

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INTRODUCTION

This paper describes the computational models for the thermal analyses for 9975 nuclear material package under the Normal Conditions of Transport (NCT) and the Hypothetical Accident Conditions (HAC). The package 9975 is a DOE certified package that has been used in the DOE complex for transportation and long term storage of radioactive material. The NCT and HAC thermal analyses for the 9975 package were performed here by taking a computational heat transfer method.

The HAC thermal models described here are identical to the models in the current DOE certified 9975 package[1]. Thermal models in this work are for an undamaged package to meet all the regulatory requirements during an HAC thermal event. The model was created using modified shielding where the lead was encapsulated in a 0.036 inches stainless steel casing. The impact of this casing was studied earlier when the modification was proposed and it was found to have minimal impact on the component temperatures. Therefore, the analyses in this paper are good for packages with or without the shielding modifications.

Analytical studies show that the realistic value for the solar absorptivity for the stainless steel surface fabricated from the rolling operation is about 0.5. [4,5] The NCT analyses documented in this report use an absorptivity value of 0.5 to get more realistic component temperature results. Sensitivity studies were also performed to assess the impact of variability in the solar absorptivity for drum surface in the previous work [2] for the NRC certification.

The analysis in this paper is based on PuO_2 in a food can as shown in Fig. 1. The food can is considered uncredited convenience containers inside the Primary Containment Vessel (PCV) of the 9975 package as shown in Fig. 2. PuO_2 has a density of 2 g/cc and a heat generation rate of 19 watts.

This calculation evaluates the thermal performance for 9975 package with food can configuration during NCT and HAC per NRC regulations in 10 CFR Part 71. The objective of the calculation is to demonstrate that the maximum component temperatures are below their design limits.

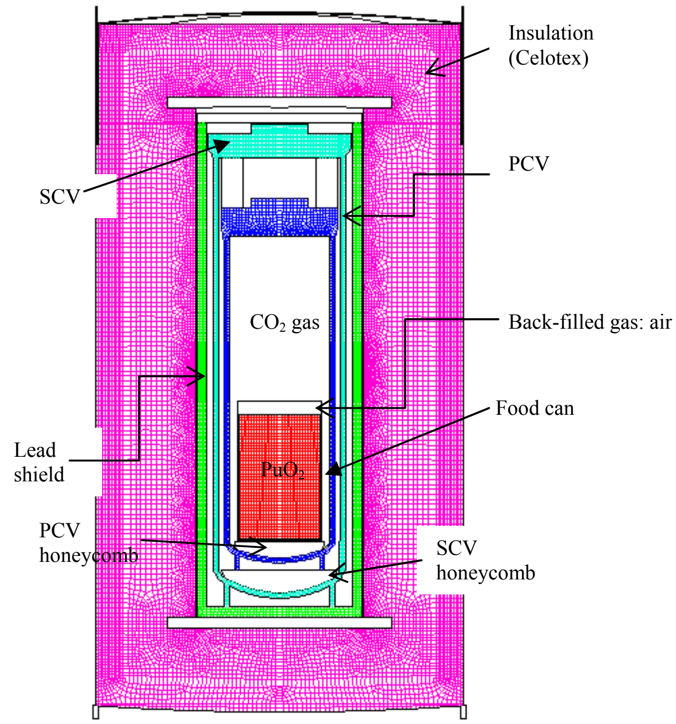

Figure 1. Material Representation of the 9975 Package containing PuO_2 material inside food can container.

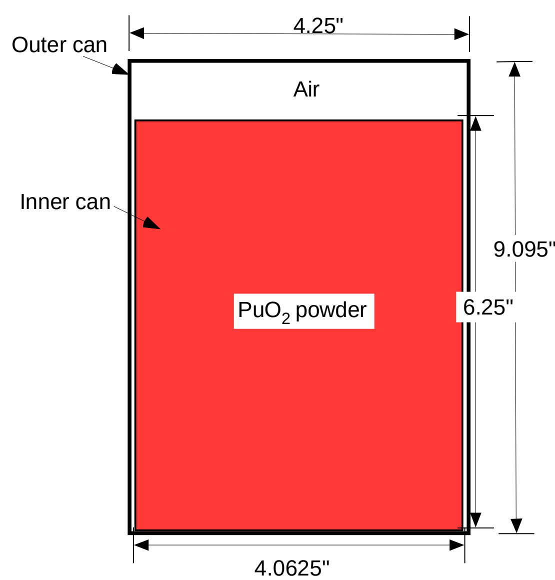

Figure 2. Food can configuration containing PuO_2)

DESCRIPTION OF THE ACTUAL WORK

The models for the Normal Conditions of Transport (NCT) were developed for the actual 9975 package geometry using a Computational Fluid Dynamics (CFD) code, FLUENT. The modeling calculations for the food can package configuration was performed by using axisymmetric modeling approach for computational efficiency. The calculations were based on conduction-radiation cooling mechanism without internal natural convection for conservative estimate. However, the wall boundary surface external to the package was cooled by conduction and convection coupled with thermal radiation. The convection correlations for the exterior wall surface of the package are:

For vertical plate with $Ra < 10^9$,

$$h=\left(\frac{k}{L}\right)\left(0.68+0.670\times Ra^{0.25}\left[1.0+\left(\frac{0.492}{\Pr}\right)^{9/16}\right]^{-4/9}\right) \quad (1)$$

For vertical plate with $Ra > 10^9$,

$$h=\left(\frac{k}{L}\right)\left(0.825+0.387\times Ra^{1/6}\left[1.0+\left(\frac{0.492}{\Pr}\right)^{9/16}\right]^{-8/27}\right)^2 \quad (2)$$

For horizontal plate with $Ra < 10^7$,

$$h=0.54\times Ra^{0.25}\left(\frac{k}{L}\right) \quad (3)$$

For horizontal plate with $Ra > 10^7$,

$$h=0.15\times Ra^{1/3}\left(\frac{k}{L}\right) \quad (4)$$

Where: Ra = Rayleigh number based on plate height.
h = Convection heat transfer coefficient.
k = Thermal conductivity of gas (air).
L = Characteristic length of plate.

The package contains PuO_2 powder contents distributed in food can geometry. In the thermal analysis, the limiting components are the containment vessels, their O-ring seals, shielding and the insulation. Temperature limits for these components for the NCT are tabulated along with predicted maximum temperatures for the individual model configurations. The 9975 model for all NCT analyses includes interior metal surfaces, namely the aluminum base plates, aluminum spacers, stainless steel and the cladding around the lead shielding. The drum surface absorptivity for the solar radiation is based on stainless steel surface with a medium finish. The absorptivity and emissivity values are obtained by integrating the solar intensity and thermal radiations over the applicable wavelength spectrum.[5] A total absorptivity value of 0.498 (≈ 0.50) and a total emissivity value of 0.21 are used in the NCT analysis. From 10 CFR 71.71, the corresponding time averaged heat fluxes are 245.77 Btu/ft^2-hr on the top of the package and 122.88 Btu/ft^2-hr on the side of the package. The applied solar fluxes using absorptivity of 0.50 are 122.88 Btu/ft^2-hr on the top of the package and 61.44 Btu/ft^2-hr on the side of the package.

All NCT calculations were performed under the following conditions:

- The drum is in an upright position.
- The bottom surface is adiabatic.
- There is radiative heat transfer from the sides and top of the drum to the ambient.
- There is natural convection heat transfer from the sides and top of the drum to the ambient. Natural convection correlations used in the model are shown in equations (1) to (4).
- The ambient temperature is 100^{o}F.
- The content contains heat source outputting a maximum of 19 watts uniformly distributed in the plutonium oxide.
- The NCT thermal model is analyzed as a steady-state conduction model coupled with radiation, neglecting a convective cooling mechanism for conservative estimate.

The HAC thermal model consists of three sequential phases, corresponding respectively to the pre-fire, fire and post-fire conditions. The pre-fire model, which is identical to the model for NCT determines the temperature profile in the package prior to the HAC fire transient. The post-fire transient phase is used to predict the maximum temperature of the components of the 9975 immediately after the fire has been extinguished. The post-fire steady state phase determines the final HAC temperatures.

Thermal models for the 9975 pre-fire, fire and post-fire HAC were developed with the FLUENT software. The models include interior metal surfaces, namely the aluminum base plates, aluminum spacers, stainless steel air shield and the cladding around the lead shielding. The limiting components of the package for the HAC are the containment vessel PCV/SCV O-ring seals. Temperature limits for components of the 9975 for the HAC are compared along with predicted maximum temperatures.

Thermal properties of the fiberboard during the HAC transient are given in Table 2. As indicated in the table, the fiberboard properties are effective properties to simulate the lumped effect of pyrolysis of fiberboard and the heat and mass transfer during the HAC fire event. The properties were determined by trial and error to match the temperatures observed during fire tests (Appendix 3.2, Reference [1]). Enhanced thermal properties essentially simulate heat and mass transfer of hot gases from the pyrolysis of fiberboard during fire into the virgin fiberboard. These properties are not applicable for the post-fire steady state conditions.

During the HAC transient, the ambient temperature was 1475ºF for the first 30 minutes and 100ºF thereafter. The initial condition for the HAC transient was identical to the steady-state NCT as mentioned previously. The results for the NCT are shown in Fig. 3. Table 3 shows maximum component temperatures along with their temperature limits. In the 30 minute fire phase, all sides of the drum (including the bottom) are heated by forced convection and radiation. The cooldown phase occurs immediately after the 30 minute fire. During this phase the drum is exposed to a 100ºF ambient temperature and insolation on the drum top and side (as in NCT) is included. During the cooldown phase, the bottom of the drum transfers heat to the ambient by radiation only. The top and sides of the drum transfer heat to the ambient via both radiation and natural convection. The entire HAC transient consists of the 30 minute fire plus 8 hours of cooldown. The results for the post-fire HAC transient are presented in Fig. 4. Summary of maximum component temperatures during HAC is shown in Table 4.

Table 1 Thermal Properties of Solid Packaging Materials

Metals	Density	Specific Heat	Thermal Conductivity
	(lbm/ft^3)	(Btu/lbm-°F)	(Btu/h-ft-°F)
Type 304 stainless steel	494.4	0.135	9.43
Aluminum	169.3	0.216	126.0
Aluminum Honeycomb	16.2	0.22	3.82 (radial) 7.62 (axial)
Aluminum spacer (6061-T6)	169.3	0.221	99.0
Kaowool blanket	6.0	0.26	0.0833
Lead	708.6	0.0315	19.6
Low-density Plutonium oxide (2.0 g/cc)	124.8	0.022	0.046

Table 2 Thermal Properties of Celotex Used in the NCT/HAC Thermal Analysis

Material	Density		Specific Heat		Thermal Conductivity	
	(ºF)	(lbm/ft^3)	(ºF)	(Btu/lbm-ºF)	(ºF)	(Btu/h-ft-ºF)
NCT – Celotex (radial)	77 187 295	16.87 17.36 17.86	77 187 295	0.306 0.360 0.417	all	0.0723
NCT – Celotex (axial)	77 187 295	16.87 17.36 17.86	77 187 295	0.306 0.360 0.417	77 187 295	0.031 0.034 0.036
HAC - Celotex (Fire)	80 475 810 1500	15.40 15.40 8.5 3.5	80 475 810 1500	0.25 0.50 0.50 0.50	80 170 200 210 500	0.035 0.450 0.550 0.090 0.070
HAC - Celotex (Charred)	all	8.1	all	0.250	100 140 200 300 500	0.07 0.07 1.0 0.30 0.07

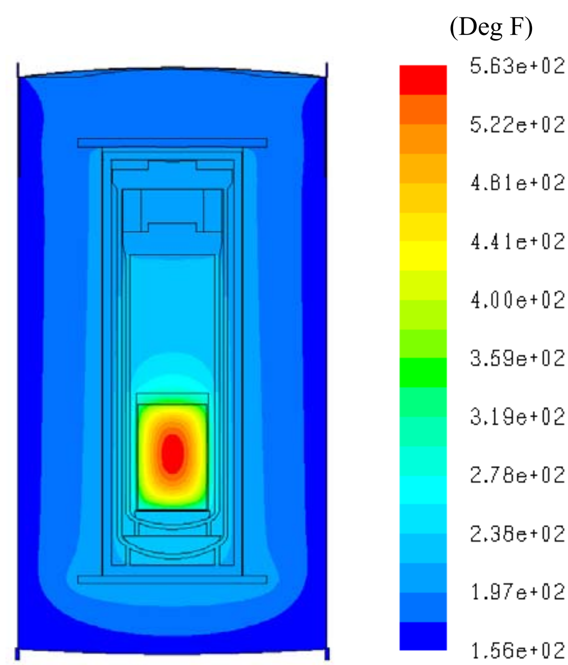

Figure 3: Temperature profiles for NCT

Table 3: Results for maximum component temperatures during NCT

Component	NCT solar (°F)	Temperature Limit (°F)
PCV	246	300
PCV O-rings	217	400
SCV	226	300
SCV O-rings	214	400
Insulation	215	250
Drum	191	800
Contents	563	NA
Shield	216	622
PCV Cavity (Average)	292	313

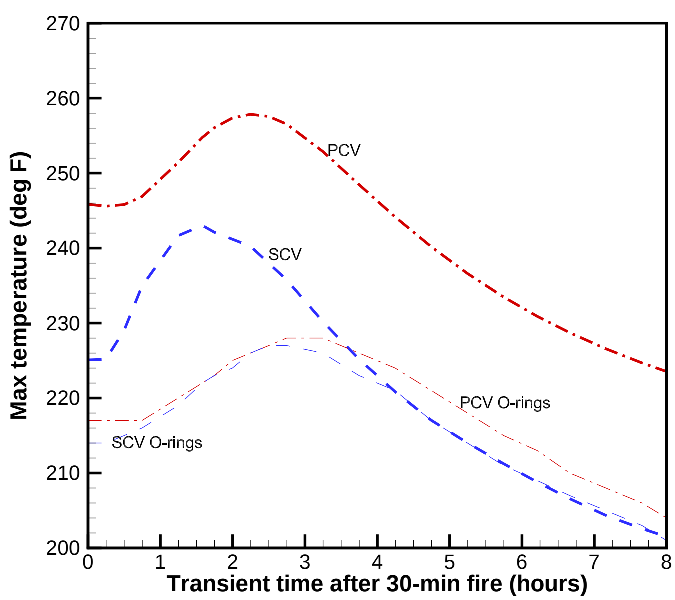

Figure 4: Transient component temperatures during post-fire

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Table 4: Summary of maximum component temperatures during HAC

Component	Fire/Post-fire (°F)	Temperature Limit (°F)
PCV/SCV	268	300
O-rings	239	400
Shield	239	662
Contents	580	N/A
Drum	1475	2650*
PCV Gas	312	313

* Drum limit based on the melting temperature of stainless steel; N/A – Not applicable.

SUMMARY

This work evaluated the thermal performance for 9975 package with food can configuration during Normal Conditions of Transport (NCT) and the Hypothetical Accident Conditions (HAC). The analysis results demonstrated that the maximum temperatures of the package components are below their design limits during NCT and HAC

REFERENCES

1. S-SARP-G-00003 Rev. 0, Safety Analysis Report for Packaging Model 9975 Type B(M)F-96, WSRC, (2008).
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